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Long Paper

Spatial Computing for Architecture and the Built Environment: Concepts, System Architectures, and Emerging Applications

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Abstract

Purpose – This work looks at spatial computing as a fast-developing area in architecture and design that puts digital information directly into the physical environment. It aims to make clear the concept, review existing research, and analyze the implications for design representation, collaboration, building operations, and urban planning.

Method – This study adopted a conceptual and systems-oriented research approach based on an integrative literature review conducted in accordance with the PRISMA 2020 reporting guideline. Peer-reviewed journal articles, conference papers, technical publications, and selected industry sources were systematically identified, screened, and synthesized to examine spatial computing concepts, enabling technologies, system architectures, workflow applications, and governance frameworks relevant to architecture and the built environment.

Results – The analysis indicates that spatial computing supports embodied visualization, shared spatial reference frames, digital twins, and real-time performance feedback across the built-environment lifecycle. These capabilities improve design communication, accelerate stakeholder collaboration, strengthen lifecycle continuity, and enable more adaptive and data-driven environments. However, technical challenges—including tracking accuracy, latency, and interoperability—as well as ethical concerns relating to privacy, surveillance, and digital inclusion require careful governance.

Conclusion – Spatial computing shifts human–computer interaction from screen-based interfaces to embodied spatial experiences. Its integration with artificial intelligence and digital twin technologies enables more responsive, context-aware, and adaptive built environments. Effective governance and human-centered design remain essential for its responsible adoption.

Recommendations – A hybrid edge-cloud architecture should be adopted by practitioners; interoperability standards should be prioritized, and safety and transparent user-centric design should be factored in. Researchers focusing on long-term objective evaluation, collaboration among multiple users, and ethical design frameworks are recommended.

Research Implications – This study contributes a conceptual framework that positions spatial computing as a socio-technical interaction infrastructure rather than a standalone technology, providing a foundation for future research in architecture and the built environment.

Practical Implications – Findings from this research will guide architects, engineers, and planners in bringing together immersive visualization, digital twins, and artificial intelligence into real workflows while managing the complexity of the integration, including cost, technical, and social risk factors.

Social Implications – The responsible deployment of spatial computing can improve involvement, multiple user access, and responsiveness of the environment in urban areas; if this is not properly governed, there will be a reinforcement of surveillance and digital inequality risk.

Keywords – Spatial computing, Digital twins, Architectural design, Immersive visualization, Built environment systems

INTRODUCTION

Spatial computing integrates the computational domain with the physical environment by embedding digital information into real-world spaces for interaction. Unlike flat screens, which are virtual and isolated, spatial computing lets three-dimensional digital objects, texts, and actions occupy real locations and interact with the physical world (Nokia, 2025). The environment becomes an interface, thereby shifting interaction from human–computer to human–world interaction.

Virtual reality is fully immersive, replacing the physical world with a simulated environment. In contrast, spatial computing overlays digital objects onto real-world spaces and allows those objects to respond to the actions of the user interacting with them. These digital elements may include text, audio, video, or even automated system responses. This two-way interaction enables the system to receive input through sensors such as cameras, depth sensors, and georeferenced detectors, while simultaneously delivering location-specific feedback to the user. The result is a situated, adaptive, and context-aware form of interaction that reduces the cognitive effort required to interpret abstract spatial information within physical environments (Nokia, 2025).

Recent advances in sensing hardware, spatial operating systems, cloud–edge infrastructures, and artificial intelligence have accelerated the practical relevance of spatial computing. Major technology firms are developing lightweight head-mounted displays, real-time mapping frameworks, spatial anchoring services, and special processors for low-power visual inference, signaling the emergence of persistent, multi-user spatial environments as a mainstream computing paradigm (Rice, 2022). These developments suggest that spatial computing should be understood not merely as a set of devices, but as a new interaction infrastructure.

Early discussions of the metaverse largely focused on fully digital and persistent virtual environments. More recent developments in spatial computing, however, emphasize the integration of digital content with the physical world, allowing users to remain engaged in everyday activities while still grounded in embodied experience. This shift is particularly important in architecture and urban design, where meaning is shaped by movement through space, spatial orientation, and material interaction. The integration of generative artificial intelligence into spatial systems further expands these possibilities by enabling contextual assistance, adaptive design workflows, and real-time spatial interpretation. Rather than replacing human decision-making, these technologies are increasingly positioned as tools for intelligence augmentation that support and refine human judgment (Yenduri et al., 2024).

Spatial computing sits at a crucial point where digital systems meet lived, three-dimensional human experience. By treating elements such as location, geometry, and bodily presence as central forms of data, it makes it possible to establish shared spatial reference frameworks that both people and machines can interpret, modify, and respond to. This capability is often described as the rise of a "spatial web," marking a meaningful shift in how information is organized, accessed, and used in real-world contexts (Yenduri et al., 2024).

For architecture and the broader built environment, these developments carry important conceptual and practical implications. Spatial computing allows designers to engage with spaces that do not yet exist as though they were already inhabited, creating a more continuous relationship between design intent and physical realization. It also shifts the understanding of buildings and cities from static objects to evolving, data-rich systems that can respond to changing conditions over time (Archinect, 2023). In practice, designers can explore unbuilt spaces through immersive simulations, evaluate performance under real-world conditions before construction, coordinate multidisciplinary teams using shared spatial models, and manage adaptive buildings or digital twins that respond to occupants and environmental changes (Archinect, 2023). Despite these possibilities, much of the existing literature remains fragmented, often focusing on isolated tools or individual applications rather than examining how spatial computing can be integrated across the full lifecycle of the built environment.

This paper responds to that gap by developing a conceptual and architectural synthesis of spatial computing for urban planning, design, and construction. Instead of presenting a deployed system or reporting on an empirical experiment, it proposes a unified framework that brings together sensing, computation, interaction, and governance as parts of a single spatial infrastructure. Through a structured examination of enabling technologies, system architectures, and their implications for professional workflows, the study illustrates how spatial computing is reshaping practices of representation, collaboration, and continuity across the lifecycle of the built environment.

LITERATURE REVIEW

This section brings together existing scholarship on spatial computing, focusing on its conceptual roots, enabling technologies, system architectures, emerging design approaches, and implications for the built environment. Instead of presenting spatial computing as a set of disconnected tools, much of the recent literature understands it as a new mode of interaction—one that links digital computation with embodied, three-dimensional human experience.

Spatial Computing as an Interaction Paradigm

Both early and more recent definitions of spatial computing highlight a shift toward treating physical environments as interactive computational surfaces. Rather than engaging with digital systems through abstract windows and menu-based interfaces, users encounter content that is anchored to real locations and behaves as part of the surrounding world (Nokia, 2025; Yenduri et al., 2024). This reorientation moves interaction away from a screen-centered model and toward what is often described as human–world interaction, in which meaning emerges through bodily movement, spatial awareness, and situated perception.

Yenduri et al. (2024) extend this line of thinking by describing spatial computing as a system in which location, geometry, and embodiment are treated as fundamental forms of data. From this perspective, digital objects are no longer simply visual representations; they become spatial entities that persist over time, respond to their surroundings, and interact with physical contexts. This view has been summarized as the emergence of a “spatial web,” pointing to a qualitative change in how information is organized and accessed, as illustrated in Figure 2.

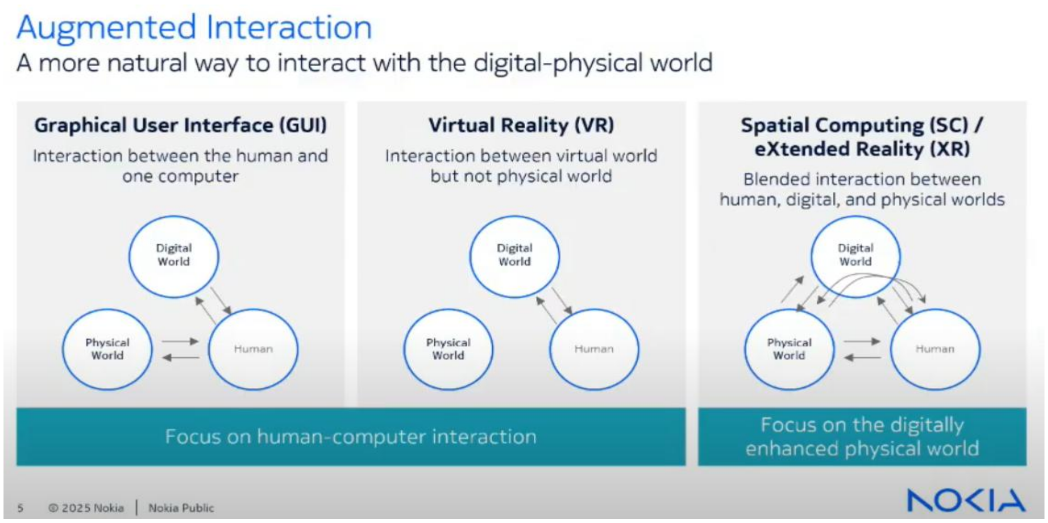

Figure 1. Augmented interaction: bidirectional feedback between physical perception and digital augmentation (Nokia, 2025).

From Virtual Worlds to Situated Augmentation

Much of the early work on the metaverse centered on persistent virtual worlds that users would inhabit in their entirety. More recent scholarship, however, draws a clear distinction between these approaches and spatial computing by emphasizing augmentation rather than the replacement of reality (Nokia, 2025). Instead of shifting experience into a wholly digital domain, spatial computing extends perception by embedding digital information within everyday physical settings.

This distinction is particularly significant for architecture, where understanding develops through bodily movement and spatial engagement. Abstract representations often struggle to convey experiential qualities such as enclosure, rhythm, or spatial compression. Spatial interfaces, by contrast, make these qualities perceptible in more direct ways, reducing the amount of cognitive translation required by traditional media (Archinect, 2023).

Enabling Technologies as Infrastructural Components

The literature commonly points to sensing, computation, and interaction devices as the core components of spatial computing systems. More recent work, however, suggests that these technologies should not be seen as isolated tools. Instead, they are better understood as interconnected infrastructural layers that together support situated and context-aware digital experiences (Fuller et al., 2020; Yenduri et al., 2024).

Sensors and Spatial Capture

Sensors such as RGB-D cameras, LiDAR scanners, inertial measurement units, and satellite-based positioning systems make it possible to translate physical environments into digital geometry. Almukhtar et al. (2021) reviewed terrestrial laser scanning (TLS) and reality capture techniques and discuss the strengths and limitations of different sensing technologies. Although they focus primarily on 3D laser scanners, they acknowledge complementary technologies and the need to select sensing approaches based on application requirements. Together, these sensing systems—covering a range of parameters listed in Table 1—allow space itself to be treated as computable, forming the foundation for processes such as mapping, alignment, and spatial reasoning.

Table 1. Categories of Parameters Used in Architecture, Design and Environmental Analysis

S/N	Category	Explanation	Common Parameters and Indicators
1	Geometric and Physical Parameters	These parameters describe the basic physical configuration of a space. They shape how large, enclosed, or visually balanced a space feels and determine its basic capacity and usability.	Dimensions and size (length, width, height), proportion (relationships between dimensions), shape and form (rectilinear, curved, irregular), and degree of boundary or enclosure (open, semi-enclosed, fully enclosed).
2	Relational and Topological Parameters	These parameters define how spaces relate to one another and how people perceive and move between them. They influence orientation, legibility, and functional efficiency.	Adjacency and proximity between spaces, spatial hierarchy (primary vs. secondary spaces), accessibility (ramps, door widths, circulation clearances), and visibility or sightlines across spaces.
3	Functional and Behavioural Parameters	These parameters reflect how spaces are used in practice. They describe patterns of movement, occupation, and change over time.	Circulation paths and flow patterns, zoning (public/private, noisy/quiet), density or occupancy levels, and flexibility or adaptability for future reconfiguration.
4	Environmental and Sensorial Parameters	These parameters capture how a space is experienced through the senses. They affect comfort, mood, and overall spatial quality.	Light exposure (natural and artificial), relationship to external views and surroundings, thermal, acoustic, and air-quality comfort, and atmospheric qualities such as material,

			colour, texture, and reverberation.
5	Anthropometric Parameters	These parameters relate architectural design directly to the human body. They ensure that spaces are comfortable, safe, and supportive of everyday activities.	Human scale, reach and movement ranges, ergonomic fit for specific tasks, and clearances for sitting, standing, walking, and working.
6	Spatial and Topographical Parameters (Physical Layout)	These parameters describe the physical form, structure, and spatial configuration of a landscape or object. They are fundamental for understanding terrain behaviour, visibility, accessibility, and spatial relationships.	Elevation (Digital Elevation Model – DEM), slope (degree of steepness), aspect (direction a slope faces), surface roughness or texture, proximity to features such as roads, rivers, or coastlines, shape and form (area, perimeter, roundness), and connectivity patterns such as stream networks or road networks.
7	Environmental and Climatic Parameters	These parameters reflect the atmospheric and environmental conditions that influence comfort, energy flows, and ecological stability. They are particularly important for climate-sensitive design and sustainability studies.	Air temperature (seasonal or daily), relative humidity, solar radiation or sunshine duration, wind speed and direction, precipitation levels, land surface temperature (LST), and air quality index (AQI), including pollutants such as NO_2, CO, SO_2, and ozone.
8	Hydrological and Soil Parameters	These parameters describe the availability, movement, and quality of water resources as well as soil properties that affect land stability, vegetation, and agricultural productivity.	Groundwater depth, water quality indicators such as pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, nutrient concentrations (e.g., nitrate and phosphorus), soil texture and organic matter content, salinity, and water flow velocity in rivers or streams.

9	Built Environment and Urban Parameters	These parameters capture human-made features and settlement patterns that shape urban form, density, and functionality. They are essential for urban planning, infrastructure management, and spatial policy decisions.	Land use and land cover (LULC) classes, building height, building coverage ratio (BCR), population density, vegetation cover measured using ambient noise levels, especially near transport corridors.
10	Biological and Ecological Parameters	These parameters describe the health and composition of ecosystems and biological productivity. They are commonly used in biodiversity assessments and environmental impact studies.	Biodiversity indices, flora and fauna density, vegetation types, and chlorophyll concentration (especially in aquatic environments).

Interaction Devices and Embodied Interfaces

Head-mounted displays, handheld augmented reality devices, and gesture-based input systems form the main interfaces through which people interact with spatial computing environments. The literature, however, makes it clear that immersion on its own is not enough; effective spatial interaction must also be supported by appropriate governance, usability considerations, and sustainable implementation strategies (Deng et al., 2021). Forms of embodied interaction—such as walking, pointing, or gesturing—anchor digital content in physical movement, supporting processes of spatial sensemaking and improving the integration of digital information with physical environments (Wang et al., 2025).

Spatial Computing as a System Architecture

Recent scholarship increasingly frames spatial computing not as a category of devices, but as a distributed system that integrates sensing, communication, analytics, and operational feedback across multiple computational layers (Fuller et al., 2020; Yenduri et al., 2024; Wang et al., 2025). In this view, cloud platforms support functions such as persistent data storage, large-scale analytics, and system-wide coordination, while edge devices manage latency-sensitive tasks like tracking and real-time rendering (Yenduri et al., 2024). This architectural perspective helps clarify how spatial computing reshapes workflows across different scales and time horizons, enabling continuous feedback between design, construction, and operation, as illustrated in Figure 10.

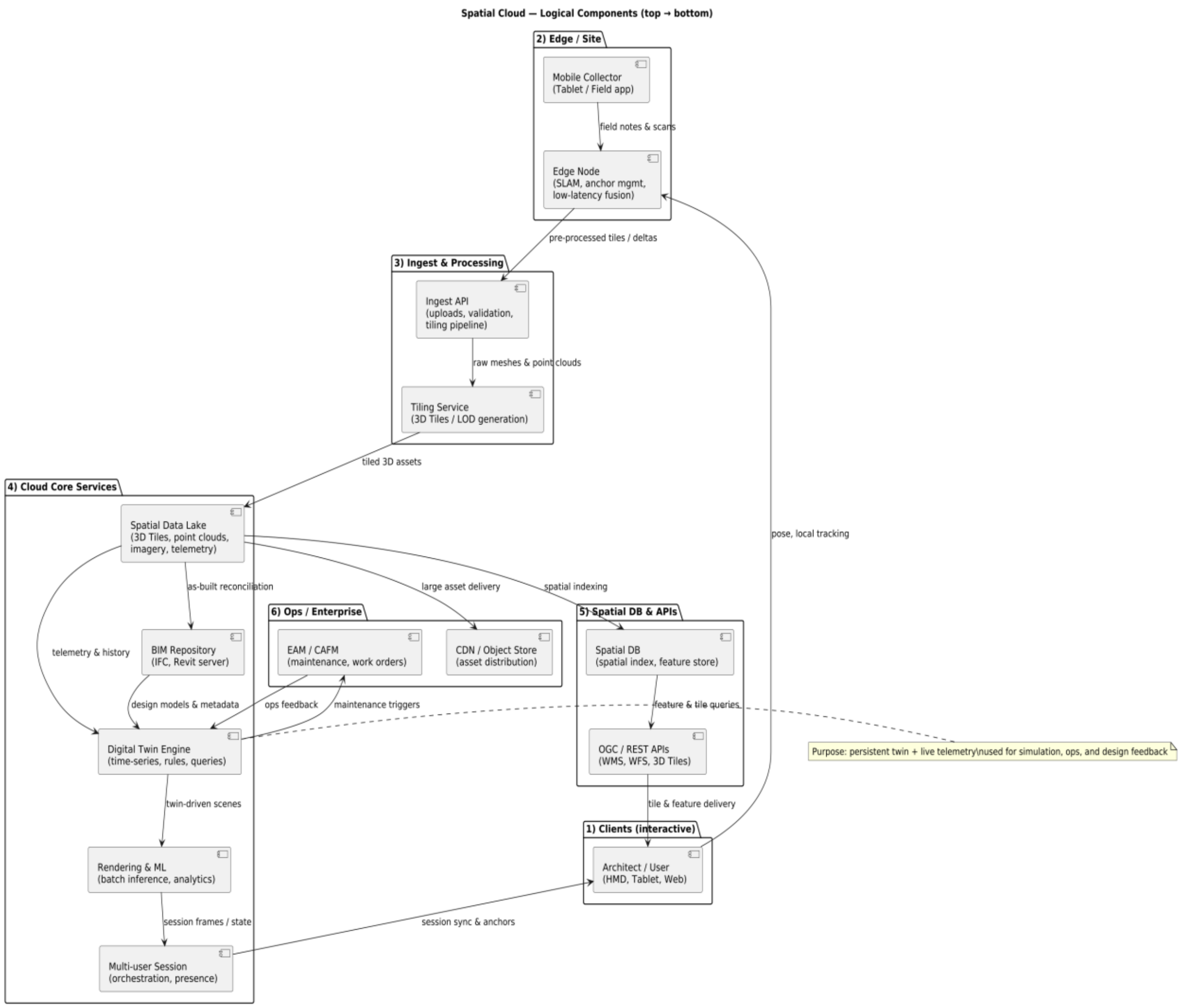

Figure 2. Conceptual Spatial Cloud Architecture

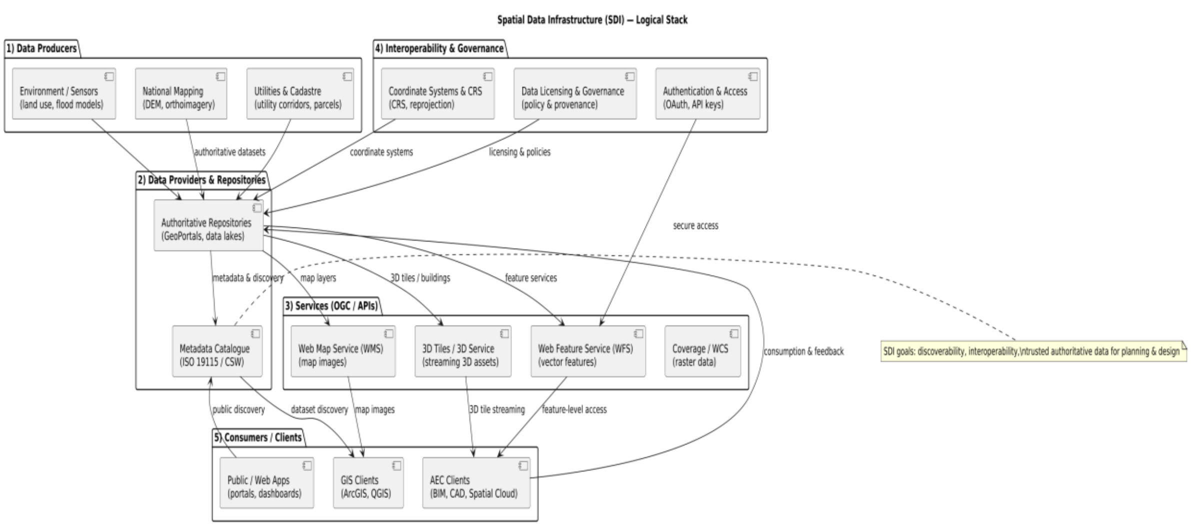

Figure 3. Conceptual Spatial Data Infrastructure

The Spatial Computing Spectrum

The literature often describes spatial computing as a continuum that ranges from fully virtual environments to hybrid overlays and, at the other end, persistent, city-scale digital twins. Each position along this spectrum comes with its own requirements in terms of latency, visual fidelity, and governance (Yenduri et al., 2024; Archinect, 2023). Seen this way, spatial computing is not a single mode of interaction, but a family of approaches adapted to different use cases and contexts, as illustrated in Figure 4.

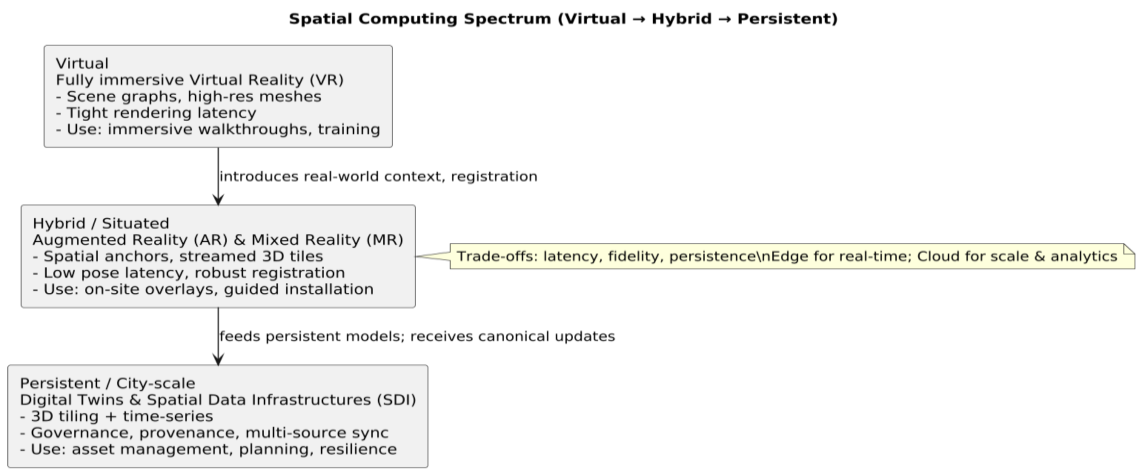

Figure 4. The Spatial Computing Spectrum

Spatial Computing in Architectural Design

Generative design, immersive visualization, and digital twins are commonly identified as three major architectural paradigms made possible by spatial computing. Recent studies suggest that the convergence of BIM and digital twin technologies is transforming asset management and lifecycle decision-making in the built environment (Lu et al., 2020; Omrany et al., 2023). Rather than replacing designers, these systems tend to broaden the range of possible solutions and make underlying trade-offs more visible (Archinect, 2023; Omrany et al., 2023). Across the literature, there is a consistent emphasis on the idea that such tools are most effective when they are used alongside human judgment, cultural understanding, and ethical reflection.

Ethical, Social, and Governance Concerns

Persistent forms of spatial sensing introduce concerns around surveillance, data ownership, and the risk of social exclusion. Deng et al. (2021) and Nica et al. (2023) argue that spatial systems therefore need to embed governance mechanisms, consent protocols, and transparency into their core design. From this perspective, ethics is no longer treated as an external constraint, but as a structural and architectural feature of spatial computing systems themselves.

Identified Gaps

Despite the rapid pace of development, much of the existing literature still approaches spatial computing as a set of discrete applications rather than as a coherent infrastructure. Relatively little work brings together sensing, computation, interaction, and governance within a single, unified framework for the built environment. This paper responds to that gap by proposing a system-level conceptual model that integrates these components across the full architectural lifecycle.

METHODOLOGY

This study adopts a conceptual, systems-oriented research methodology to examine how spatial computing can be integrated into architectural and urban design workflows. Rather than evaluating a deployed system or conducting controlled experiments, the study focuses on conceptual synthesis, system decomposition, workflow analysis, and scenario-based interpretation. This approach was selected because spatial computing functions less as a standalone technology and more as a socio-technical interaction infrastructure that reshapes how spatial information is generated, interpreted, shared, and acted upon within the built environment (Yenduri et al., 2024; Nokia, 2025; Deng et al., 2021).

The methodological framework combined an integrative literature review with qualitative analytical synthesis. The review process focused on identifying recurring concepts, architectures, workflows, and governance concerns associated with spatial computing in architecture, urban systems, digital twins, immersive visualization, and intelligent built environments.

To improve the transparency and reproducibility of the review process, this study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) reporting guideline. Although this research is conceptual rather than a statistical meta-analysis, the PRISMA framework was adopted to guide the systematic identification, screening, eligibility assessment, and inclusion of relevant literature. This ensured that the review process was conducted in a structured, transparent, and reproducible manner.

The methodological process was organized into four stages:

1. Conceptual abstraction,
2. Architectural decomposition,
3. Workflow mapping, and
4. Scenario-based synthesis.

Literature Search Strategy and Review Protocol

Following the PRISMA 2020 reporting guideline (Page et al., 2021), the literature review drew from peer-reviewed journal articles, conference papers, technical reports, industry publications, and standards-related documentation published primarily between 2020 and 2025. A limited number of earlier foundational studies were also included where they provided seminal contributions to spatial computing, Building Information Modeling (BIM), digital twins, and augmented reality in the built environment.

Literature was identified through systematic searches of Google Scholar, IEEE Xplore, ScienceDirect, SpringerLink, and MDPI. Additional sources were identified through citation searching and selected authoritative industry websites, including Nokia, NVIDIA, Archinect, and Digital Twin Insider, to provide contemporary definitions, technological developments, and industry perspectives relevant to spatial computing.

The literature identification and selection process is summarized in Figure 5 using the PRISMA 2020 flow diagram. Figure 5 illustrates the systematic literature identification, duplicate removal, screening, eligibility assessment, and final study selection process undertaken in accordance with the PRISMA 2020 reporting guideline. The studies retained through this process formed the basis of the qualitative synthesis presented in this paper.

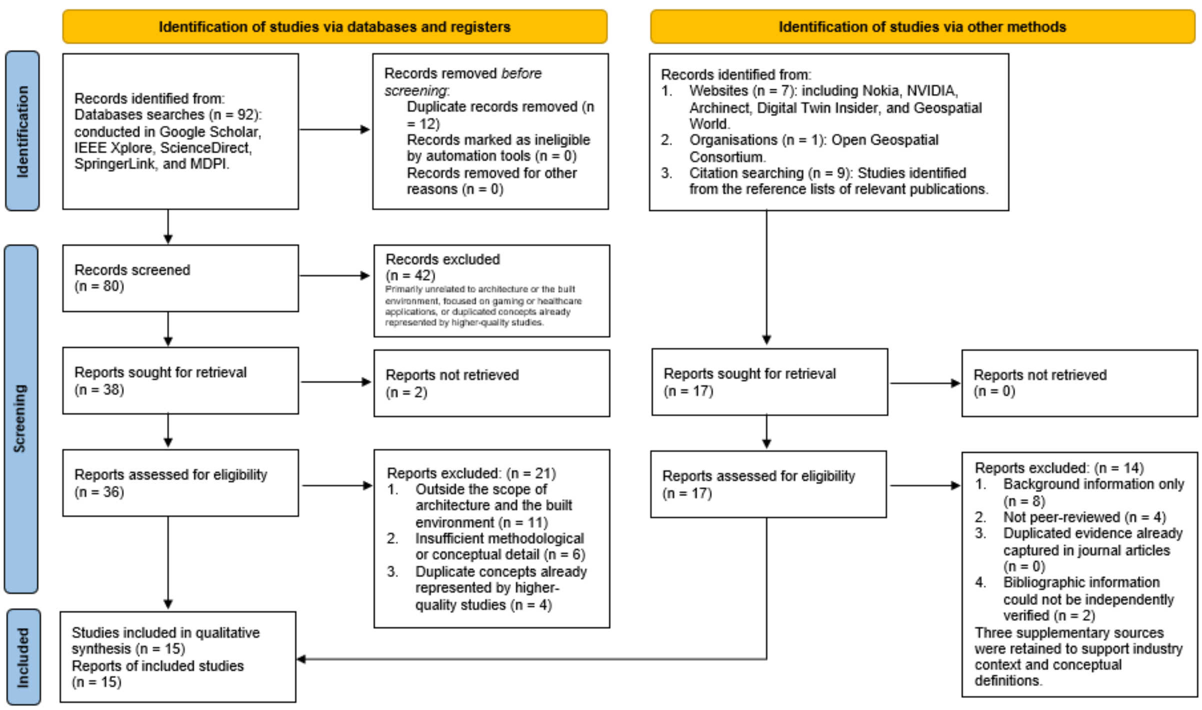

Figure 5. PRISMA 2020 flow diagram illustrating the literature identification, screening, eligibility assessment, and study selection process adopted in this study.

Search terms included combinations of:

- “Spatial computing,”
- “Digital twins,”
- “Architecture and immersive systems,”
- “Built environment analytics,”

- "Augmented reality in architecture,"
- "Spatial data infrastructure," and
- "Human-centered spatial interaction."

The inclusion criteria focused on studies that:

1. Addressed spatial computing or digital twin systems,
2. Examined architectural, urban, or built-environment applications,
3. Discussed sensing, interaction, system architecture, or governance frameworks, and
4. Provided conceptual, technical, or workflow-oriented insights relevant to spatial environments.

The exclusion criteria removed studies that:

1. Focused exclusively on gaming or entertainment applications,
2. Lacked relevance to spatial or built-environment systems,
3. Contained insufficient methodological or conceptual detail, or
4. Repeated concepts already represented in higher-quality sources.

Selected sources were reviewed iteratively and grouped according to recurring themes, technologies, workflows, and governance concerns.

Conceptual Abstraction

The first analytical stage focused on abstracting spatial computing away from individual tools or commercial platforms and reframing it as a broader interaction paradigm. Existing definitions describing spatial computing as an environment-centered interface were synthesized to establish a unified conceptual foundation (Nokia, 2025).

This abstraction step was necessary to avoid reducing spatial computing to specific devices such as head-mounted displays or augmented reality applications. Instead, the analysis positioned spatial computing as a design and interaction logic applicable across multiple platforms, workflows, and scales.

Architectural Decomposition

The second stage involved decomposing spatial computing into a layered system architecture to clarify how information flows between sensing, computation, storage, interaction, and operational control systems (Fuller et al., 2020; Wang et al., 2025).

Five conceptual layers were identified:

1. Sensing and capture,
2. Edge and ingestion,
3. Cloud and core services,
4. Interaction and presentation, and

5. Operations and actuation.

This decomposition enabled the study to examine how latency-sensitive operations occur near the user while persistent analytics, synchronization, and coordination functions are managed through cloud-based infrastructures.

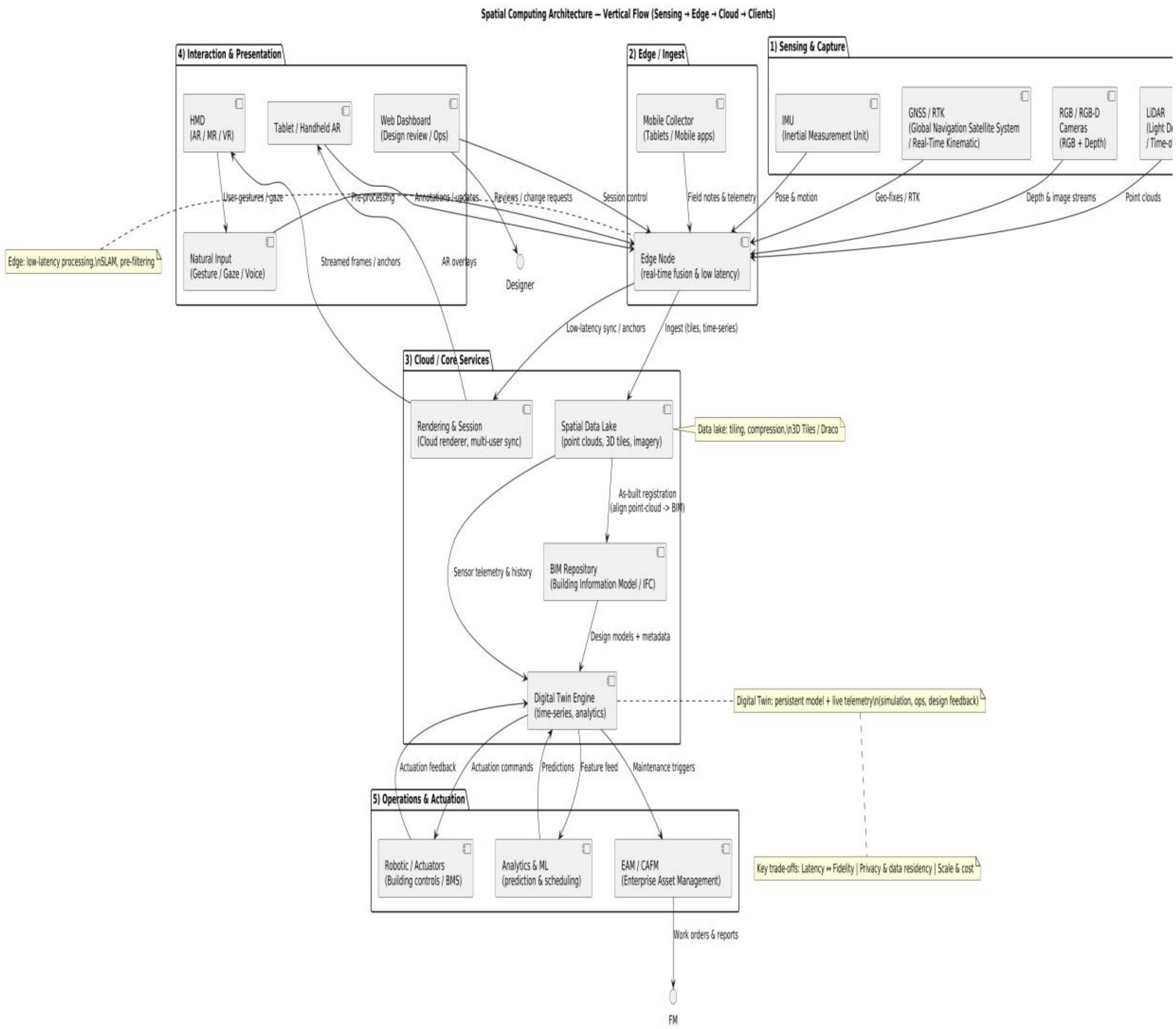

Figure 6. Conceptual *spatial computing architecture for the built environment*

Table 2. Conceptual Layers of a Spatial Computing System

S/N	Layer	Primary Function	Architectural Role
1	Sensing	Capture geometry & context	Reality digitization
2	Edge	Low-latency processing	Real-time interaction
3	Cloud	Persistence & analytics	Long-term reasoning
4	Interface	Human engagement	Embodied sensemaking
5	Operations	Feedback & control	Lifecycle continuity

Workflow Mapping

The third stage mapped spatial computing capabilities onto key architectural and urban-design workflows identified in the literature. The purpose was not to measure workflow performance quantitatively, but to analyze how spatial computing alters representation, coordination, and lifecycle continuity across different design contexts.

Four recurring workflows were selected due to their frequency and relevance in the reviewed literature:

1. As-built capture and Building Information Modeling reconciliation,
2. Immersive visualization and stakeholder communication,
3. On-site augmented guidance and construction support, and
4. Digital twin–based planning and operations.

Each workflow was examined using four analytical dimensions:

- Representation and spatial understanding,
- Collaboration and coordination,
- Temporal continuity across lifecycle stages, and
- Human-centered usability and cognitive load.

These dimensions functioned as qualitative evaluation criteria for comparing conventional digital workflows with spatially enabled workflows.

Scenario-Based Synthesis and Analytical Interpretation

The final stage employed scenario-based reasoning to interpret how different stakeholders—including architects, planners, engineers, contractors, and facility managers—might interact with spatial systems under realistic operational conditions.

Scenario construction was guided by recurring workflow situations identified in the literature, such as:

- immersive client walkthroughs,
- real-time construction overlays,
- digital twin monitoring, and
- adaptive building control.

Rather than predicting exact outcomes, the scenarios were used analytically to identify:

1. System affordances,
2. Coordination constraints,
3. Governance implications,
4. Human-centered interaction challenges, and
5. Operational dependencies.

The analytical process followed a thematic synthesis approach in which recurring patterns, relationships, and infrastructural dependencies were identified across reviewed sources. This improved methodological transparency and strengthened replicability by clearly defining how concepts were selected, grouped, and interpreted throughout the study.

ANALYTICAL SYNTHESIS OF FINDINGS

This section brings together insights from the reviewed literature, the proposed system architectures, and the workflow analyses. In doing so, it consolidates the conceptual findings that emerge when spatial computing is understood as an integrated socio-technical framework and clarifies what this perspective enables within architectural and urban design contexts.

The synthesis is structured around four core domains: (1) representation and perception, (2) decision-making and collaboration, (3) lifecycle continuity, and (4) governance and human-centered constraints.

Spatial Representation as an Embodied Medium

One of the central conceptual contributions of spatial computing lies in how it reshapes representation. Traditional architectural media—such as drawings, renderings, and screen-based models—require users to mentally convert two-dimensional abstractions into three-dimensional spatial understanding. Spatial computing reduces this cognitive gap by placing digital content directly within physical space, allowing it to be perceived in relation to the body and its surroundings (Nokia, 2025; Yenduri et al., 2024).

This shift reframes architectural models from descriptive artifacts into situated experiences. Instead of merely observing a representation of space, users come to inhabit it. As a result, qualities such as scale, circulation, and enclosure can be evaluated perceptually and in context—something that static media alone cannot fully support (Delgado et al., 2020).

Table 3. Conceptual Comparison of Representation Modalities.

S/N	Modality	Interaction Style	Cognitive Load	Spatial Fidelity	Context Awareness
1	2D Drawings	Abstract	High	Low	None
2	3D Renders	Visual	Medium	Medium	Low
3	Virtual Reality	Immersive	Medium	High	None
4	Augmented Reality	Situated	Low	High	High
5	Spatial Computing	Embodied	Lowest	Highest	Highest

Shared Spatial Reference Frames and Collaborative Sensemaking

A second major conceptual insight concerns how spatial computing reshapes collaboration and shared understanding. Conventional digital workflows often rely on symbolic references—such as layer names, coordinates, or textual annotations—that require additional interpretation before meaning can be fully understood. Spatial computing reduces this level of abstraction by introducing shared spatial reference frames, allowing multiple stakeholders to perceive and interact with the same anchored digital content within a common physical or virtual environment (Archinect, 2023; Yenduri et al., 2024). As a result, design discussions become less dependent on abstract negotiation and more grounded in embodied exploration. Participants can point, move, gesture, and annotate directly within space itself, reducing interpretive ambiguity and supporting clearer, more immediate collaboration.

Continuity Across the Built Environment Lifecycle

A recurring limitation of conventional architectural workflows is their tendency toward fragmentation, with early design, construction, and operation often treated as separate and loosely connected phases. Spatial computing offers a conceptual alternative by supporting lifecycle continuity through persistent spatial models that evolve from initial conception through to occupation and use (Omrany et al., 2023; Abdelrahman et al., 2025).

Within this framing, digital twins are no longer understood as static replicas. Instead, they function as dynamic, semantically rich representations that integrate geometry, behavior, and operational information throughout the building lifecycle (Boje et al., 2020; Abdelrahman et al., 2025). This form of continuity makes it possible for design intent to remain visible during construction, for as-built conditions to feed back into ongoing planning, and for operational data to inform future design decisions (Al-Sehrawy et al., 2021).

Table 4. Lifecycle Integration Enabled by Spatial Computing.

S/N	Phase	Traditional Workflow	Spatial Computing Framework
1	Design	Isolated	Linked to future operation
2	Construction	Document-based	Situated overlays
3	Operation	Sensor dashboards	Spatial twins
4	Renovation	Manual surveys	Continuous models

Human-Centered Constraints as System Requirements

The synthesis also underscores that spatial computing is not only a technical system, but a fundamentally human-centered one. If poorly designed, immersive environments can overwhelm perception, contribute to fatigue, or even obscure physical hazards. For this reason, concerns such as ergonomics, legibility, and safety need to be treated as core system constraints rather than as secondary considerations (Deng et al., 2021; Nica et al., 2023).

Key conceptual constraints identified in the literature include:

1. Visual occlusion limits,
2. Cognitive load thresholds,
3. Social co-presence,
4. Privacy boundaries, and
5. Fallback interaction modes,

Taken together, these constraints reframe interface design as a form of architectural practice. Spatial interfaces must be composed of the same level of care, intentionality, and responsibility as physical spaces.

From Tools to Infrastructures

The final synthesis is that spatial computing should not be understood as a single device or isolated application, but as an infrastructure. Much like Building Information Modeling, it reshapes workflows, redistributes professional roles, and alters expectations about how spatial information is produced, shared, and maintained.

From this infrastructural perspective, successful adoption depends on several conditions:

1. Interoperability standards,
2. Effective coordination between edge and cloud systems,
3. Governance models, and
4. Institutional alignment.

Without these elements in place, spatial computing is likely to remain a technological novelty rather than developing into a stable and durable professional platform (Opoku et al., 2023; Lu et al., 2020).

Summary of Analytical Findings

Conceptually, spatial computing enables several interrelated capacities:

1. Embodied spatial reasoning,
2. Shared spatial cognition,
3. Lifecycle continuity,
4. Human-centered digital environments, and
5. Infrastructure-level integration.

Taken together, these do not represent incremental improvements to existing practices. Rather, they point to structural shifts in how architectural knowledge is generated, shared, and acted upon.

DISCUSSION

This paper sets out to develop a conceptual and architectural synthesis of spatial computing for the built environment, rather than to evaluate a specific deployed system or report empirical measurements. The preceding analysis has shown how spatial computing reshapes key dimensions of architectural practice, including representation, collaboration, lifecycle continuity, and governance. This section interprets those findings in relation to existing scholarship and considers their implications for theory, design methodology, and professional practice.

Spatial Computing as a Paradigm Shift in Representation

One of the central implications of this study is that spatial computing should be understood not as a modest improvement in visualization, but as a more fundamental shift in how architectural space is represented and reasoned about. Traditional media—such as plans, sections, renderings, and even conventional 3D models—require users to translate between abstract representations and lived, embodied experience. This process of translation often introduces ambiguity, misinterpretation, and, in many cases, late-stage design revisions.

The literature suggests that spatial computing reduces this representational gap by embedding digital models directly within spatial experience itself (Nokia, 2025; Yenduri et al., 2024). The analytical synthesis developed in this paper supports this view, indicating that spatial interfaces operate less as depictions of space and more as extensions of it. This reframing resonates with phenomenological traditions in architecture, which place embodied perception at the center of spatial understanding.

From Collaboration to Co-Presence

A second major point of discussion concerns collaboration. Much of the existing literature on digital collaboration in architecture concentrates on mechanisms such as file sharing, version control, and asynchronous communication. Spatial computing, however, introduces a qualitatively different mode of engagement: co-presence.

By establishing shared spatial reference frames, spatial systems allow multiple stakeholders to perceive, annotate, and manipulate the same spatial elements at the same time. Instead of coordinating through abstract symbols or detached representations, teams coordinate through situated action within a common spatial context (Archinect, 2023; Yenduri et al., 2024). This shift has implications not only for efficiency, but also for the dynamics of participation and authority in design conversations, as spatial interfaces can broaden access to understanding and reduce expert–novice asymmetries.

This perspective also helps explain why immersive walkthroughs and situated overlays often feel more intuitive to non-experts than traditional drawings or parametric interfaces.

Lifecycle Thinking and Persistent Spatial Models

The synthesis also reframes buildings as persistent information systems rather than as static artifacts. Recent work on digital twins increasingly emphasizes that spatial models should evolve, incorporating sensor feedback, patterns of occupancy, and performance data while maintaining semantic links between physical assets and their digital counterparts (Boje et al., 2020; Digital Twin Insider, 2023b; Omrany et al., 2023; Abdelrahman et al., 2025).

What this paper contributes is a conceptual unification of these ideas. It suggests that spatial computing enables continuity not simply through the accumulation of data, but through spatial legibility. Designers, operators, and occupants engage with the same underlying model, but at different moments and through different interfaces, allowing meaning and intent to remain interpretable across time.

Human-Centered Constraints as Architectural Requirements

A key theoretical contribution of this paper lies in its treatment of ethics, cognition, and ergonomics as architectural requirements rather than as secondary considerations. Much of the technology-oriented literature tends to frame these issues as constraints or limitations to be managed. By contrast, the framework developed here treats them as core design parameters that actively shape how spatial systems should be conceived.

This perspective aligns with Deng et al. (2021), who emphasize that digital twin cities require robust governance frameworks, effective data management, and institutional coordination to ensure responsible implementation. Interfaces that compromise privacy, lack transparency, or fail to incorporate appropriate governance mechanisms ultimately undermine user trust and the long-term adoption of spatial computing systems (Deng et al., 2021).

Together, these insights suggest that the future of spatial computing may depend less on technical novelty and more on compositional restraint—on designing systems that are not only powerful, but also intelligible, humane, and responsibly integrated into everyday life.

Why Infrastructure Matters More Than Tools

Another important point of discussion concerns scale and durability. Many spatial computing initiatives struggle to move beyond pilot stages because they are conceived primarily as tools rather than as infrastructures. When systems are designed in this way, they tend to remain localized, fragile, and difficult to sustain over time (Opoku et al., 2023).

The framework developed in this paper emphasizes that lasting impact depends on several interrelated conditions:

1. Interoperability,
2. Shared standards,
3. Robust governance, and
4. Institutional integration.

Without these foundations, spatial computing is likely to remain fragmented and vulnerable to obsolescence, rather than developing into a stable and enduring professional platform (Open Geospatial Consortium, 2022).

Limitations of This Study

This paper is intentionally conceptual in scope and therefore does not offer empirical validation. While this allows for broader theoretical generalization, it also limits the extent to which claims can be made about real-world performance, patterns of adoption, and cost structures.

Future research could address these limitations by testing specific aspects of the framework through longitudinal field studies, participatory design experiments, and policy-oriented analyses.

Summary

This discussion positions spatial computing as a paradigmatic shift in how the built environment is conceived, represented, and governed. Its central contribution lies not in the introduction of another tool, but in a new way of organizing spatial knowledge, coordinating action, and structuring professional practice.

CONCLUSIONS AND RECOMMENDATIONS

This paper has developed a conceptual synthesis of spatial computing as an emerging interaction infrastructure for architecture, construction, and urban design. Rather than approaching spatial computing as a collection of isolated tools—such as head-mounted displays, digital twins, or augmented reality applications—it reframes it as a systemic transformation in how spatial information is represented, shared, and acted upon. By bringing together sensing, computation, interaction, and governance within a unified framework, the study clarifies how spatial computing reshapes architectural workflows across the full lifecycle of the built environment.

The central conclusion is that spatial computing introduces a qualitative shift in spatial representation. Instead of asking users to translate abstract symbols into mental models of space, spatial interfaces allow digital content to be encountered as part of the physical environment itself. This movement from symbolic to embodied interaction fundamentally alters how designers, clients, and operators reason about scale, enclosure, circulation, and performance. The literature suggests that this experiential mode of representation reduces ambiguity, supports shared understanding, and enables more informed forms of decision-making.

Second, spatial computing enables new forms of collaboration grounded in shared spatial reference frames. When digital objects are anchored to physical or virtual locations, coordination becomes situated rather than abstract. This has important implications for participatory design, interdisciplinary teamwork, and client engagement. Instead of negotiating meaning through drawings, layers, and annotations, stakeholders can interact directly with the same spatial entities. This supports co-presence, reduces misinterpretation, and fosters more immediate forms of shared understanding.

Third, the framework developed in this paper highlights the role of spatial computing in supporting lifecycle continuity. Conventional architectural workflows remain highly fragmented, with limited feedback between design, construction, and operation. Persistent spatial models—often described as digital twins—make it possible for built environments to be continuously updated, monitored, and reinterpreted over time. This form of continuity supports adaptive planning, predictive maintenance, and long-term resilience, aligning with recent work on smart buildings and urban analytics.

Finally, the study emphasizes that spatial computing is not merely a technical innovation, but a socio-technical infrastructure. Its success depends not only on sensing accuracy or rendering fidelity, but also on ethical legibility, cognitive sustainability, and institutional governance. Issues such as privacy, consent, accessibility, and safety must therefore be treated as architectural requirements rather than as external constraints. Without these considerations, spatial systems risk becoming intrusive, exclusionary, or unsafe.

Design-Oriented Recommendations

Based on the conceptual synthesis developed in this paper, spatial computing systems should prioritize embodied legibility over visual complexity. Spatial interfaces are most effective when they support intuitive spatial understanding rather than overwhelming users with excessive overlays or information density.

Design strategies such as clear visual hierarchy, appropriate contrast, and minimal interface clutter can improve usability and safety. In addition, spatial computing should be approached as a long-term infrastructure rather than as a collection of isolated devices. Sustainable value depends on interoperability, institutional integration, and continuity of data across the project lifecycle.

Ethical considerations, including privacy, consent, explainability, and accessibility, should be embedded directly into system architecture from the earliest stages of design.

Furthermore, hybrid interaction models that allow users to move seamlessly between immersive, augmented, and conventional interfaces should be encouraged to accommodate varying task requirements and user preferences.

Finally, spatial models should be treated as living assets that persist beyond design, supporting construction, operation, maintenance, and future adaptation of the built environment.

Policy and Institutional Recommendations

The findings of this study suggest that public agencies, professional bodies, and standards organizations have an important role to play in guiding the responsible adoption of spatial computing technologies.

Clear spatial data governance frameworks should be established to define ownership, access rights, security requirements, and data-retention policies. Greater support for open standards and interoperable data formats is also needed to facilitate collaboration across platforms and disciplines.

Capacity-building initiatives should be promoted to reduce disparities in access to spatial computing tools and expertise, particularly within developing regions and under-resourced institutions. In addition, ethical guidelines governing the use of spatial sensing technologies in public and semi-public environments should be developed to address concerns related to privacy, surveillance, transparency, and public trust.

Directions for Future Research

As a conceptual study, this paper opens several opportunities for future empirical and applied research. Longitudinal investigations are needed to examine how spatial computing technologies are adopted, integrated, and sustained within architectural and construction organizations over time.

Comparative studies evaluating immersive and conventional design workflows would provide valuable evidence regarding their relative effectiveness in supporting design communication and decision-making. Additional research is also needed to explore spatial data governance in smart-city environments, particularly in relation to privacy, accountability, and public participation.

Furthermore, participatory studies involving diverse user groups could help improve the accessibility, inclusiveness, and human-centered design of spatial interfaces. Such investigations would contribute to validating and refining the conceptual framework proposed in this study while supporting its practical application across different professional and cultural contexts.

Concluding Statement

Spatial computing expands the architect's conceptual vocabulary. It allows designers to think about unbuilt spaces as if they were already inhabited, supports continuous feedback between digital intent and physical reality, and reframes buildings and cities as adaptive, data-rich systems. When used responsibly, it has the potential to make design processes more transparent, participatory, and environmentally responsive.

Yet its long-term success will depend less on technological novelty than on how thoughtfully it is integrated into professional, institutional, and civic practices. The challenge, then, is not only technical but also cultural: to design spatial systems that enhance human judgment, respect social values, and remain legible to the people who ultimately live within them.

IMPLICATIONS

This section considers the broader implications of the conceptual framework developed in this paper for architectural theory, professional practice, education, urban governance, and research at the intersection of spatial computing and artificial intelligence. These implications are drawn analytically from the synthesis presented in the preceding sections and are intended to inform future adoption, policy development, and scholarly inquiry.

Implications for Architectural Theory

Spatial computing challenges long-standing assumptions about how space is represented and understood in architectural theory. Traditionally, design thinking has relied on symbolic abstractions—plans, sections, and diagrams—as the primary means of reasoning about spatial form. The framework developed in this paper points toward a different model, one based on embodied representation, where spatial understanding emerges through situated experience rather than through mental reconstruction alone.

This shift carries important theoretical implications for how space, form, and meaning are conceptualized. Spatial computing brings architectural theory into closer dialogue with phenomenological and embodied cognition perspectives, which emphasize movement, perception, and context as central to how spatial knowledge is formed (Yenduri et al., 2024). From this viewpoint, representation is no longer simply a tool for communicating design intent; it becomes an active component of spatial experience itself.

Implications for Professional Practice in Architecture and Construction

For professional practice, the framework suggests that spatial computing is likely to function less as a specialized visualization tool and more as a coordination infrastructure. By enabling shared spatial reference frames, spatial systems can reduce interpretive gaps between designers, engineers, contractors, and clients, supporting more direct and grounded forms of collaboration.

This shift implies a reconfiguration of established workflows, in which spatial models persist across design, construction, and operation rather than being discarded at each phase. Such continuity aligns with emerging BIM-to-digital-twin strategies that support long-term asset management and operational intelligence (Lu et al., 2020). Practices that adopt spatial computing strategically may benefit from greater clarity, earlier identification of issues, and more transparent decision-making processes. At the same time, the framework highlights that such benefits are not automatic. Firms will need to invest in governance structures, standards alignment, and training to avoid fragmented or ad hoc forms of adoption (Omrany et al., 2023).

Table 5. Practice-Level Implications Across the Project Lifecycle

S/N	Project Phase	Conventional Practice	Spatial Computing Implication
1	Concept Design	Abstract representations	Embodied spatial exploration
2	Design Development	File-based coordination	Shared spatial reference
3	Construction	Document interpretation	Situated spatial guidance
4	Operation	Isolated dashboards	Persistent spatial twins

Implications for Architectural and Built-Environment Education

The framework also carries important implications for education and training. If spatial computing becomes a foundational mode of interaction, architectural education will need to move beyond teaching individual tools in isolation. Instead, curricula should place greater emphasis on spatial reasoning, systems thinking, and the ethical design of digital environments.

Spatial computing environments can allow students to experience scale, circulation, and environmental performance more directly, helping to narrow the gap between studio abstractions and real-world spatial conditions. At the same time, educators must remain attentive to the risks of over-reliance on immersive technologies, ensuring that these systems augment—rather than replace—critical thinking, reflection, and design judgment.

Implications for Urban Planning and Governance

At the urban scale, spatial computing enables new forms of planning, simulation, and public engagement through city-scale digital twins and spatial analytics. The framework developed in this paper suggests that such systems can support scenario testing, resilience planning, and infrastructure coordination by making complex datasets legible through spatial interfaces.

At the same time, the implications extend well beyond technical capability. Urban-scale spatial systems raise significant governance questions related to data ownership, surveillance, and public accountability. As these models increasingly come to represent lived environments, planners and policymakers will need to establish transparent governance structures and participatory mechanisms to maintain public trust and legitimacy (Deng et al., 2021; Rice, 2022; Nica et al., 2023).

Implications for Artificial Intelligence and Human–Computer Interaction Research

The framework presented here positions artificial intelligence as an enabling component of spatial computing, responsible for interpreting sensor data, supporting generative processes, and enabling adaptive behavior. This has important implications for AI research, particularly in areas such as multimodal reasoning, explainability, and human–AI collaboration.

Rather than being optimized solely around numerical performance metrics, AI systems operating in spatial contexts must function within human-centered constraints, including legibility, trust, and accountability. This points toward a shift away from opaque forms of optimization and toward more transparent, assistive systems that are designed to support—rather than replace—human judgment in spatial environments (Yenduri et al., 2024).

Implications for Standards and Interoperability

Finally, the framework highlights the importance of standards and interoperability. Spatial computing systems operate across multiple domains—such as Building Information Modeling (BIM), Geographic Information Systems (GIS), Internet of Things platforms, and immersive interfaces. Effective integration across these domains depends on interoperable data structures and semantic mappings between BIM and geospatial systems (Deng et al., 2016). Without shared standards, these systems risk becoming fragmented, limiting their scalability and long-term viability.

This places professional bodies and standards organizations in a critical position. By supporting open data exchange, consistent spatial referencing, and long-term accessibility, they help shape whether spatial computing develops as a durable professional infrastructure or remains a set of disconnected technologies (Deng et al., 2016; Al-Sehrawy et al., 2021).

Summary of Implications

In summary, the implications of this work extend well beyond questions of technology adoption. Spatial computing reshapes how space is represented, how teams collaborate, how buildings are operated, and how cities are governed. Its successful integration into the built environment will depend as much on theoretical clarity, ethical governance, and institutional alignment as on technical capability.

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DECLARATIONS

Conflict of Interest

The author declares no conflict of interest.

Informed Consent

Not applicable.

Ethics Approval

Not applicable. This study is based solely on literature review and conceptual analysis and did not involve human participants, personal data, or animal subjects.

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Appendix A

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