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EDITORIAL

Open Access Journal

The Urban Canvas: Spatial Computing in Planning, Analysing, and Representing the Cityscape

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Abstract

This thematic issue is dedicated to the memory of Heejung Kwon of Yonsei University. Her research, intellectual generosity, and the many enriching conversations over the years helped shape its vision. We challenged the contributors to consider how urban planning, a discipline long reliant on visual tools like maps, plans, and models, might evolve through spatial computing. While these traditional forms of representation have been effective for communicating and evaluating urban changes, they often limit people's ability to directly experience proposed environments. The articles in this issue show how spatial computing draws on a broad range of approaches, including: augmented, virtual, and mixed reality; digital twins; photogrammetry; situated visualisation; and audio-based experiences. Together, these approaches help bridge this gap by enabling immersive and participatory encounters with our lived environments. Spatial computing emerges as a set of practices that reconfigure relationships among planners, citizens, data, and place. It positions *space* not solely as an object of analysis, but as an interactive medium. Rather than focusing exclusively on technological development, the collection explores how digital and physical environments are becoming increasingly intertwined and its implications for how urban space is experienced, understood, and produced. The contributions reveal spatial computing as an evolving field whose significance lies as much in the questions it raises as in the tools it provides. Issues of access, governance, and representation run throughout the collection, highlighting the ways in which spatial media reshape the relationship between digital systems and urban life, opening new possibilities for the future of planning.

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Keywords
digital futures; participatory urbanism; phygital city; public engagement; spatial computing; urban situated media

1. Remembering Heejung Kwon

This thematic issue is published in memory of Heejung Kwon of Yonsei University, our co-editor and colleague, who passed away before the issue she helped shape could appear in print. Heejung brought to this collection a combination of intellectual generosity and curiosity about the seams where the physical and the digital meet. She had a unique take on spatial computing, focused on 3D multi-user representations of place and space within interaction and design. We remember with gratitude the many conversations, collaborations, and exchanges we were fortunate to share with Heejung over the past 10 years and the work we did together on the proposal for this thematic issue. Heejung will be missed and we dedicate the issue to her memory.

2. Framing

Urban studies have long been a visual discipline. Maps, plans, renderings, and increasingly photorealistic digital models have been the medium through which planners test scenarios, monitor the performance of urban form, and hold conversations with the people who live in the places being designed. This reliance on visual representation has served the field well, but it has also bounded it. A drawing communicates and abstracts what a place is and what it might become, but it rarely lets a citizen stand inside a future that has not yet been built, feel its scale, or move through its uncertainty. The premise of this issue is that spatial computing is beginning to loosen that boundary between the physical and digital places. Through augmented, virtual, and mixed reality, through digital twins, photogrammetry, soundwalks, synthetic data, situated visualisation, and game engines repurposed as civic instruments, the city itself becomes a canvas: a surface onto which data, memories, and possible futures can be layered, inhabited, and contested.

Spatial computing reframes space as a medium rather than merely a subject. The growing accessibility of capture and display technologies, accelerated by companies such as Meta, Apple, Snap, and Niantic, together with advances in reality-capture methods, is democratising the production of immersive urban content. Similar to the way social media transformed content creation in the early 2000s, spatial computing is enabling a much broader community of users to create and share spatial content. Gaming frameworks already allow planners and citizens to engage with urban scenarios; spatial computing extends that capability into multi-sensory, layered, and contextualised environments that promote participation and enrich the design process. What interests us, and what unites the contributions gathered here, is less the novelty of the hardware than the question of what these tools do to the relationships between planners, citizens, data, and place. A new digital layer is rapidly becoming part of the urban fabric, visible to those with devices, invisible to those without, and that asymmetry is itself a planning problem. It creates opportunities, but also disparities when access to technology is constrained by cost, the expertise required to use it, or the technical jargon that surrounds it; it offers new ways of capturing everyday experiences, while also raising questions about whose experiences are represented, amplified, or hidden; it invites participation, while simultaneously foregrounding issues of ownership and control.

3. Contributions' Highlights

The articles that follow approach spatial computing from different positions, showing how digital systems are reshaping the ways urban environments are represented, experienced, and discussed. Rather than forming a single argument, they overlap and diverge, sketching the contours of a field still in formation, across disciplinary boundaries and through technologies that continue to evolve. Together, they present spatial computing not as a fixed set of tools, but as an evolving set of practices through which relations between people, data, and place are being reworked.

The impacts for the planning system are profound, yet the concepts the issue addresses are barely on the planners' radar, let alone legislated for in this newly emerging digital space. This is the central concern of "Spatial Computing and the Phygital City: Towards Digital Habitation" (Hudson-Smith, 2026), which proposes that the relationship between cities and digital technology is moving through a structured, three-stage transition. The first stage, the Smart City, is by now an established condition in which sensor networks and real-time analytics form the digital nervous system of urban life. The second, the Phygital City, is the condition currently emerging: one in which physical and digital layers are experienced simultaneously and inseparably within the lived environment. The third, Digital Habitation, is a speculative horizon in which physical geography ceases to be the primary frame of reference for work, commerce, and sociality. The article's central claim is a planning argument rather than a technological one. Naming the phygital phase matters, it contends, because planners and policymakers cannot govern a condition for which they lack adequate vocabulary, and the instruments fashioned for smart-city sensing are insufficient for the experiential and ethical complexities of phygital urbanism. The article treats this transition as a planning horizon requiring anticipatory governance rather than a technological inevitability, and that caution sets a useful tone for the issue as a whole.

If the phygital framing supplies the vocabulary for understanding hybrid urban conditions, "City as Canvas: Situating Digital Layers Across Urban Spaces" (Signorelli, 2026) offers a method for thinking about how digital layers can be situated within the city itself. It reframes the decline of Metaverse hype as an opportunity to focus on the digital traces, datasets, interfaces, and infrastructures already embedded in the urban environment. Drawing on two exploratory workshops, the article shows how situated visualisation can reconnect data, narratives, and environmental phenomena to the places from which they emerge, positioning the city not as a neutral surface for digital overlays, but as a contested environment where data, memory, infrastructure, and lived experience are continuously negotiated.

Where Signorelli (2026) focuses on digital layers in the present city, "Morecambe Area Gaming Environment (MAGE): An Applied Case Study for Coastal Futures and Adaptations" (Cureton et al., 2026) applies spatial computing to the challenge of coastal change. Flooding, sea-level rise, and long-term shoreline adaptation involve complex uncertainties that are difficult to communicate through conventional plans or reports. The article explores how game-based and interactive spatial tools can help communities engage with these futures more directly, testing possible interventions and understanding their consequences through situated and participatory forms of interaction. In doing so, it presents spatial computing as a way of making climate adaptation more tangible, allowing communities to enter the decision space of shoreline management rather than simply receive its conclusions.

"The Virtual Embodied Experience: Virtual Reality as a Medium for Computing, Analysing, and Representing the Cityscape" (LLabres-Valls, 2026) starts from the growing use of VR within professional frameworks for architectural visualisation and design communication. The article then asks whether this use has moved beyond representation towards more analytical forms of engagement. Through a systematic review across Scopus and CumInCAD, it shows that VR is well established as a medium for visualisation and communication, but that embodied interaction with spatial data remains limited. Its proposed concept of the virtual embodied experience therefore reframes VR not only as a display tool, but as a cognitive interface through which urban data might be experienced, explored, and interpreted.

The issue also turns to the question of how artificial urban environments can be built for testing, comparison, and experimentation. Synthetic cities are important because they allow researchers and practitioners to explore urban scenarios without relying only on costly, incomplete, or sensitive real-world data. "Creating Synthetic Road Networks Using Large Language Models: An Iterative Calibration Framework" (Kasiński & Szufel, 2026) extends this discussion by focusing on how LLMs can generate and calibrate road-network structures for virtual urban testbeds.

Sound expands this discussion by showing that spatial computing does not have to be primarily visual. "'Town Built From Fleeting Matter': Audiowalking San'ya's Hidden Histories as Practice-Led Spatial Inquiry" (Woite, 2026) uses a geolocated audiowalk in San'ya, Tokyo, to explore how audio can shape movement, attention, and interpretation while keeping participants grounded in the physical environment. By engaging hidden histories and marginalised spaces, the article shows how sound can make absence, memory, and contested urban narratives perceptible, broadening spatial computing beyond visual and model-based approaches.

Finally, "Within the Flows: Participatory 3D Scanning in Asian Techno-Industrial Hinterlands" (Müller, 2026) widens the issue's geography and its politics. Working at the peri-urban margins of Chennai and Hsinchu, sites bound together as hinterlands within global high-tech supply chains, the article proposes participatory photogrammetry as a lightweight, smartphone-based practice. The method generates embodied encounters within rapidly changing landscapes while producing digital fragments that can circulate across contexts and invite comparison. It is an important counterweight to the issue's other contributions, a reminder that spatial computing is not only a tool of the global-city centre but can be turned toward contested edges, multiplying viewpoints without smoothing real differences into a single narrative of progress.

4. Conclusions

Together, the articles show that spatial computing is not one method, but a set of emerging practices for connecting digital systems with urban life. These approaches open different ways to model, experience, interpret, and contest urban environments. Their significance lies not only in technical innovation, but also in how they are shaped by access, representation, maintenance, and the uneven conditions of urban life. It is with sadness that Heejung Kwon did not see this issue completed. The questions it raises about how we bridge the physical and the digital were questions she was asking herself when she proposed this issue. We hope the collection honours that contribution.

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Conflict of Interests

The authors declare no conflict of interests.

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ARTICLE

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Spatial Computing and the Phygital City: Towards Digital Habitation

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Abstract

Spatial computing is reshaping the relationship between cities and digital technology, yet planning and governance frameworks have not kept pace with the transition now underway. This article proposes a three-stage model of urban digital transition: from the Smart City, in which sensor networks and real-time analytics form the digital nervous system of urban life; through the Phygital City, in which physical and digital layers are experienced simultaneously and inseparably within the lived urban environment; and towards "digital habitation," a condition in which physical geography ceases to be the primary frame of reference, and work, socialising, commerce, and leisure occur in immersive digital environments. Existing frameworks, including code/space (Dodge & Kitchin, 2005), hybrid space (de Souza e Silva, 2006), and platform capitalism (Srnicek, 2017), have captured aspects of this transformation, but we argue that the intermediate Phygital City phase represents a qualitatively distinct planning condition that these frameworks have not adequately named or addressed. Naming it matters: Planners cannot effectively govern a condition for which they lack adequate conceptual vocabulary, and the governance instruments of the smart city are insufficient for the experiential, spatial, and ethical complexities of phygital urbanism. Drawing on emerging empirical cases, including urban digital twins and spatial computing platforms, the article develops the Phygital City concept across three registers—interface design, domestic space, and urban form—and situates the framework within established urban theory. We treat the three-stage transition as a planning horizon requiring anticipatory governance rather than a technological inevitability, and identify the Phygital City as the most tractable site for immediate policy and design intervention.

Keywords

digital habitation; digital twins; metacities; phygital city; spatial computing; urban informatics; virtual environments

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1. Introduction

The physical city has always been more than bricks and asphalt; it is a repository of information, a vast hardware system of roads, buildings, and services activated by the people who move through it. That fabric of interaction, the way we use, interpret, and experience urban space, is now approaching what we argue is a three-phase transition: from the Smart City, through an emerging Phygital City, towards a future of predominantly digital occupation we term "digital habitation." Batty (1997), in "*The Computable City*," argued that computers becoming embedded in urban life would change the structure and dynamics of the city itself, transforming every urban function from transport to utilities into digitally driven processes. To date that influence has been felt mainly through computing used to understand the city, rather than through a shift in the cityscape itself. Predating Batty, Gelernter (1991) fashioned the concept of "mirror worlds," envisaging cities as the prototypical digital replicas: software models sustaining a million views and remembering their own history in perfect detail. These were early visions of the now-emerging 3D modelling of cities and the collection of data via the Internet of Things, which Hudson-Smith et al. (2021) identify as the current driving force in the built environment. We argue that the shift goes beyond the current state of digital and urban form into a change in how we not only interact with but occupy the city itself, arriving not precisely as either Batty or Gelernter envisaged, but as a merging of their two visions.

These are valuable lenses, but each was built around a condition in which physical and digital remain separable registers, linked through software dependency, mobile social practice, or the geography of online content, rather than experienced as a single layer. What the Phygital City points to, which we define fully in the next section, is the moment at which that separability becomes hard to sustain: The augmented reality (AR) overlay is not consulted; it is simply there, woven into the visual field rather than held alongside it. As such, the Phygital City is not a fourth item to add to an existing list of frameworks, but a claim about when and how the boundary those frameworks all assume starts to break down, and a view that this breakdown carries planning consequences that the existing vocabulary of the city does not, on its own, surface.

It is necessary to acknowledge the substantial theoretical work already grappling with the relationship between physical urban space and digital technology. Dodge and Kitchin's (2005) code/space named the constitutive role of software-mediated processes in producing urban experience; de Souza e Silva's (2006) hybrid space described physical and digital merged through mobile social practice; and Zook and Graham's (2007) digiplace drew attention to the uneven, geographically structured way digital representations overlay physical space and reproduce spatial inequalities. More recently, Kitchin et al. (2015), Graham (2004), and Helbing and Argota Sanchez-Vaquerizo (2022) have further developed this terrain. The question is what the Phygital City adds to a conversation already theoretically rich.

While the term "phygital" has gained traction in urban design, placemaking, and architectural practice applied to public space (Bazzanella et al., 2014), to designed artefacts within it (Cevallos Andrade & del Blanco García, 2025), and to individual spatial behaviour (Mieli et al., 2024), these applications remain largely descriptive or design-oriented, they qualify a site, an object, or a practice. None names the city itself as phygital. They typically address discrete sites or events rather than the systemic urban condition that emerges when persistent, spatially coincident digital layers become part of everyday public experience.

Similarly, recent proposals for augmented urban planning focus on the socio-technical integration of urban digital twins to improve the planning process itself, enhancing interdisciplinary collaboration, stakeholder engagement, and operational decision-making (Azadi et al., 2025). In contrast, the Phygital City framework advanced here names a distinct planning threshold: the moment at which spatial computing renders the digital layer experientially inseparable from physical urban space for citizens, not merely for planners. This generates governance demands, zoning of digital objects in public space, regulation of persistent AR content, procurement of public AR services, and management of differential access to the lived city, that existing smart-city instruments and design approaches do not address. Naming this intermediate condition supplies the vocabulary required for anticipatory spatial planning.

The first of the two conditions this article names is the more imminent, arriving within about five years, as the physical and digital aspects of the city overlap spatially into a new information scape. We formally define this as the Phygital City: an urban environment in which physical and digital layers are experienced simultaneously, interactively, and increasingly inseparably, with spatial computing, AR, and layers of data experienced directly on top of physical space and the bodies that move through it. The term "phygital" is generally attributed to Chris Weil of Momentum Worldwide, who is said to have coined it around 2007 to describe strategies for blending in-store and online retail, although the attribution is contested and later origins have also been claimed; its subsequent adoption across cultural heritage, education, and urban studies (Del Vecchio et al., 2023) reflects the breadth of the phenomenon it names. Its marketing origins are, arguably, a liability. We use it because its foregrounding of the simultaneous physical–digital condition, rather than the transition between or interaction of the two, most precisely captures the planning threshold we seek to name. The premise is that spatial computing, encompassing AR, virtual reality (VR), and mixed reality (MR), is fundamentally altering urban function, creating a continuous, layered experience of the city from the public realm to the interior of the home. The article explores the coming decade and speculates, with caution, on the next fifty years, taking a three-stage model, which we introduce, as its conceptual spine.

2. Foundations of the Phygital City

The Computable City has arguably become the Smart City, which has its origins in the late 1990s as part of the broader "smart growth" movement in the United States (Harrison & Donnelly, 2011). Bowerman et al. (2000) provided some of the earliest technical frameworks for infrastructure efficiency, and IBM's Smarter Planet initiative propelled the concept into mainstream urban policy. As Hollands (2008) noted in an early and influential critique, the label was often self-congratulatory and lacked definitional precision, masking assumptions about the role of corporate technology in shaping urban futures. Hudson-Smith et al. (2020) offered a clarification, defining SMART as self-monitoring, analysis and reporting technologies, grounding the concept in sensor networks. Kitchin (2014) and Kitchin et al. (2015) refocused the concept around real-time data streams and urban dashboards, converting computational analytics into actionable intelligence. Smart traffic management, environmental monitoring, energy optimisation, and data-driven public health interventions are now routine worldwide, and the computer has become the gatherer and processor of urban information. The smart city is not an era we are leaving behind but an ongoing condition of contemporary urbanism, the digital nervous system upon which the next layer of innovation is being built.

Where the smart city focused on optimising urban flows through data collected and processed at a distance, the Phygital City concerns the experience of occupying partial digital space within the physical environment.

This transition is bolstered by the maturation of urban digital twins. Established in manufacturing by Grieves (2014) and later applied at urban scales by Shao and Helu (2020), the digital twin is starting to ground data in the real world. The Phygital City, we suggest, is reached when spatial computing, living digital twins, and AR systems are sufficiently mature to layer digital experience directly and continuously onto the physical environment. Del Vecchio et al. (2023) identify citizen experience as underexplored relative to the consumer and marketing literature; the Phygital City reframes phygital as an urban planning challenge rather than a commercial design problem. It is not a replacement for the smart city but the stage that follows provides the data infrastructure, the Phygital City the immersive layer through which citizens interact with urban environments. Digital habitation, the sustained occupation of digital space for activities currently associated with the physical city, lies beyond.

This is no longer wholly speculative. The Virtual London (ViLO) model, developed at the Centre for Advanced Spatial Analysis, overlays real-time transport and environmental data onto a detailed three-dimensional model of the city, while the commercial VU.CITY platform, used by numerous London boroughs and other UK and Irish cities, integrates a city-wide 3D model with planning data and regulation, letting stakeholders assess the visual, physical, and regulatory impact of proposals from a shared baseline. These remain planning and visualisation tools rather than spatially coincident AR experiences in the fuller sense developed below, but they show that the data infrastructure the Phygital City depends on is already operational in several major cities.

2.1. A Three-Stage Model: Smart City, Phygital City, Digital Habitation

The Smart City is characterised by observation and response: The city collects data about itself, analyses it, and adjusts accordingly, with the citizen largely a subject of measurement rather than a participant. The Phygital City moves from observation to participation: The citizen interacts with a digital layer spatially coincident with the physical environment, through devices that dissolve the boundary between screen and world. AR overlays in public spaces, haptic wayfinding systems, and mixed-reality planning consultations are all Phygital City phenomena. Digital habitation, by contrast, moves beyond the physical city as its frame of reference entirely, describing a condition in which a substantial portion of what we currently associate with urban life—work, socialising, commerce, and entertainment—occurs in immersive digital environments that need not bear any relation to physical geography. As noted in the introduction, the argument concerns the transition between these stages; Figure 1 sets out the three phases.

The Phygital City is the bridge between them: The condition in which physical and digital are simultaneously present and mutually constitutive, rather than one being a representation of the other. This has practical implications for planning, not merely for taxonomy. Smart city governance centres on data infrastructure: sensor networks, procurement, data-sharing agreements, and oversight of automated systems. These instruments are silent on questions of spatial experience: Who may place a digital object at a specific location, how conflicting AR overlays are arbitrated, what obligations attach to digital-layer content in public space, and how access is governed when that layer is produced by transnational platforms rather than public bodies. A planning authority equipped only with smart city tools confronting the arrival of persistent AR infrastructure would have no legal mechanism to zone the digital layer, no procurement process for AR public services, no design standards for spatial interfaces in public space, and no equity framework for managing differential access. These are not trivial administrative gaps: They are the phygital equivalents of the 20th-century planning failures that occurred when cities lacked frameworks for managing private

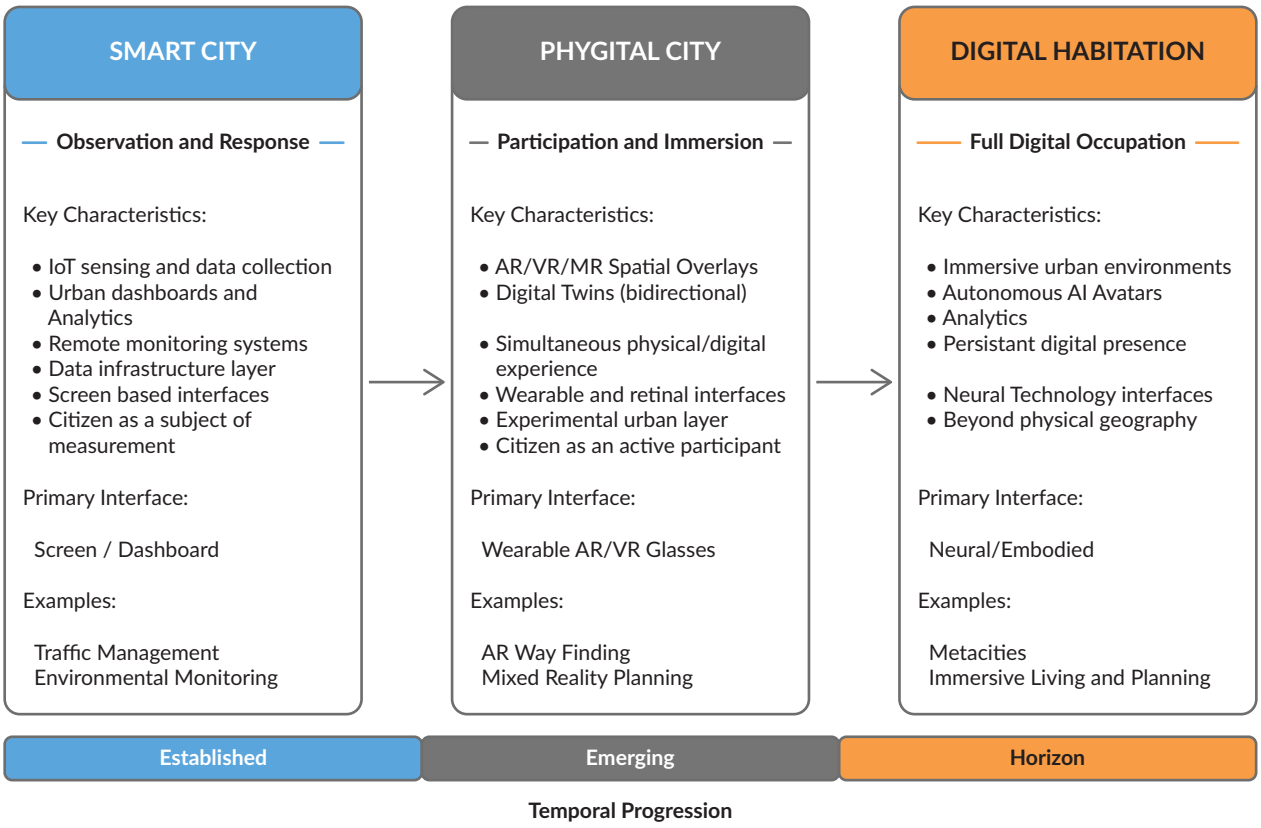


Figure 1. The three-stage transition from Smart City to digital habitation.

automobile infrastructure or regulating industrial land use. Identifying the Phygital City as a distinct phase is the first step towards building the instruments it requires. Allam, Sharifi, et al. (2022) note that the transition carries implications for sustainability and social equity that existing frameworks have not addressed; the Phygital City provides the staging post at which those can be identified before the full transition to digital habitation occurs.

2.2. On Interaction, Habitation, and the Digital Threshold

A substantial tradition in phenomenology and humanistic geography, running from Heidegger's (1971, pp. 141–160) concept of dwelling as a mode of being-in-the-world to Tuan's (1977) account of topophilia, argues that the distinction between "interacting with" and "dwelling in" a space is less clear than it appears. Arguably, with this view we already inhabit our digital environments: The hours spent in online social networks, gaming worlds, and video-call routines constitute a form of spatial occupation that perhaps deserves to be called habitation rather than interaction.

Yet this seems too limited a view, the domestic digital spaces produced by television, the internet, and social media already constitute genuine forms of extended spatial practice, what we are suggesting is a level beyond this. From Meyrowitz (1985) on the geography of television to Wellman and Haythornthwaite (2002) on the internet in everyday life, researchers have documented how successive communication technologies restructure the spatial boundaries of home and community, not by replacing the physical but by layering new presence and practice on top of it.

The Phygital City framework does not contradict this continuity; it identifies a threshold within it. What distinguishes the phygital condition from earlier forms of partial digital habitation is not the fact of digital–physical co-presence, which is, as noted, already established, but its spatial specificity and embodied simultaneity. Previous digital technologies mediated between physical and digital through screens that maintained a visible frame. The telephone extended voice but not vision; television brought remote events into the living room but not the street; the smartphone placed a digital layer in the pocket but preserved the distinction between looking at the screen and looking at the world. Spatial computing removes that frame: The AR layer is not accessed through a device held at a distance from the body but experienced as spatially coincident with physical reality. This is not a difference in degree but a difference in the governance and planning implications: When the digital layer is spatially coincident, it, we argue, should become subject to spatial planning in a way that mediated-screen technologies are not.

Three properties distinguish the phygital condition, and each is a planning property rather than a technological one. The first is persistence: a digital object anchored to a location remains there independently of any individual's session, in contrast to the transient, practice-produced hybridity that mobile devices generate. The second is inter-subjectivity: the same anchored object is encountered by multiple users at the same coordinates, which makes it less like content and more like street furniture. The third, and the most consequential for planning, is its effects on non-users. Code/space, hybrid space, and digiplace all describe conditions experienced by the person holding the device, whereas a persistent overlay produces effects for those not using it at all, including the resident whose shopfront carries an anchor they cannot see and the passer-by recorded by another's glasses. Planning has always concerned itself with precisely such third-party effects, from rights to light to amenity and signage control. This is the sense in which the difference is qualitative rather than one of degree.

2.3. Current Precursors and Early Experiments

Although full phygital urbanism with continuous, city-wide AR overlays remains emergent, several platforms and municipal initiatives already demonstrate the technical and experiential precursors of spatially coincident digital layers.

One prominent case is the inCitu AR platform, deployed across cities including New York, Phoenix, and Columbus, which allows residents and planners to view proposed developments at full scale in their actual context via smartphone, scanning a QR code to see how a transit corridor or housing development would appear in situ (Lincoln Institute of Land Policy, 2025). This moves beyond screen-based visualisation towards an embodied, location-anchored digital layer experienced at the site itself, spatially coincident with physical reality in the sense the Phygital City framework describes.

A more systemic example is Rotterdam's Citiverse initiative, an integrated urban digital twin linked to extended reality tools supporting citizen co-design of public space, allowing residents and planners to manipulate street furniture, green infrastructure, or climate-adaptive features within the model and view the results overlaid on the physical location through AR (Rotterdam Citiverse, 2025; RSM, 2025). The approach is framed as human-centred and inclusive, combining real-time data with immersive visualisation to democratise development decisions. These projects show that the spatial mapping, real-time data integration, and AR delivery mechanisms required for phygital experience are already operational in at least some major cities, well ahead of the governance frameworks needed to manage them at scale.

Together, these precursors demonstrate that the transition is not purely speculative: the technical substrate exists and is being tested in participatory contexts. They also surface the questions of access equity, content control, and public-space governance that the remainder of this article argues must now be brought into planning discourse.

3. The Interface of the Phygital City

The primary interface for the smart city was the screen: mobile phones, control room dashboards, and public displays. These provide access to the digital layer of the city while maintaining a deliberate and visible separation between the user and the data. Spatial computing removes that frame entirely. As Kitchin et al. (2015) have shown, urban dashboards reify particular ways of knowing the city; immersive spatial computing disrupts this, placing the user inside the data environment rather than before it. The city is no longer something you read off a screen; it is something you walk through, layered and augmented, simultaneously physical and digital. Hudson-Smith et al. (2025) provided a view of what the user would see, although they did not use this term, treating it merely as an AR overlay (see Figure 2).



Figure 2. Concept image of data in the Phygital City.

Google Glass, launched as a development build in 2013, is usually filed away as a hardware failure, but its more durable lesson concerns timing. Its technical constraints, a small display, short battery life, limited rendering power, mattered less than a social one: It let people record their surroundings with only a minimal visible signal, and no regulator, platform policy, or social convention yet existed to govern ambient recording in public space (Bilton, 2015). The lesson is not that the technology is doomed to fail again, since sensor and display hardware has moved on, but that whoever builds the governance layer after the hardware ships rather than alongside it risks repeating that mistake at a larger scale.

There are several reasons why platform governance is insufficient. First, the spatial specificity of AR overlays makes them analogous to physical infrastructure in a way social-media content is not: A digital object anchored to a street corner or building façade occupies that space, so governing what may be placed where,

by whom, and on what terms is functionally equivalent to zoning and signage regulation, and there is no reason private platforms should make those determinations unilaterally for public space. Second, the public-interest dimension is high: AR layers will shape wayfinding, access to public services, political advertising, emergency communications, and the lived experience of public space for all users, including those without AR devices who are nonetheless surveilled by those who have them. Third, jurisdictional authority already exists in nascent form: local authorities regulate signage, hoardings, street furniture, and public-realm design, and extending that authority to digital equivalents is legally coherent even if it requires new instruments. Srnicek (2017) argues that platform capitalism externalises costs onto the public while privatising network effects; in AR urbanism those costs include the erosion of visual public space, the normalisation of ubiquitous surveillance, and access hierarchies that deepen existing inequalities. Just as twentieth-century planning confronted who the physical city was built for, twenty-first-century planning must confront who the Phygital City is rendered for, a new form of zoning that planners have not yet begun to theorise.

This necessitates a new urban interface ethics: a framework for asking who determines the content of the AR layer, who bears the cost of access, and who arbitrates when the digital shadow of the city systematically misrepresents, excludes, or surveils particular communities. The case for public intervention requires careful argument, since the obvious response is that these questions will be resolved by platform governance: Meta, Apple, and Google are already developing AR infrastructure and will presumably develop terms of service to govern it.

Indeed, at the time of writing, March 2026, Google has pre-launched Android XR, an AI-powered operating system for headsets and glasses that brings digital information together with the real world (Android, 2026). Others will follow: wearables closer in form to ordinary spectacles, capable of beaming information directly onto the retina while allowing physical reality to show through. This is "true AR," and with it the prospect of genuine phygital urbanism, a continuous overlay of digital information on physical space, experienced not through a held device but through the act of simply looking at the city. This resonates with Castell's (1996) "space of flows," but adds a spatial dimension: the flows are not merely informational but experiential, sensory, and immersive. As Graham and Marvin (2001) argued, the uneven distribution of digital infrastructures risks producing "splintered" urban experience; in the Phygital City that splintering acquires new depth, since those without access to the AR layer inhabit a literally different version of the same physical space.

A degree of precision about timing matters, since the governance argument depends on it. Over roughly the next five years the more probable development is not full sensory AR but a lighter step: glasses-format devices carrying persistent, location-anchored information. A genuinely continuous AR overlay across public space, with the spatial mapping infrastructure it would require, sits further out, plausibly into the 2030s, contingent on battery and optics improvements not yet realised. The governance case rests on both horizons, close enough to warrant a proactive rather than reactive planning response.

4. Digital Habitation: Redefining Domestic and Urban Space

It is worth pausing on how unoriginal the claim of domestic rupture actually is. Each prior communications technology, the telephone, broadcast television, the home computer, the smartphone, arrived with similarly dramatic forecasts: that distance would cease to matter, that offices would empty out, that private and

public life would no longer hold apart. None proved entirely wrong; none proved straightforwardly right. The domestication of technology literature (Haddon, 2004; Silverstone & Hirsch, 1992) describes a more modest pattern: New technologies are folded into existing household routines rather than overturning them. Two things follow. First, expect a similar pattern of partial, socially mediated adoption here, which should temper some of the broader suggestions below. Second, the home was already some distance towards being a hybrid space before spatial computing arrived; what is new is not hybridity but its form, digital content seemingly untethering from the screen and distributing itself across the physical surfaces of the room.

The Phygital City is the transitional condition; digital habitation is, arguably, its destination. Where domestic space was traditionally defined by walls and a roof, it comes to be defined by bandwidth and immersion. The physical home becomes a portal: through MR the walls of a small urban apartment can dissolve to reveal a virtual vista, or expand to host friends present only as high-fidelity avatars. The transition is one of degree rather than kind, but the urban consequences are substantial.

4.1. The Evolution of the Frontier

Visions of future cities have always blended utopia and dystopia. From the neon-lit megastructures of *Blade Runner* to the haptic metaverse of *Ready Player One*, these imagined worlds are mirrors of societal aspiration and anxiety. Stephenson's (1992) coining of "metaverse" in *Snow Crash* gave a name to a concept circulating since the earliest experiments in collaborative virtual environments. The significance of that lineage lies not in terminology but in framing: the metaverse as a virtual space conceived as an urban phenomenon, a city at the scale of digital space. Hudson-Smith et al. (2025), in their book *Cities in the Metaverse*, building on Radoff (2021), define five layers required to form the frontier cityscape: connectivity infrastructure, the human interface of headsets and glasses, a decentralisation layer underpinning the exchange of digital assets, spatial computing itself, and the experiences layer of metaverse workplaces, venues, and shops.

Early experiments demonstrated both the potential and the constraints of the technology: cities mirrored in the computer and occupied by avatars, unrestrained by geography and physics. As Benedikt (1991) argued in one of the earliest explorations of the then called "cyberspace," virtual worlds are not real in any conventional sense; the laws of physics can be violated, suspended, or reinvented. What has changed is that the tools are now consumer-grade, the environments spatially coincident with the physical world, and the distinction between model and modelled philosophically untenable.

That philosophical challenge is what makes the Phygital City so significant. As Batty (2018a) observes, as models approach greater fidelity they begin to converge with the system they represent, raising the question of whether a complete digital twin running in real time remains separate from that system or becomes it. Goodchild et al. (2024) complicate this further, arguing that all digital twins are characterised by inherent uncertainty, while Lei et al. (2023) confirm that technical sophistication has outpaced the governance frameworks available to manage them. The Phygital City and beyond is the moment at which the convergence between model and modelled becomes experientially real.

4.2. The State of the Metaverse

The metaverse is best described as frontier territory under mixed development, with an expanding ecosystem of platforms, developers, and investors across the gaming, social, and enterprise sectors (Park &

Kim, 2022). It has moved in boom-and-bust cycles: abandoned worlds have grown steadily in number, and platforms that once seemed dominant, most notably Active Worlds and Second Life, are now shells of their former selves. Meta's Horizon has joined them: the tens of billions invested in Reality Labs since 2021, alongside the renaming from Facebook, came full circle when Meta announced in March 2026 that Horizon Worlds would be withdrawn from VR and continue as mobile-only, only to reverse that decision some 48 hours later after user outcry. Despite this outcry, the system and with it the current state of the Metaverse, is what could be described as underwhelming, especially compared to its previous highs. Park and Kim (2022) identify premature platform death as a structural feature of the space, linked to the difficulty of sustaining network effects at scale. These abandoned worlds are not merely failures; they are the digital city's archaeological layer. Despite this, platforms on the edge of the metaverse, Roblox, Fortnite, and similar, continue to attract huge audiences: Roblox averaged 85.3 million daily active users in the final quarter of 2024 (Roblox Corporation, 2025), perhaps offering a glimpse of the next hype cycle.

This merits examination beyond simple product failure. The social dimension of digital space is not reducible to rendering quality: Users did not find Horizon Worlds meaningful as a place, and better graphics did not resolve that. The threshold for digital habitation is therefore cultural and social as much as technological, involving spatial attachment, social practice, and economic activity built up over time. The Phygital City may in fact be a necessary cultural precondition for full digital habitation rather than simply a technical stepping stone, and the failure of attempts to "skip" straight to it is consistent with this.

Central to all these devices is a screen. The Phygital City is based around spatially aware AR glasses worn in the city itself; digital habitation is anchored in the home, where MR headsets such as Apple's Vision Pro and Meta's Quest track walls, windows, and furniture in order to augment new scenes onto them. This creates the illusion of extended space, and with it the central context for digital habitation: the view from a window overlooking a main road could instead present a live stream from Times Square, the ocean, or a chosen metaverse. We illustrate the concept in Figure 3, where the view is of a city but could in reality be anywhere.



Figure 3. An illustration of future digital habitation.

The domestic implications are profound and not without dystopian potential. Urban living could become increasingly dense, fitting more people per square metre into our cities; windows may become virtual, and spaces that are physically small experientially infinite. This "TARDIS effect," infinite digital space nested within physical boundaries, is the domestic expression of the broader Phygital City logic: The physical is the container; the digital is what is experienced within it. Mitchell (1995) anticipated that digital technologies would alter the relationship between physical space and functional capacity. As Bibri and Allam (2022) have argued, the hyper-connectivity and datafication inherent in these systems raise acute concerns about privacy, surveillance, and the algorithmisation of urban society that existing regulatory frameworks are poorly equipped to address.

4.3. The Locomotion Problem

The translation of physical movement into virtual space remains one of the key problems in the field: If you put on a headset and walk across a street in the metaverse, you run out of room in your living room. Current workarounds, teleportation, flying, controller-based navigation, are functional but non-immersive, and the first home-based platforms enabling continuous full-body movement remain niche and far from mass adoption.

The importance of this barrier extends well beyond convenience. As Lefebvre (1974/1991) argued, space is produced through bodily practice; the capacity to walk, to navigate, to encounter others in motion is constitutive of the urban experience. A metaverse in which one can only teleport offers a fundamentally different spatial experience from one in which one can walk continuously. The Phygital City, where physical walking activates digital overlays, preserves that bodily relationship to space; digital habitation, with full locomotion, would extend it into environments unconstrained by physical geography. It is once this barrier has been crossed that digital habitation becomes a possibility, and with it the implications for the physical city.

4.4. AI and Digital Habitation

AI is central to digital habitation and thus to the future city. It matters first through avatars, the representation of the self. Where the avatars of Active Worlds and Second Life could merely wave or perform a limited set of dances, current systems track facial expression and full-body movement, and a photorealistic digital twin of yourself, at least from the neck up, is now a practical reality rather than a research prototype. In the Phygital City, the avatar is not merely seen; it is the instrument through which the citizen navigates between the physical and digital layers of the urban environment. In digital habitation, the avatar becomes the primary up-front social presence.

Avatars will soon be indistinguishable from human beings in visual fidelity. More significantly, your avatar may be able to act in the metaverse on your behalf while you are offline, eating, sleeping, or engaged in the physical world. In effect, these are AI agents working across environments on your behalf, looking like you but purely artificial, akin to the emerging AI desktop agents but operating in the metaverse. Handling routine social and commercial transactions autonomously, they would create a "persistently inhabited" digital city that never sleeps, not because its human population is perpetually awake but because their digital proxies maintain continuous presence. This blurs the boundary between human and artificial urban populations in ways that extend Graham's (2004) account of the remediation of urban life, and raises legal, ethical, and philosophical questions that current urban theory is only beginning to frame.

Secondly, AI is central to the creation of world scenes. Persistent, AI-driven gaming worlds are not merely entertainment; they are the environments in which the norms, economies, and social contracts of the future city are being developed and tested. As Fraser (2023) argues in her geographical analysis of gaming, VR, and metaversal thinking, gaming environments are not neutral spaces of play but active sites of spatial knowledge production whose conventions will shape how people expect to inhabit digital cities. Games already create whole universes: *No Man's Sky* is effectively infinite, generating novel planets through procedural algorithms, while AI can populate such landscapes with plausible vegetation, weather, and self-sustaining ecosystems. This allows for "metacities": not static backdrops but evolving entities, complex systems exhibiting emergent properties irreducible to their components, a characteristic Batty (2005) identified as definitional to real cities. The procedural metacity is, in this sense, more like a city than any conventional urban model has ever been. As the metaverse provides an expanding digital habitat for AI, the question arises: Could AI, within the metacity, be said in some meaningful sense to inhabit it? Recent AI modifications of games such as *The Elder Scrolls V: Skyrim*, giving non-player characters memory, lore, and voice conversation, offer a glimpse of a future in which digital cities are populated by AI avatars living alongside digital representations of actual people. The question, as Floridi (2014) has framed it, is whether we are entering an age of "onlife," a condition in which the distinction between online and offline is no longer meaningful.

5. The Changing Role of the Physical Centre

If work, socialising, and entertainment can occur in high-fidelity phygital and digital environments, the necessity of the physical centre as a place of transaction diminishes. This does not diminish the city but elevates its role as a place of experience, of the sensory, embodied, and serendipitous encounter that remains, for now, irreducibly physical. The Phygital City is not the end of the physical city but the beginning of a new relationship between the two: landmarks such as the Eiffel Tower or Times Square will persist as physical objects and simultaneously as anchoring points in phygital space.

The prediction that digital communication would render cities obsolete has been made repeatedly and proved wrong repeatedly. When the internet went mainstream in the early 1990s the expected dispersal of offices did not occur; cities became technology hubs. As Glaeser (2011) argues, physical proximity enables the informal exchanges that drive creativity and economic growth, and Batty (2018b) makes a similar point. Yet the current transition is qualitatively different: it is not about shopping on a screen or meeting via webcam but the recreation of place and space online, and with it the experience of the city itself.

5.1. The Fifteen-Minute City and the Logic of Digital Proximity

The "fifteen-minute city," advanced by Moreno et al. (2021) and adopted as policy in Paris and elsewhere, proposes that essential urban services be accessible within a fifteen-minute walk or cycle from home. The Phygital City and digital habitation together strengthen rather than undermine this case. If substantial portions of work, education, entertainment, and social interaction migrate to digital environments, the remaining physical functions become overwhelmingly local and service-oriented: food provision, healthcare, exercise, maintenance of the built environment, and forms of sensory and social experience that cannot yet be replicated digitally. Digital habitation thus strengthens the fifteen-minute foundation by displacing non-local functions into digital space, freeing the physical city to concentrate on hyper-local services and

embodied experience. As Allam, Bibri, et al. (2022) argue, the fifteen-minute framework offers a foundation for sustainability, liveability, and health that the digital transition may reinforce rather than erode.

5.2. The Service Hub and the Hyper-Local City

Physical cities may therefore evolve into service hubs: less oriented towards mass transport and commercial office space, more focused on food, local amenities, healthcare, and experiential offerings that remain irreducibly physical. Perry's (1929) neighbourhood unit, the self-contained residential community with schools, shops, and amenities within walking distance, was once a planning ideal. The Phygital City and digital habitation may, in effect, return us to a modernised version of that ideal, embedded within a global digital infrastructure that handles everything else. Rather than Ebenezer Howard's (1898) town–country magnet, the vision presented here is a town–digital, where the pull is not green space but the digital spaces of mixed reality and digital habitation.

6. Towards a Research Agenda

It is worth recalling the terminological boundaries established earlier: AR is an interface technology, not the Phygital City itself; a digital twin is a representational tool within the infrastructure of both; the Phygital City is the planning condition of simultaneous, spatially coincident physical–digital habitation; and digital habitation is the further condition in which immersive environments become the primary frame of reference for activities previously associated with the physical city.

The arguments advanced here suggest a research agenda organised around the three-stage model itself, since each stage names a distinct planning condition and generates distinct questions. The priority is not to study digital urbanism in general but to distinguish what the Smart City to Phygital City transition requires, what challenges define the Phygital City in its own right, and what the trajectory towards digital habitation raises. The model allows planning institutions to sequence their responses rather than treating the digital transition as a single undifferentiated challenge.

At the transition from smart city to Phygital City, the most pressing questions concern the readiness of existing data infrastructure and governance frameworks for the shift from observation to participation. Digital twins are evolving from static visualisation tools towards inhabited, real-time environments; research is needed on the point at which a twin becomes a phygital environment in the planning sense, and on the regulatory relationships this creates between planning authorities, platform operators, and citizens (Batty, 2018a; Lei et al., 2023). The methodological toolkit of urban studies (Batty, 2013) must be adapted for environments in which physical and digital data are simultaneously generated and experienced. The inCitu and Rotterdam Citiverse deployments are early instances of this transition; systematic comparative research across such initiatives would build the evidence base anticipatory governance requires.

Within the Phygital City itself, the most urgent priorities concern governance, equity, and ethics. The governance gap identified here, the absence of planning instruments for the digital layer of public space, requires both conceptual development and empirical investigation: who determines the content of persistent AR overlays, by what mechanisms, by what democratic processes, and with what regulatory instruments, analogous to planning law or public utility regulation, to ensure the Phygital City serves all its

inhabitants. Equity must be designed in from inception rather than retrofitted once exclusions become visible, a lesson the smart city era has already taught. Graham and Marvin's (2001) concept of splintered urbanism acquires a new dimension when the splintering occurs between residents experiencing different spatial realities simultaneously. Research on the distributional profile of phygital access, on the implications of differential access to AR-mediated public services for civic participation, and on accessible interface design for those with sensory and cognitive disabilities or without high-cost devices should be central to this agenda rather than supplementary.

Looking towards digital habitation, priorities become longer-horizon but no less consequential. The difficulties encountered by Horizon Worlds (Section 4.2) suggest that social and cultural conditions for sustained digital habitation are as significant as technical ones; research on meaningful place-attachment in digital environments, and on the cultural preconditions under which immersive space generates the social capital associated with physical urban life, would substantially advance understanding. Questions of jurisdiction, labour rights, taxation, and social exclusion in virtual environments are not merely future concerns; the gaming and platform economies in which the norms of digital habitation are being formed already raise them at scale (Fraser, 2023; Park & Kim, 2022). Environmental implications also require attention: reduced commuting could yield carbon benefits, but the energy demands of cloud computing, AI training, and the manufacture and disposal of spatial computing devices present counter costs that must be modelled alongside any transition scenario. Although, the drive towards increasing consumerism and the pace of technology development and uptake may well simply override this. Together, these three tiers of the agenda, transition readiness, phygital condition, and digital habitation horizon, map directly onto the three-stage model and provide the structured basis for the interdisciplinary collaboration between urban planners, geographers, computer scientists, legal scholars, and ethicists that the Phygital City will require.

This article has argued that the transition from the Smart City to full digital habitation is not a single step but a structured progression, and that the intermediate phase, the Phygital City, is the crucial and under-theorised stage at which physical and digital realities become simultaneously and continuously present in the lived urban experience. That progression is the urban expression of what the World Economic Forum has characterised as a fourth industrial revolution of "cyber-physical systems," a fusion of technologies blurring the lines between the physical, digital, and biological spheres (Schwab, 2016); but the form it takes in the city is specific to the city, and it requires a vocabulary of its own.

The smart city has given us dashboards and sensing infrastructure. The Phygital City will give us layered, immersive, spatially coincident digital experience embedded in the physical environment. Digital habitation will take us beyond the physical city as a frame of reference entirely. Each stage requires different governance frameworks, different design principles, and different conversations about equity, access, and what cities are for. Planners must become system architects, designing not only for the physical body but for the digital presence; geographers must extend their frameworks to hybrid physical-digital territories; economists must model value creation in virtual layers. The challenge for urban scholarship and practice is to ensure that this digital habitation is shaped not by technological determinism or corporate capture, but by the same values of access, inclusion, and democratic participation that have animated the best traditions of urban planning.

For three decades, Batty's computable city and Gelernter's mirror world stood as two separate propositions: computation embedded within urban function on the one hand, and a parallel software model of the city on

the other. The Phygital City is the condition in which they converge into a single visual field. The city is no longer computable, the city of the future is a computer, and we are beginning to live inside it.

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City as Canvas: Situating Digital Layers Across Urban Spaces

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Abstract

As the hype around the metaverse fades, with declining public interest and industry investment, this moment should not be seen as a missed opportunity. Instead, it offers a chance to rethink the metaverse not as a fully immersive virtual destination, but as digital overlays woven into the environments we already inhabit. These digital layers include multiple forms of digital traces, from social media posts to sensor networks and institutional datasets, which often remain detached from their spatial origins. Reframing the city as a canvas for data-driven and context-dependent experiences highlights how handheld devices, ambient displays, and augmented reality frameworks can make digital information increasingly accessible in situ. As urban space becomes a hybrid environment where physical infrastructures and digital overlays coexist, situated visualisation offers a way to reconnect digital materials with the urban contexts that produce them. This article asks how such reconnection can support more place-based, participatory, and context-aware engagements with urban data. Two workshops conducted in London's Royal Docks and Queen Elizabeth Olympic Park are used as exploratory case studies, illustrating how situated visualisation can be developed from co-creation activities. The cases also reveal ongoing challenges, including access, representation, reliance on remote infrastructures, and the governance and reliability of supporting systems. The article positions the city as a canvas not as a neutral surface for technical overlays, but as a social, spatial, and infrastructural environment in which data, memory, and urban experience are co-produced and curated.

Keywords

augmented reality; co-creation; data visualisation; living lab; metaverse; situated visualisation; spatial computing

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1. Introduction

Digital environments have long provided a testing ground for new forms of presence, interaction, data visualisation, and co-creation. In the mid-1960s, Ivan Sutherland imagined computer displays capable of representing multiple senses beyond the visual, describing "The Ultimate Display" (Sutherland, 1965) as a room that a user could inhabit, a computer-generated multimodal environment that responded dynamically to their behaviour. His development of the first head-mounted display introduced core principles such as spatial tracking, embodied interaction, and perspective-correct rendering (Sutherland, 1968), all of which underpin today's immersive and augmented reality (AR) systems. A few decades later, Nicholas Negroponte argued that future social life would be shaped increasingly by the circulation of bits rather than atoms, as individuals inhabited fluid, networked environments no longer bound by physical borders (Negroponte, 1996). His early work highlighted how users inhabit, construct, and leave traces within digital spaces, and how these environments gain texture, memory, and social meaning through the activities of their participants. Seen through this lens, contemporary immersive virtual environments do not appear as sudden innovations but as continuations of longstanding efforts to build shared digital worlds.

Over the decades, the idea of inhabiting digital worlds has taken many different forms, from virtual replicas that closely mirror physical places to completely abstract environments with no fixed boundaries. These approaches differ widely, yet they share several core conceptual features: their persistent nature, meaning they continue to exist even when no one is present; their synchronous social and economic interactions; and the fact that they are typically experienced through some form of avatar-based presence. Various attempts have been made to group these environments under shared definitions, including "mirror worlds" (Gelernter, 1993), "collaborative virtual environments" (Churchill & Snowdon, 1998), and the more broadly known "metaverse" (Weinberger, 2022). The term "metaverse" originates from Neal Stephenson's science fiction novel *Snow Crash*, which described a large-scale virtual environment inhabited through digital avatars (Stephenson, 1992). Though his depiction was largely dystopian, later interpretations have highlighted more techno-positive dimensions, extending the concept beyond themes of control or escape from a destabilised physical world. In Stephenson's narrative, the metaverse operates as a vast digital universe composed of multiple co-existing spaces, each with its own infrastructure, aesthetics, and social organisation, through which users can navigate while maintaining persistent identities. Therefore, the metaverse depends on inhabitation; these environments are not just technological artefacts, but socio-technical constructs sustained by people, relationships, and networks of interaction (Bibri, 2022). Without active users, social exchanges, or community practices, even the most advanced environment becomes a digital ruin, an abandoned space that persists only as long as the servers remain online. Just as in the physical world, it is time, and the ongoing accumulation of persistent digital traces, from social media platforms to crowdsourced inputs and datasets generated by local authorities, that binds digital environments together and gives them meaning (Hudson-Smith et al., 2025, pp. 79–93).

Although these traces exist within the digital realm, they are typically rooted in physical contexts, produced by users and devices situated in real-world settings. As we move through urban and natural environments, we also move through a surrounding layer of digital traces: sensor networks streaming data from kilometres away, synchronised and unsynchronised datasets, historical information, and everyday digital records tied to specific places. Yet the movement of digital material remains predominantly one-directional, flowing from the physical into the digital or circulating within the digital domain. How can situated visualisations reconnect

digital traces, environmental data, and place-based narratives to the urban contexts from which they emerge, and what opportunities and limitations do co-creation practices reveal for planning, education, and public engagement? To address this question, the article develops situated visualisation as an urban practice through two exploratory workshops in London's Royal Docks and Queen Elizabeth Olympic Park.

2. The Fragile Materiality of the Digital Layer

During the early 2020s, the metaverse attracted significant attention from technology companies, cultural organisations, and education institutions, influenced in part by the surge in remote presence technologies during the pandemic lockdowns. Substantial investment initially flowed into immersive virtual platforms and spatial computing technologies. Major technology companies promoted it as the successor to the internet and to digital social interaction, a narrative not entirely new, echoing earlier waves of enthusiasm for immersive online worlds that attracted considerable attention in the 1990s. While the conceptual vision of the metaverse emphasised user-generated, interconnected worlds animated through social presence, the consumer offerings that materialised framed it largely as a virtual-reality-centric environment. This approach placed primary emphasis on the technologies themselves, often detached, intentionally or not, from the social and spatial complexities that developers and users inevitably carried with them from the physical world into the digital one. When combined with the physical strain of wearing a fully enclosed and not particularly comfortable device for extended periods, and with the absence of any capacity to transfer digital identities and assets across different walled garden platforms, these limitations created a fundamental mismatch between the metaverse's conceptual vision and its practical implementation in daily life (Chen et al., 2021; Xi et al., 2023). As social platforms, metaverse environments have struggled to establish viable business models, especially when compared with more targeted uses in industrial and training contexts. Revenue strategies such as virtual-land speculation, avatar-based microtransactions, advertising, subscriptions, and data extraction have been difficult to sustain against the high costs of data-centre infrastructure, user support, and content moderation. As a result, several initiatives were abandoned or scaled back before demonstrating long-term viability (Hudson-Smith et al., 2025, pp. 79–93). By late 2023, corporate attention had shifted rapidly towards artificial intelligence (AI), whose marketable benefits, even when still speculative, appeared more immediate than the costly and longer-term vision of a persistent three-dimensional internet. This moment should not necessarily be read as the collapse of the metaverse but as a corrective shift, in which early platform models built around virtual-reality-centric experiences and emerging forms of digital asset ownership give way to systems centred on spatial computing and AI. Rather than signalling an endpoint, this transition creates an opportunity to rethink the metaverse as a superimposed layer of data woven into the places where we live, a layer of information that already surrounds us but remains largely inaccessible in everyday experience. The underlying conceptual proposition of the metaverse is still valid; social interactions, economic activities, and representational logics rooted in the idea of a digital mirror or augmented layer of the physical world remain relevant; and the growing integration of AI serves not as an obstacle but as a potential enabler of this next phase. This digital layer is neither abstract nor immaterial. It relies on physical infrastructures, from sensor networks to data centres, and becomes visible and impactful through the ways data are produced, consumed, and displayed in everyday settings, including bus-stop arrival screens, advertising panels, mapping interfaces, and social media geographies (Wang et al., 2025). At the same time, the digital layer is not singular but composed of overlapping forms of data that reflect the physical conditions, social interactions, and lived experiences of the environments in which they are generated.

3. Contextual Grounding of the Digital Layers

Building on this understanding of the digital layer as overlapping strata rooted in the built environment, this section explores what these data forms are and why reconnecting them to place is important. Although much of this information originates in specific locations, it is rarely encountered within those same settings; instead, it circulates through interfaces and platforms that detach it from the contexts that shape and inform its meaning. Within this context, the data layer can be understood as consisting of three main strands. The first strand consists of data produced through social interaction. For example, social media content, community platform activity, everyday communication, and user-generated archives. While not always explicitly spatial, such material is often implicitly tied to place through the communities, practices, stories, images, and memories that situate it within local contexts. The second strand concerns automated data generated by sensor networks. Internet of things (IoT) infrastructures, environmental monitoring systems, mobility-tracking tools, and similar technologies produce continuous streams of measurements, often unstructured. These flows are typically transmitted to remote locations, unless processed locally on the device itself, where they are analysed, interpreted, and visualised. Similar to the socially generated data, the resulting information becomes largely detached from the place of its production, since it is usually accessed through remote dashboards. The third strand consists of authored or institutional data produced by regulated bodies such as planning authorities, government agencies, cultural organisations, and heritage institutions. This includes planning documents, zoning maps, spatial statistics, cultural inventories, and environmental assessments. Although explicitly tied to a place, these datasets typically exist within archives, databases, or planning portals. They inform decisions and shape policy, yet they seldom appear in situ. For this discussion, I excluded unpublished or restricted-access data withheld for privacy, security, or commercial reasons, as these datasets present additional methodological and ethical challenges related to their collection and access, whether conducted remotely or in situ.

Planning has long been concerned with the relationship between place, representation, and collective interpretation. Places are understood not only through physical form or function, but also through memories, practices, narratives, conflicts, and everyday use. This connects with work on networked urbanism, which shows how infrastructures and digital systems shape urban development and social relations (Graham & Marvin, 2002), with planning literature on storytelling and narrative knowledge (Sandercock, 2010), and with debates on informational rights to the city, where code, content, control, and access shape how urban information is produced and governed (Shaw & Graham, 2017). It also relates to work on geocoded digital information as a representation of place (Zook & Graham, 2007). Reconnecting data to the places they describe can therefore make digital traces more legible in relation to lived conditions, histories, and communities of the same places. The issue is not only how digital information is displayed in space, but how it contributes to the production and interpretation of urban knowledge. Reconnecting data to place makes these relationships easier to read: sensor readings gain relevance in the environments where their effects are felt; social memories gain depth in the places that hold them; and institutional datasets become more accessible when embedded in the settings their policies and classifications shape. Moreover, it opens up new ways to connect data with place-based interpretation, public engagement, and collective decision-making. Satriadi, Tag, and Dwyer (2023) similarly argue that contextualisation depends on the experiential and interpretive conditions through which people engage with their surroundings. This raises a broader question about how environmental context supports memory and understanding. Smith (2007, p. 112) addresses this directly, arguing that “memory is said to be context-dependent because experiences

always occur within context, and memories of events depend upon the contexts in which those experiences occur." Contextual cues shape how people remember and interpret information, including familiarity with a place, social atmosphere, emotional state, and past experiences. Reconnecting data to place also challenges the one-way movement of information away from its source, into platforms, dashboards, data centres, and archives, by making it visible again in the settings that produce it. In this way, data can support more situated forms of engagement. The aim is not simply to display data locally, but to make them part of urban experience and public interpretation, helping residents, planners, and communities recognise local risks and act on them. Flood warnings provide essential guidance, yet the data behind them are rarely connected to visible cues in the places affected. Similarly, during heatwaves, general warnings may overlook local differences in access to green spaces, cooling amenities, or safe indoor environments, limiting people's ability to respond to risk where they are.

4. Situated Visualisation

Research aimed at linking digital information back to the physical environments from which it originates has roots in early work on ubiquitous computing. Mark Weiser's foundational work at Xerox PARC in the early 1990s proposed a vision of computation embedded within everyday surroundings and integrated into daily life (Weiser, 1991). As this vision evolved, the availability of mobile phones equipped with increasing computational power, built-in sensors such as GPS, and higher-resolution cameras made it far easier, and far more widespread, to consume digital content anchored to specific locations (Azuma, 1999; Feiner et al., 1997; Papagiannakis et al., 2008). Together, these developments laid the conceptual and technical groundwork for the emergence of situated visualisation (White & Feiner, 2009), an inherently interdisciplinary notion drawing on human–computer interaction, urban informatics, data visualisation, and pervasive computing (Bressa et al., 2022). At the core of situated visualisation is the principle that digital information should be embedded within the physical world, its environments, objects, and other specific physical referents that the data correspond to (Willett et al., 2017) rather than confined to remote or abstracted screens (Elmqvist & Irani, 2013). When information is encountered in its relevant context, it can be interpreted through the spatial, social, and experiential cues of that setting (Satriadi, Tag, & Dwyer, 2023), enabling forms of understanding that differ from those offered by conventional visualisations (Bressa et al., 2022). Everyday urban displays already show how digital information can be experienced in place. AR extends this approach by overlaying digital content onto the physical environment in real time, creating hybrid spatial conditions in which digital elements appear anchored to a place, object, or the user's immediate surroundings (Azuma, 1997; Feng et al., 2008). AR systems situate digital content in physical space through either marker-based or markerless approaches. Marker-based AR uses predefined visual markers, such as QR codes, fiducial patterns, or printed images, to position digital overlays. Markerless AR instead relies on environmental sensing, including feature detection, plane estimation, depth sensing, location data, and simultaneous localization and mapping to keep digital objects stable and aligned with the user's surroundings (Feng et al., 2008). Speculation about how this technology might redefine our relationship with the urban environment has circulated for decades. Utopian and dystopian imaginaries across media culture have long envisioned futures in which digital information permeates and reshapes everyday space. The anime *Dennō Coil*, released in 2007 at a moment when AR was conceptually established but wearable systems had not yet matured, depicts children navigating an augmented city structured around invisible data layers and virtual entities, using wearable AR glasses to interact with hidden objects, creatures, and digital traces embedded in their surroundings (Roquet, 2016). *Hyper-Reality* by Keiichi Matsuda offers

another visually striking example, presenting a world in which location tracking, QR-coded interactions, and persistent augmented interfaces saturate the physical environment (Matsuda, 2016). These visions echo long-standing critiques that ubiquitous computing and augmented interfaces risk commodifying urban environments (Dourish & Bell, 2011; Mattern, 2014) and fragmenting shared urban experience by layering personalised, commercially driven information over public space (Greenfield, 2013). Earlier theoretical perspectives also anticipated these kinds of imaginaries. In *Hamlet on the Holodeck*, Murray (1998) proposed that digital media would increasingly shape how stories, environments, and interactions are experienced, signalling the spatial and experiential blending central to AR. These examples remind us that speculative imaginaries frequently act as informal laboratories for experimenting with alternative interaction models, offering early critiques and provocations that continue to resonate today (Bina et al., 2017; Miller & Bennett, 2008).

While such cultural visions help articulate the possibilities and risks of digitally augmented environments, work within urban informatics and spatial computing has begun to explore how situated visualisation might be applied in real urban settings, where conceptual ideas must be tested under practical and environmental constraints (Bressa et al., 2022; Jansen et al., 2022; Martins et al., 2023; Valkanova et al., 2015; White & Feiner, 2009; Willett et al., 2017; Zollmann et al., 2016). What was once confined to fictional or conceptual explorations has now become part of a technically mature and increasingly accessible ecosystem. Portable LiDAR sensors embedded in mobile devices, together with emerging 3D modelling techniques such as 3D Tiles (Cozzi, 2015) and Gaussian splatting (Kerbl et al., 2023), now enable detailed spatial models of the environment to be captured rapidly and with high fidelity. When combined with spatial anchors, allowing digital content to be fixed to specific locations and shared across devices and users, these models make it possible to construct persistent, multi-user experiences that remain stable over time. Visual positioning systems (VPS) make AR more accurate by recognising visual features in the surrounding environment rather than relying only on GPS. By matching what the device sees with shared spatial maps, they can position digital content more reliably in dense urban areas, where satellite signals often struggle. Machine-learning models add another layer by helping AR systems recognise objects, understand scenes, and respond to changes in the environment (Chamusca et al., 2025). Alongside these advances, major technology companies (e.g., Meta, Snap, Google, Samsung) are introducing lightweight wearable AR glasses that integrate real-time spatial tracking, eye-tracking, AI-powered perception, and multimodal interaction, further expanding the possibilities for embedding digital information into everyday settings.

Together, these advances shift AR from a display technology towards a spatial computing infrastructure capable of supporting context-aware interaction. This provides the basis for situated analytics, where information can be explored, interpreted, and used to support sense-making and decision-making within real environments (ElSayed et al., 2016; Shin et al., 2024; Thomas et al., 2018). The question is therefore no longer only what AR can technically enable, but how data can be meaningfully situated in place, designed for specific contexts, and used in practice. To understand what makes a visualisation or analytic system situated, three forms of grounding are important: where it is deployed, when it is experienced, and whose expertise shapes its creation and interpretation. The spatial dimension is not straightforward. Situatedness is often understood as direct in-situ deployment, where a visualisation is embedded in the physical setting from which its data emerge. However, it can also be produced in controlled environments, such as laboratories or studios, when these settings meaningfully recreate, reference, or interpret the place in question. Satriadi, Cunningham, et al. (2023) describe this as proxi-situated visualisation, where a proxy object or spatial

analogue stands in for a real-world referent that may be too large, remote, inaccessible, or complex to engage with directly. Situatedness, however, is not only spatial. A visualisation linked to live data offers different possibilities for interpretation and action than one based on historical or aggregated datasets. Temporal situatedness therefore concerns how data are encountered over time, whether they are live, updated, stabilised, or recontextualised, and how these conditions shape perception, activity, memory, and experience. As situated visualisation and situated analytics grow in technical, methodological, and conceptual sophistication, they increasingly require forms of expertise that extend beyond any single discipline. Designing, implementing, and evaluating these systems demands hybrid knowledge spanning multiple disciplines. This, in turn, requires transdisciplinary approaches in which designers, technologists, urban practitioners, community groups, and any other subject experts collaborate to fully account for the spatial, social, technical, and experiential dimensions of the situated visualisation needed to be developed. This raises educational and training challenges, and how students and practitioners should be prepared to work with heterogeneous datasets, embodied interaction, and co-creation methods to explore contextual grounding across its spatial, temporal, and epistemological dimensions.

5. Situated Visualisation Through Collaborative Practice

To trace how these issues play out in practice, this article draws on two exploratory workshops ARGH Mateys! (2020) and Here and There (2025). Together, they suggest how situated visualisation can be shaped through collaborative urban practice. The workshops took place in two East London (UK) contexts: ARGH Mateys! in the Royal Docks, a waterfront area in Newham shaped by former dock infrastructure and ongoing regeneration, while Here and There in the Queen Elizabeth Olympic Park, the former 2012 Olympic site, now a publicly accessible park with waterways, residential areas, cultural institutions, and the emerging East Bank cultural district. ARGH Mateys! explored situated visualisation through intangible memories, local history, and web-based AR, showing how low-tech methods can still support spatial anchoring and contextual connection. Here and There explored a transdisciplinary approach to prototype development, bringing together students from different disciplinary backgrounds to explore how environmental data, spatial datasets, and local observations could be translated into situated forms of interaction for the general public. The workshops are treated as practice-based cases rather than comprehensive evaluations of situated visualisation as a method. Their value lies in showing how situated visualisation can be developed through co-creation and transdisciplinary collaboration, while identifying practical dimensions and limits around accessibility, representation, digital infrastructure, and decision-making.

5.1. ARGH Mateys! AR for Grounded Heritage

ARGH Mateys! explored how intangible memories, creative narratives, and locally meaningful stories can be situated within the physical environment through simple visualisation techniques. The workshop involved seven young people from across the Royal Docks, supported by local organisations including Fight for Peace, the Royal Docks Learning and Activity Centre, the West Silvertown Foundation, and Youth Empowerment. The participants engaged with the urban environment as an active interpretive interface (Galloway, 2012), using the physical setting to surface intimate, historical, and imaginative dimensions of place. Their narratives were anchored to specific sites through the writing process and the design of markers that triggered AR content based on participants' memories. The workshop activities took place between October and November 2020, during the Covid-19 pandemic, when national restrictions had eased but significant

distancing and gathering measures were still in place. As access to cultural activities was severely reduced, the workshop provided an opportunity for participants to re-engage with their local environment and with their peers through creative practice. These conditions shaped the method: Activities had to remain outdoors where possible, group sizes were limited, and digital tools needed to support quick, low-barrier engagement. Technically, the project relied on a web-based AR framework, AR.js, derived from the ARToolkit marker-based AR systems (Kato & Billinghurst, 1999). This choice was deliberate; AR.js allowed the team to prototype rapidly with participants and provided a simple interaction for members of the public, who could access the experience through a standard mobile browser, effectively removing the obstacle of installing an app (Lovett et al., 2024). Over five weeks, participants combined creative writing and site-based exploration with the design of AR markers. The process began with a walking workshop in which each participant selected a personally meaningful location in the Royal Docks (Figure 1). While on site, they drafted creative texts in response to a series of prompts that encouraged close engagement with place, for example "Choose a feature within this space and write as that feature" or "Write about a memory connected to this site."



Figure 1. The first activity of the programme was a walk around the Royal Docks, during which participants selected the locations where their memories would later be embedded.

As the writing progressed, participants designed the AR markers that would eventually be installed at their chosen sites. Beginning with hand-drawn sketches, they translated their ideas into digital content that responded directly to the tone, imagery, and themes of their texts. The markers were conceived not as neutral triggers but as expressive components of the narrative itself, small artistic artefacts that visually signalled the atmosphere of the stories they unlocked. Alongside the markers and project credits, a QR code provided access to the web-based application. When the marker designed by each participant was scanned, it triggered a digital porthole model through which viewers could see an image selected by the participant and listen to their recorded voice reading the text developed during the workshop (Figure 2). Printed on aluminium for durability and weather-resistance, many of these markers remained in place nearly two years later, functioning as material points of connection between personal narratives and the public spaces in which they are situated (Figure 3).



Figure 2. The AR digital content developed for the ARGH Mateys! project. Scanning each target marker triggers a digital model of a porthole showing an image and playing the text recorded by the participants of the workshop.



Figure 3. One of the seven panels placed around the Royal Docks, each functioning as an AR marker designed by participants.

Through this process, ARGH Mateys! showed how memories, stories, and personal reflections can be embedded within the urban environment, and how low-tech, co-created artefacts can function as situated visualisations that anchor lived experience to specific locations. Despite the Covid-19 restrictions in place at the time, the installation recorded over 500 interactions through the web-based interface. Although these conditions prevented us from gathering extensive public feedback, the partners involved responded positively to the project, and the funder decided to extend its duration beyond the initial plan. For the young participants, engaging with AR content in this way was a new experience, and the workshop also introduced them to how the technology works. It offered an opportunity to experiment with combining creative

storytelling and spatially anchored digital media during a period when cultural activities were otherwise severely limited.

5.2. Here and There: Communicating Tangible and Intangible Phenomena in Urban Contexts

The Here and There workshop introduced the concept of situated visualisation to a mixed international cohort of 29 students who had not previously engaged with this field. Held in May 2025 at Queen Elizabeth Olympic Park in East London, the workshop brought together students from CY Cergy Paris Université's master's in geomatics applied to urban studies and risks, and University College London's (UCL) MSc in connected environments, MSc in urban spatial science, MSc in sustainable heritage, and BA in media. The workshop centred on communicating tangible and intangible aspects of the urban environment, with particular attention to transforming environmental and spatial datasets into communicative artefacts for park visitors, local residents, and site managers (Figure 4).

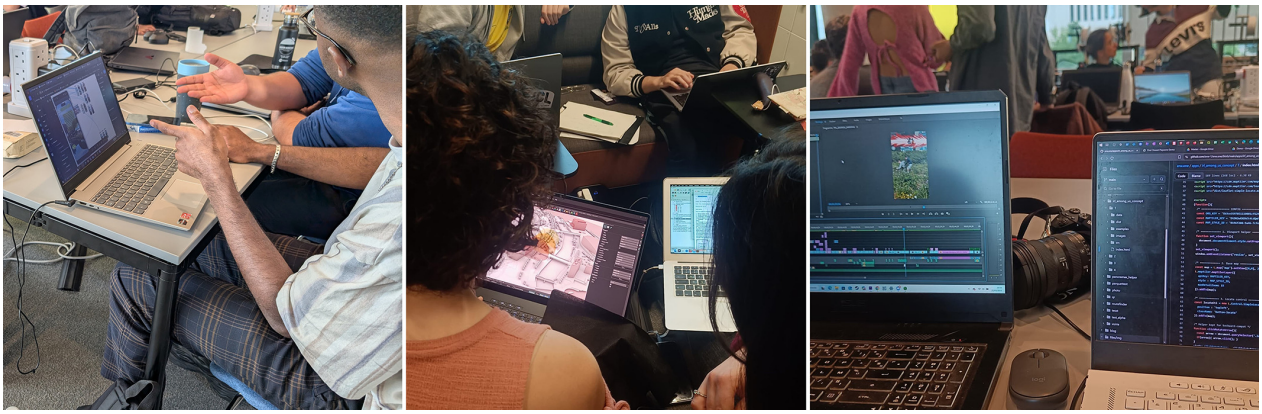


Figure 4. Students during the workshop activities explored ways to make environmental data from Queen Elizabeth Olympic Park more accessible to visitors and park managers, drawing on the technical and theoretical knowledge developed through their respective programmes.

Supported by Bluesky International, Gentian.io, and Queen Elizabeth Olympic Park Innovation District, the week-long workshop combined fieldwork, analysis, and rapid prototyping. A guided walk led by the park's Royal Society for the Protection of Birds biodiversity manager introduced students to its habitats, biodiversity work, changes since the 2012 Olympic Games, and overlapping visitor uses, providing ecological context for interpreting environmental data and park management (Figure 5). Students worked with digital tools for collecting, analysing, and visualising environmental and urban data, drawing on skills and methods familiar from their academic programmes and professional experiences. They used these tools to explore how data could be meaningfully embedded in place. A central element was the beta-testing of the Digital Frontiers data platform, a prototype environment that aggregates datasets on climate, health, and mobility around Queen Elizabeth Olympic Park. Student feedback directly informed the development of its successor, the UCL East Living Lab platform, which now offers datasets, tools, and methodological support for collaborative research and community engagement. The workshop therefore served both as a pedagogical activity and as a live testbed for refining how location-specific data could be accessed and used.



Figure 5. One of the field walks undertaken during the week-long workshop to better understand the park environment and identify key sites for situated visualisations.

Students worked in mixed-disciplinary groups, each responding to a shared design challenge. Their diverse academic backgrounds encouraged a wide range of interpretive and technical approaches, revealing how different forms of expertise shape the design of situated visualisation. The workshop concluded with a public presentation, during which approximately 80 visitors engaged with the six prototypes and explored the concepts that informed their development. Collectively, the projects illustrated how the students developed an understanding of situated visualisation as a relational and experiential mode of engaging with data, rather than one concerned solely with their representation. For example, the project WaterSlide raised awareness of human impacts on the River Lea by collecting field data on water pH, colour, and water levels. The group proposed a mobile app combining a GIS map and an AR overlay projected onto the ArcelorMittal Orbit, a viewing tower and public artwork in Queen Elizabeth Olympic Park designed by Anish Kapoor and Cecil Balmond. Users could explore the river's condition remotely through the GIS map or experience the data in situ via the AR view when near the river (Figure 6).

Naturwhisp focused on improving understanding of the park's biodiversity by revealing how ecological conditions have changed over time. Using data from iNaturalist, 2006 satellite imagery, recent photographs, and basemaps, the group proposed a location-based app that guides users along routes showing past and present species. After selecting options such as past or present, short or long route, or flora or fauna, users follow a GPS-enabled trail that presents species once found in the park or those present today with the use of AR, and contribute new observations, encouraging public participation in monitoring biodiversity. MuVz transformed visibility data into an auditory running experience, allowing users to sense how exposed or enclosed they were in the park through changes in sound. Using 3D building models, park boundaries, and walking-path data, the group calculated visibility scores with an isovist algorithm (Benedikt, 1979) and mapped them onto the park's paths. The proposed mobile app generates a dynamic soundscape that shifts as runners move into areas with different visibility levels, with new instrumental layers fading in or out to signal spatial change. Across these projects, students grounded information in place, time, and experience. Their prototypes integrated self-collected measurements, open datasets, spatial analyses, and narrative elements, prioritising engagement and embodied interpretation. The workshop also helped students confront different disciplinary perspectives and work together to solve a shared challenge, using situated



Figure 6. The WaterSlide prototype, which envisions the ArcelorMittal Orbit as a large-scale display for conveying real-time water quality information to park visitors.

visualisation as both an analytical and communicative practice that links environmental and social data to lived experience.

6. Analysis

The analysis draws on materials produced during and around the two workshops, including prototype concepts, field observations, project documentation, interaction records, and available feedback. These materials are treated as evidence of the design decisions, interpretations, and negotiations through which situated visualisation concepts were developed. The cases are analysed through four themes: spatial anchoring, which considers how digital content was connected to specific locations and gained meaning through place; co-production of knowledge, which examines how participants shaped what was represented, how it was communicated, and whose perspectives informed the outputs; data-to-experience translation, which considers how memories, environmental data, spatial analyses, and site observations were

transformed into interactive or experiential forms; and limitations around access, representation, and infrastructure, which address participation, visibility, exclusion, reliability, and sustainability.

Across both workshops, situated visualisation depended on building meaningful relationships between information and location. In ARGH Mateys!, this was achieved through physical markers installed at specific sites in the Royal Docks. Each marker acted both as a visual artefact and as a spatial trigger, linking a participant's story, recorded voice, and selected image to the place that inspired it. The marker was therefore not only a technical device for activating AR content, but part of the situated experience itself, making the digital layer visible, durable, and publicly accessible in the urban environment. In Here and There, spatial anchoring was broader and more speculative. Student prototypes linked environmental data and spatial analysis to recognisable features of Queen Elizabeth Olympic Park, including landmarks, walking routes, waterways, and habitats. Air and water quality, biodiversity change, and visibility analysis were translated into experiences tied to specific sites, routes, and environmental conditions. Together, the two workshops show that spatial anchoring is not simply about placing digital information at a coordinate. It involves shaping relationships between content, site, interface, and embodied experience.

The two workshops show situated visualisation as a process of co-producing knowledge and translating it into experience. In ARGH Mateys!, young participants chose locations, wrote texts, shaped markers, recorded audio, and contributed memories or imagined stories that became a WebAR experience accessed in place. Although the application was developed by the UCL team, the WebAR prototype was developed and adapted during the workshop process. Because it was web-based, changes could be tested quickly without building or compiling a dedicated app. This allowed the experience to respond directly to participants' suggestions and materials, while also helping them understand how their markers would be recognised and how this affected their design choices. The project therefore showed how situated visualisation can include intangible urban knowledge such as memory, atmosphere, and personal perception. Here and There involved a different form of co-production. Students from different disciplinary backgrounds worked with environmental and spatial materials, including water measurements, biodiversity records, satellite imagery, field observations, and visibility analysis. They decided what mattered, how it should be communicated, and how users might encounter it, developing these materials into AR overlays, route-based biodiversity interfaces, and soundscapes.

The workshops suggest that the value of situated visualisation lies not only in making data visible, but in making them experienceable. This is especially relevant for environmental communication, where many important conditions are difficult to perceive directly. Air quality, biodiversity change, flood risk, visibility, noise exposure, and historical transformation can be translated into forms that people interpret and discuss in context. In some cases, such as flood warnings or heatwave events, situated visualisation can also support local action by helping residents, planners, and communities understand how a wider risk applies to a specific place. At the same time, the translation from data to experience is never neutral: choices must be made about what to simplify, what to emphasise, and how to frame the relationship between evidence and interpretation.

The two cases also reveal important limitations. The workshops differed in participants, technologies, outputs, and timeframe, including the five-year gap between them, which shaped the tools available and the forms of situated visualisation explored. In ARGH Mateys!, web-based AR reduced some access barriers by

avoiding the need for a dedicated app, and the physical markers gave the project a visible presence in public space. However, participation still depended on having a suitable mobile device, network connectivity, and confidence in scanning the markers. Covid-19 restrictions also limited in-person encounters, public engagement, and follow-up evaluation, while interaction records could not fully show how different publics interpreted the experience. In Here and There, the projects remained at an early prototype stage. They were presented publicly but not deployed over time or tested in everyday use with residents, visitors, or park stakeholders. Their value therefore lies mainly in what they reveal about the design process and the possibilities of interdisciplinary experimentation, rather than evidence of long-term impact. The temporary presence of the international student cohort also limited time for development and evaluation. Both workshops show that seemingly lightweight digital experiences still depend on content maintenance, platform governance, interface reliability, and technical support. The challenge is not only to create digital layers in place, but to keep them accessible, interpretable, accountable, and sustainable. Together, the two workshops show that situated visualisation can work across different levels of technological complexity, from marker-based storytelling to speculative spatial-computing prototypes, when shaped through collaboration across disciplines and forms of expertise. Despite their differences, both cases show how digital layers can be connected to place through shared practice.

7. Discussion

This article reframes the decline of metaverse hype as an opportunity to focus on the digital layers already embedded in urban life, and on how situated visualisation can reconnect data, narratives, and environmental conditions to the places from which they emerge. For planning practices, the significance of situated visualisation is not only technical, but its value lies in shaping how urban knowledge is produced, interpreted, and acted upon. Planning already depends on maps, datasets, models, consultation materials, and narratives, all of which influence how places are understood. Situated visualisation extends this representational field by allowing information to be encountered within the spatial and experiential contexts it describes. The workshops demonstrate this through different forms of practice: ARGH Mateys! brought memories, voices, and creative narratives into the public environment of the Royal Docks, while Here and There translated environmental and spatial datasets into prototype experiences in Queen Elizabeth Olympic Park. In both cases, information gained meaning through its connection to specific places, routes, landmarks, and forms of experience. This also raises questions of power and representation. If digital layers influence what becomes visible in the city, then decisions about what data are included, how they are visualised, who can access them, and who can contribute to them are also planning questions. This connects to longstanding critiques of cartographic representation, which show how maps simplify, select, and frame spatial knowledge (Monmonier, 2018), as well as to work on urban dashboards and data-driven urbanism, which argues that dashboards, computational models, and platform interfaces shape particular ways of knowing the city (Kitchin et al., 2016; Mattern, 2021). Situated visualisation can make environmental risk, biodiversity, mobility, memory, or heritage more legible, but it can also exclude other experiences, simplify complex relations, or privilege those with the technical capacity to produce and maintain digital systems. The city should therefore be understood as a contested spatial environment in which data, infrastructure, memory, and public life are continuously negotiated. The cases also show that situated visualisation involves choices about what is included and who participates in shaping it. These processes suggest that situated visualisation is not a neutral display technique, but a curatorial practice. Decisions about data, stories, perspectives, and access shape how places are understood and whose knowledge is recognised.

Many urban data interfaces still work as one-way communication, presenting information rather than allowing users to contribute, annotate, or challenge it. The two workshops suggest how situated visualisation might move towards more reciprocal forms of engagement, even if neither fully realised this possibility. In ARGH Mateys!, the work was co-created with participants, but visitors could only access the stories rather than add their own memories, photos, or feedback. In Here and There, students imagined more interactive forms of engagement, including public contributions to biodiversity observations, although these remained at the prototype stage. These limits also point to the educational value of situated visualisation. Working with situated digital layers requires skills across planning, geography, data visualisation, spatial computing, environmental analysis, interaction design, and community engagement. Workshops can therefore provide a useful setting in which students and practitioners learn to connect data, place, and public interpretation through co-design. Rather than a single technological solution, situated visualisation should be understood as a flexible set of methods for storytelling, environmental communication, site interpretation, and public engagement. Beyond educational settings, which are often limited by project duration, situated visualisation also requires attention to who can access, shape, maintain, and interpret digital layers, especially when they begin to influence how places are understood and decisions are informed.

Overall, the comparison frames situated visualisation as both a technical and socio-spatial practice. It anchors information to place, but also raises questions about what knowledge is represented, how it becomes experiential, who can access it, and what infrastructures sustain it. The city as canvas is therefore not a blank surface for digital content, but a contested environment where data, memory, infrastructure, and lived experience are continuously negotiated.

8. Conclusion

This article has explored how situated visualisations can be created through collaborative work grounded in specific places. Rather than treating digital layers as separate virtual domains, it has considered how data, narratives, and environmental phenomena can be reconnected to the places from which they emerge. The two workshops show different forms of this reconnection. ARGH Mateys! used low-barrier WebAR and co-created markers to anchor memory, voice, and local storytelling in the Royal Docks. Here and There used interdisciplinary prototyping to turn environmental and spatial datasets into situated experiences in Queen Elizabeth Olympic Park. Together, they show that situated visualisation is not only a way of displaying information in place, but a collaborative practice through which urban knowledge is selected, interpreted, and made visible. Their limitations point to the need for longer-lasting interventions, clearer maintenance processes, and more reciprocal forms of communication, where users can not only access information but also contribute, respond, or annotate it. Future work will also need to account for changing AR technologies, including emerging wearable interfaces and the risk of tools or platforms becoming obsolete, as these conditions shape how situated visualisations are designed, sustained, and accessed over time.

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About the Author



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ARTICLE

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Morecambe Area Gaming Environment (MAGE): An Applied Case Study for Coastal Futures and Adaptations

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Abstract

Large regions and coastal urban communities face significant climate-related risks, including coastal and river flooding, inundations, and sea-level rise. However, long-term predictions of coastal flooding, coastal change, and associated risks involve uncertainties that are difficult to communicate to those affected. This, in turn, can hinder the adaptation of coastal communities to future changes. In our proof-of-concept case study, MAGE (Morecambe Area Gaming Environment), we developed five research tools to enhance engagement between local government and local residents on coastal change, its effects on settlements, and the existing shoreline management plan (SMP) policies. First, we created an open community mapping platform to gather voluntary geographic information (VGI). Second, we developed a mini tabletop game for KS3 Geography for secondary schools. Third, a serious tabletop game that simulates coastal systems and places in North-West UK, playing with communities and schools as a precursor to informing and developing the fourth tool: a sandbox computing system. The portable digital chessboard sandbox that visualises thousands of what-if scenarios in 2055 and 2105 uses Lancaster University's high-end computing (HEC) resources and a VR experience (our fifth tool). This article concentrates on the decision table, using numerical coastal models, GIS, and algorithms ported to a game engine; the MAGE system features interactive play pieces that the public can move in a 3D environment. Users simulate future climate scenarios for their area and choose interventions and mitigation measures for coastal flooding or change, whether nature-based solutions or hard engineering. Research results identified a specific communication need enabled by spatial computing, allowing communities to interact within the planning decision space and provide rich experiences to mitigate climate change. The MAGE prototype and case study serve as both an educational and participatory tool for coastal communities to map adaptation pathways for transitions between SMP policies. MAGE, as a situated planning artefact, effectively bridges large-scale coastal territories—both rural and urban—to plan for coastal futures.

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Keywords
adaptation pathways; climate resilience; coastal management; coastal modeling; regional planning; spatial computing

1. Introduction

The etymons of "mage"—French, *mage*; Latin, magus—"constitute a [person]…of exceptional wisdom and learning" (Mage, n.d.). Could models, simulations, and game engines constitute an equivalent knowledgeable function to mediate, forecast, and provide information—a [system] "of exceptional wisdom and learning". How would such a system function? What would be its agency? How could spatial computing contribute to knowledge formation and decision-making in a rigorous way, be transparent in uncertainty, and actively involve a range of communities and stakeholders? These constructions and research questions formed the basis of the double acronym MAGE (Morecambe Area Gaming Environment), which explored coastal management options in collaboration with coastal communities across North-West UK. This project is part of the larger Our Future Coast project, led by Wyre Council and funded by the Environment Agency and the Department for Environment, Food and Rural Affairs (DEFRA), UK.

Coastal management planning in England and Wales is based on shoreline management plans (SMPs), a policy framework that addresses the risks of coastal change along stretches of coastline over the short (0 to 20 years), medium (20 to 50 years), and long term (50 to 100 years), or three epochs. There are four policy options in SMPs: hold the line, advance the line, managed realignment, and no active intervention. SMPs are non-statutory plans intended to inform strategic planning, including the UK national planning policy framework (NPPF) on sustainable development in coastal areas. They also provide a basis for determining coastal change management areas (CCMAs) for planning decisions by local planning authorities. SMPs consider coastal processes, historic settlements, the built environment, and the natural environment in combination. Thus, SMPs address sustainable development goals SDG 11, 13, and 14 in primary urban areas, small towns and villages, and urban and rural communities. As part of the challenge, the wider Our Future Coast team aims to address the issues of unsustainable coastal protection by working with nature, as protecting coastal communities from flooding and erosion through hard-engineering structures becomes unsustainable due to rising costs and environmental impacts (Stojanovic, 2025); working with nature approaches are becoming a viable alternative. However, these approaches still have low social acceptance (Apine & Stojanovic, 2026) and require raising awareness and actively engaging communities to appreciate their wider benefits; a game-based method is utilised. MAGE supports this ambition to promote nature-based solutions through gameplay and decision support.

For this thematic issue, this article explores broader coastal and territorial practices of participation through a range of game-based methods, engaging communities in examining climate adaptation in response to climate disruptions. As a broad research challenge, coastal communities are on the front line of the climate challenge. It is not always possible to protect the whole coast with hard rock and concrete; there are not enough resources, and there is no good long-term solution. Many communities around the UK coastline will experience policy transitions in the coming decades, whether from holding the line to managed realignment or to no active interventions. This will require engagement with local communities to raise awareness of coastal changes across a wide range of urban and rural settlements, as well as co-developing adaptation

pathways with affected communities to support the transition from areas impacted by coastal erosion and associated risks (e.g., the Coastal Transition Acceleration Programme; see Environment Agency, 2026). These drivers are embedded in MAGE's game development and purpose.

Methods for visualising and communicating coastal change have appeared in many different forms, including tabletop games and digital game engines. A games publisher, Asmodee, claims that 30% of adults in the UK regularly play board games and that 26% play at least once a week, making tabletop games a key, accessible medium (Asmodee, 2025). In digital games, coastal applications include the Rising Tides project in Morecambe Bay, delivered via an immersive Igloo dome (Sairo Studios, 2023). Additionally, game engines are in ongoing use with the Environmental Protection Agency, Ireland, through digital twin approaches (Shakespeare & Stubbs, 2024; Strannegård, 2022; Strannegård, et al., 2023), and marine spatial planning challenge (Breda University of Applied Sciences, 2011) and engagement tools such as CoastCraft, a Minecraft education experience in Cornwall, developed in the Making Space for Sand project (CoastCraft, 2025). "Serious games," a term coined by Clark C. Abt, are defined as games with purpose, which are game processes used to explore questions and scientific viewpoints in various fields, including planning and government (Abt, 1970, p. 10). Serious games also appear to facilitate policy interventions and decision-making in areas such as urban mobility (Käyhkö et al., 2025), local planning (Cureton et al., 2026), and climate adaptation pathways planning (Sommerauer et al., 2026), defined as "sequences of actions that can be implemented progressively, depending on how the future unfolds, and on the development of knowledge and stakeholder preferences" (Werners et al., 2021, p. 371).

Adaptation-focused serious games and role-play simulations are used as interactive and experiential forms of engagement to build community readiness, communicate climate change, foster collaborative capacity, and involve stakeholders in adaptation pathway processes, including in flood risk management (e.g., Blackett et al., 2022; Kelly & Kelly, 2023; Nabong & Opdyke, 2024). Games typically place participants in realistic yet fabricated scenarios to understand the uncertainties, perspectives, interests, and responsibilities involved in complex decision-making processes (Kelly & Kelly, 2023; Rumore et al., 2016; Sommerauer et al., 2026). One of the most widely publicised games is the New England Climate Adaptation Project (NECAP) in the USA, which developed role-play simulations for four fictional towns—each linked to climate projections for a real-life locality (Rumore et al., 2016). Findings from NECAP and the wider literature highlight the value of adaptation role-play simulations and serious games for engaging wider stakeholders, building adaptive responsibility, and promoting social learning (Flood et al., 2018; Forrest et al., 2022; Rumore et al., 2016).

Building on the state of the art in community engagement, numerical coastal models, and SMPs, MAGE gaming and simulation environments are designed to visualise future climate uncertainty and facilitate participatory, local, and co-created approaches. Visualisation, co-creation, and coastal management strategy are intrinsically intertwined (Feagan et al., 2025; Kim et al., 2024; Ranson et al., 2024; Wolff et al., 2025; Yang et al., 2024). For this article, MAGE's spatial computing, in particular its digital chessboard, is aligned with augmented sandboxes that have a longer pedigree, such as JBA Trust's augmented reality sandbox created in 2020, which has hand gesture controls to demonstrate water movement through varying topography, the MIT's City Scope augmented platform for urban planning alongside agent-based models, such as Netlogo or GAMMA (Taillandier et al., 2019), and the use of serious games via augmented sandboxes for river resource management (Haan, 2018).

2. Structure

This article provides an overview of five tools developed as part of MAGE. However, this article focuses on the 4th tool: a digital chessboard sandbox that serves as a learning system to engage stakeholders in the decision space of coastal adaptation planning.

The tools are the following:

1. A mobile app for voluntary geographic information (VGI) and public coastal perceptions.
2. MAGE mini game for KS3 Geography as part of the Morecambe Bay Curriculum co-designed with Richard Spencer at Bowland High School, UK, covering SMPs, coastal interventions, and coastal adaptation pathways. MAGE mini includes supporting fieldwork and lesson plans.
3. A large-scale tabletop game of the North-West coast and game system developed after the Environment Agency's policy and SMPs (playable up to 20 people and running for more than 45 minutes).
4. MAGE digital chessboard sandbox for decision-making.
5. A virtual reality experience of OFC sites with sound actions and high-resolution drone-derived models and GIS data based on the main MAGE system.

VGI was used as the basis for creating the Map.Social web and mobile app to gather community viewpoints. A tabletop game was created to consider the SMP policy and engage communities and foster dialogue in this process (3rd tool; Cureton, 2025). The tabletop game works as a precursor for the computational thinking developed with the 4th tool, the MAGE digital chessboard, including its design, modelling, pipeline, and interaction methodology. Figure 1 shows the tools and configurations in relation to audiences and outcomes. This intentional flexibility in tooling is the result of diverse audiences, differing goals, and decision-support tasks. Figure 2 demonstrates the numbered tools.

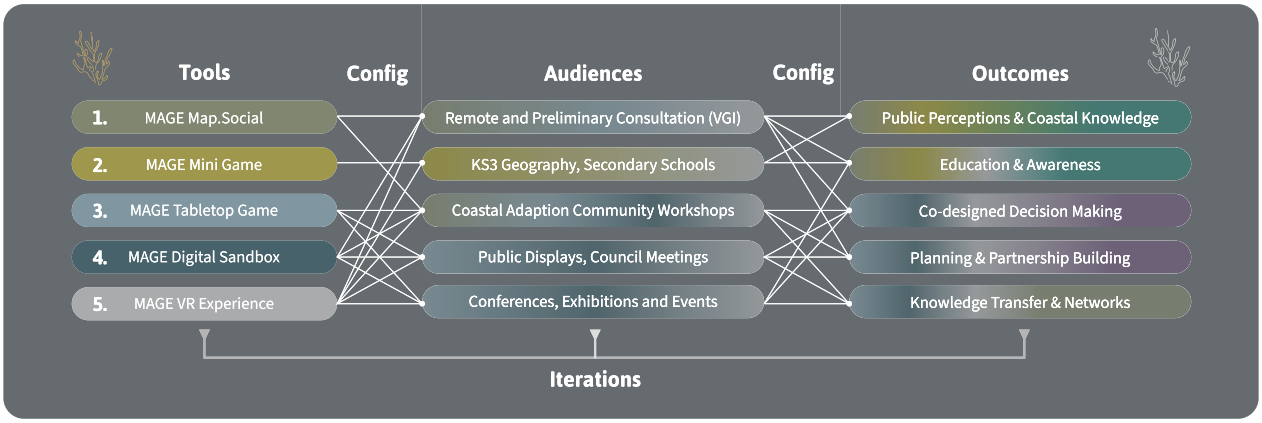


Figure 1. MAGE tools knowledge graph, the varying configurations and deployments, types of audiences, and configurations for outcomes.

The configuration and tool selection depend on in-situ local conditions, co-design workshop durations, the number of stakeholders, the levels of decision-making (from community to local government), and the required outcomes, ranging from educational awareness to specific coastal decision outputs via MAGE. This flexibility is intentionally designed to accommodate the range of stakeholders and the iterative nature of the collaborative participation framework.

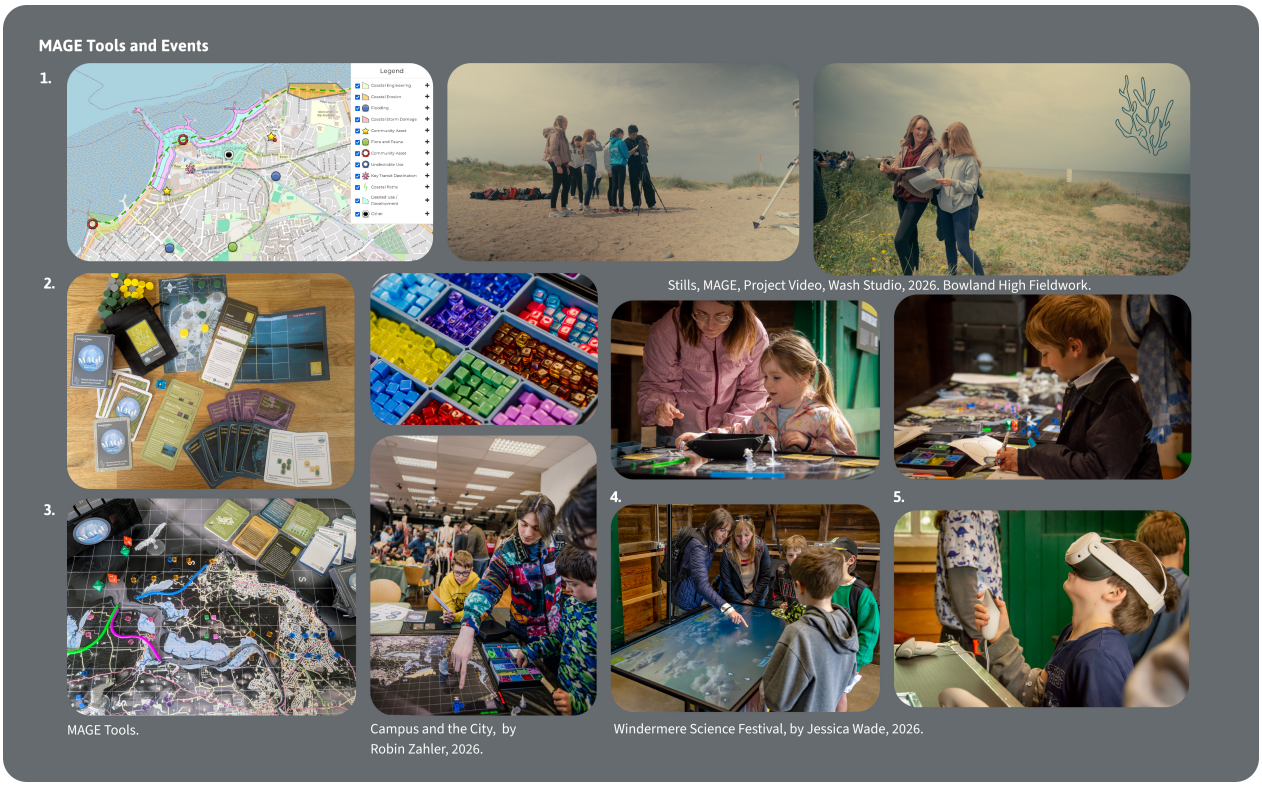


Figure 2. Image of 5x MAGE tools, including the VGI app (1), ESRI web platform (2), MAGE mini game (3), MAGE tabletop game and (4) MAGE digital sandbox, and (5) MAGE VR experience from various project events (5). Photography by Robin Zahler, Jessica Wade, and Wash Studio.

The methodology of the 4th tool is discussed at length in terms of spatial computing, as this uniquely combines numerical coastal models with a visual pipeline implemented in a game engine to simulate morphological change, with GIS data on buildings and vegetation forming a large, varied visualisation of flood risk in a portable, interactive sandbox with playable physical pieces. This aspect is one core achievement of the research to date, and has not been achieved in this research space.

Finally, the article discusses the results and limitations and identifies the potential replicability of the digital chessboard and its relationship with coastal adaptation strategies, key approaches to coastal resilience. The article, however, does not discuss proof-of-concept testing and the extended results of coastal adaptation workshops in depth, as this warrants a standalone article with detailed reporting and extensive analysis of gameplay and the resulting community decisions. Instead, it focuses on the schema of spatial computing and the detailed construction process that provides socio-technical approaches.

3. MAGE Tools

Using Houseal Lavigne's Map.Social platform, an app built on ESRI ArcGIS Online, a VGI interface was created for web and mobile devices via anonymous (guest) login to label the coastline from Liverpool to Millom. The base map includes one base layer and five toggleable layers:

1. Base layer: DEFRA, Environment Agency OGL Data—SurfZone DEM 2019 (2m).

2. National coastal erosion risk mapping data (NCERMS), which projects areas at risk of erosion for two time periods: medium term (up to 2055) and long term (up to 2105).
3. DEFRA, Environment Agency OGL Data—Spatial flood defences including standardised attributes.
4. DEFRA, Environment Agency OGL Data—Saltmarsh Extents 2016–2019.
5. Marine conservation zones—Natural England.
6. Sites of special scientific interest—Natural England.

The data includes two management scenarios: SMPs delivered and "no future intervention." Three climate scenarios are also used: present-day climate (as of 2020), higher central allowance, and upper-end allowance. The higher and upper percentile allowances use sea-level rise data from UKCP18 RCP8.5 at the 70th and 95th percentiles to model extreme climate risks (Environment Agency, 2024). Let's Map Our Future Coast features 12 annotation layers for public labelling, including photo uploads, with all annotations and anonymous media exportable as CSV or PDF for reporting. The platform is designed to capture perceptive values, observations, and local knowledge. The platform is also designed as one of the five MAGE tools within wider coastal adaptation projects, staged as a framing device and starter for discussions and early workshop phases to record local viewpoints (see Figure 1).

The MAGE tabletop game was designed for public dialogue. A game system was designed to translate policy and management practices into a strategic, interactive game while considering the accessibility and popularity of tabletop games. Such a process would allow consideration of the range of "gameplay" limitations and inform the development of inputs and parameters, prior to dedicating resources for spatial computing in the digital chessboard (the 4th tool). MAGE has been played at the boardroom level, in academia, and at youth-focused festivals, with n. 1800 participants across seven events at the time of writing, providing educational enrichment to an area with a limited understanding of SMPs and coastal management approaches. The game, the 2nd tool, consists of large A1, 1:25,000-scale map gameboards that connect to form the NW, UK extent, game characters, game tokens, and a card deck. Players must strategise to complete scenarios involving storm events, flooding, rapid urbanisation, and the placement of defences, among other actions (flexible strings represent defences in Figure 2). Players interact with one another and discuss community values, strategies, and local observations, with an expected gameplay time of 45 minutes to 1.5 hours.

The first iteration of the game required much clearer win conditions and clarity on game rules and mechanics, which provided a useful framework and a further iteration of the tabletop game for the framing of the digital chessboard, as did an additional requirement for the 2nd tool—the short-form game for school settings, called MAGE-mini (15–30 mins), played with 140 children in KS3 Geography. This early-stage tool provided valuable data to frame what a digital sandbox requires in terms of interaction and to specify future computational development of the 4th tool (Liapis & Denisova, 2023). Capturing dialogue through gameplay and game decisions as an experience also requires a robust computational mechanism. Both tools have been deployed together in engagement events. However, the 4th tool has been specifically embedded in coastal adaptation pathway workshops. Gameplay results also vary between analogue and digital approaches. Results can vary by participant cohesion, enjoyment, game motivations, and conditions, and can be wildly affected by the resulting qualitative and quantitative gameplay data. Each has challenges in capturing gameplay decisions and motivation for play (Garcia-Soriano et al., 2025). In addition, MAGE and its digital equivalent are not connected as analogue and digital devices, unlike many blurred game systems that translate game flows between the two media in augmented experiences (Han et al., 2026).

4. MAGE Digital Chessboard

The digital chessboard was devised to create a proof-of-concept demonstrating that a portable sandbox using dynamic coastal morphological data could respond to real-time public interactions and decisions regarding coastal management, including nature-based solutions. The testing remit was that the digital chessboard could function as an engagement tool with communities, as a means of communicating complex coastal science, and as a way to involve stakeholders in the decision space with regard to four management principles set out below and the sub-interventions required for shoreline management planning, required for coastal management and SMP policies' implementation, ranging from hard engineering structures such as sea walls to nature-based solutions such as potato starch lattices for salt marsh restoration through reducing wave energy and erosion (Forrester et al., 2024). MAGE frames SMP policies as a playbook for future coastal change, immersing the public in nature-based decision-making and offering varied solutions with real-time feedback (Figure 3).

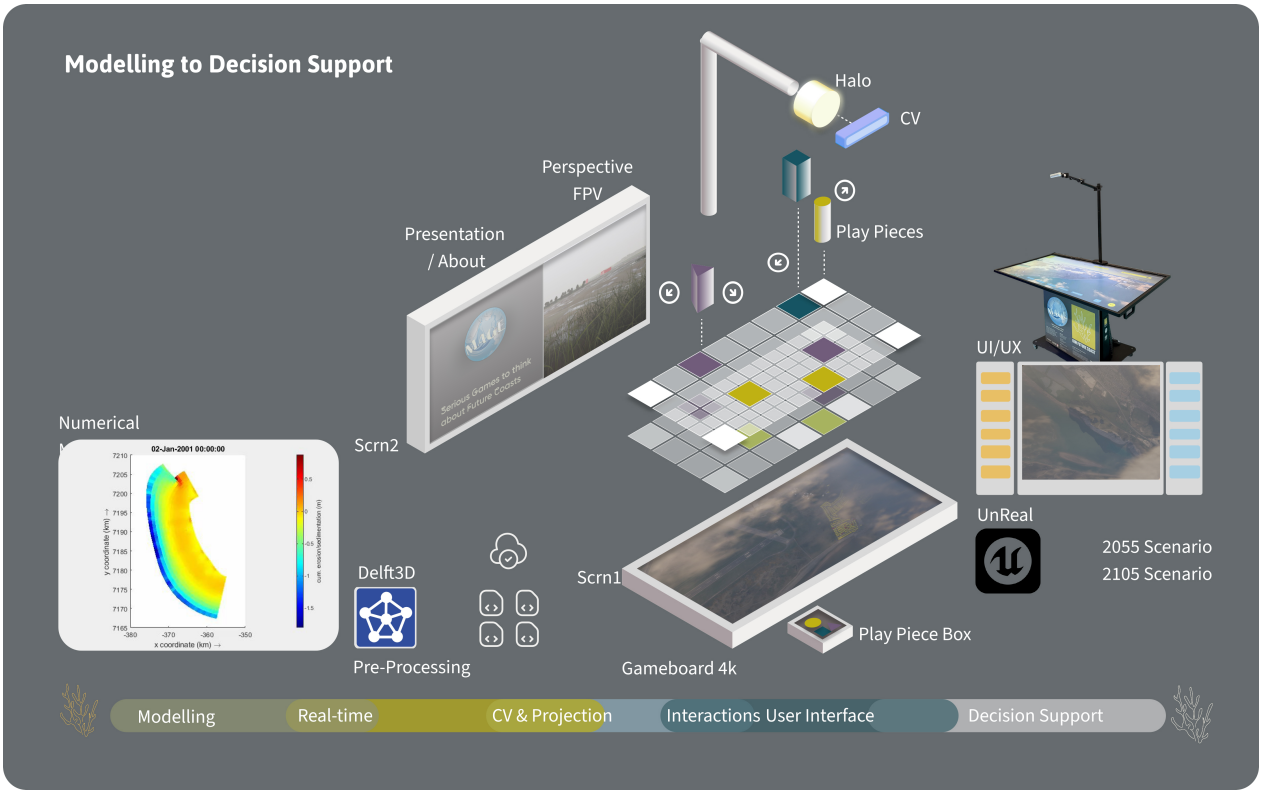


Figure 3. MAGE schema digital chessboard. Notes: Each Delft3D-FM model run was pulled through a novel Unreal Engine vision transformer blueprint to simulate the coastal model run when a UI button feature is activated (or a physical play-piece) is moved on an interactive 65" screen via a mounted depth camera and halo light for consistent lighting and CV mapping; a second 65" screen features an FPV view of the game zone and a presentation that explains the design of MAGE and provides explanations of model uncertainty.

The modelling context and rationale for MAGE is based on the selection of UK primary coastal cells—number 11 (Motyka & Brampton, 1993). Coastal Cell 11 features high levels of social deprivation across aspects of health, employment, education, and opportunity (ONS 2020; see Asthana & Gibson, 2021) in major coastal towns, including Barrow, Blackpool, Morecambe, and Fleetwood, amongst others. MAGE is a spatial computing intervention that shows coastal change and property risk, and also features a deprivation layer highlighting inequalities alongside other data such as 3+30+300. In addition, for Cell 11, sea-level rise

predictions are +0.24m in 2050 and +0.65m in 2100, with tidal predictions at +0.06m and +0.15m under the RCP 8.5 projection, and the area has a high–high risk classification used by policymakers for understanding the risks for climate mitigation, adaption, and resilience (Arnell et al., 2025; Bricheno & Rulent, 2025a,2025b, 2025c).

Coastal change is usually simulated by coastal area morphodynamic modelling software that can predict changes at various spatial and temporal resolutions. These models consist of hydrodynamic modules such as wave transformation and nearshore current models, a sediment transport module, a morphological change module, and may include coastal structures. These nearshore models are typically informed by ocean models and can include open-coast, estuarine, and riverine environments. Software includes CoastalFOAM, MIKE21, Delft3D-FM, XBeach, among others, and results are often post-processed in ESRI ArcGIS and MATLAB.

MAGE used SMP policies as frames to bridge numerical model outputs in a dynamic interactive environment and was guided by modelling principles: (Environment Agency, 2019, 2025). Our research development considered three broad issues from the decision-making matrix for suitability: (a) expected coastal trends, (b) management impacts at the site, and (c) nearby management impacts and climate change impacts (see Environment Agency, 2019, p. iv). Modelling aspects ultimately consider a range of interventions based on the four coastal management approaches set out in the SMP policies:

1. Hold the line—maintenance of artificial defences.
2. Advance the line—new seaward defences and land reclamation.
3. Managed realignment—natural repositioning of shoreline.
4. No active intervention—no planned investment for the zone.

Three distinct game zones, Unreal Engine game setups (or sites), were established and will later be expanded to eight sites across the Northwest Coast in early 2027 as part of the Our Future Coast programme. The proof of concept is structured in four sub-sections: (a) data assimilation, (b) modelling phases enacted, (c) vision pipelines established, and (d) custom user interface development. For example, one gamezone, Walney Island, a landmass east of the Walney Channel, shelters a heavily industrialised town, Barrow-in-Furness, and the Port of Barrow, a significant UK defence asset for nuclear submarine construction (Figure 4). Beyond a 100-year scope of study, in 2014, unmanaged erosion could form channels cutting across the island with impact to the port, among many other challenges, including large-scale risk to property (Barrow Borough Council, 2014, p. 9). Another game zone site, Hest Bank above Morecambe and below Polton le Fylde, features saltmarsh requiring restoration and a critical embankment that hosts the West Coast Mainline railway line (London to Glasgow) infrastructure and housing, both of which are prone to long-term flood and erosion risks. Both game zones indicate varying challenges, community needs for resilience, and climatic effects.

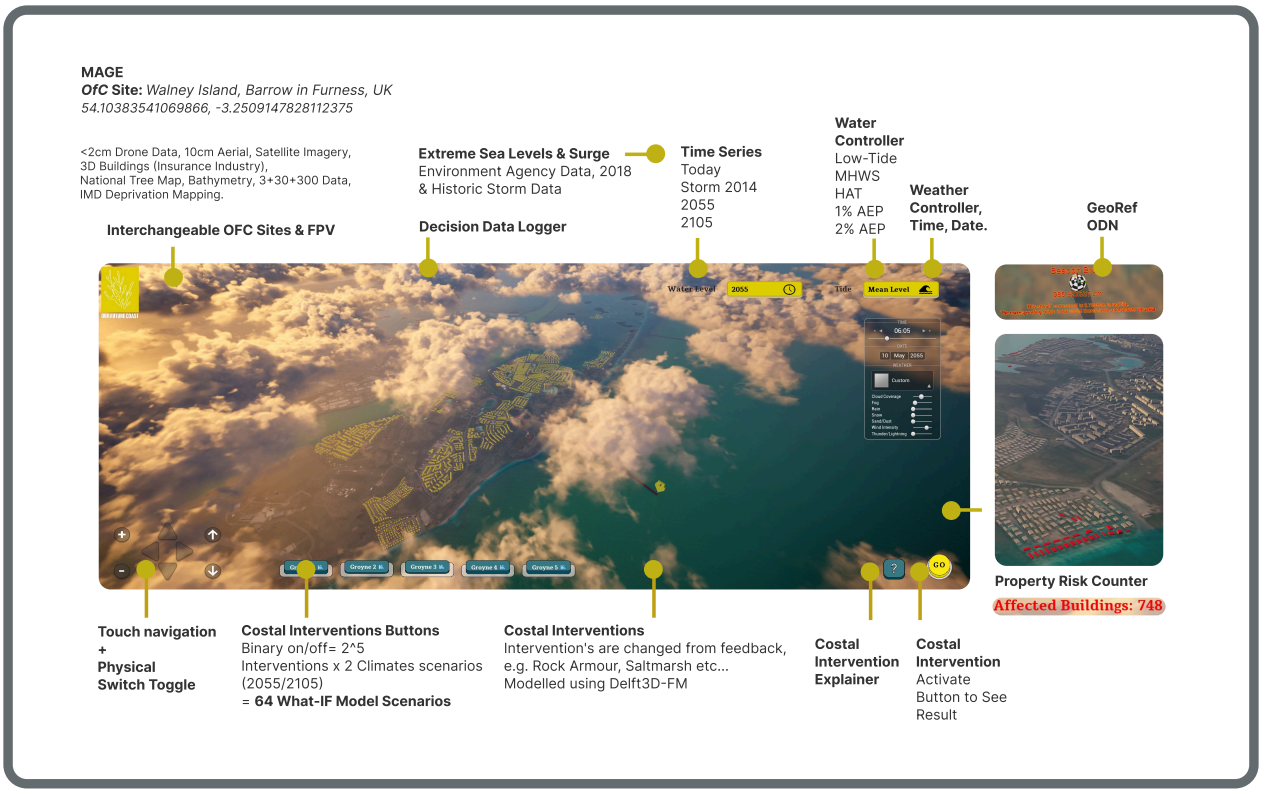


Figure 4. MAGE game HUD, one "game zone" environment, and interventions built, Walney Island, Cumbria, UK.

5. MAGE Data

Several monitoring instruments and supporting data were also available for MAGE, including radar, buoys, tidal predictions, existing commissioned coastal models, and a variety of local authority GIS data, which were incorporated into MAGE and computed in a variety of software, including LECIA Cyclone Register360, DJI Terra and Modify, ESRI ArcGIS, ESRI CityEngine and Unreal Engine. Data incorporated included the UK Tide Gauge Network, which forms part of the National Tidal & Sea Level Facility, National Oceanography Centre, National Network of Regional Coastal Monitoring Programmes, data catalogue, EDINA, and Environment Agency multibeam 50 cm bathymetry and FCERM near-shore LiDAR surveyed by Andrew Martin (Sefton Council). Additional data included National Tree Map data, which consists of height, location, and canopy/crown extent of trees; the 3+30+300 dataset, which uses proximity to natural environments as a health indicator; and Verisk 3D buildings used in property insurance, underwriting, and risk management, covering 46 attributes such as EPC rating, age, dwelling type, etc. UAVs have a unique role in coastal adaptation and monitoring (Tadić et al., 2022). For MAGE, repeat precision drone surveys were conducted at several sites to map intertidal zones using Structure from Motion (SfM) and Gaussian splatting post-processing. Surveys were conducted using Real Time Kinematic (RTK) multi-station and ground control points (GCPs > 5) to produce <1.5–2.5cm GSD resolution maps by the authors, with flight design depending on site restrictions, such as adapting mitigations for site of special scientific interest (SSSI) areas. Such a combination of data would create a 3D environment in which future scenarios can be observed and interventions added to the "chessboard." Post-processed drone surveys were exported as OBJ file types for

integration via MetaQuest 3, VR headsets, PICO4 HMD, and X-Real Aura Glasses, via ESRI ArcGIS Online for initial short community experiences of virtual sites and the development of the 5th tool.

6. MAGE Modeling

Utilising Lancaster University high-end computing (HEC) resources, multiple model runs were computed using Delft3D FM and a unique output code naming convention and temporal aspect number. Using Delft3D-FM, its engine allows users to apply unstructured grids that efficiently capture complex coastlines and bathymetry while maintaining computational performance. The hydrodynamic module solves the shallow-water equations to model water levels, currents, storm surges, and tidal flows with high accuracy, making it suitable for flood-risk assessment and coastal-engineering studies. Complementing this, the integrated wave module (based on advanced spectral wave formulations) simulates wave generation, propagation, refraction, diffraction, and wave–current interaction. Together, the hydrodynamic and wave modules provide a fully coupled framework that can represent complex physical processes in dynamic marine and freshwater environments, supporting both research applications and practical engineering design, which provides utility for MAGE interactions. For each MAGE "gamezone" (Figure 4), a new simulation is created with its own specific mesh or grid. The game zone of interest is determined in consultation with stakeholders, which in turn informs the numerical model's boundary. Several possible coastal protection interventions have been previously agreed upon, and their impacts are then simulated in the numerical model through iterations.

To support grid generation, the coastline polyline was imported into the GIS environment. The computational grid (mesh) was constructed in accordance with the defined coastline of the game zone. Bathymetric (bed-level) data were incorporated into the model, and selected intervention measures were implemented using the available modelling capabilities within the flow module. The wave and flow simulations were initially run separately. The wave model was run on a structured grid, using appropriate boundary conditions. The hydrodynamics were simulated on an unstructured grid utilising the Delft3D-FM framework. Boundary conditions were specified to simulate tidal water-level variations along the model domain's open boundaries. The use of an unstructured mesh enabled spatial refinement in areas of particular interest identified during the stakeholder consultation phase by increasing the grid point density in these locations. The spatial extent of the flow model domain was nested within the larger wave model domain, enabling wave propagation to be simulated prior to interaction with the hydrodynamic processes resolved by the flow model.

Once both the wave model and the Flexible Mesh flow model were verified to function independently as intended, they were coupled to create an integrated model. The integrated model was then exported, generating a set of files in various formats, including netCDF.

7. MAGE Vision Pipeline: Mesh Generation and Transformation

Translating numerical coastal model outputs into a real-time, interactive game-engine environment was one of the most technically demanding stages of the MAGE pipeline and a core contribution to this field in simulating natural coastal processes and housing and urban risk. Delft3D-FM produces simulation results on an unstructured flexible mesh: a computational grid composed of irregular polygonal cells whose resolution

varies spatially to concentrate computational effort where it is most needed (e.g., near coastal structures, tidal inlets, and regions of morphological interest). Each simulation run is exported. However, the unstructured nature of the Delft3D-FM mesh, in which individual computational cells have no fixed rectilinear adjacency, poses a fundamental challenge for raster-based visualisation and integration into game engines, both of which typically operate on regular grids.

The transformation pipeline begins by extracting face-centred mesh coordinates and associated hydrodynamic variables from the netCDF outputs. For each run, the two-dimensional face positions define the spatial location of each computational cell centroid in projected coordinates (EPSG:3857, Web Mercator). Physical quantities of interest are derived from variables such as water surface elevation, water depth, and sediment bed level. Prior to any spatial processing, valid timesteps are identified by scanning each variable's time dimension for non-NaN (not a number) entries; incomplete outputs, arising from spin-up periods, boundary effects, or early termination, are discarded. Cells outside the active domain are masked to prevent propagation of invalid values.

Coordinate reference system (CRS) alignment is a prerequisite for integration with the wider MAGE geospatial dataset. Delft3D-FM outputs must be reconciled with the British National Grid (EPSG:27700) used by the Environment Agency LiDAR Digital Terrain Model (DTM) tiles and the aerial imagery baseline. CRS metadata is extracted directly from the netCDF files by inspecting CF-Conventions grid-mapping variables, coordinate-variable attributes, and global dataset metadata. Where reprojection is required, the unstructured point set of mesh face centroids is transformed prior to interpolation, ensuring that all subsequent spatial operations occur in a consistent projected coordinate frame with metrically meaningful distances and extents.

The central transformation step interpolates irregularly sampled model outputs onto a regular rectilinear grid. This is implemented via scattered-data interpolation using linear triangulation: A Delaunay triangulation is constructed over valid mesh centroids, and values are linearly interpolated within each triangle to evaluate the field at target grid nodes. The target grid extent and resolution are defined by the intersection of the Delft3D-FM model domain with the LiDAR DTM mosaic footprint, ensuring that interpolated hydrodynamic layers and terrain elevation share a common spatial support. The resulting rasters represent hydrodynamic variables at a resolution that balances visual fidelity against computational tractability for real-time rendering.

Following interpolation, hydrodynamic grids are co-registered with the LiDAR DTM mosaic. The terrain baseline is assembled by stitching together multiple high-resolution LiDAR tiles that span the core MAGE study region. Both the interpolated model outputs and the DTM are warped to a common square raster using bilinear resampling, with dimensions selected to satisfy Unreal Engine Landscape resolution constraints (of the form $n = (2^p \times k) + 1$)). Elevation values are then normalised to the full 16-bit unsigned integer range (0–65,535), encoding the study-area elevation span as a 16-bit grayscale heightmap. The heightmap is exported using a binary-accurate 16-bit pipeline to preserve sub-metre precision, avoiding quantisation artefacts associated with standard 8-bit image export.

In parallel, an 8-bit RGB aerial texture is generated by warping the aerial imagery baseline to the same spatial extent and resampling to a power-of-two resolution consistent with common game-engine texturing conventions. Pixels outside valid data coverage are filled to delineate no-data boundaries. Together, the

16-bit heightmap and the co-registered aerial texture form a georeferenced terrain asset pair. These assets are imported into Unreal Engine as Landscape Actors, thereby reconstructing a three-dimensional terrain surface onto which hydrodynamic outputs are subsequently rendered. This pipeline presents model-driven environmental dynamics as an interactive coastal simulation environment for MAGE participants.

Within Unreal, the model run dynamics and translation in the vision pipeline simulate a permutation. Some permutations affect housing and infrastructure stock, in which the Unreal water actor touches the structures and activates a numerical counter button. This action also activates and highlights affected structures through a visible change in colour code within the 3D environment, highlighting and building fabric affected in any scenario.

8. MAGE Interface

The user interface is implemented as an on-screen overlay within the Unreal Engine environment. The interface is organised into three control groups (a, b, c): (a) climate scenario controls are positioned in the upper-left corner to specify the scenario year used to visualise the simulation output; (b) a dropdown menu in the upper-right corner allows players to switch between game zones (i.e., different coastal locations); and (c) intervention controls are anchored along the lower edge of the screen, enabling rapid and repeatable selection of adaptation strategies. This layout distinguishes between contextual parameters (scenario year and location) and management actions (interventions), thereby clarifying how different inputs shape the simulation.

8.1. Scenario and Game Zone Selection (a)

The climate scenario control is presented as a two-state toggle corresponding to NCERMS scenarios 2055 and 2105. This toggle format frames climate futures as discrete, comparable temporal horizons that can be toggled quickly during exploration. Functionally, it separates temporal framing from the interventions that modify the coastal landscape, thus enabling a structured comparison: players can hold the intervention set constant while switching the climate scenario year to assess how the same intervention strategy performs under different climate conditions. Game zone selection is provided through a dropdown menu. Separating location selection from the intervention interface reinforces the conceptual distinction between where an intervention is applied and what intervention is chosen. Available interventions vary by location, reflecting site-specific coastal characteristics.

8.2. Intervention Selection (b)

Interventions are represented as a set of consistently styled buttons. The interface supports both single- and multi-selection logic, enabling players to apply a single intervention or explore combined strategies. This is important for coastal adaptation, where interventions are often deployed as portfolios rather than isolated actions, and where combined effects may yield outcomes different from those of each measure applied independently. To support recognition and reduce interaction effort, the intervention buttons are deliberately large and visually uniform, incorporating both text labels and icons. This design is intended as a real, pressable button to make it clear to players which intervention is taken. Interaction sound effects provide additional feedback, reinforcing that a selection has been made and supporting confident, iterative

exploration. Upon activation, interventions are 3D-labelled in the game zone, assisting cognition and observation of coastal dynamics. A separate, highly salient GO button is placed at the bottom-right to formalise the transition from configuration to execution. This two-stage interaction reduces accidental activation and clarifies when the system will commit the chosen scenario/intervention set to the simulation update.

8.3. Pop-Up Information Panels (c)

Selecting an intervention triggers a pop-up information panel that provides a concise explanation of the intervention and its classification as a strategy. These panels provide just-in-time interpretive support in accessible language, without requiring users to navigate to a separate help screen. They are semi-transparent so that the coastal scene remains visible, maintaining continuity of visual attention and reinforcing the primacy of landscape interpretation. A close button enables a smooth exploration cycle that encourages repeated testing and comparison: select → check meaning → close → run/compare.

Across these interface elements, the following four design considerations guided implementation. First, landscape visibility was prioritised by confining controls to screen edges and using semi-transparent overlays to avoid obscuring the simulation view. Second, stable control placement was used to reduce cognitive load and build familiarity across repeated testing cycles. Third, the interface structure supports structured comparison by allowing users to vary one dimension (year, zone, or intervention set) while holding others constant, with a clear separation between contextual parameters and interventions. Finally, error prevention and reversibility are supported through toggleable intervention selection, dismissible pop-ups, and the explicit execution step enabled by the GO button. MAGE provides complete temporal control across time, dates, and years, and features a controllable weather system for dynamic effects, including built-in sounds that enable slide-controller control of clouds, rain, thunder, fog, and many other elements.

9. Discussion

MAGE, a proof of concept spanning five digital tools, is an experiment informed by tabletop game design for spatial computing. MAGE is intended to serve as a discussion point in coastal adaptation workshops and to educate communities on SMP policies, facilitated by specialists during post-play discussions to explore the decisions and options made during play. Marine-based serious games have a number of precedents, such as Dilemma Game: The Wind at Sea (OLAMUR, 2025), adaptation decisions (NIWA, 2025), and climate risks for cities (CCA, 2015). The range of serious games provided parameters for framing, natural systems, reasoning and decision-making, and computational thinking around puzzles and logic (Parekh et al., 2021; Poole et al., 2022).

9.1. Limitations

The digital chessboard (4th tool) adopts a human-in-the-loop approach intended to capture ideas not accounted for and provide strategic input to further Delft3D-FM model interactions. However, while a number of what-ifs run through MAGE, there is an obligation to explain the uncertainty inherent in the approach that has been designed. Coastal management requires confidence in results, and quantifying these values is critically important through model calibration and validation and uncertainty explanations (Kroon

et al., 2025; Lyddon, 2020; Lyddon et al., 2023). MAGE's approach to addressing uncertainty is to provide transparency in its presentation section by explaining the limitations of scenarios. MAGE's lightweight coastal numerical model also requires further resources and further detailed uncertainty assessments. The proof-of-concept of MAGE numerical modelling was intended to be "lightweight," meaning that high-density models and calibration and validation phases require more rigorous development due to resource constraints. While MAGE has a twinned aspect from the variety of assembled data sources and the model aspect, its virtualisation and simulation require careful deployment and co-design integration in workshops to be effective instruments, guided by coastal engineers and scientists to qualify and support queries raised by the general public. Visualisation and the presentation of quantifiable information are key aspects that will require multiple iterations (Percival et al., 2020). Ultimately, reflecting on how MAGE, as a system, would function, it relies on careful curation and embedding as an artefact for engagement and decision-making.

Developing three tools for MAGE has achieved significant advances in the state-of-the-art through the transformer function that links numerical coastal models to game engine simulations, and a custom gameplay interface. MAGE, as a system, can be replicated across additional game zones (study areas) using computational resources and a game-engine pipeline, and will be released at the end of the project cycle as open science in 2027. However, long-term challenges exist around utilisation and the embedding of the tools within wider gamezones of significant areas of risk under NCERMS in the UK. In addition, MAGE, as a simulation artefact, can present sensitive visualisations of "what-ifs" to people whose properties may be affected by coastal erosion and flood risk during community consultation at scenario time points. Careful coastal adaptation pathway workshops are required to frame discussion about future preparation through co-design. Again, reflecting on the open questions in the introduction, MAGE, as a sandbox, has agency in expressing a number of future possibilities, educational learning, and experiences that are framed with stakeholders.

MAGE is limited as a learning system for pre-processing coastal scenarios compared to real-time computation, and there is a significant opportunity to explore surrogate AI models for synthetic coastal data. In addition, the replicability of MAGE as a proof of concept relies on expertise, access to HEC infrastructure, and the processing times of coastal model runs. Furthermore, existing investments in data sources and UK national data providers create a unique ecosystem that is not necessarily replicable in other countries. MAGE is a highly multidisciplinary team embedded within a wider Our Future Coast programme and work streams that hold particular team expertise and connectivity that would be difficult to apply in smaller research teams. In addition, MAGE, as a proof of concept, requires socio-technical collaboration and careful management of expert boundaries and scientific overlaps.

The extent to which risk is quantified in simulations is a current limitation; while this may be preferable for hazard and risk underwriting professionals and researchers, the rationale rests on two decisions. First, this quantified risk aspect has been limited in the current iteration. MAGE remains a black box due to deployment considerations in communities that could be affected by major changes across the two scenario phases. Second, further co-design of coastal adaptation workshops is required to embed the process and is limited from an ethical perspective. Our research acknowledges the large body of further work to be undertaken around hazard risk, uncertainty and visualisation. However, MAGE tools are open processes and replicable practices that can be adapted for purpose and deployment across other sites, or gamezones, such

as coastal cells in the UK (e.g., The Humber, Cell 1, Norfolk, Cell 3 or Cornwall, Cell 6 & 7) with higher sea-level and coastal erosion risks, or further afield.

10. Conclusion

MAGE is a proof-of-concept case study that has developed interrelated tools for SMP policies, coastal adaptation, and community education in the North-West. MAGE will develop and deliver additional game zones and community consultation events, wider dissemination activities, and further iterations of the 4th tool, particularly around the visualisation of risk and the coastal modelling of nature-based solutions alongside virtual and augmented variations of MAGE in the 5th tool. The MAGE contribution to knowledge is the translation of SMP policies into strategic serious games to enable participation, alongside the translation of numerical coastal models into a game engine and a unique interface. The MAGE sandbox and its portability enable deployment at workshop events with communities directly affected by a number of future simulations and scenarios, shifting the role of participation from one-way interaction to a co-designed, two-way experience, placing users at the heart of the decision-making space for coastal management.

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Conflict of Interests

The authors declare no conflicts of interests.

Data Availability

Three of the five MAGE tools are available here: mobile app for VGI and public coastal perceptions (https://imagination.lancaster.ac.uk/project/lets-map-our-future-coast), large-scale tabletop game of the North-West coast (https://research.lancaster-university.uk/en/publications/mage-a-serious-game-for-coastal-futures), MAGE mini game for KS3 Geography (https://research.lancaster-university.uk/en/

publications/mage-mini-a-serious-game-for-coastal-futures). The remaining tools will be hosted in 2027: https://futureenvironmentslab.co.uk.

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No LLMs have been used in the production of this research article.

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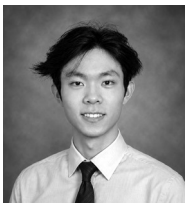
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ARTICLE

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The Virtual Embodied Experience: Virtual Reality as a Medium for Computing, Analysing, and Representing the Cityscape

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Abstract

The increasing availability of urban data has transformed how the built environment is analysed and designed, yet the tools used to represent and interpret that data remain largely abstract and symbolic. Virtual reality (VR) offers the possibility of engaging with spatial data immersively, but its role in architectural and urban research remains predominantly confined to visualisation and simulation. The extent to which VR supports embodied interaction with data, where users experience and interpret information through spatial presence and movement, remains underexplored. This article addresses this gap through a systematic literature review of Scopus and CumInCAD (Cumulative Index of Computer Aided Architectural Design), comparing interdisciplinary and architecture-specific research across three dominant themes: representation and analysis, simulation, and embodied interaction. The findings reveal a conceptually fragmented field: While computational research has advanced VR simulation significantly, embodied approaches remain weakly integrated with data-driven workflows. To address this divide, the article proposes virtual embodied experience (VEE), a framework that positions VR as a cognitive interface through which environmental data are navigated as a spatial condition rather than consulted as an abstract output. The implications of VEE are discussed in relation to emerging professional requirements established by the Architects Registration Board and the Royal Institute of British Architects around climate literacy, lifecycle thinking, and ecological design.

Keywords

built environment; embodied interaction; immersive analytics; spatial computing; virtual reality

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1. Introduction

The increasing availability of digital data has transformed how the built environment is analysed, designed, and managed. Advances in sensing technologies, computational modelling, and urban data infrastructures have enabled architects and planners to access unprecedented volumes of information relating to energy consumption, environmental performance, mobility patterns, and ecological systems. Moreover, virtual reality (VR) and spatial computing offer new ways to interact with these data, opening a possibility where architectural practice moves from drawing and modelling toward data-driven and experience-based modes of design.

This transformation is reinforced by evolving professional frameworks, particularly those established by the Architects Registration Board (ARB) and the Royal Institute of British Architects (RIBA). Both institutions now mandate climate literacy, lifecycle thinking, energy performance, and biodiversity awareness as core professional competencies (ARB, 2024; RIBA, 2021). These requirements demand a more direct engagement with complex datasets, integrating them into the design process. However, despite the growing importance of data, the tools used to represent and interpret them remain largely rooted in abstract and symbolic formats, such as drawings, diagrams, and dashboards. While effective for communication, these modes of representation often fail to capture the spatial and experiential dimensions of environmental data, limiting their role in decision-making.

VR enables users to engage with spatial information in an immersive way. However, while VR adoption for visualisation, simulation, and communication within architecture and urban planning is extensive, its role remains largely confined to representation and presentation, with limited integration into analytical and decision-making processes. In particular, the extent to which VR supports embodied interaction with data, where users experience and interpret information through spatial presence and movement, remains underexplored.

This article addresses this gap by examining how VR is currently used in the built environment and to what extent it has progressed from representation toward embodied interaction with data and simulations. It proposes the concept of virtual embodied experience (VEE) as a framework for understanding VR as a cognitive interface through which spatial data can be experienced and interpreted. By situating this concept within broader developments in spatial computing and embodied cognition, the article aims to bridge the divide between computational and experiential approaches to VR.

Methodologically, the study adopts a systematic literature review (Page, Moher, et al., 2021) of Scopus and CumInCAD (Cumulative Index of Computer Aided Architectural Design), enabling a comparison between interdisciplinary and architecture-specific research. The analysis identifies three dominant themes—representation, simulation, and embodied interaction—and evaluates their relative development within the field.

The article is structured as follows: Section 2 establishes the theoretical framework across spatial computing, embodied cognition, and VEE; Section 3 describes the methodology; Section 4 presents results across the three themes; Section 5 discusses the disciplinary divide and positions VEE as a bridging framework; and Section 6 addresses implications for professional practice in relation to ARB and RIBA. Despite VR maturing as

a technological platform, its potential for embodied interaction with data remains underdeveloped. Addressing this limitation is essential for advancing data-driven design practices in the built environment.

2. The Urban Canvas and Embodied Experience

2.1. Spatial Computing in Architecture

In spatial computing, digital information is embedded within and interacted with through 3D space. It is the integration of computation with 3D environments, enabling users to interact with digital content as if it were part of the physical world (Greenwold, 2003; Shekhar & Vold, 2020). This approach has paved the way for advances in VR and AR (augmented reality), positioning space itself as the primary interface for computation.

Spatial computing in architecture and urbanism aligns two streams: a shift toward data-driven design and a need for more tacit, embodied interaction with data in the design process. As Batty (2013, 2018, 2024) argues, contemporary urban analysis relies on computational models that simulate and predict urban processes. Digital twins extend this logic further, enabling real-time synchronisation between physical environments and their virtual counterparts (Grieves & Vickers, 2017). However, while these tools have improved our ability to analyse data, their interfaces are often hard to navigate, relying on dashboards, maps, and models (Chen et al., 2017; Miranda et al., 2024). Spatial computing, especially in immersive environments, offers something different: It lets people experience urban data in a more physical way, not just as symbols. This technology can be seen as an "urban canvas," a digital space where data, simulation, and design come together (Batty & Hudson-Smith, 2005).

2.2. Embodied Cognition

The theoretical underpinnings of spatial computing in architecture lie in the concept of embodied cognition, which challenges the view of cognition as purely abstract or computational. Spatial perception is situated in the body and shaped by sensory engagement (Mallgrave, 2013; Merleau-Ponty, 1962). Polanyi (1973) distinguishes between tacit and codified knowledge, where tacit knowledge requires face-to-face contact and embodied experience; a distinction extended into architectural theory by Hale (2017) and Robinson and Pallasmaa (2015). Cognitive scientists argue that human reasoning is grounded in bodily experience and spatial narratives (Varela et al., 1991). Jelić et al. (2016) have proposed that designed environments enact embodied cognitive processes through relational coupling between person and environment.

Architecture is a multisensory and embodied experience (Pallasmaa, 2012). Yet representations of architecture performance datasets remain abstract, creating two separate disciplinary regimes: one concerned with precision and data gathering through sensor simulations and digital twins, and another that deals with the narrative as well as qualitative counterpart of visual representation, scale, and atmosphere. VR systems induce a sense of "being there," allowing users to perceive and respond to virtual spaces in ways analogous to physical environments (Slater, 2009; Slater & Wilbur, 1997). More recent work on presence and immersion demonstrates the possibility of operationalising embodiment within digital environments through sensors, simulations, and digital twins (Slater, 2018; Slater & Sanchez-Vives, 2016). Traditional representations, plans, sections, and even GIS visualisations abstract spatial experience into symbolic

formats, often failing to capture the social and experiential dimensions of urban space critical to supporting design decision-making (Dembski et al., 2020; C. Zhang et al., 2021).

2.3. VEE

VEE results from the convergence of spatial computing and embodied cognition within immersive environments. Unlike conventional visualisation, which positions the user as an external observer, VEE situates the user within the data space itself, where understanding arises through interaction, movement, and scale rather than observation. Environmental data—temperature gradients, pollution levels, and energy flows—are perceived as experienced spatial conditions, enabling a more situated and intuitive form of interpretation.

This trajectory builds on Negroponte's (1975, 1995) anticipation of computation as an interactive design medium, extended by Batty (2007, 2024) and Kalay (2004) into urban systems capable of simulation and analysis. Recent work in immersive analytics, including Bach et al. (2018), Marriott et al. (2018), and Safikhani et al. (2024), demonstrates that interaction and immersion enhance users' ability to interpret complex datasets, suggesting a progression from representation to simulation to experience. However, immersive analytics has largely focused on abstract datasets; its application to the built environment remains limited. This article extends that trajectory by proposing VEE as a cognitive interface for architectural research and design, through which the urban canvas becomes not merely a visualisation of the city but an experiential medium for engaging with its data.

3. Methodology: Systematic Literature Review

This article employs a systematic literature review (Page, McKenzie, et al., 2021; Page, Moher, et al., 2021) to examine the extent to which developments in VR applications within the built environment have engaged with the emerging concept of VEE. It addresses the following research question:

> To what extent are embodied interactions with data and simulations developed in academic research on VR in the built environment?

3.1. Database Selection

Two databases were selected to balance interdisciplinary breadth with domain-specific depth. Scopus provides broad coverage of peer-reviewed literature across computer science, engineering, social sciences, and environmental studies, ensuring coverage of VR research, human–computer interaction, and immersive technologies. CumInCAD complements this with a focused repository of architecture and design computation research, capturing practice-oriented and experimental work not typically indexed in broader databases.

3.2. Search Strategy and Screening

Keywords were organised into three thematic blocks: (a) immersive technologies, (b) urban and architectural contexts, and (c) analytical or representational functions, combined using Boolean operators. A representative

Scopus query is: ("virtual reality" OR VR OR "immersive environment*" OR "spatial computing") AND (urban OR city OR architecture OR planning) AND (analysis OR simulation OR visualisation OR representation). Searches were limited to 1993–2023 across Engineering, Social Sciences, Arts and Humanities, Environmental Sciences, and Computation. Three targeted searches were conducted for each theme: representation and analysis, simulation, and embodied interaction. The same three themes were applied in CumInCAD using the queries "data analytics," "simulation," and "embodied experience."

Following PRISMA 2020 guidelines (Page, McKenzie, et al., 2021), duplicates were removed, and titles and abstracts were screened against inclusion criteria: peer-reviewed articles and conference papers focused on urban design, architecture, or spatial planning involving spatial data, environmental modelling, or design processes. Studies unrelated to the built environment, including gaming and entertainment applications, medical VR research, hardware-only papers, and non-peer-reviewed sources, were excluded. However, studies using game engines as tools for constructing urban simulation environments were retained where relevant, as these are distinct from gaming applications. From the remaining pool, five key papers per theme per database were selected based on relevance to the research question, citation impact, and methodological fit, yielding 15 core studies across the three themes. The full screening process is illustrated in the PRISMA flowchart (Figure 1).

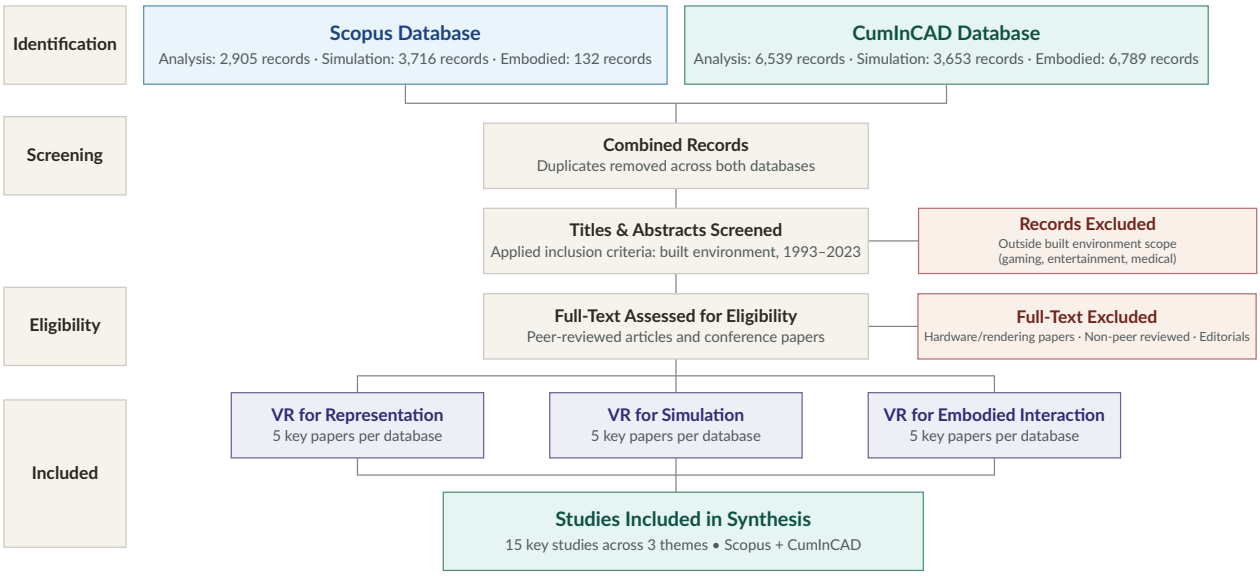


Figure 1. PRISMA 2020 flow diagram: VEE systematic literature review. Source: Adapted from Page, McKenzie, et al. (2021).

4. Results: Three Dominant Research Themes (Scopus + CumInCAD)

The systematic literature review, conducted following PRISMA 2020 guidelines (Page, McKenzie, et al., 2021), identified three dominant research themes in the use of VR within the built environment: (a) representation and analysis, (b) simulation, and (c) embodied interaction. Structured searches in Scopus, complemented by parallel searches in CumInCAD, enabled a comparison between broader interdisciplinary research and architecture-specific discourse.

4.1. VR for Urban Representation (Analysis Search)

The analysis-focused search returned 2,905 documents in Scopus. Much of this work remains at the level of enhanced visualisation rather than rigorous analytical processing. Y. Zhang et al. (2020), in a bibliometric review of 229 Scopus articles, found that VR research predominantly addresses visualisation, design communication, and stakeholder engagement rather than data analysis. Shehadeh et al. (2025) confirm this pattern, demonstrating that Building Information Modelling–Virtual Reality integration in urban development primarily serves design precision and communication, reporting a 62% increase in stakeholder engagement and a 48% improvement in spatial awareness, while data-driven analytical functions remain secondary. Portman et al. (2015) offer an early and widely cited example, concluding that VR's primary contribution lay in enabling users to navigate and visualise spatial proposals rather than interrogate underlying data. The CumInCAD dataset, returning approximately 6,539 results, reinforces this pattern: Most studies emphasise design exploration and visualisation over computational analysis. Across both datasets, VR is predominantly used to communicate design intent and support architectural presentation.

4.2. VR for Simulation (Simulation Search)

The simulation search returned 3,716 documents in Scopus, the largest of the three themes, and approximately 3,653 in CumInCAD. Both datasets show a move away from static representation toward dynamic, data-rich environments, though the character of that movement differs between sources.

Scopus simulation research is primarily technically rigorous. Hu (2025) developed a VR-based system for green building environment design and thermal energy management, demonstrating a 20% improvement in energy consumption prediction accuracy and a 30% reduction in design cycle time. Shawash and Marji (2023) integrated VR into an architectural pedagogy workflow for daylight design, showing VR enabling real-time environmental modelling. In both cases, however, interaction remains mediated through interfaces: Users adjust parameters within dashboards rather than experiencing data as spatial conditions.

CumInCAD presents a contrasting orientation, where simulation tends toward design experimentation. Loyola et al. (2019) deployed a game engine-based VR environment, distinct from gaming or entertainment applications, in a participatory urban design process in Santiago, Chile, enabling community members with no prior digital experience to navigate and evaluate spatial proposals. Similarly, Dembski et al. (2020) developed an interactive VR urban model of Herrenberg, Germany, prioritising citizen engagement over technical performance outputs. This suggests two parallel directions: one grounded in engineering precision, the other in design-led exploration and public engagement.

4.3. VR for Embodied Interaction (Embodied Search)

The embodied search returned only 132 documents in Scopus, markedly fewer than representation and analysis (2,905) or simulation (3,716). This imbalance reflects a genuine limitation of the field rather than a methodological gap: Embodied approaches to VR remain marginal within interdisciplinary research. That the theme was nonetheless identified as a distinct category reflects its conceptual significance, confirmed by CumInCAD, where the equivalent search returned approximately 6,789 results, demonstrating that embodied and experiential approaches are well established within architectural discourse specifically.

Hilmer (2024) and van Leeuwen et al. (2018) demonstrate VR's capacity to capture the qualitative aspects of urban environments, enabling communities to experience and evaluate design scenarios rather than merely observe them. Van Leeuwen et al. (2018) tested VR headsets with 1,302 citizens during a ballot on competing park designs, finding immersive VR equally effective as other display technologies in informing decision-making. However, a critical limitation emerges: Embodied interaction remains weakly integrated with data-driven workflows. The PaKOMM project (Hilmer, 2024) deployed VR and AR tools in a Hamburg participatory design workshop, enabling shared spatial understanding among residents, yet environmental and infrastructural performance data remained outside the immersive experience. This structural separation is representative across the field.

This divide is not between technical and academic research—both streams are academically rigorous—but between two epistemological orientations: a computational orientation, dominant in Scopus, prioritising measurable performance outputs; and a design-experiential orientation, dominant in CumInCAD, prioritising perception, presence, and qualitative spatial understanding (Kvan, 2000; Schnabel, 2009).

4.4. Synthesis

The review reveals a critical disciplinary divide. The Scopus dataset highlights research focused on representation and simulation driven by computational concerns, where users remain external observers of data (Hu, 2025; Shehadeh et al., 2025; Y. Zhang et al., 2020). In contrast, CumInCAD reveals a strong engagement with experience, perception, and embodiment, evidenced by the authors' participatory work (Hilmer, 2024; Loyola et al., 2019; van Leeuwen et al., 2018).

Representation, simulation, and embodiment should be understood not as separate categories but as overlapping trajectories. Yet the disciplinary landscape remains too fragmented for this progression to be fully realised. The computational orientation prioritises measurable outputs, while the design-experiential orientation emphasises lived spatial understanding, and integration between the two remains limited. VEE addresses this gap, proposing a framework that integrates data, simulation, and experience, positioning VR as a cognitive interface for the built environment.

5. Discussion: From Representation to VEE

This article examines the extent to which academic research on VR in the built environment has advanced toward embodied interaction with data and simulations. The results reveal a rapidly expanding field, but one that remains conceptually fragmented. VR adoption is widespread for representation and simulation. However, its development as a medium for embodied interaction is uneven. This section interprets these findings, highlighting a divide between computational and experiential approaches, and positioning VEE as a framework to address this gap.

5.1. Fragmentation Between Computational and Experiential Paradigms

The comparison between Scopus and CumInCAD reveals a disciplinary divergence in how VR is conceptualised and applied. Y. Zhang et al. (2020) characterise the resulting body of knowledge as vast, diverse, and fragmented. Scopus literature is dominantly technical, with a strong emphasis on simulation,

data integration, and analytical performance. As demonstrated by Hu (2025) and Shehadeh et al. (2025), the primary metrics of success in this stream are efficiency gains and energy prediction accuracy, outcomes measured through quantifiable outputs rather than spatial understanding. In contrast, CumInCAD reflects a design-oriented perspective, foregrounding perception, experience, and interaction (Loyola et al., 2019; van Leeuwen et al., 2018). This divergence is epistemological. The result is a fragmentation into two parallel streams: a computational stream where VR enhances analysis but lacks embodied engagement, and an experiential stream where VR supports interaction but remains weakly integrated with data.

5.2. Representation, Simulation, and the Limits of Interaction

The three dominant themes can be understood as stepping stones, but integration between them is neither linear nor complete. In the analysis-focused literature, exemplified by Portman et al. (2015) and Shehadeh et al. (2025), VR primarily extends traditional visualisation techniques. Data are treated as a visual output rather than an experiential condition. Simulation, as demonstrated by Hu (2025) and Shawash and Marji (2023), introduces greater interaction, enabling users to explore dynamic environmental systems. However, users manipulate parameters rather than engaging with data spatially. In the embodied stream, Ergan et al. (2019) and van Leeuwen et al. (2018) demonstrate VR's capacity to capture situated, physiological responses to spatial conditions. Nevertheless, environmental performance data, energy loads, carbon outputs, and material lifecycles remained external to the immersive experience in each case. The transition from observing data to experiencing them remains incomplete.

5.3. Embodied Interaction as an Underdeveloped Trajectory

The Herrenberg digital twin (Dembski et al., 2020) illustrates the core tension: A game engine-based urban VR model prioritised citizen engagement, while environmental performance data remained confined to external dashboards. Similarly, the PaKOMM workshops (Hilmer, 2024) provided shared spatial understanding through VR, yet disconnected from the analytical data informing those decisions. Embodied interaction is consequently treated as an enhancement rather than a fundamental mode of engaging with data, limiting VR's capacity to support the decisions that matter most in practice: choices about energy use, material selection, carbon reduction, and biodiversity that require both analytical rigour and spatial intuition to evaluate meaningfully.

5.4. VEE as a Framework

VEE is proposed as a cognitive interface through which data can be experienced spatially. Rather than representing or manipulating data, users navigate environmental variables—temperature, pollution, and energy flows—as perceived spatial conditions. VEE extends existing approaches in two directions. It embeds simulation data, of the kind produced by Hu (2025) and Shawash and Marji (2023), within spatial experience, making environmental performance perceptible as a quality of space. It also brings the embodied approaches of Hilmer (2024) and van Leeuwen et al. (2018) into direct contact with data-driven workflows. Ergan et al. (2019) provide an early indication of this convergence, capturing physiological responses to spatial conditions within immersive environments. VEE extends this by proposing that data themselves become part of the immersive experience, enabling a shift from Representation → Simulation → Experience within a unified conceptual model.

5.5. Implications for Research and Practice

The findings carry several implications. First, VR must move beyond its established role as a representational and analytical tool (Portman et al., 2015; Y. Zhang et al., 2020) toward one in which data are experienced rather than merely visualised. Second, greater integration between computational and design-oriented approaches is needed, combining the strengths demonstrated by Hu (2025) and van Leeuwen et al. (2018), respectively. Finally, as architectural practice confronts climate change, energy performance, and urban resilience, tools supporting intuitive, experiential understanding of data will become essential. VEE offers a framework for this, positioning VR as a medium for informed, situated decision-making in the built environment.

6. Implications for Practice: Aligning VEE with ARB/RIBA Agendas

The ARB's *Strategic Statement on Climate Change and Sustainability* establishes that all architects must maintain competence in the skills, knowledge, and behaviours required to address climate change through sustainable architecture (ARB, 2021, 2024). Architects Registration Board's (ARB) continuing professional development (CPD) framework specifies competencies including designing low- and zero-carbon buildings, preserving natural habitats to encourage biodiversity, and applying whole-life carbon analysis. The RIBA 2030 Climate Challenge reinforces these requirements, mandating submission of operational energy, embodied carbon, and water performance data, biodiversity net gain, and post-occupancy evaluation (Hasman, 2022; RIBA, 2021, 2024). Together, these frameworks signal a profession-wide shift toward data-intensive, ecologically conscious practice, one that current representational tools are ill-equipped to support (Dembski et al., 2020; C. Zhang et al., 2021).

VEE offers a direct response. Where ARB requires architects to understand the relationship between buildings and a changing climate, VEE enables those relationships to be experienced spatially, with energy flows, temperature gradients, and carbon loads becoming perceptible conditions within a navigable environment rather than abstract numerical outputs. Lifecycle thinking, central to both frameworks, is similarly served: As demonstrated by Hu (2025) and Shawash and Marji (2023), immersive simulation environments can model material and energy dynamics in real time. VEE extends this by making lifecycle data experienceable, enabling designers to perceive the consequences of design decisions as spatial conditions rather than spreadsheet outputs. Biodiversity requirements, which demand understanding of ecological systems as spatial and dynamic, are addressed through VEE's participatory potential, enabling non-expert stakeholders to engage with ecological data meaningfully, as demonstrated by Loyola et al. (2019) and van Leeuwen et al. (2018).

However, realising this potential requires more than technological development. Current VR applications in practice remain largely siloed, aligned with representation and simulation when data are present, and with embodied experience when atmosphere is the primary concern, but rarely both simultaneously. For VEE to influence ARB and RIBA agendas meaningfully, it must be integrated into professional workflows and design education curricula, positioning immersive environments not as presentation tools but as cognitive interfaces through which architects develop the climate literacy, lifecycle thinking, and ecological awareness that professional frameworks now demand.

7. Conclusion

This article has examined the extent to which academic research on VR in the built environment has progressed from representation toward embodied interaction with data and simulations. Through a systematic literature review of Scopus and CumInCAD, following PRISMA 2020 guidelines (Page, McKenzie, et al., 2021), three dominant research themes were identified: representation and analysis, simulation, and embodied interaction.

The findings reveal a rapidly expanding but conceptually fragmented field. VR is widely adopted for visualisation and simulation, as demonstrated by Hu (2025), Shawash and Marji (2023), Shehadeh et al. (2025), and Y. Zhang et al. (2020), yet these applications position users as external observers of data rather than experiential participants within them. Embodied and participatory approaches, exemplified by Ergan et al. (2019), Hilmer (2024), Loyola et al. (2019), and van Leeuwen et al. (2018), are conceptually well developed within architectural research but remain weakly integrated with data-driven workflows. Data interaction does not necessarily lead to embodied understanding.

This article proposes VEE as a framework to address this divide, positioning immersive environments as cognitive interfaces through which environmental variables such as energy flows, carbon loads, and biodiversity conditions are navigated as spatial conditions rather than consulted as abstract outputs. This reframing has relevance given the professional requirements established by ARB and RIBA around climate literacy, lifecycle thinking, and ecological design, where the capacity to interpret complex data spatially and intuitively is increasingly essential.

As VR technology matures, its potential for embodied interaction with data will only grow. Realising that potential will require both technical innovation and a conceptual shift across research, education, and practice, toward immersive environments understood not as tools of presentation, but as media through which the built environment is analysed, experienced, and ultimately designed.

Conflict of Interests

The author declares no conflict of interests.

LLMs Disclosure

The author used Claude (Anthropic) during the revision and final preparation of the manuscript to check in-text citations against the reference list, format references to the journal's APA guidelines, verify bibliographic details of cited works against publisher records, and copy-edit for grammar and consistency. No content, analysis, or argument was generated by the tool. All suggested changes were reviewed and verified by the author, who takes full responsibility for the content of the article.

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Creating Synthetic Road Networks Using Large Language Models: An Iterative Calibration Framework

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Abstract

Digital twins are used to represent and analyse urban environments, providing a basis for simulation, scenario testing, and communication among stakeholders. While effective, such models are typically developed as unique, data-intensive representations of specific cities. Synthetic cities extend this paradigm by enabling the systematic generation of entire families of digital twins. They provide controlled, repeatable, and easily calibratable environments, making it possible to conduct analyses that are more general, reproducible, and independent of costly or sensitive field data. Generating synthetic cities addresses several key needs in urban research. It supports the design and evaluation of regulatory scenarios, facilitates climate adaptation analyses, and enriches participatory design by providing semantically meaningful models for discussion. By decoupling experimentation from real-world data constraints, synthetic cities provide a robust framework for testing alternative urban forms and policies while preserving privacy and reducing costs. This article introduces a novel method for generating synthetic cities using large language models (LLMs). Specifically, we propose an iterative LLM-guided framework in which the model directly generates high-level synthetic road structures and calibrates them through tool-based structural feedback. Unlike procedural generators and neural generative models, which usually require manual parameter tuning and offer limited ways to enforce high-level semantic constraints, our LLM-based framework translates natural-language requirements into quantitative specifications and validates generated networks against target metrics. This supports the creation of adaptable, semantically meaningful synthetic cities suitable for simulation and scenario analysis.

Keywords

digital twins; large language models; synthetic cities; urban modelling

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1. Introduction

In recent years, spatial planning decisions have increasingly relied on simulation methods such as agent-based models (Barthelemy, 2019). Bonabeau (2002) points out that approaches grounded in microfoundations are especially valuable because they capture the complex behaviours of individual agents that cannot be properly represented in an aggregated model. However, these simulations require realistic environments in which agents can operate, and digital models—or "synthetic cities"—have recently become popular for this purpose, building on earlier work on virtual urban representations for visualisation, simulation, and scenario exploration (Batty & Hudson-Smith, 2001; Bilal et al., 2025). These synthetic environments help policymakers forecast the outcomes of their decisions (Zheng et al., 2023). At the same time, agent-based models are prone to artefacts that may be difficult to trace (Galán et al., 2009). Therefore, when testing new urban policies in a virtual city model, more robust conclusions may be obtained by evaluating them on a population of cities with similar structural properties rather than on a single city instance. Kim et al. (2018) argue that synthetic cities are particularly useful when they preserve the key structural features of real-world agglomerations—such as their transportation networks—while abstracting from irrelevant city-specific details, thereby providing standardised testbeds for policy evaluation. Such structures have been applied in contexts ranging from autonomous vehicle trials (Kim et al., 2018) and resilience analyses (Therias & Rafiee, 2023) to energy-demand forecasting (Roth et al., 2020).

Beyond enabling cross-regional comparability, synthetic cities also provide reproducibility for controlled experiments (Barbie & Hasselbring, 2024), cost-effective scenario testing without field deployments (Almirall et al., 2022), and privacy-preserving abstractions of sensitive urban data (Papyshev & Yarime, 2021). Xu et al. (2024) further point out that synthetic cities enable benchmarking of algorithms—from traffic-flow optimisers to emergency-evacuation planners—under identical conditions and facilitate rapid "what-if" analyses of land-use changes or infrastructure investments.

Existing approaches to synthetic city generation can be grouped into six families according to how the generation process is controlled: procedural (rule-based), graph-based (roads represented as abstract networks), tensor-field-based (street orientations encoded as spatial fields), simulation-based (agent- or process-based simulation driving growth), example-based (stitching together real-world fragments), and learning-based (neural generative models). A detailed review of these families is provided in Section 2.

To compare these approaches, we focus on four capabilities that are particularly important for using synthetic cities as reusable experimental testbeds:

1. Calibration: Adjusting the generator so that selected output metrics match a reference city;
2. Conditional attribute controllability: Explicitly constraining the generated city to satisfy user-specified quantitative or semantic attributes;
3. Zero-shot customisation: Supporting novel, user-specified design requirements without retraining or fine-tuning the generator;
4. Semantic reasoning: Interpreting high-level, natural-language urban concepts and translating them into consistent structural constraints.

As shown in Section 2 and summarised in Table 1, existing method families typically support only a subset of these capabilities. In particular, no single non-large-language-model (LLM) approach combines calibration and conditional control while also allowing zero-shot customisation, which motivates the contribution of this article.

The proposed approach offers two major benefits for digital twin developers. First, it decouples experimentation from real-world data, enabling easier construction of spatial simulation models. Second, it supports generating families of cities with desired spatial properties, which enables the development of more robust simulation models of urban environments.

The article is organised as follows. After this introduction, Section 2 presents the relevant literature. Section 3 introduces the proposed model, and Section 4 describes the experimental setup and evaluation procedures. Section 4.1 presents the experimental design, Section 4.2 reports the empirical results, and Section 4.3 discusses their implications. Finally, Section 5 concludes.

2. Literature Background

The goal of this section is to review the existing literature and motivate our contribution. The relevant work can be divided into three groups: synthetic city generation methods and their properties (Section 2.1), network comparison metrics used to assess the quality of a generated synthetic city (Section 2.2), and LLMs in the context of synthetic data modelling (Section 2.3). After reviewing these strands in Section 2.4, we present our contribution.

2.1. Synthetic City Generation Methods

Synthetic city generation methods can be grouped into six broad categories: procedural, graph-based, tensor-field-based, simulation-based, example-based, and learning-based. Each category is discussed in detail below.

Procedural methods generate cities through predefined rules. Parish and Müller (2001) proposed an extensible framework based on an enhanced L-system, in which roads are generated from production rules derived from global objectives and local constraints, after which the urban area is subdivided into plots and populated with building geometries. This design also allows additional city layers, such as points of interest, to be aligned with the road network. Weber et al. (2009) extended this approach to support more irregular and organically evolving layouts, while Beneš et al. (2014) introduced a dynamic variant in which trade, water transportation, and traffic simulation drive road-network growth over time. Overall, procedural methods are flexible and can generate complete, even dynamically evolving urban structures, but their outputs depend strongly on the predefined rules, parameters, and constraints.

Graph-based approaches represent roads as abstract networks and generate synthetic cities by reproducing structural properties of real-world road systems, such as hierarchy, sparsity, connectivity, and routing behaviour. In this line of work, Bauer et al. (2010) compared a Voronoi-based generator (Fortune, 1986) and the Abraham et al. road-network generator (Abraham et al., 2010) with OpenStreetMap-derived networks using structural and routing-based measures, including contraction hierarchies (Geisberger et al., 2008).

Both generators outperformed simple grid and unit-disk baselines, while the Voronoi-based approach more closely matched the hierarchy, sparsity, and routing performance of actual road systems. Lüscher and Weibel (2013) extended graph-based city modelling by incorporating semantic and functional data, such as topographic databases, points of interest, and user annotations. Overall, graph-based methods reproduce key structural properties of real-world road networks, but they may still generate unrealistic characteristics, such as excessive density or overly high node degrees.

Tensor-field approaches encode local street orientations in a spatial field and generate road networks by tracing streets along tensor-derived direction fields. G. Chen et al. (2008) introduced this approach by encoding local orientations through tensor eigenvectors and tracing streamlines to form hierarchical street networks. Sun and Dogan (2023) later extended the framework by allowing each tensor cell to store not only directional information but also land-use priorities, population density, and other non-geometric factors. In this way, tensor-field methods generate coherent directional patterns and can incorporate additional spatial information, although the resulting network depends strongly on what is encoded in the tensor field.

Zhang and Shi (2022) integrated a tensor-field framework with a simulation-based approach, illustrating the broader logic of simulation-based methods. In this family, road networks emerge through dynamic processes, making these approaches well-suited to capturing evolving and naturalistic urban structures. Their main advantage is the ability to represent hierarchy and local adaptation over time. In related work, Song and Whitehead (2019) proposed an agent-based method in which roads emerge through agents' interactions with resource nodes. Their main limitation is that the resulting form depends strongly on the behavioural rules, thresholds, and environmental factors specified in the simulation.

Example-based methods construct new layouts by copying and stitching fragments derived from real-world cities. Yu and Steed (2012) modelled existing urban structures as graphs and synthesised new nodes and edges by matching unfinished nodes with similar samples using a neighbourhood similarity measure, thereby supporting both entirely new structures and incremental network growth. Nishida et al. (2016) combined example-based and procedural techniques by fitting distinctive subgraphs from real-world cities into the target network and using a procedural fallback, guided by statistical features such as average road length and curvature, when no suitable patch was available. Overall, example-based methods preserve characteristic patterns from real-world cities, but the generated structure depends strongly on the quality and representativeness of the source examples.

Learning-based methods generate synthetic road networks by training neural models on examples of real urban layouts. Their main advantage is the ability to learn complex structural regularities directly from data, including patterns related to street density, hierarchy, connectivity, and block structure. Existing approaches include image-based models trained on rasterised road maps, graph-based models that operate directly on street-network representations, and sequential generative models that construct networks step by step. For example, Hartmann et al. (2017) used a generative adversarial network on binary rasters of OpenStreetMap road networks, Neira and Murcio (2022) proposed a graph-based approach combining a transformer with a variational graph auto-encoder, and Chu et al. (2019) introduced a sequential model, called "neural turtle graphics," for vector road graphs. Overall, these methods can capture rich structural patterns, but they typically require large training datasets and offer limited flexibility for imposing new constraints without retraining.

2.2. Network Comparison Metrics

Urban transport networks can be compared using methods that emphasise functional performance, structural topology, or latent graph representations. Existing work can be grouped into four broad families: (a) transport and routing metrics that quantify functional similarity; (b) graph edit and optimal-transport methods; (c) topological data analysis that captures higher-order connectivity and shape; and (d) graph kernels and neural approaches that embed graphs into feature spaces for statistical comparison. The following review summarises representative studies in each category.

Transport metrics compare urban networks by functional similarity rather than purely geometric or topological form. Common measures include density, degree distribution, shortest-path distance distributions, average road-segment length, intersection density, and circuity, which together capture connectivity, navigability, and route directness (Bauer et al., 2010; Neira & Murcio, 2022). The average path length similarity (APLS) metric extends this perspective by measuring mean relative deviations in shortest-path lengths between corresponding nodes (Chu et al., 2019).

Graph edit distance quantifies structural dissimilarity via the "cost" of transforming one transport network into another. For example, Li et al. (2014) adopt an optimal-transport perspective: They represent each city's metro system as a graph and measure pairwise differences with the Wasserstein distance, capturing both spatial arrangement and topology in a geometry-aware comparison.

A further line of work compares the topological shape of transport networks using topological data analysis (TDA), most commonly persistent homology. Feng and Porter (2020) used persistence diagrams to quantify connectivity and loops and to classify cities into broad morphological groups that differ in regularity and spatial organisation. Relatedly, Corcoran and Jones (2022) introduced persistence density functions to characterise connectivity across street classes and compared these distributions using the Wasserstein distance.

Another strand compares urban networks in an embedding space using graph kernels and graph neural networks (GNNs). Graph kernels represent each graph through features capturing local or global connectivity. For example, the shortest-path kernel compares all-pairs shortest-path lengths to measure similarity in overall distance structure, whereas the graphlet kernel counts small induced subgraphs, such as triangles and 4-cycles, to capture local motifs (Borgwardt & Kriegel, 2005; Shervashidze et al., 2009).

2.3. LLMs

Due to the novelty of this area, only a few studies have applied LLMs to synthetic city generation. Long et al. (2024) point out that LLMs have been used successfully for generating synthetic data. Rasal and Boddhu (2024) introduced NavGPT, a multimodal LLM that ingests aerial imagery and directly outputs precise road-network geometries. J. Chen et al. (2026) proposed network generation artificial intelligence (NGAI), an LLM-driven system that orchestrates specialised external plugins to produce fully routable road networks from either natural-language or image prompts. These studies demonstrate the potential of LLMs in road-network generation, but they do so either through multimodal input processing or by using the model primarily as an orchestration layer for external generation modules. By contrast, our article proposes an iterative LLM-guided framework in which the model itself directly generates and calibrates high-level

synthetic road structures using tool-based structural feedback. The novelty of our approach therefore lies in using the LLM itself as the core generator within an iterative calibration loop, rather than primarily as an orchestration layer for specialised external modules.

2.4. Contribution

The desired capabilities of synthetic city generators identified in the literature include the ability to calibrate against real-world data, conditional attribute control, zero-shot customisation, and the inclusion of semantic reasoning in the generation process. Calibration against real-world data involves adjusting the parameters of synthetic city models so that generated outcomes align closely with real-world urban metrics, such as road density, street connectivity, and traffic patterns (van Vliet, 2013). Conditional attribute control allows users to explicitly specify characteristics or constraints for city generation. For instance, users might define transportation network requirements, enabling highly customised synthetic urban network generation tailored to specific analytical or planning objectives (Gan et al., 2024). Zero-shot customisation describes the ability of generation systems to respond to novel design requirements without prior task-specific training or parameter tuning. In the present article, this capability is studied in a reference-conditioned setting, where the framework generates calibrated variants of a reference urban structure in response to new prompts rather than unconstrained cities from scratch. This feature is particularly valuable for exploring new scenarios quickly and efficiently, significantly extending the versatility and applicability of synthetic city generation (Rasal & Boddhu, 2024). At present, conventional methods do not support this capability. Finally, semantic reasoning involves the capacity to interpret and incorporate conceptual urban knowledge within the generation process. This might include identifying appropriate zones for residential, commercial, or industrial development, or placing amenities and infrastructure in a way that reflects high-level urban planning principles (Webb et al., 2023).

Existing families of methods (procedural, graph-based, tensor-field, simulation, example-based, deep-learning) each miss one or more important capabilities—such as zero-shot customisation, or true semantic reasoning—while only LLMs theoretically cover them all (Table 1). Moreover, prior systems either depend on specialised external modules or target only narrow facets (e.g., roads), and cannot spontaneously capture higher-order phenomena like emergent city centres without explicit rules. The literature lacks an end-to-end, LLM-guided approach for calibrated, vector-based synthetic city generation that affords conditional attribute control, zero-shot modifications, and semantic understanding of urban structure (Brown et al., 2020; Webb et al., 2023). Our article fills this gap by proposing exactly such an LLM-centric framework.

Table 1. Synthetic city generation methods comparison by selected features.

Feature	Procedural	Graph-based	Tensor Fields	Simulation-based	Example-based	Deep learning-based	LLM
Is calibrated	X	X	✓	X	✓	✓	✓
Conditional attribute controllability	X	X	X	X	X	✓	✓
Zero-shot customisation	X	X	X	X	X	X	✓
Semantic reasoning	X	X	X	X	X	X	✓

3. Synthetic City Generation

The proposed framework focuses on high-level road-network structure within synthetic cities. This section presents a novel LLM-backed method for synthetic road-network generation. It has two parts. First, we formalise the road-network model and introduce a distance metric for comparing synthetic road networks. Next, we describe the proposed LLM-based generation framework, which produces synthetic road networks that satisfy both qualitative user requirements and quantitative calibration constraints.

3.1. City Modelling

3.1.1. Road Network

We assume that the road network is represented in the form of a weighted, undirected (simple) graph $G = (V, E, w)$, where V is a finite set of vertices, $E \subseteq \{\{u, v\} \subseteq V : u \neq v\}$ is the set of edges of the graph (represented as unordered pairs of vertices), and $w : E \to \mathbb{R}_+$ assigns a positive weight to each edge.

A synthetic city is represented by $\mathcal{C} = (G, \phi, \kappa)$, with the underlying graph $G = (V, E, w)$ representing the road network. Vertices correspond to junctions, edges correspond to road segments, $\phi : V \to \mathbb{R}^2$ assigns planar (ENU) coordinates to vertices, and $\kappa : E \to \mathcal{K}$ assigns a road class to each edge where $\mathcal{K} = \{1, \ldots, K\}$, $K \in \mathbb{N}$ is a set of road classes. We denote by $\mathfrak{C}$ the set of all synthetic cities of this form.

3.1.2. City Similarity Distance

Let $\mathcal{C}_1 = (G_1, \phi_1, \kappa_1)$ and $\mathcal{C}_2 = (G_2, \phi_2, \kappa_2)$ be two synthetic cities. A similarity distance between cities is a function:

$$d : \mathfrak{C} \times \mathfrak{C} \to \mathbb{R}_{\geq 0} \tag{1}$$

We define d as an edge-length distribution discrepancy. $d(\mathcal{C}_1, \mathcal{C}_2)$ measures the discrepancy between the empirical distributions of road-segment lengths in the two cities. Let L_1 and L_2 denote the random variables "road-segment length" in cities $\mathcal{C}_1$ and $\mathcal{C}_2$ respectively, and let F_1 and F_2 be their cumulative distribution functions (see Togninalli et al., 2019). We define:

$$d(\mathcal{C}_1, \mathcal{C}_2) = \int_0^1 \left| F_1^{-1}(q) - F_2^{-1}(q) \right| dq \tag{2}$$

Where $F_i^{-1}(q) = \inf\{x : F_i(x) \geq q\}$ is the quantile function and $q \in [0, 1]$.

3.1.3. Road Network Compression

Road networks extracted from real-world cities often contain many degree-2 nodes that do not represent actual junctions or structural features, but instead encode road curvature. To simplify the graph for topological analysis, we apply a node-compression operation that removes these degree-2 nodes while preserving the network's overall connectivity and distances.

For the road network $G = (V, E, w)$ we define a node compression operation. Let $\deg(v) = |\{u \in V : \{v, u\} \in E\}|$ be the degree of a vertex $v \in V$. Consider a path $P_{\deg=2}$ in graph G, $P_{\deg=2} = (v_0, v_1, \ldots, v_k)$, $(v_0 \neq v_1 \neq \ldots \neq v_k)$,

$k \geq 2$, $\{v_i, v_{i+1}\} \in E$ such that the path's internal vertices all have degree 2 (i.e., $\deg(v_1) = \cdots = \deg(v_{k-1}) = 2$) and the first and last vertex have a different degree than 2 (i.e., $\deg(v_0) \neq 2 \wedge \deg(v_k) \neq 2$). We define *path compression* as deleting the vertices $v_1, \ldots, v_{k-1}$ from G and replacing the chain $(v_0, v_1, \ldots, v_k)$ with a single edge $\{v_0, v_k\}$. The weight of the new edge is set to the length of the compressed path, i.e.:

$$w'(\{v_0, v_k\}) = \sum_{i=0}^{k-1} w(\{v_i, v_{i+1}\})$$

If an edge $\{v_0, v_k\}$ already exists in G, then in the compressed graph we keep a single edge between v_0 and v_k with the minimum weight (distance). Additionally, if a connected component of G is a cycle whose all vertices have degree 2, then we delete this component entirely during compression. By the *compressed graph* $G' = (V', E', w')$ we mean the graph obtained after compressing all $P_{\deg=2}$ paths. Note that the compressed graph contains no vertices of degree 2.

3.2. Method

The method aims to generate a synthetic road network that satisfies both qualitative user requirements and quantitative similarity constraints with respect to a reference city. The workflow comprises two stages and is illustrated in Figure 1. The first stage produces a planar, high-level road network using an LLM-guided iterative loop with external validation tools. The second stage refines the accepted high-level structure by generating lower-level streets within planar regions using a Voronoi-based procedure, yielding a hierarchical, multi-layer road network.

The inputs to the procedure are a reference city $\mathcal{C}_0$ and a user specification $\mathcal{S}$. The reference city $\mathcal{C}_0$ serves as the calibration target and is represented as a compressed road-network graph. The user specification $\mathcal{S}$ is a natural-language prompt describing the intended structure of the target city. It may include qualitative descriptors (e.g., grid-like, radial, organic) as well as quantitative preferences, such as an acceptable calibration tolerance. The first stage generates a sequence of candidate cities $\mathcal{C}_k$ indexed by the iteration counter k. The loop starts at $k = 0$ and is bounded by the maximum number of iterations $k^{\max}$. Thus, k denotes the current iteration and $k^{\max}$ denotes the hard stopping criterion. The variable δ denotes the current calibration discrepancy between the reference and the candidate, i.e., $\delta = d(\mathcal{C}_0, \mathcal{C}_k)$, where $d(\mathcal{C}_0, \mathcal{C}_k) \geq 0$ is the city-to-city distance defined in Equation 1. In this article, d is operationalised as the one-dimensional Wasserstein distance between the empirical distributions of road-segment lengths in $\mathcal{C}_0$ and $\mathcal{C}_k$ (Equation 2), so δ measures how far the candidate's length distribution deviates from the reference distribution. At the beginning of the loop, we set $\delta = \varnothing$, which denotes the absence of feedback from a previous candidate. In subsequent iterations, δ becomes a numeric value that is used as structured feedback passed into the generator. The acceptance threshold is denoted by ε, and a candidate is considered sufficiently calibrated if $\delta \leq \varepsilon$.

At each iteration, the LLM agent invokes the generative routine `genHighLevelRoadNetwork`$(\mathcal{S}, \delta)$ to produce a candidate city $\mathcal{C}_k$. The term "LLM agent" refers to an LLM-driven controller that (a) synthesises a candidate high-level road structure consistent with $\mathcal{S}$ and (b) decides whether to regenerate based on tool-based validation results. Two tools are available to the agent. The tool `isPlanar`$(\mathcal{C}_k)$ returns a boolean value indicating whether the candidate road graph is planar, and the tool `wassersteinDistance` computes the calibration discrepancy $\delta = d(\mathcal{C}_0, \mathcal{C}_k)$. Planarity is treated as a hard feasibility requirement because the subsequent hierarchical refinement procedure relies on extracting planar regions

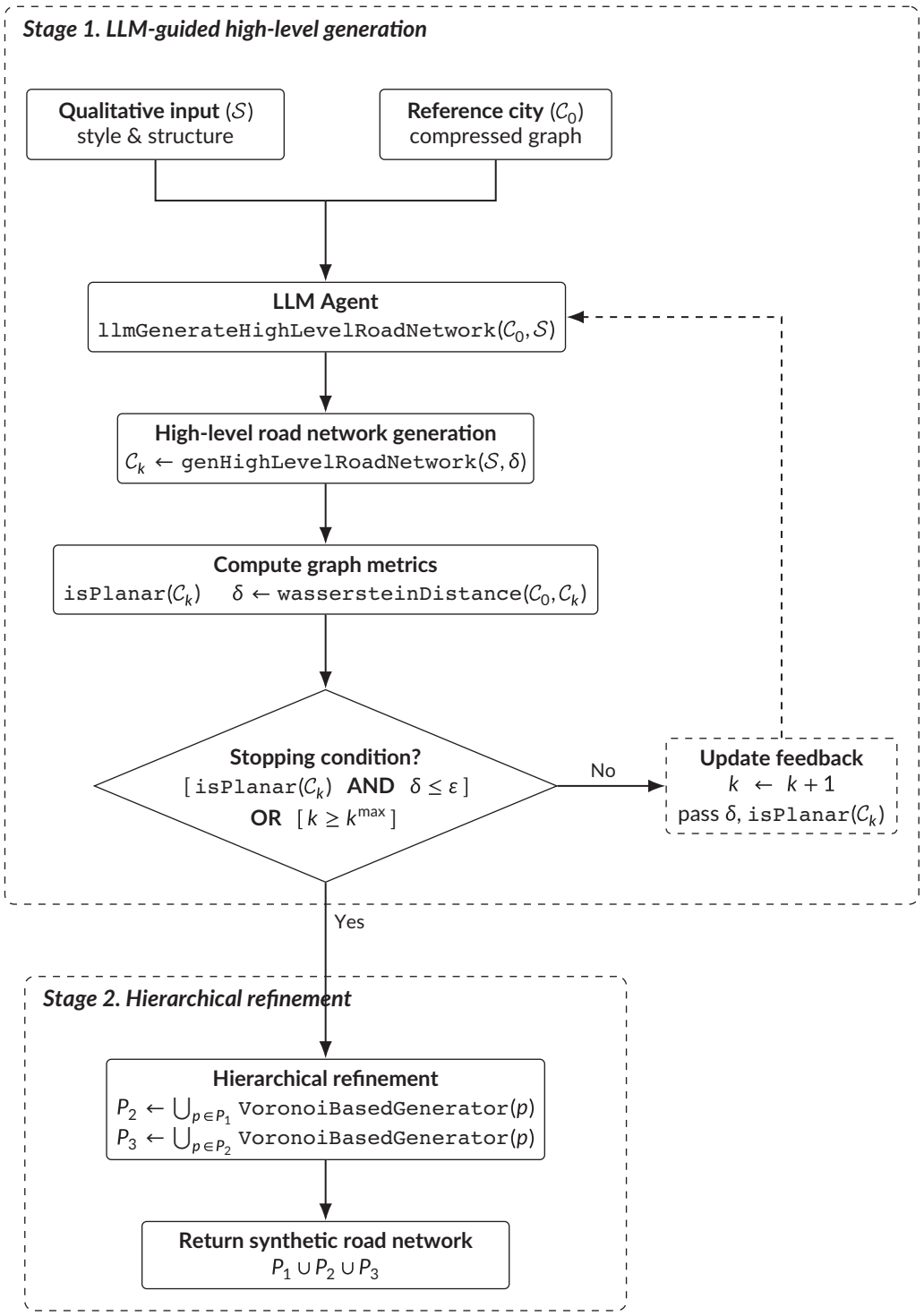


Figure 1. Flowchart of the proposed two-stage framework, where an LLM-guided iterative loop generates a planar high-level road network and a hierarchical Voronoi-based refinement adds lower-level streets.

(faces/polygons) from the road embedding; therefore, non-planar candidates are rejected by the stopping condition. The loop terminates when either the acceptance condition holds, i.e., when $\texttt{isPlanar}(\mathcal{C}_k)$ is true and $\delta \leq \varepsilon$, or when the iteration budget is exhausted, i.e., when $k \geq k^{\max}$. The output of the first stage is the final accepted high-level candidate $\mathcal{C}_k$, which provides the arterial backbone for further refinement.

The second stage (shown in Figure 1) performs hierarchical refinement of the accepted high-level planar road network by populating lower-level streets within the planar regions induced by the backbone. Let P_1 denote the set of level-1 regions (faces) obtained from the planar subdivision defined by the high-level network returned by `llmGenerateHighLevelRoadNetwork`$(\mathcal{C}_0, \mathcal{S})$. For each region $p \in P_1$, the procedure `VoronoiBasedGenerator`(p) generates an internal lower-level street layout and returns a set of sub-regions, i.e., new polygons created by this refinement. Conceptually, the Voronoi-based generator samples seed points inside p, constructs the Voronoi tessellation induced by these seeds, and then converts selected cell boundaries into street segments, thereby partitioning p into smaller blocks. Aggregating these sub-regions across all level-1 regions yields the level-2 region set P_2, and applying an analogous refinement step once more to all regions in P_2 yields the level-3 region set P_3. The final multi-level city representation is the union $P_1 \cup P_2 \cup P_3$, which encodes the full three-level hierarchical subdivision and the corresponding street network generated within each level. The synthetic streets obtained at each level are assigned the corresponding road classes.

4. Numerical Experiments and Validation

We evaluate the LLM-backed synthetic city modelling method by conducting a set of experiments where the target was the main road network of Warsaw's Ochota district. The goal was to generate a synthetic high-level road graph that (a) matches a selected statistical property of the reference system—namely, the distribution of road-segment lengths—and (b) is planar, because planarity is required for extending the network with lower-level streets using a Voronoi-based procedure. In addition to this main experiment, we conducted supplementary analyses to assess the applicability of the framework to reference systems with different spatial organisations, its robustness across different LLM backends, and its sensitivity to the temperature parameter. We start by describing the experimental design (Section 4.1); next, we present the computational results (Section 4.2); and finally, we discuss the experimental outcomes (Section 4.3).

4.1. Experimental Design

The experiment tests whether the proposed LLM-centred framework can reproduce selected quantitative characteristics of a real-world district without copying its geometry. We use the Ochota district in central Warsaw (approximately 3 km in diameter) as the reference system. The intended outcome is therefore not a geometric replica of Ochota, but a structurally plausible alternative road network that matches the chosen calibration targets and can serve as a backbone for hierarchical refinement.

Road network data for Ochota were obtained from OpenStreetMap and converted into a weighted, undirected graph as described in Section 3.1. We retained only roads labelled with the OpenStreetMap tags "motorway," "trunk," "primary," and "secondary," treating them as the district's high-level transportation skeleton. The graph was then cleaned so that vertices correspond only to true junctions and endpoints: Intermediate shape points along road polylines were removed by compressing degree-2 paths into single weighted edges while preserving total segment lengths (Section 3.1.3). The resulting preprocessed graph constitutes the reference city $\mathcal{C}_0$ used for calibration.

To isolate the contribution of the LLM layer, we compare two generation settings that share the same reference city $\mathcal{C}_0$, the same acceptance thresholds, and the same evaluation pipeline: (a) a non-agentic

baseline in which a high-level road network is generated using the Voronoi-based generator without iterative parameter updates (Bauer et al., 2010) and (b) an LLM-guided loop in which the full iterative procedure in Stage 1 is executed, i.e., the LLM produces candidate networks and uses tool-based feedback (`isPlanar`, `wassersteinDistance`) to refine its subsequent proposals until acceptance. For the LLM-guided experiments, we used Claude Opus 4.5 with temperature set to 1.0, top $p = 1.0$, a context window of 200,000 tokens, and a Wasserstein acceptance threshold of $\varepsilon = 0.05$. In the LLM-guided setting, we use a hard stopping criterion of $k^{\max} = 30$ iterations. If the acceptance conditions are not met within the budget, the best-so-far candidate is retained for reporting.

In both settings, we quantify similarity to the reference using the road-segment length distribution discrepancy defined in Section 3.1.2. Concretely, for each generated graph, we compute (a) the one-dimensional Wasserstein distance between the normalised empirical road-segment length distributions of the reference and the generated network (Equation 2) and (b) the two-sample Kolmogorov–Smirnov (KS) distance between the corresponding empirical cumulative distribution functions (ECDFs; Equation 3, defined in Section 4.2.1).

After obtaining an acceptable planar high-level graph, we apply the Voronoi-based subdivision procedure twice to generate two additional lower road levels, producing a three-level synthetic road network consistent with the hierarchical generation setup in Stage 2. These extended networks are used for qualitative illustration. To quantify variability, we run each setting for $n = 16$ independent trials. The next section reports the distributions of Wasserstein and KS distances, along with representative qualitative examples of generated networks.

4.2. Results

4.2.1. LLM-Based Approach and Voronoi-Based Approach Comparison

We evaluate whether the proposed LLM-centred loop (Stage 1) improves calibration of synthetic road networks relative to a non-agentic Voronoi-based baseline. In both settings, the reference city $\mathcal{C}_0$ is fixed, and each run produces a candidate high-level network $\mathcal{C}_k$. In the baseline setting, a single candidate $\mathcal{C}_1$ is generated directly by the Voronoi-based generator using fixed (default) settings (i.e., without iterative updates of generation parameters). In the LLM-guided setting, candidates are generated iteratively and updated using tool-based feedback, and the loop terminates when $\texttt{isPlanar}(\mathcal{C}_k)$ holds and $\delta \leq \varepsilon$, or when $k \geq k^{\max}$. For each generated graph, we compute the one-dimensional Wasserstein distance $d(\mathcal{C}_0, \mathcal{C}_k)$ (Equation 2) between the normalised empirical road-segment length distributions of the generated network and the reference Ochota graph. The implementation of the proposed framework, together with example prompts and selected response logs, is publicly available at https://github.com/AdamKasinski/synthetic_cities.

Using the Voronoi-based generator, we generated $n = 16$ independent graphs and computed the Wasserstein distance for each run. Figure 2 shows two sample synthetic cities generated after Stage 1 (blue) and after Stage 2 (red). The baseline achieved a mean Wasserstein distance of $\overline{W} = 0.105$ with a standard deviation of 0.0316.

With the LLM-guided generation, we executed the full LLM-guided loop (Stage 1) for $n = 16$ independent trials with a hard stopping criterion of $k^{\max} = 30$ iterations. In all 16 trials, the method returned a planar high-level graph within the iteration limit and produced the Wasserstein distances reported in Table 2. The number of iterations required for acceptance varied substantially across runs, ranging from 2 to 28, with a mean of 14. The observed variability was strongly affected by the conversational context in which the model was run.

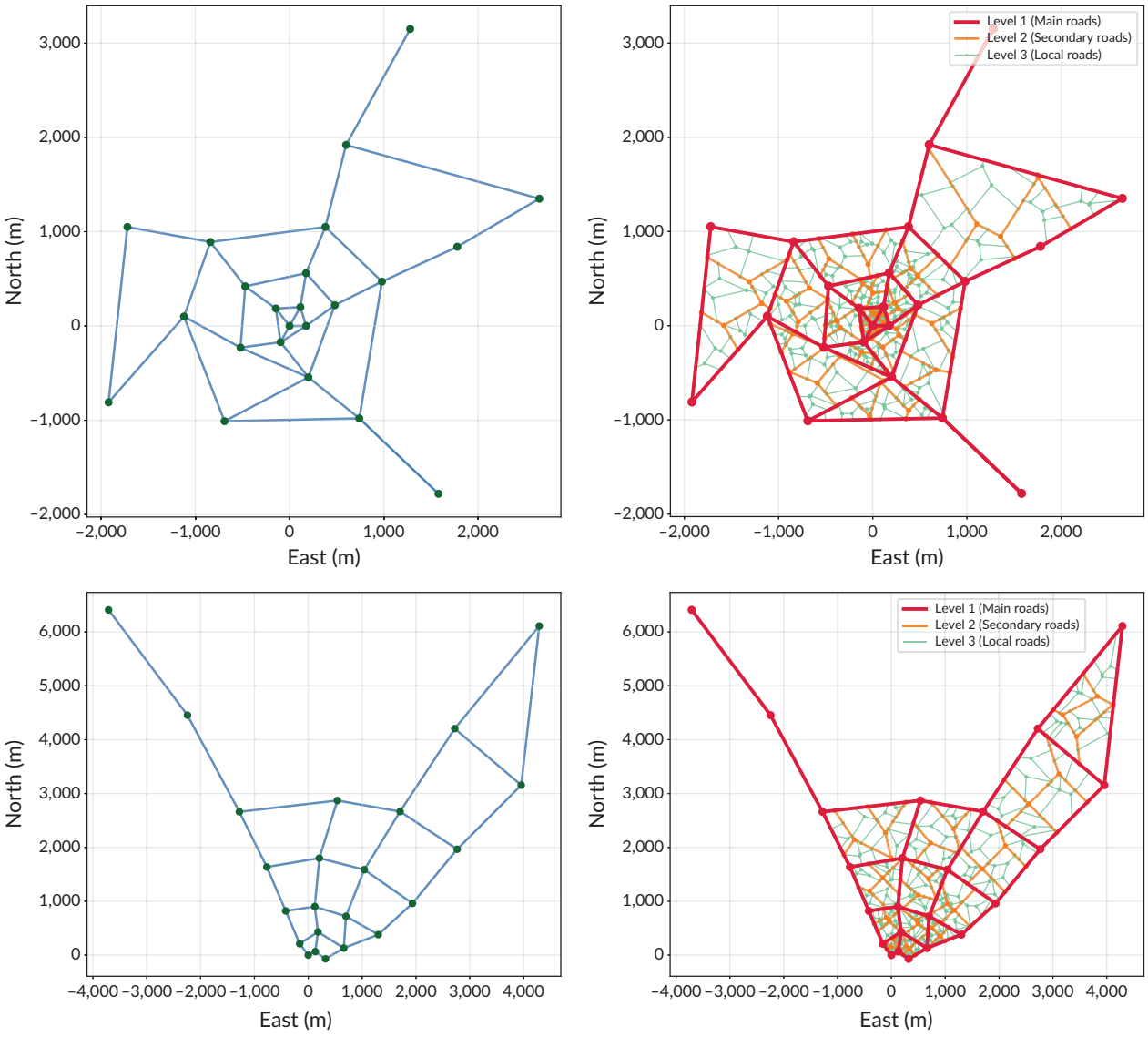


Figure 2. Two examples of the synthetic city generation process for Ochota District. The left column shows the planar high-level road backbones generated in Stage 1, and the right column shows the corresponding three-level networks obtained by two Voronoi-based refinement steps in Stage 2.

We also assessed distributional similarity using the two-sample KS distance, which captures the maximum pointwise deviation between ECDFs. Let $\hat{F}_0$ and $\hat{F}_k$ denote the ECDFs of the (normalised) road-segment length samples from the reference city $\mathcal{C}_0$ and a generated candidate $\mathcal{C}_k$, respectively. The KS distance is defined as:

$$D_{\mathrm{KS}}(\mathcal{C}_0, \mathcal{C}_k) = \sup_{x \in \mathbb{R}} \left| \hat{F}_0(x) - \hat{F}_k(x) \right| \tag{3}$$

Table 2. Wasserstein, KS, and Cramér–von Mises (CvM) distances for the 16 LLM-guided runs (planar and within $k^{max} = 30$ iterations).

Run	Wasserstein distance	KS distance	CvM distance
1	0.058	0.098	0.028
2	0.042	0.135	0.072
3	0.050	0.161	0.088
4	0.041	0.076	0.024
5	0.019	0.073	0.013
6	0.002	0.049	0.008
7	0.044	0.061	0.015
8	0.059	0.122	0.031
9	0.038	0.073	0.019
10	0.054	0.126	0.053
11	0.049	0.179	0.114
12	0.073	0.122	0.047
13	0.048	0.110	0.032
14	0.050	0.073	0.020
15	0.043	0.089	0.028
16	0.025	0.049	0.011
Mean	0.043	0.100	0.038
Std	0.016	0.039	0.030

Across $n = 16$ runs, the Voronoi baseline achieved a mean KS distance of $\overline{D}_{KS} = 0.156$ with standard deviation 0.026, whereas the LLM-guided procedure achieved $\overline{D}_{KS} = 0.100$ with standard deviation 0.039.

We also report the two-sample Cramér–von Mises (CvM) discrepancy, which captures the overall difference between the ECDFs. Across 16 runs, the Voronoi-based baseline achieved a mean CvM distance of 0.0881 (std. 0.0400), compared with 0.0377 (std. 0.0302) for the LLM-guided procedure, indicating a closer overall match to the road-segment length distribution. The following visual comparisons show two randomly selected examples from each method.

Figure 3 visualises the ECDFs of road-segment lengths for the reference Ochota network (solid blue) versus representative synthetic outputs (dashed red). The two upper panels (Voronoi-based) exhibit visibly larger vertical gaps between the ECDFs, indicating systematic distributional mismatch. Depending on the run, the Voronoi generator tends to over- or under-represent certain length ranges—most noticeably in the lower-to-mid segment lengths—which translates into a larger maximum ECDF deviation. In contrast, the two lower panels (LLM-guided) show the red curve closely tracking the blue curve across most of the support, with only small local departures.

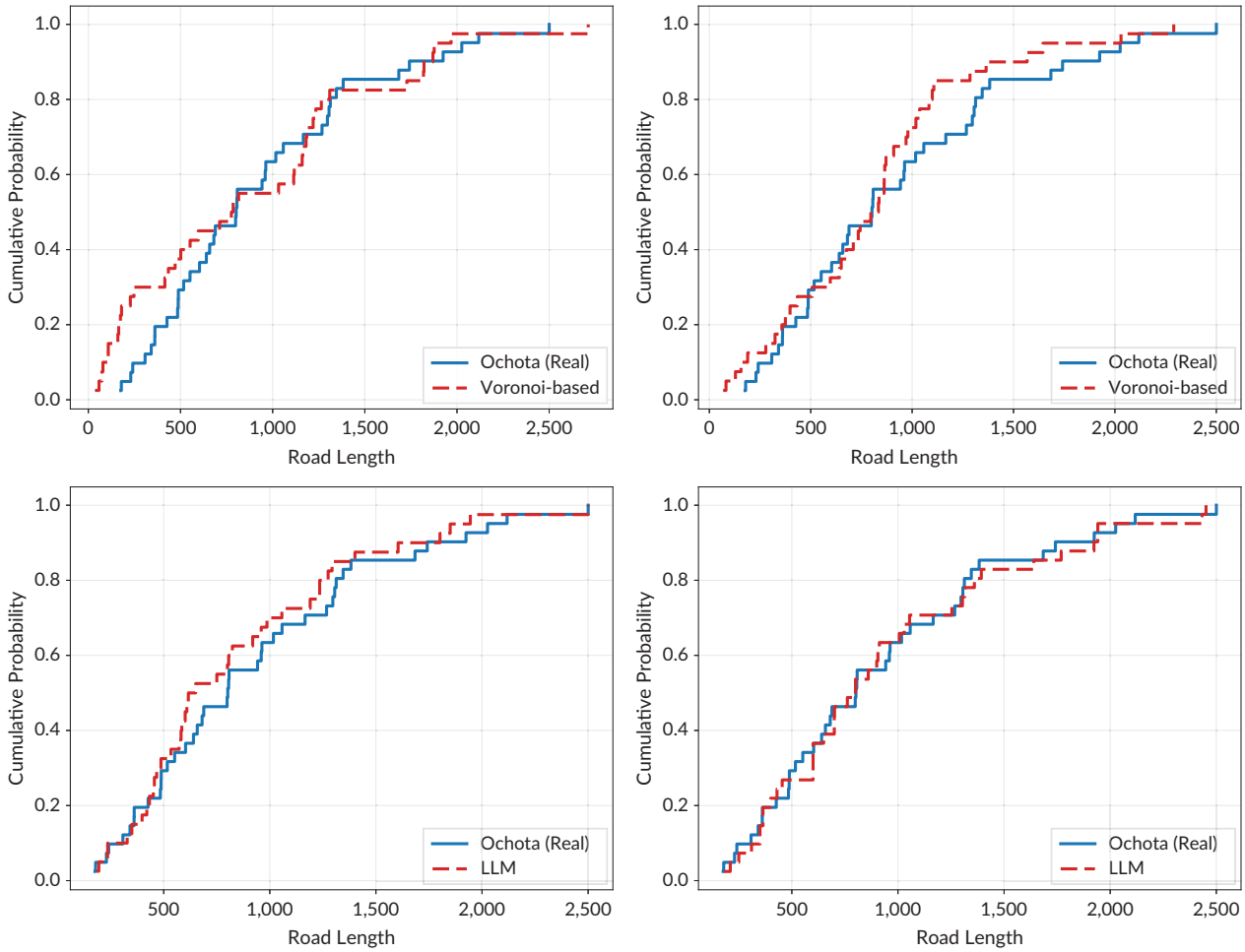


Figure 3. ECDFs of road-segment lengths for Ochota (blue) and synthetic networks (red). Top row: Voronoi-based; bottom row: LLM-guided.

Figure 4 shows the pointwise absolute differences between the ECDF of road-segment lengths in Ochota and the ECDF of each synthetic network, i.e., $\left|\hat{F}_{\text{Ochota}}(x) - \hat{F}_{\text{synthetic}}(x)\right|$. In the Voronoi-based examples, the difference curves exhibit higher and more frequent peaks, indicating larger local mismatches between the cumulative distributions over specific length ranges. In contrast, the LLM-guided examples display generally lower amplitudes and fewer pronounced peaks, meaning that the cumulative distribution of synthetic segment lengths tracks the reference more closely across most of the support.

While the absolute-difference curves quantify the magnitude of the mismatch, Figure 5 reports the corresponding signed ECDF differences, $\hat{F}_{\text{Ochota}}(x) - \hat{F}_{\text{synthetic}}(x)$, which reveal the direction of the deviation. Positive values indicate that Ochota accumulates probability mass faster up to length x—i.e., Ochota has relatively more short segments, so the synthetic network under-generates short segments up to that threshold. Negative values indicate the opposite—the synthetic ECDF is higher, meaning the synthetic network over-generates short segments up to x. In the representative Voronoi-based runs, the signed differences show larger and more persistent departures from zero across parts of the length range, suggesting systematic over-or under-generation in specific regimes, whereas the LLM-guided runs remain closer to zero, indicating fewer directional biases and a closer overall match to the reference distribution.

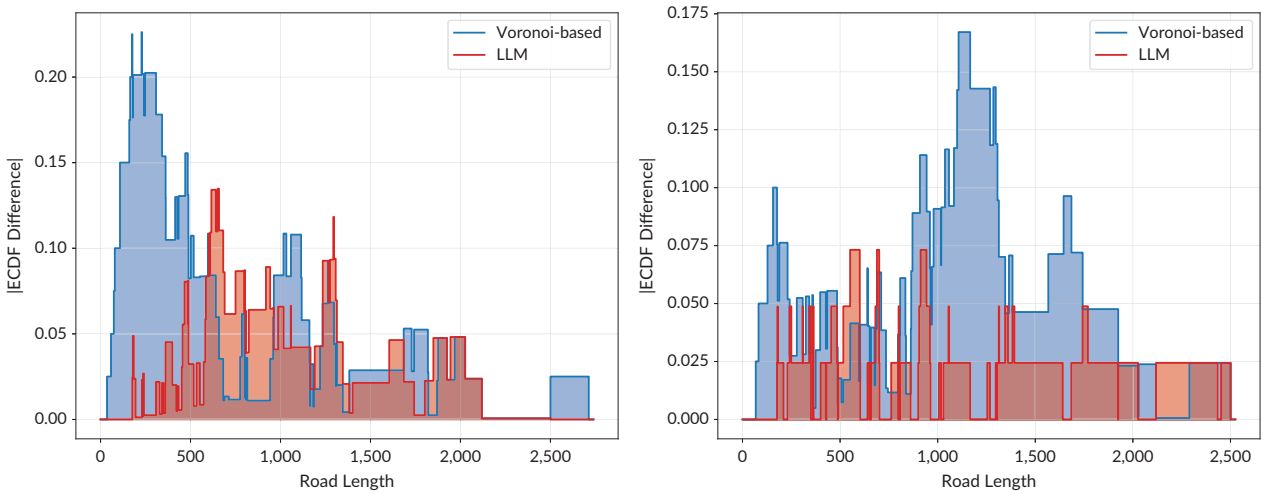


Figure 4. Overlay of absolute ECDF differences between Ochota and synthetic road-length distributions: Voronoi-based (blue) vs. LLM-guided (red), shown for two representative runs.

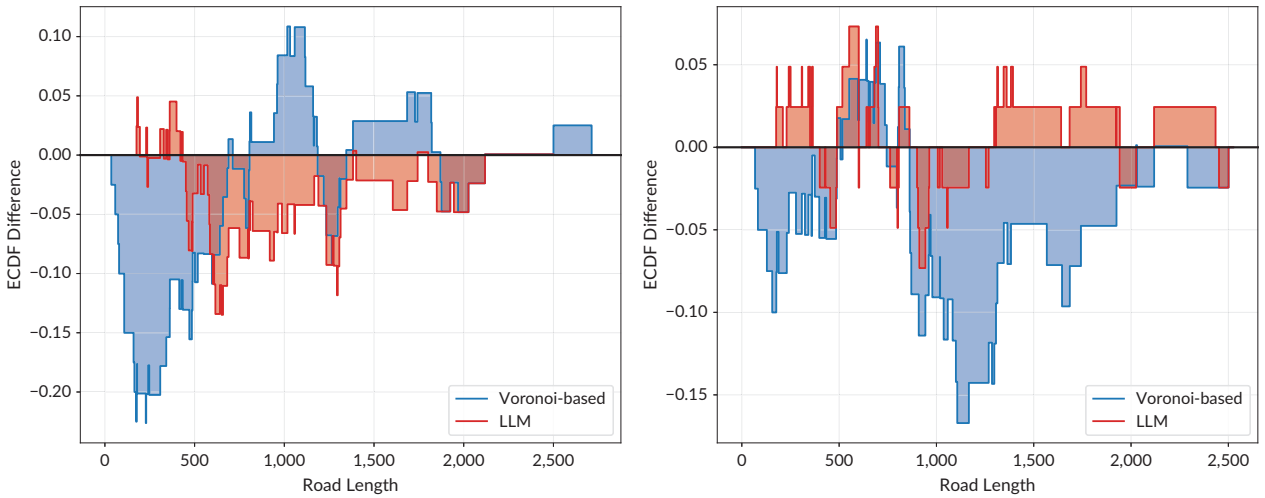


Figure 5. Overlay of ECDF differences between Ochota and synthetic road-length distributions: Voronoi-based (blue) vs. LLM-guided (red), shown for two representative runs.

Figures 6 and 7 summarise how the synthetic road-segment length distributions compare to the Ochota reference. In Figure 6, the Voronoi-based examples show several bins where the synthetic distribution visibly departs from Ochota, indicating local over- and under-representation of specific length ranges. The LLM-guided examples still differ across bins, but the most visually prominent mismatches are typically less pronounced in these representative runs. Figure 7 complements this by comparing quantiles directly: points closer to the $y = x$ line indicate better agreement across the full distribution, while systematic deviations from the diagonal reveal mismatches in particular length regimes (e.g., short or long segments). In the shown examples, the LLM-guided outputs track the reference quantiles more closely than the Voronoi-based baseline.

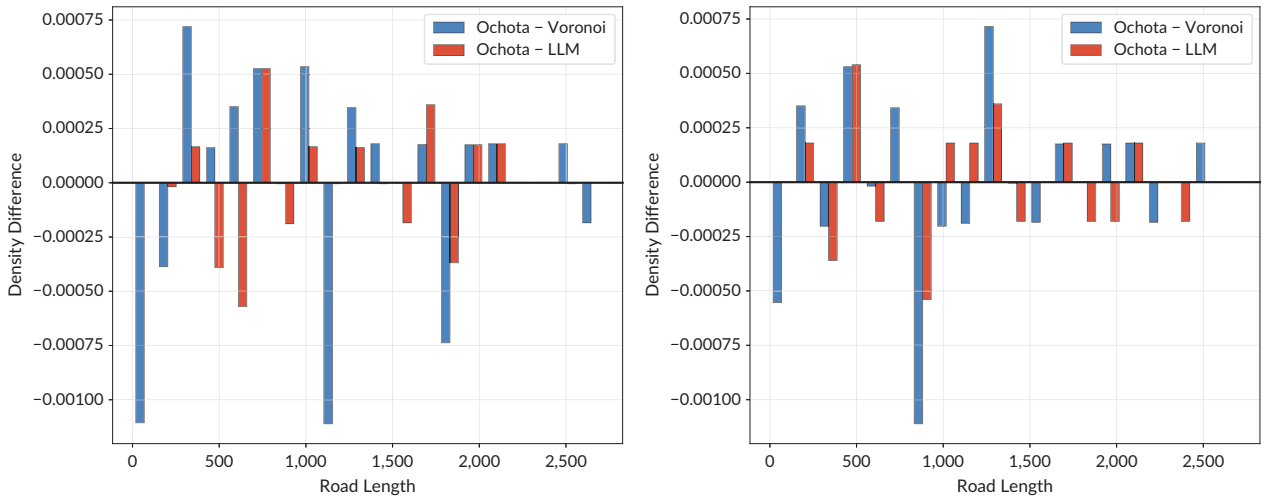


Figure 6. Differences between density histograms of road-segment lengths (Ochota minus synthetic), overlaid for Voronoi-based (blue) and LLM-guided (red), shown for two representative runs.

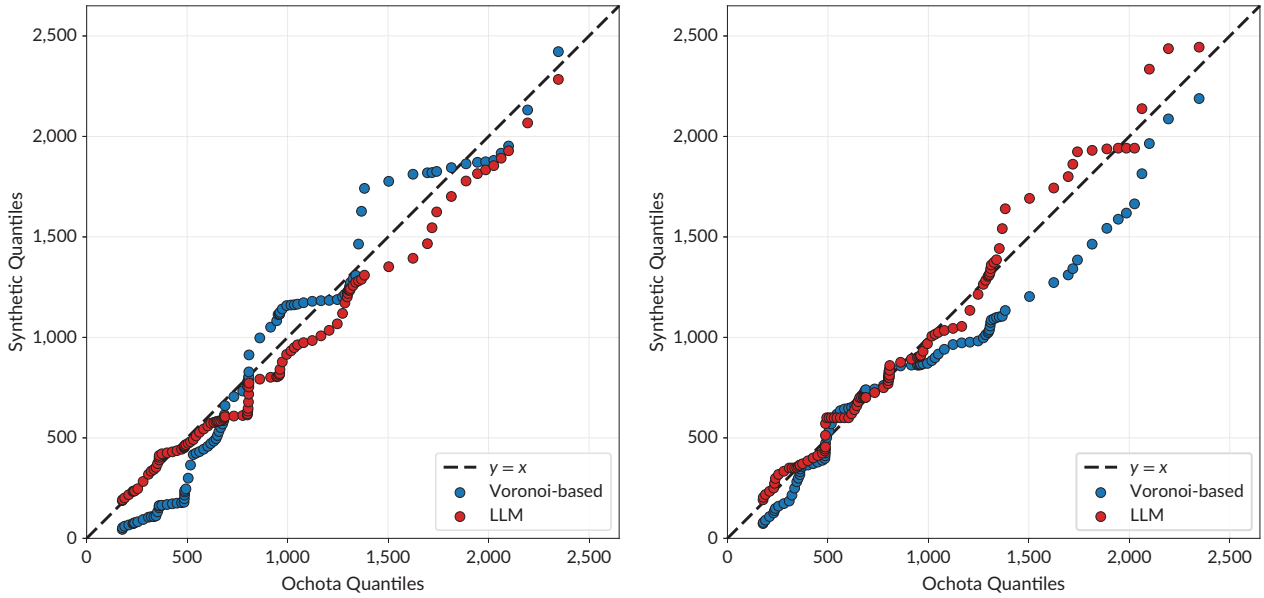


Figure 7. Q–Q plots of synthetic vs. Ochota road-segment lengths for two representative runs. The dashed line ($y = x$) indicates perfect agreement. Deviations from the diagonal indicate quantile-level mismatch.

This visual pattern is consistent with the quantitative KS results: The LLM-guided procedure reduces the maximum ECDF discrepancy (smaller KS distance), meaning it better matches not only the average segment length but also the overall distributional shape, including the relative mass of short, medium, and long road segments.

4.2.2. Results Across Different Reference Structures

To further assess applicability across urban structures, we generated synthetic cities for two additional reference areas: Vienna's Innere Stadt, representing a circular form, and Downtown Philadelphia, representing a grid-like structure. The synthetic examples were generated using the same procedure as in

the Ochota experiment, so that the results remain directly comparable across cases. In both additional reference areas, all generated cities were planar and satisfied the same Wasserstein acceptance threshold of 0.05. The mean Wasserstein distances were 0.024 for Innere Stadt and 0.049 for Downtown Philadelphia, compared with 0.043 for Ochota. The corresponding KS values were 0.141, 0.153, and 0.100, while the CvM values were 0.115, 0.235, and 0.038, respectively. The weaker performance for Downtown Philadelphia should be interpreted in light of the greater size and structural complexity of the reference system, which contains approximately 70 road segments, compared to about 40 in the Ochota case. At the same time, the obtained discrepancies remained below the adopted Wasserstein threshold and were still better than those observed for random graphs of comparable size, which yielded mean values of 0.09 for Wasserstein, 0.40 for KS, and 1.73 for CvM. Figure 8 presents representative high-level road networks generated for the additional reference structures under different prompts at the first stage of the framework, before hierarchical refinement is applied, showing that the method can produce multiple variants while preserving the main structural characteristics of each reference layout. Taken together, these results indicate that the framework generalises beyond a single reference morphology, although calibration becomes more demanding for larger and more structurally complex road systems.

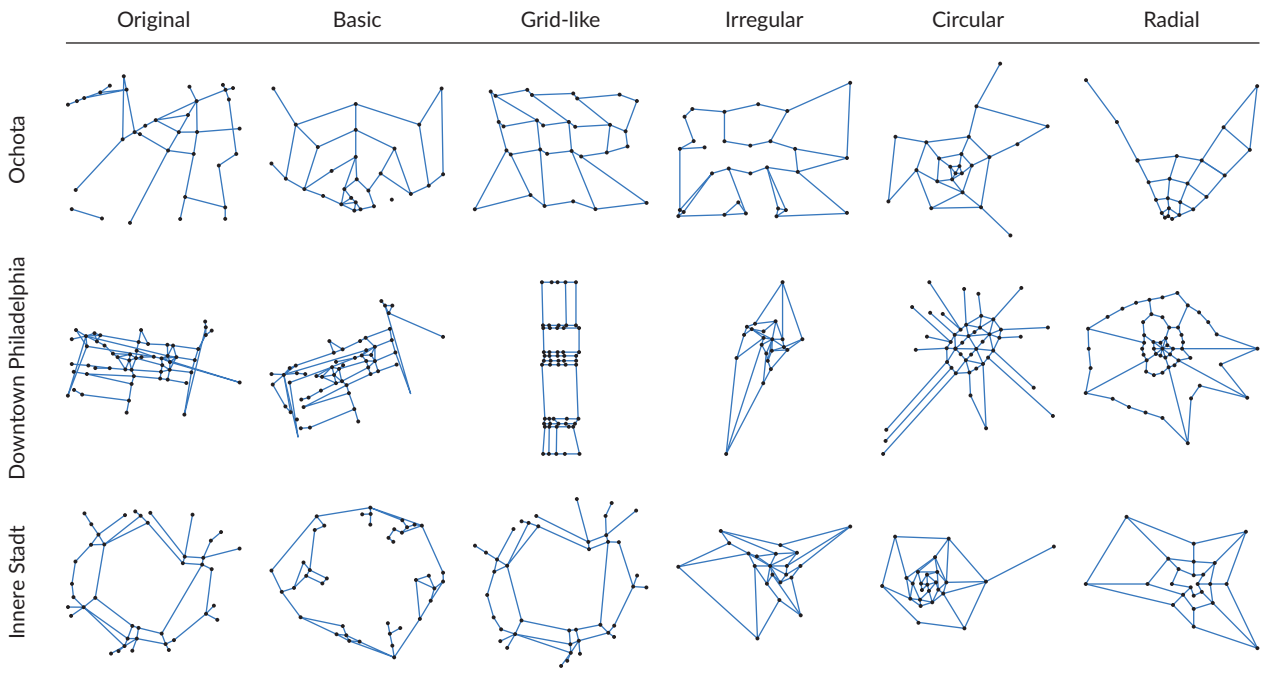


Figure 8. Synthetic road networks generated for three reference districts under five prompt types, illustrating the diversity of outputs obtained for each input layout.

4.2.3. Cross-Backend Comparison

To evaluate the robustness of the proposed method across different model families, we replicated the Ochota experiment using several LLM backends, namely Claude Opus 4.5, Gemini 3, Qwen 3.5, and Kimi K2.5. These supplementary experiments were intended to assess whether the proposed framework depends strongly on a specific model backend, or whether the same generation-and-validation procedure can be applied more broadly across different LLMs. All experiments were conducted under the same configuration, with the Ochota district as the reference structure, a Wasserstein acceptance threshold of 0.05, and identical remaining generation parameters. For each backend, we generated 16 synthetic cities. In all cases,

the convergence rate to a valid output was 100%. The results show that the proposed framework remains effective across different LLM backends, although the relative ranking of models depends on the metric considered. Claude Opus 4.5 and Gemini 3 achieved the same mean Wasserstein distance of 0.043, but Claude produced lower KS and CvM discrepancies (0.100 and 0.038, respectively) than Gemini 3 (0.131 and 0.087). Qwen 3.5 achieved the lowest mean Wasserstein distance (0.016), yet this was accompanied by higher KS and CvM values (0.150 and 0.109), indicating a weaker match of the overall road-segment length distribution. By contrast, Kimi K2.5 achieved the lowest mean KS distance (0.091) while also maintaining competitive Wasserstein and CvM values (0.040 and 0.038). Taken together, these results indicate that the proposed framework is transferable across the tested LLM backends, in the sense that the same generation-and-validation procedure remains applicable across multiple models. At the same time, backend choice affects which aspect of distributional similarity is matched most closely.

4.2.4. Temperature Sensitivity Analysis

In the main experiments, the temperature parameter was set to 1.0. This choice was motivated by the exploratory character of the proposed framework. Because the method operates within an iterative generation-and-validation loop, a higher temperature was intended to encourage the model to explore a broader range of candidate network structures rather than produce overly deterministic outputs, while the external validation procedure—including the planarity check and the Wasserstein-distance-based feedback—acts as a stabilising mechanism that filters out invalid or poorly calibrated candidates. To assess the sensitivity of the framework to this parameter, we conducted a controlled temperature analysis. Due to technical constraints of the command line interface environment used for the primary Claude experiments, the temperature parameter could not be directly modified in that setting. We therefore repeated the Ochota experiment using the Gemini backend and evaluated the framework at four temperature values: $T = 1.0$, 0.5, 0.2, and 0.0. The results suggest that the proposed framework is only moderately sensitive to temperature within the tested stochastic range. The mean Wasserstein distances for $T = 1.0$, 0.5, and 0.2 were relatively similar, at 0.043, 0.046, and 0.045, respectively. The most pronounced deterioration was observed for the deterministic setting $T = 0.0$, for which the mean Wasserstein distance increased to 0.089. The KS and CvM values also varied across temperature settings, but they did not reveal a strong or monotonic relationship. Overall, these results indicate that temperature influences the outputs of the framework, but that the differences among stochastic settings remain limited, whereas fully deterministic generation performs less favourably.

4.3. Discussion

The results show that the LLM-guided procedure produces high-level road networks whose road-segment length distributions are closer to the reference layout than those generated by the non-agentic Voronoi baseline. Using Wasserstein distance as the primary calibration measure, the LLM-guided runs achieved a lower mean discrepancy ($\overline{W} = 0.043$, std. 0.016, $n = 16$) than the baseline ($\overline{W} = 0.105$, std. 0.0316, $n = 16$), corresponding to an approximately 2.5-fold reduction in mean error. The same pattern appears for the KS distance, whose mean decreased from $\overline{D}_{\mathrm{KS}} = 0.156$ (std. 0.026) for the baseline to $\overline{D}_{\mathrm{KS}} = 0.100$ (std. 0.039) for the LLM-guided runs. Taken together, these results indicate that the iterative LLM-guided loop more consistently steers generation towards candidates whose segment-length statistics align with the reference distribution.

In all 16 runs, the LLM-guided procedure returned a planar high-level graph within the iteration limit. This is important because the subsequent hierarchical extension relies on extracting faces and refining them with the Voronoi-based subdivision. The qualitative examples in Figure 2 show that the accepted planar backbones can be extended into coherent multi-level synthetic networks.

Additional experiments broaden these findings in three directions. First, applying the framework to Vienna's Innere Stadt and Downtown Philadelphia showed that it can generate planar synthetic cities for reference systems with markedly different spatial organisation, although calibration becomes more demanding for larger and more structured networks. Second, experiments with Gemini 3, Qwen 3.5, and Kimi K2.5 showed that the same generation-and-validation procedure remains applicable across multiple LLM backends, even though the relative ranking of models depends on the metric considered. Third, the temperature-sensitivity analysis indicated only moderate sensitivity within the tested stochastic range, while the deterministic setting performed less favourably.

At the same time, the current framework uses a simplified high-level representation to keep the structural description concise and easier for the LLM to process reliably. This representation can subsequently be extended in a post-processing step to obtain a more realistic transport network. In particular, each undirected edge may be converted into one or two directed edges to represent one-way and two-way streets, while the hierarchical information already used in the model can serve as a basis for assigning road classes and related attributes. Additional restrictions, such as turn limitations at intersections, may then be introduced probabilistically, with their likelihood depending on the classes of the intersecting roads. The relevant parameters could be estimated from spatial or transport datasets, allowing the generated structures to be enriched with more realistic operational detail without changing the core generation procedure.

5. Conclusion

This article presents a new approach to synthetic city generation that uses LLMs to connect high-level natural-language requirements with quantitative validation. The proposed framework has two stages. First, an LLM-guided iterative loop generates a planar, high-level road network (the arterial backbone) and refines successive candidates using tool-based feedback. Second, the accepted planar backbone is hierarchically refined using a Voronoi-based procedure that generates lower-level streets within the planar regions induced by the backbone, yielding a multi-level road network.

We demonstrate the method's applicability on a real-world OpenStreetMap dataset. Numerical experiments show that the proposed method improves similarity to the reference city relative to a non-agentic Voronoi-based baseline. When calibration is defined by the road-segment length distribution, the LLM-guided runs achieved lower discrepancies than the baseline in both Wasserstein distance (mean 0.043 vs. 0.105 over $n = 16$ runs) and KS distance (mean 0.100 vs. 0.156). In addition, all LLM-guided runs produced planar high-level graphs, enabling the downstream hierarchical extension step based on planar subdivision.

Supplementary experiments further showed that the framework remains applicable across reference systems with different spatial organisation and across multiple LLM backends, although calibration becomes more demanding for larger and more structured networks and model rankings depend on the evaluation metric.

Temperature sensitivity was moderate within the tested stochastic range, while fully deterministic generation performed less favourably.

The main advantage of the proposed method is that it simultaneously exhibits four desired properties that are largely missing from existing approaches: It supports calibration to a reference city, enforces conditional constraints such as planarity and a similarity tolerance, supports zero-shot customisation through new prompts and reference inputs, and uses semantic reasoning to translate qualitative requirements into measurable checks. In this way, we demonstrate that LLMs can be incorporated into the synthetic city generation process and that doing so improves the quality of the generated cities under the adopted evaluation metrics.

The current evaluation focuses on a single calibration target: the normalised distribution of road-segment lengths. Future work should extend the calibration objective to include additional complementary transport-network characteristics (e.g., intersection density and degree statistics, orientation distributions, circuity, or routing-based measures such as APLS), and investigate multi-objective calibration in which several metrics are optimised simultaneously. Another important direction for future work is to enrich the simplified high-level graph representation with additional transport attributes, such as directionality, road classes, capacities, or turn restrictions, thereby improving the realism of the generated networks and broadening their applicability in simulation studies.

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Conflict of Interests

The authors declare no conflict of interests.

Data Availability

The source code and supplementary materials supporting this study, including the implementation of the proposed framework, example prompts, and selected response logs, are openly available in the public repository at https://github.com/AdamKasinski/synthetic_cities.

LLMs Disclosure

During the preparation of this work, the authors used the LLM models Overleaf Writefull and OpenAI's ChatGPT to improve the readability and language of the manuscript, correct grammatical and spelling errors, and enhance overall language quality and clarity. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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"Town Built From Fleeting Matter": Audiowalking San'ya's Hidden Histories as Practice-Led Spatial Inquiry

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Abstract

This article revisits the audiowalk *placeless: San'ya*, originally produced in 2021 and re-staged in 2025 with geolocated audio technology. Using a practice-led approach and drawing on qualitative interviews and observational field notes, the study examines audio-based walking practices as a form of spatial computing in which digital sound is embedded in physical space and activated through movement. The case is situated in San'ya—a district name that officially no longer exists but remains associated with marginalization—within Tokyo's continually changing urban fabric, where the past is often only weakly articulated in the built environment. The audiowalk traces layered histories, from the site's adjacency to the Kozukappara execution grounds in the Edo period, through its history as a settlement for the stigmatized Burakumin caste, and its present-day role as home to an ageing population of day laborers. By keeping the narrative content constant while altering its technical mediation, the re-staging isolates how geolocation and contingency shape participant experience. The study contributes to spatial computing discourse by demonstrating that geolocated audio can function as a spatial interface that reconfigures movement and attention without displacing embodied awareness from the environment. It suggests that such practices can foster engagement with non-monumental urban histories without stabilizing absence into fixed narratives, while also foregrounding ethical questions about mediated presence in socially uneven spaces.

Keywords

audiowalk; embodied experience; geolocated audio; locative media; non-monumental memory; practice-led research; San'ya (Tokyo); spatial computing; urban marginality

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1. Introduction

Recent scholarship on mobile and location-aware technologies has increasingly emphasized how digital systems shape the experience of urban environments through embodied and situated interaction. In these contexts, spatial computing is approached as an experiential arrangement in which physical space, digital content, and bodily presence are continuously negotiated, with space understood as dynamic and relational rather than as a stable and abstract container for information (de Souza e Silva & Sheller, 2014; Dourish, 2001; Farman, 2012). In this sense, computation is encountered as embedded in streets, buildings, devices, and everyday routines and is integral to how urban life unfolds (Kitchin & Dodge, 2011).

This study contributes to spatial computing discourse from a practice-led perspective by examining geolocated audio as a mode of spatial mediation that has received comparatively little attention within the field. In urban planning and design contexts, spatial computing has been predominantly explored through data-driven modeling and simulation approaches, such as digital twin frameworks and interactive urban models, which are oriented toward authoritative and stable representations of urban space. While augmented and mixed reality technologies have extended this into immersive visual experiences, the auditory dimension remains largely unexplored, yet offers a distinct set of experiential qualities that expand what spatial computing can mean in practice. Unlike visual overlays, which redirect attention toward a screen or display, audio operates as an additive layer (Ihde, 2007). Environmental sounds and bodily sensations remain perceptible alongside the mediated content and keep the listener grounded in physical space even as a narrative layer is introduced.

The case study at the center of this article is *placeless: San'ya*, an authored audiowalk in which essayistic spoken-word texts, written as letters addressed intimately to the listener, accompany walking through specific sites in the district. The narration engages with the site's histories and atmospheres through affective and associative framing without imposing a definitive interpretation or a set route. The work was originally presented in 2021 and re-staged in 2025 using geolocated audio technology. The re-staging provided an opportunity to examine how the same narrative material unfolds under altered technical conditions and within a changing urban environment. Within this framework, the audiowalk functions as both an artistic work and as a research instrument. Drawing on participant interviews and observations, the article examines how listeners experience the audiowalk under the contingent conditions of a specific urban environment. The work is not evaluated in terms of usability or effectiveness; instead, participant accounts are treated as situated reflections on how geolocated sound, movement, and urban space interact in practice. This study is thus situated at the intersection of locative media, sound studies, and spatial computing, providing a perspective that is grounded in artistic practice and participant experience.

San'ya, a neighborhood located in northeastern Tokyo, presents a particularly instructive site for this investigation. Its urban fabric is shaped by transient populations, inexpensive lodging, aging infrastructure, and the proximity of sites associated with labor, passage, and death. Many of these histories are only weakly marked in the built environment, or have been deliberately obscured through redevelopment and administrative restructuring. In this context, audio-based walking practices offer a way of engagement without resolving absence or instability into fixed narratives.

This study thus offers three main contributions. First, it expands understandings of spatial computing by demonstrating how audio operates as an additive spatial interface that layers digital content onto physical experience without displacing embodied attention from the environment. Second, it demonstrates that contingency and misalignment can function as productive features of geolocated audio works, as they generate interpretive engagement with urban histories that resist authoritative representation. Third, it reflects on the ethical and experiential complexities that arise when walking through socially uneven spaces with narrative mediation.

The article is developed across the following sections: Section 2 outlines the conceptual framework, drawing on theories of sound, walking, and situated knowledge. Section 3 contextualizes San'ya within Tokyo's layered urban history. Sections 4 and 5 introduce the audiowalk and its re-staging. Sections 6 and 7 detail the methodology and participant experiences. Section 8 discusses the implications of these findings for spatial computing and urban research, followed by a conclusion that reflects on the broader relevance of audio-based, practice-led approaches to spatial computing discourse.

2. Walking, Listening, and Spatial Mediation

Engagement with sound in this study is approached as a mode of situated and embodied knowledge production. Central to this orientation is sound's temporal and bodily character: It unfolds in time and remains inseparable from the listener's presence in space, resisting the tendency of visual representations to stabilize space into legible and seemingly complete forms (Ihde, 2007; Voegelin, 2010). Listening occurs in relation to movement, proximity, distraction, and interruption, and is shaped as much by what is partially heard or missed as by what is clearly perceived (LaBelle, 2019). These qualities make sound-based practices particularly suited to engaging with fragmented or contested urban histories (Bradley, 2016; Huyssen, 2003). Crucially, the perceptual structure of sound differs from that of visual media. Auditory perception is omnidirectional and ambient, surrounding rather than focusing attention, and cannot be selectively closed off the way vision can (Ihde, 2007). An audio layer, therefore, does not displace attention from the environment and allows environmental sounds, bodily sensations, and spatial awareness to remain present alongside mediated content.

Because listening is inseparable from bodily orientation and movement through space, sound-based practices often intersect with walking as a mode of spatial engagement (Biserna, 2022). In this article, walking is understood as a situated method that produces partial and relational forms of knowledge, since factors such as bodily capacity, social norms, environmental conditions, and infrastructural constraints all influence the walker's habits and experience (de Certeau, 1984; Haraway, 1988). In artistic contexts, walking has long been explored as a practice that simultaneously reads and writes space, particularly in peripheral or marginal urban environments (Biserna, 2024; Careri, 2002).

These considerations are particularly relevant in audio-based walking practices, where movement is paired with mediated listening. Given their position between sound art, mobility, and locative media, the terminology for such works remains imprecise (Bradley, 2016). While listening walks and soundwalks are commonly associated with acoustic ecology and the World Soundscape Project and emphasize attentive listening to the existing sonic environment (Schafer, 1977; Westerkamp, 1974), in this article the term audiowalk will be used to describe authored, pre-recorded works that accompany walking through a specific

site and operate "at the interface of fixed media and the unstable environment of the street" (Biserna, 2022, p. 7). The work examined here draws on this tradition, particularly the authored, site-specific audiowalks of Janet Cardiff and George Bures Miller (Cardiff, 2005). Other notable works include Graeme Miller's *Linked* (2003). Miller used radio transmitters to broadcast oral history recordings from former residents along the route of a demolished East London community (Butler & Miller, 2005). While most audiowalks are aimed at single participants, Rimini Protokoll's *Remote X* (2013–), staged in cities worldwide, guides large groups of participants through urban spaces via headphone audio and produces experiences that are at once collective and individual (Rimini Protokoll, n.d.). These works share an orientation toward sound as a means of surfacing what visual or monumental forms of urban representation tend to leave out; a concern that directly informs the approach taken in this study.

Developments in locative media and mobile technologies have introduced new conditions for audiowalk practices by enabling sound to be triggered in relation to geographic position (de Souza e Silva & Sheller, 2014; Farman, 2012; Gordon & de Souza e Silva, 2011). In this broader sense, audiowalks can be understood as a minimal form of spatial computing, in which geolocated content is embedded in physical space and activated through bodily movement, producing situated experience through sound rather than visual overlay. This aligns with understandings of spatial computing as fundamentally concerned with embodied, contingent interaction between digital systems and physical environments (Dourish, 2001; Kitchin & Dodge, 2011), even as those frameworks do not explicitly address audio-based forms. Embedded in the dynamics of the urban environment, audiowalks unfold differently depending on movement, pacing, attention, and situational conditions, and thus reinforce the inherently situated and subjective nature of both walking and listening (Ihde, 2007; LaBelle, 2019).

Since the site for this research is San'ya, a neighborhood whose histories of social marginalization are neither fully erased nor clearly articulated through monuments or official narratives, this article also engages with non-monumental approaches to a contested urban memory. Where histories persist primarily through informal traces and practices, methods that can accommodate incompleteness without resolving it into authoritative explanation become especially relevant (Biserna, 2022; Huyssen, 2003).

3. San'ya as a Situated Case

San'ya is located in northeastern Tokyo, centered around Minami-Senju Station and the Namidabashi intersection (Figure 1). A defining characteristic of the area is that, in an administrative sense, it no longer exists as a named district. Revisions to the residential address system in 1966 divided San'ya between Taito and Arakawa wards and removed the name from official maps (Fukushi Zaidan, n.d.). This restructuring was part of a broader effort to dissociate the area from long-standing associations with homelessness, poverty, violence, and the concentration of transient day laborers (Gill, 1994, p. 276). Responsibility for employment and welfare provision was consequently fragmented across multiple jurisdictions, which often resulted in bureaucratic ambiguity and limited accountability (Gill, 1994). Despite this official erasure, the name San'ya persists in everyday usage and local identity and appears in the names of labor unions, social initiatives, and businesses, as well as in shrine inscriptions and informal speech (McCurry, 2019). This coexistence of administrative non-recognition and lived continuity produces a form of spatial ambiguity that is central to the audiowalk discussed in this article.

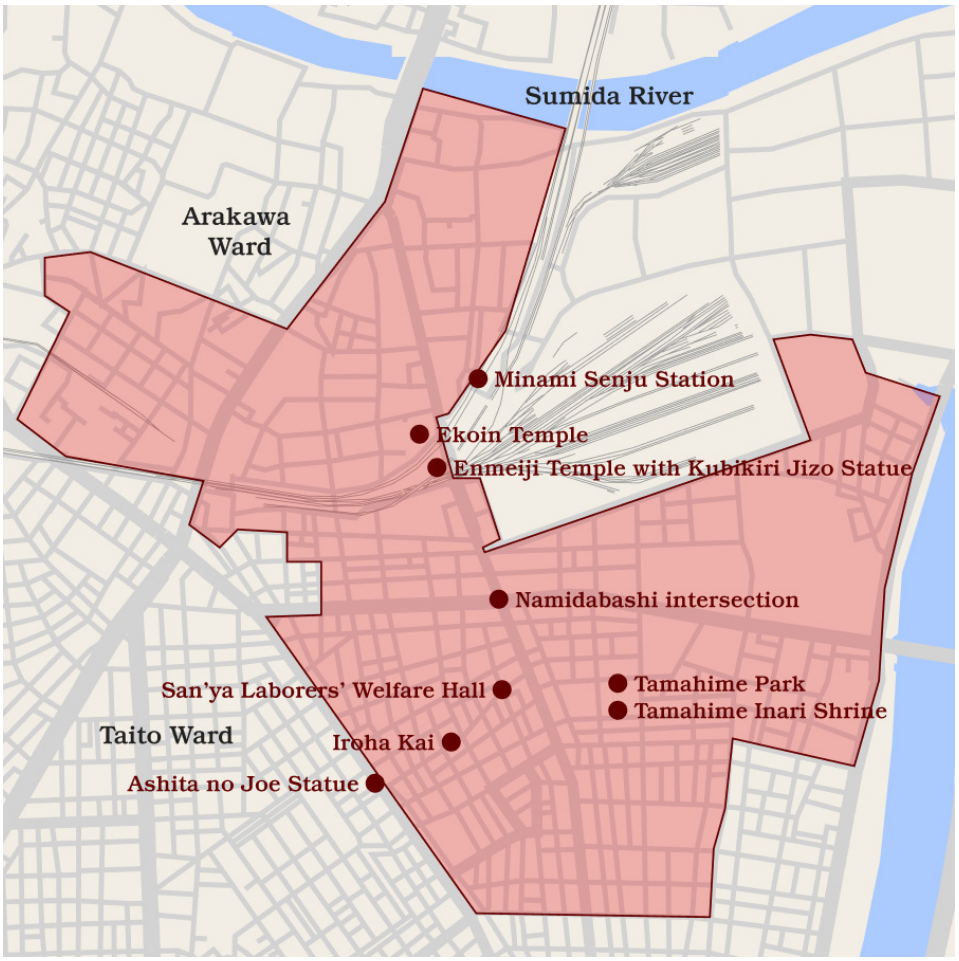


Figure 1. Map of San'ya with key locations for this study.

San'ya's marginality is rooted in long and layered histories of spatial and social exclusion. During the Edo period, the area formed part of the city's northeastern fringe, adjacent to major highways, and was associated with transient populations and temporary lodging (McCurry, 2019). This peripheral positioning was closely tied to systems of exclusion that structured Edo society. Kozukappara, one of the city's principal execution grounds, was established at San'ya's northern edge in 1651, with tasks related to execution assigned to Burakumin outcaste communities settled nearby. Together with the neighboring pleasure quarters of Yoshiwara, the area formed a constellation of sites dedicated to activities that were deemed necessary but morally troubling, which reinforced its association with social stigma (DeVos & Wagatsuma, 1967).

Following the Meiji period and accelerating after World War II, San'ya developed into Tokyo's largest *yoseba*, functioning as a recruitment hub for day laborers employed in construction, infrastructure, and postwar reconstruction. Low-cost lodging houses (*doya*) supported this system by accommodating transient workers under conditions of long-term precarity. As demand for day labor declined toward the end of the twentieth century, many workers aged in place, transforming parts of the district into zones of concentrated elderly poverty and converting former doya into de facto retirement homes (Fowler, 1996; Takada, 2018). While the social vulnerability of the area persisted, its history became increasingly obscured through administrative division and urban modernization.

Even though Kozukappara was a key site within Edo's urban and symbolic order, its history was never consolidated as a singular historical site. Instead, the former execution grounds were gradually fragmented and rendered largely invisible by railway infrastructure and adjacent developments. The Kubikiri Jizo (beheading Jizo) statue, which was part of the original site and now sits at Enmeiji Temple, remains one of the few material markers referencing this history (Takeuchi, 2020). It reflects how San'ya's violent or uncomfortable pasts are mostly folded into everyday urban life without being formally resolved.

In recent decades, the district has undergone further transformation through the growth of low-cost tourism, with former doya repurposed as budget hostels. This shift has produced a heterogeneous social landscape in which elderly former laborers, unhoused residents, long-term locals, and international visitors coexist (Kahan, 2025). While San'ya has long attracted photographers seeking alternative urban imagery, the post-pandemic tourism boom has further intensified decontextualized representations on social media. Images of derelict or overgrown buildings have come to circulate as aesthetic curiosities, often read or framed in ways that detach them from their function as residential infrastructure for vulnerable populations. Such framings risk transforming spaces of ongoing social precarity into consumable backdrops and raise ethical questions about exposure, spectatorship, and responsibility.

These conditions make San'ya difficult to read through conventional forms of urban representation. Its histories are neither fully erased nor clearly articulated through landmarks or official heritage narratives, but persist through absences, informal practices, and partial markers. This ambiguity renders the district particularly suited to audio-based, walking-centered engagement.

4. The Audiowalk in Its Original Context (2021)

The audiowalk *placeless: San'ya* was created in 2021 for the inaugural Sairai San'ya Art Festival, an annual local event organized by the collective 3ducksDADA (SAIRAI Art Fest, n.d.). The festival aims to engage with San'ya as a heterogeneous and marginal urban zone by inviting artists to produce site-specific works that are presented in public spaces and local businesses.

During Sairai San'ya 2021, the audiowalk was accessed via QR codes printed on a festival map distributed at the reception. Each audio segment was associated with a specific site, but playback was not technically bound to geographic position. Scanning a QR code linked listeners to a SoundCloud page hosting the recordings (https://on.soundcloud.com/TCyTPb5Rhz4KD3Wk3B), which allowed the audio to be accessed freely and without enforced spatial boundaries. This low-threshold setup was chosen to ensure accessibility across devices and levels of technical familiarity, and to avoid the need for a dedicated application. While most visitors attempted to listen to the recordings close to their assigned locations, the format also allowed listening elsewhere, including outside the district.

Placeless: San'ya forms part of an ongoing artistic series that explores liminal spaces within Tokyo. As in other iterations of the project, the audio takes the form of essayistic spoken-word texts written as letters addressed directly to the listener as "my dear," to establish an intimate mode of address. Rather than providing historical explanation or guidance, the narration engages with the place in an affective and associative manner. Across four audio segments, themes of passage, boundary-crossing, impermanence, and erasure recur, drawing on layered references without prescribing a linear sequence or a fixed route. To reinforce the work's open and

non-directive structure, listeners were neither required to follow a specific order nor to complete all segments (Figure 2). The placement and content of the segments are introduced in the following section.

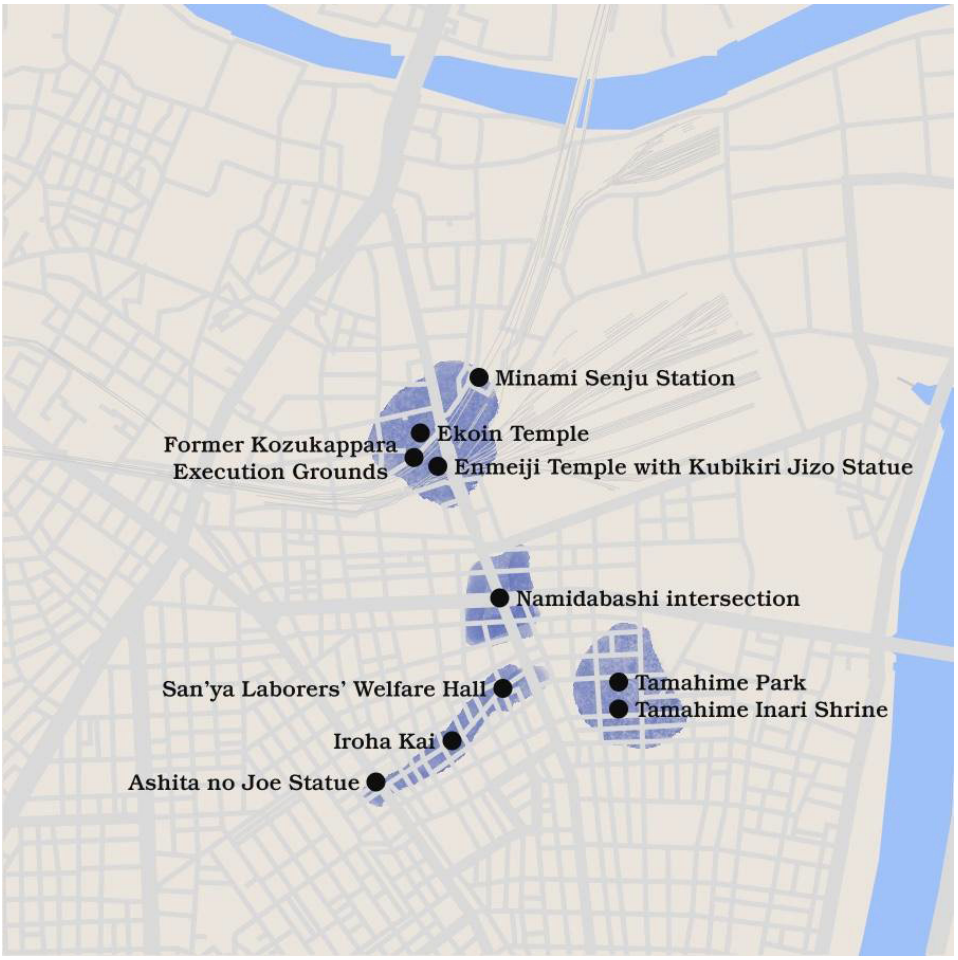


Figure 2. Locations of the four audiowalk segments within San'ya.

4.1. The Audiowalk Segments

The segment situated near Minami-Senju Station addresses the former Kozukappara execution grounds and introduces the site as a non-monumental zone of liminality. The narration opens with the speaker's bodily fatigue and disorientation upon arrival, thus using sensory experience as an entry point into the area. While avoiding linear or didactic historical narration, the segment evokes the scale and aftermath of violence through tone and imagery. Attention is then directed to the present landscape where cemeteries, railway infrastructure, and quotidian activities intersect (Figure 3).

At Namidabashi intersection, the audiowalk frames the site as a layered threshold. Setting a contrast to the unremarkable appearance of the crossing, the narration recalls its historical significance as the "bridge of tears" that marked the final passage for those led towards execution at Kozukappara (Nikkei, 2016). Through simple bodily prompts aligned with traffic signals and ambient sound, listeners are invited to become aware of the intersection as a space where temporal, spatial, and symbolic boundaries overlap, while remaining conscious of their present-day freedom of movement (Figure 4).



Figure 3. Part of the former Kozukappara execution grounds: Enmeiji Temple with Kubikiri Jizo statue.



Figure 4. Namidabashi intersection.

The remaining segments extend these concerns and themes through other sites in the district. At Iroha Kai shopping street (Figure 5), the narration emphasizes absence and disappearance, and juxtaposes San'ya's role in supporting Tokyo's postwar urban expansion through day labor with the lack of monumental recognition for this history. At Tamahime Inari Shrine (Figure 6), attention shifts to the symbolic and administrative erasure of the name San'ya itself. Naming practices, ritual gestures, and contemporary use of the surrounding space are linked to longer histories of impermanence and marginalization.



Figure 5. Iroha Kai shopping street.



Figure 6. The main entrance at Tamahime Inari Shrine.

The following extract from the Iroha Kai segment gives a sense of the audiowalk's voice and approach:

> Some quick notes on things that are absent, my dear. San'ya, town built from fleeting matter, everything here is non-permanent save for the lasting reputation. Homes of transit, lodging houses and cheap hostels, people born in other places. Elsewhere in Tokyo: the expressway, monorail, sports

> stadiums, and the sewage system underneath us; all those cold, inhuman structures that were once built by warm, calloused hands. It was at San'ya's *yoseba*, where those hands shook the ones of labor brokers in agreement to build the metropolis' recent monuments. A Sisyphean rhythm. Morning labor market, crack of dawn, liminal time, liminal way of life, hand to mouth, attack to attack. I am approaching the entrance of what was once Iroha Kai shopping street. To my right, for decades, the Nodaya liquor store, now a new nondescript apartment building. "Avenir ici" [アヴニールイシ]—the future is here….They say that Iroha Kai was a twilight space long before its demolition in 2019. The bubble burst and, as the stream of jobs for strong men dried up, so did the life inside the arcade. San'ya, the muscle of the modern metropolis. Now old men's town, formed by absence and fading. Of course, the center of San'ya is a passage that is no longer there.

While the narrative content of *placeless: San'ya* remained unchanged, its re-staging in 2025 introduced new technical and methodological conditions. The following section details these changes and examines how altered modes of access and spatial constraint shaped its use as a research instrument.

5. Re-Staging the Audiowalk (2025)

The decision to restage *placeless: San'ya* in 2025 was motivated by both artistic continuity and a renewed research interest. Returning to the area several years later revealed further social and infrastructural shifts and raised questions about how site-specific works age under changing urban conditions. Tokyo's rapidly transforming cityscape provides a particularly compelling context for such questions, as site-specific interventions are more likely to encounter altered conditions within relatively short timeframes (Huyssen, 2003; Jinnai, 1995). The re-staging, therefore, functioned as an opportunity to examine how an audiowalk engages with the city as a palimpsest that is continually reworked through demolition and redevelopment.

Instead of QR codes, the 2025 re-staging employed the Echoes platform (https://explore.echoes.xyz/collections/uYBmB1WcrDQBorGE), which enables geolocated audio playback. In this configuration, each audio segment is embedded within a defined geographic zone on a digital map, and playback is only triggered when the listener physically enters the area and stops when they step out of the zone (Echoes.xyz, n.d.). The work thus shifts from functioning as a portable soundtrack to operating as a spatially contingent experience that is dependent on the listener's movement and decisions.

The re-staging further marked a shift in the author's position from an exhibiting artist to a researcher working with the audiowalk as a practice-led inquiry. In this sense, the re-staging does not aim to produce a definitive or improved version of the work, but rather to test how the same narrative material unfolds differently when re-embedded in a changing city and under altered technical conditions. By keeping the narrative content constant while altering its spatial logic, the 2025 iteration isolates the role of geolocation as a structuring force. These considerations informed the design of the participant study discussed in the following sections.

6. Research Design and Methodology

This study adopts a practice-led research approach in which the re-staging of an existing artistic work functions as both method and site of inquiry. Rather than treating the audiowalk as a neutral instrument for data collection, the work itself is understood as an experimental situation through which questions of spatial

perception and embodied knowledge can be explored (Candy & Edmonds, 2018). This made it possible to observe how navigation, pacing, attention, and orientation were affected by the interaction between narration, bodily movement, and urban context (Biserna, 2022; Careri, 2002).

The participant study consisted of individual audiowalks followed by semi-structured interviews with nine participants. Each participant experienced the audiowalk alone, using their own smartphones and headphones. To approximate the conditions of the original festival presentation, a brief verbal introduction and minimal contextual information were provided before the walk began. Participants were informed that there was no set order, route, or requirement to complete all audio segments. This openness was intended to preserve the exploratory character of the work, allowing for autonomous navigational and interpretive decisions. Participants furthermore recorded their movement trajectories with a GPS tracking application, which was later visualized (Figure 7). All walks took place between noon and sunset, with variations in weather and pedestrian activity depending on the day of the week. These variations were not controlled for but treated as integral to the study, as they reflect the contingent experience of an urban environment.

The interviews focused on the participants' embodied experience. Questions addressed how the geolocated audio influenced movement and attention, how moments of alignment or misalignment were perceived, and how narrated histories related to immediate surroundings (Pink, 2015). Interviews were audio-recorded, transcribed, and anonymized, with participants identified by numerical codes (P1–P9). Although individual differences are acknowledged, the analysis focuses on recurring patterns and shared tensions across accounts. An overview table presents anonymized background information about gender, age range, and relationship to Japan, to contextualize positional differences (Table 1).

Table 1. Overview of participant characteristics.

Participant	Gender	Age	Relationship to Japan
P1	female	20s	local
P2	female	30s	long-term resident
P3	male	20s	local
P4	male	40s	long-term resident
P5	female	30s	long-term resident
P6	male	30s	long-term resident
P7	female	20s	local
P8	male	20s	local
P9	male	30s	long-term resident

The analysis follows a qualitative, interpretive approach based on a close reading of interview transcripts and field notes. Themes were developed iteratively and read in relation to the conceptual framework outlined earlier in the article. The study does not aim to evaluate usability or generalize findings beyond this context. Reflexivity is acknowledged as integral to the practice-led setup, with the researcher's dual role treated as part of the methodological condition (Berger, 2013; Enosh & Ben-Ari, 2015).

7. Findings: Participant Experiences

7.1. Entering the Walk: Expectations and Orientation

This section presents participants' initial encounters with the audiowalk and the ways they oriented themselves to both the medium and the site. The walk gave rise to individual paths and affective readings of San'ya. Participants described their early experience as unfolding through an interplay between narration, environmental conditions such as light and weather, the affordances and frictions of the app, and their own habits and positionalities as walkers.

None of the participants had prior experience with audiowalks, and all reported little to no knowledge of San'ya. Several explicitly noted that they began the walk with "no particular expectations" beyond a general curiosity about the format. As a result, the first minutes were largely spent becoming acquainted with the medium itself: understanding how the audio was triggered, how closely one needed to attend to the map, and how freely one could move without interrupting playback. Early orientation took different forms, ranging from exploratory wandering guided "by instinct" or habit to more cautious navigation focused on avoiding missed content. In all cases, participants described these moments less as confusion than as a period of adjustment.

In reflecting on these early stages, participants often framed the audiowalk in relation to more familiar guided urban formats, such as transport-based sightseeing tours with fixed timing and trajectories. In contrast, the audiowalk was described as allowing for deviation and self-directed movement. Simultaneously, the distinct audio zones created a loose structure that made the walk feel intentional without being prescriptive. One participant characterized this balance as providing "freedom, but not randomness."

Curiosity about the medium also shaped expectations. For some participants, encountering the Echoes platform prompted interest in audiowalks as a broader way of engaging with the city, particularly as a means of accessing local narratives. Others initially approached the experience with a focus on how to "do it right," with considerations for where to start, whether there was an optimal order, and how to maintain continuity between segments. Even though participants were informed that there was no fixed starting point or required sequence, the spatial distribution of the audio and a desire to encounter what was perceived as the walk's "foundational" historical layer often generated emergent sequencing. In practice, this frequently meant beginning at Kozukappara, moving on to Namidabashi, and continuing toward either Iroha Kai or Tamahime Inari Shrine.

Across accounts, these first moments reveal that orientation was both spatial and conceptual. Participants negotiated how the audiowalk should be understood, while simultaneously learning how their own movement, attention, and decision-making would shape what unfolded. The audiowalk thus began as a process of calibration, through which expectations, interest, habits, and technical conditions gradually aligned to produce an individualized entry into the district.

7.2. Emergent Navigation

Across participants, the audiowalk produced movement patterns that differed noticeably from their everyday walking habits in an urban environment. Instead of moving efficiently from one point to another, they slowed down, paused, circled back, or paced in place to remain within audio zones, complete recordings, or locate

elements referenced in the narration. The walk thus functioned as a set of loosely connected spatial prompts that reorganized how participants moved through the neighborhood.

Several participants became aware that their habitual walking pace did not align with the temporal structure of the recordings. One participant noted that moving too quickly through a zone with a longer audio segment required turning back to hear the recording to the end, while another described how their initially "goal-oriented" pace shifted as they adjusted to the rhythm imposed by the audio:

> At first, when I started it, I was walking very fast…and then maybe by the third recording, I started slowing down…you realize that you don't have a specific place to be and you have to pace yourself to hear the recording to the end.

Differences between the duration of recordings and the spatial size of their zones generated distinctive forms of movement. When audio segments were short relative to their zones, participants reported having time to explore after playback had ended. When recordings were long in relation to their zones, participants moved particularly slowly or walked repeated loops within the area. One participant simply paused at the edge of the Namidabashi zone and observed their surroundings until the recording finished.

Several accounts suggest that participants actively integrated these altered movement patterns into the narrative they constructed. One participant realized they had missed the Kozukappara segment after arriving at Namidabashi. Because the narration framed the crossing as a border between the living and the dead, they decided they "wanted to hear the history of the dead first" and chose to retrace their steps to encounter what they perceived as the walk's foundational historical layer. Together with other factors discussed later in this section, these decisions produced highly individualized routes within the shared goal of completing all four segments. The recorded sequence and timing data illustrate this further. Walking times ranged from 46 to 91 minutes, and the GPS traces (Figure 7) show that no two paths were identical. Even where participants followed the same sequence, individual route choices, detours, and returns produced distinct spatial experiences within a shared framework.

7.3. Spatial Boundaries and Technical Constraints

Across accounts, spatial constraint by the geolocated audio emerged as a defining feature of the audiowalk experience. Access to the recordings depended on remaining within predefined geographic zones, and participants frequently described the walk as open in principle but restricted in practice. One participant summarized this tension succinctly: "I felt restricted…because of the zones and the audio…you have to pay attention to not get out of the zone to keep the audio going…restricted is the right word, but not directed."

This sense of restriction did not stem from the narration itself, which was frequently described as more poetic than commanding, but from the app's spatial logic. A recurring experience was the audio stopping unexpectedly when stepping out of a zone, which sometimes produced frustration. Participants described moments of absorption in the story, followed by sudden silence. Since the recording would always resume from the beginning instead of the point of interruption, these occurrences shifted attention away from the environment and back toward the phone and map. This increased awareness of the technical system often conflicted with an expressed desire to involve the visual interface as little as possible.

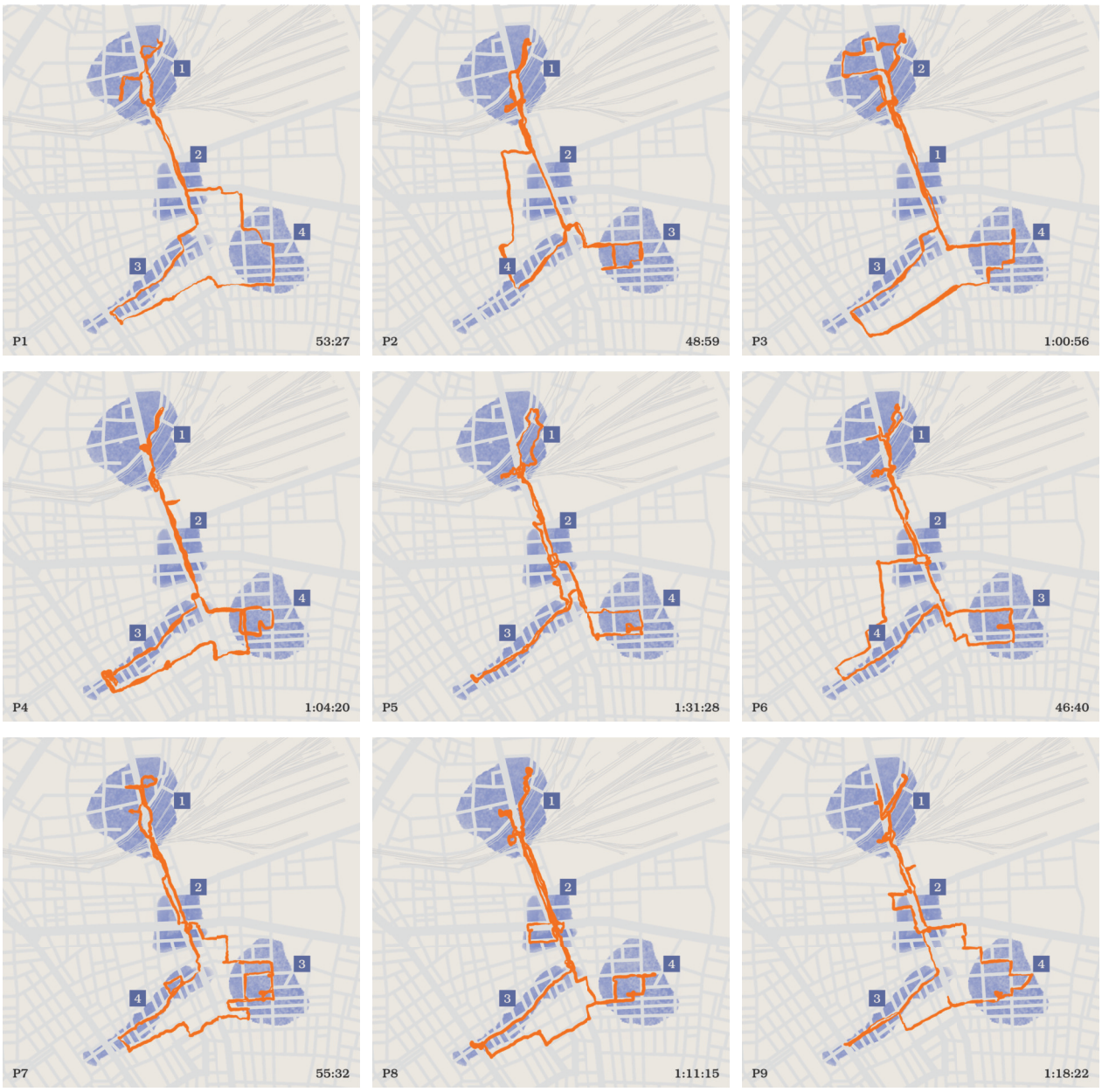


Figure 7. Participant paths.

At the same time, these limitations were also experienced positively, as participants became aware of how their own movement activated or deactivated the narrative. Several accounts emphasized that the bounded zones encouraged attentiveness to spatial boundaries and navigation choices. One participant described this as surprisingly pleasurable, connecting it to a broader reflection on digital media habits:

> It felt more, like, exciting that way, actually….Because if it had just kept playing, then I would have just walked anywhere. But then this forced me to kind of stay on a track, and I guess to look at certain things in tandem with the narrations. I felt less random, I suppose…because we're always on social media or whatever, YouTube and stuff, and you can play everything two times speed and skip forward and skip back….I liked how this was out of my hands, so I didn't have the urge to even look at my phone and try and scroll or play back.

7.4. Narrative Alignment and Misalignment

Participants repeatedly noted that the strongest and most memorable moments occurred when the narration aligned closely with what they were seeing. When spoken descriptions corresponded with visible features in the environment, they felt a sense of synchronization and were more anchored in the narrative.

One participant described such a moment of alignment:

> But in the last area…the recording matched the location where I was…the blue tile building on the right and the concrete building on the left. And it was super cool because you really pay attention to what the recording is saying, and it's easier to imagine the details and the place.

Conversely, when the narration referenced a feature that the participant could not locate, or when they entered a zone from an unexpected direction, the experience could feel disjointed and confusing. The same participant expressed disappointment when the narration referenced a sign bearing the kanji for San'ya that they were unable to find.

Others experienced such misalignments more positively. One participant characterized the process as involving "a lot of back and forth," likening it to a treasure hunt and an ongoing process of assembling fragments. Another participant extended this perspective further, explicitly valuing moments of drift, lag, and mismatch: "It didn't feel like a tour where everything is supposed to line up perfectly. It felt more…alive. Like things were happening at the same time, but not necessarily matching."

7.5. Atmosphere and Narrative Framing

Emotional responses to the area varied significantly, even with comparable environmental conditions. While some felt a sense of peaceful everyday life, routines, and neighborhood intimacy, or more neutral quotidian impressions, others experienced the area as unsettling and tense. Importantly, several accounts suggested that the audiowalk did not simply add information but actively framed how the environment was interpreted. The segment on the Kozukappara execution grounds, located closest to the meeting spot, frequently became the opening segment and was particularly influential. Hearing about the scale of executions immediately shaped one participant's experience of the walk: "That spooked the hell out of me….I started looking behind my shoulder…trying to see if anyone's following me." Here, the story created an affective lens through which ordinary street encounters became charged with suspicion and unease.

For others, the walk produced a more reflective or even poetic attentiveness. Several participants described the walk as making them aware of San'ya's juxtapositions, such as old and new buildings, graveyards next to railways, and "forgotten" structures alongside everyday life. One participant described Minami-Senju as a place where boundaries "like living and dead, past and present, sin and non-sin" collapse and noted that this perception emerged specifically through the framing of the audio.

7.6. Sensory Contingencies

Variations in sensory conditions played an important role in how the audiowalk unfolded. While each participant completed the walk only once, some noted that changes in weather, time of day, or seasonal

conditions would likely create a vastly different experience. Sunlight, in particular, was frequently mentioned as affecting both perception and navigation. One participant described the late afternoon light that filtered through the low-rise buildings as creating a "mystic" atmosphere, while another assigned it a "peaceful" quality. This visual atmosphere stood in tension with the narration's darker themes. For another participant, glare made it difficult to see and prompted them to change streets, demonstrating how the route of the walk could be altered by environmental conditions.

Beyond light, participants also mentioned smell and other sensory impressions. Passing "dumpster-like" smells, for instance, triggered associations with other places and memories and produced an unexpected emotional resonance.

One participant recalled a sonic overlap while walking through Iroha Kai shopping street, when a single shop was playing a Billie Eilish song. Listening with one earphone in, the song faded in and out as they moved past, and collided with the audiowalk's narration and the surrounding scene of aging buildings and passersby. The moment was described as "a super strange collage" and raised a lingering sense of temporal dislocation:

> To hear that kind of, like, approach and then pass me by while [the audio is] talking about the history of that street….Like, where am I? What time period is this? There's only old people on that street, and everything is kind of falling apart, and it's just Billie Eilish's beautiful voice. It was the *Birds of a Feather* song. It's kind of haunting, right? But also super contemporary.

7.7. Social Positioning and Ethical Tensions

All participants described a heightened awareness of their social position while walking through a non-touristic residential area, emphasizing moments of self-consciousness and the feeling of being watched and visually marked in space. One participant linked this directly to her visible difference as a young foreign woman, describing how the atmosphere of the narration intensified her sense of exposure and inhibited her from lingering despite curiosity. A similar sense of outsiderhood was expressed by a male local participant, who nonetheless described feeling that he "didn't belong here" when moving through the neighborhood.

Several participants used the word "witness" to describe their role during the walk. One elaborated on this in terms of attention and partial knowledge: "I felt like a witness, I felt like a sort of a social scientist….I was looking *to* see something, and I was also looking *for* something." Another described witnessing as distinct from mere observation and connected it to the temporal layering of the audiowalk:

> Observing is just seeing what's going on at the present moment…but because there's that history to it, it feels more like you're witnessing the whole history….Imagining, flashback. I think that's why I resonate closely with the word "witness."

At the same time, this mode of attentive presence raised ethical questions among participants. One described a feeling of "invading the space" and of mentally consuming people as part of the walk's narrative, noting the unease of "looking with intention" and imagining others through a historical frame they had not consented to:

> Being there, like, consuming as content…felt sometimes a bit wrong…these people that are there, you kind of piece them together with the past. So in a way they become a part of the experience, part of the audio…they become the content of the walk…when they don't expect to be consumed in that way.

8. Discussion

The following reflects on what the re-staging of *placeless: San'ya* reveals about geolocated audio as a form of spatial computing. Drawing on the participant accounts outlined in Section 7, it explores what such practices offer for engaging with contested urban space.

8.1. Audiowalking as Spatial Computing

The findings of Section 7 suggest that the audiowalk functions as a form of spatial computing in a practice-led, experiential sense: a situated arrangement in which geolocated sound, bodily movement, and physical space are continuously negotiated through walking and listening. This positions the format in a productive tension with dominant modes of spatial computing in urban contexts, such as data-driven urban modeling and simulation, which tend to produce comprehensive, legible accounts of urban space oriented toward predictability and control (Kitchin & Dodge, 2011). The spatial logic of the audiowalk, by contrast, is contingent and incomplete. Some of this contingency is rooted in the perceptual characteristics of audio established in Section 2. Since sound unfolds in time and surrounds rather than focuses attention, it produces an inherently situated and partial experience. This becomes particularly significant in the context of San'ya, whose histories resist the kind of stable representation that prevailing spatial computing approaches are designed to produce. Accordingly, the audiowalk did not provide an authoritative reading of the district but instead engaged participants with what is absent and officially unacknowledged.

Sound as a spatial interface has a further distinct quality. While screen-based media can also augment environmental perception, the audio layer operates without requiring any visual attention or mediation of a display. Participants described environmental sounds and bodily awareness as remaining present alongside the narration, with the audio shaping but not prescribing movement and attention. Even so, the system carried its own infrastructural demands, as attention shifted back to the screen and map whenever participants stepped outside a zone.

8.2. Spatial Structure and Participant Agency

The unusual, non-linear movement patterns participants described emerged from the interaction between the audiowalk's spatial structure and their decision-making. The zones, along with the duration and content of the audio, influenced where participants paused, how they paced themselves, and what they noticed. Beyond the macro level of the audio zones, participants were also searching for small details that were made meaningful by the narration. The findings thus indicate that the geolocation functioned not merely as a trigger for audio playback but as a spatial system that reorganized how participants moved through and attended to the neighborhood.

As it produced experience through contingency and participant-driven navigation, the audiowalk thus stands in productive contrast to the top-down spatial logic of prevailing modes of spatial computing in urban contexts that are oriented toward control and predictability.

8.3. Productive Misalignment

Accounts consistently showed that both alignment and misalignment between narration and place were experienced as meaningful. Participants described working toward a sense of narrative coherence that did not depend on perfect synchronization between audio and place. When the audio did not match their surroundings, they felt compelled to recall details and search for missing elements. Spatial and informational gaps were filled through imagination, and participants remained curious and actively engaged with their environment and the narration.

Because audiowalks, in the form that is explored here, are necessarily embedded in spaces that contain more than is anticipated and change independently of it, this friction is inherent to the medium. In contexts where historical facts are intended to be conveyed efficiently, such mismatches might be understood as a design limitation. In the case of this work, however, the findings suggest that misalignment can be a useful device for engaging with contested histories and unstable atmospheres. For San'ya, this imperfect coupling between physical site and digital content thus proved particularly productive. Places such as Kozukappara are experienced as sites whose significance had to be imagined and inferred while standing within the rhythms of everyday urban life. The audiowalk, therefore, supports an understanding of urban memory as a situational process that is shaped by encounter and interpretation.

8.4. Witnessing and Non-Monumental Memory

As described in Section 7, participants reported moments of unease due to feelings of being or being perceived as an outsider. The reasons ranged from visible foreignness and gendered vulnerability to simply understanding spaces as not socially coded for them. These feelings generally did not stem from a sense of risk, but instead were framed as social and moral questions of "intruding" by moving through a residential neighborhood with the explicit intention of observing it. This raises an important point for geolocated works deployed in socially uneven spaces where experiences of visibility and belonging are not shared equally, as the audiowalk, beyond mediating historical narratives, also mediates the relationship between walker and local life. By framing the neighborhood through a particular narrative lens, there is a risk of turning the space into an object of aesthetic or historical consumption. At the same time, the discomfort of the participants suggests that the work may also induce ethical reflexivity, as it confronts the walker with their own position and gaze.

This tension is especially relevant in the context of changing attitudes toward foreign presence, tourism, and (perceived) outsiders in Japan. It highlights that the audiowalk and its interpretation cannot be separated from its temporal context, shifts in public mood, and the politics of belonging. During times of heightened suspicion toward foreigners, a walker's sense of intruding, being watched, being judged, or not belonging becomes part of the work's contemporary meaning.

Within this context, the audiowalk positions participants as witnesses, a term and role several of them invoked. Witnessing here involves attentive presence and acknowledgment of situatedness and partial understanding, without claiming resolution or certainty. The walk sustains this unsettled position by allowing historical and narrative fragments, contemporary life, and personal interpretation to coexist. These dynamics show the potential of geolocated audioworks to support non-monumental, ethically attentive engagement with marginalized urban histories, which avoids their reduction to spectacle.

8.5. Limitations and Design Implications

While participant accounts indicate that the audiowalk shapes movement and attention, the findings also highlight limitations that could inform future versions. One issue concerns the technical boundary system. The zones produced a sense of enclosure and excitement for some participants, but were also a source of frustration, as interruptions shifted attention back to the map on the phone screen. If screen-based mediation is to be reduced, future iterations may need to reconsider how boundaries are communicated or how audio continuity is maintained. Although the Echoes platform supports features such as automatic audio resumption upon re-entry, spatialized playback, and fade-in/fade-out cues, these features were not available within the version of the software used in this study.

Another limitation concerns narrative sequencing. Some participants voiced a desire for greater linearity or more clearly defined starting points, while others valued the freedom to wander. This tension may not need to be resolved, as it can be understood as integral to the work's conceptual approach. It does, however, raise design questions about how much coherence is required for participants to feel securely oriented.

9. Conclusion

This study examined a geolocated audiowalk as a form of spatial computing and what participants' experiences revealed about audio-based spatial mediation in a historically and socially contested urban context. Through the re-staging of *placeless: San'ya* and a qualitative participant study, it explored how geolocated sound, bodily movement, and urban space interact to produce situated forms of knowledge.

The findings demonstrate that geolocated audio can function as a spatial interface that reconfigures movement and attention without displacing embodied awareness. Where dominant spatial computing approaches model the city as predictable and controllable, the audiowalk produced experience through contingency and participant-driven navigation. It shaped how participants moved, paused, and attended to their environment, but left interpretive and navigational decisions in their hands.

The study further shows the misalignment between narration and place as a productive feature. Gaps and imperfect correspondences compelled active interpretation, with participants assembling meaning through fragments and inquiry. In San'ya, with its contested histories and unstable representation, this mode of engagement points to an understanding of urban memory as emerging through situational encounter.

The audiowalk also foregrounded ethical dimensions that spatial computing discourse does not always explicitly address. Moving through a socially marginalized space with a narrative frame raised questions about positionality and the risk of turning places of ongoing precarity into objects of consumption. Instead

of resolving these tensions, the work rendered them perceptible and positioned participants as witnesses in an unsettled and ethically attentive sense.

For spatial computing research and urban planning, this study contributes a practice-led perspective that demonstrates how audio-based approaches can engage with what prevailing modes are not designed to accommodate. The study is necessarily situated, as it reflects a specific site, a small number of participants, and the dual role of the author as artist and researcher. Future research could build on this through comparative studies examining how different spatial logics and audio structures shape participant experience, as well as through longer-term or collaborative engagement with communities in socially contested spaces. Taken together, the findings point to a broader understanding of spatial computing, which accommodates absence, embodied attention, and ethical complexity alongside the data-driven and visual approaches that currently dominate the field.

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Conflict of Interests

The author declares no conflict of interests.

Data Availability

Due to the nature of the research, data sharing is not applicable to this article.

LLMs Disclosure

To assist with improving the manuscript's grammar and stylistic clarity, the author used ChatGPT (OpenAI) in some parts. Interviews were conducted primarily in English; however, several bilingual participants occasionally shifted into Japanese when expressing more nuanced experiences. As the researcher is a non-native Japanese speaker, ChatGPT and DeepL were also used to support the translation of selected excerpts from Japanese into English. These tools were used solely as aids, and all generated text and translations were carefully reviewed and manually verified against the original recordings and transcripts to ensure accuracy and contextual fidelity.

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About the Author



Lisa Woite is an artist and doctoral candidate at Musashino Art University, Tokyo. Her research examines site-specific audiowalks as a means of engaging with non-monumental urban histories through embodied movement and listening. Her work has been shown at Museum für Fotografie Berlin and Lichtsicht Projection Triennale, among other venues.

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Within the Flows: Participatory 3D Scanning in Asian Techno-Industrial Hinterlands

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Abstract

The peri-urban remains a slippery category, widely used to describe spaces at the edges of cities yet rarely pinned down in ways that enable meaningful readings across contexts. This article argues that both literature and methods pertaining to peri-urban spaces require frameworks capable of holding two positions in tension: an embedded, place-based lens that centres on-the-ground narratives and experiences, and a comparative approach that sustains the peri-urban as an umbrella term across contexts. Tracing the scholarship of peri-urbanisation through notions of the hinterland and "hyperbuilding," the article examines two state-planned industrial enclaves at the rural/urban margins of Chennai, India and Hsinchu City, Taiwan, drawn into comparative focus as interconnected nodes within global high-tech supply chains, exemplifying a mode of peri-urbanisation characterised by the circumvention of everyday urban realities and sustained by exceptional governance. Drawing from lens-based methodologies that centre walking and sensorial engagement, this article proposes participatory 3D scanning (photogrammetry) as a method to engage the transformations occurring at this interface of the ordinary and the exceptional, the local and the planetary. This method is operationalised via two workshops, revealing a perceived and comparative sense of inexorability across participant outputs. The article concludes by detailing the aggregation of workshop outputs onto a web-based platform (Techno-Urban Atlas), reflecting upon the circulation of digital objects to extend the epistemological scope of peri-urban transformations and generate new opportunities for user-led comparison.

Keywords

3D scanning; comparative urbanism; hinterlands; India; participatory methods; peri-urban; photogrammetry; Taiwan

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1. Introduction: The Peri-Urban

With the rapid expansion of urban areas worldwide, peri-urban spaces have emerged at the peripheries of cities, characterised by rural-to-urban transformations generating a mosaic of mixed morphologies, livelihoods, ecologies, and practices (Iaquinta & Drescher, 2000). Especially within the rapidly urbanising landscapes of Asia, peri-urbanisation is marked by increasingly heterogeneous socio-economic composition, accompanied by the uneven interaction between economically asymmetrical industries, land speculation, ecological destruction, and increased informalisation (Webster & Li, 2020). Peri-urban spaces are characteristically regarded by sectoral and institutional actors as blank canvases for the exertion of civic interests (Allen, 2014), configured as strategic resources for metabolic flows, receiving waste and landfill while storing the key resources required to maintain urban energy, food, and water security (Gallent & Shaw, 2007). As expanding cities exert growing pressure on contiguous areas, peri-urban spaces are defined by stark contrasts: Hyper-development exists alongside vast underserved tracts, enclaves of wealth border expanses of marginality, and forward-looking visions of urban futures coexist with contested legacies of the past.

An overarching definition of the peri-urban remains uncertain due to the differences that are observed across urban and rural systems, generated and persistently shaped by regionally specific dynamics. Drawing from McGee's (2015) formative efforts to inscribe situated specificity into the peri-urban lexicon, Wu and Sui (2016) argue that the rural–urban interfaces of Asian urbanisms require a lens capable of engaging the abundant ambiguous typologies that exceed classical Western models premised on a distinct rural–urban dichotomy. From this perspective, the lack of discursive consensus suggests a concept that overly emphasises the rural–urban interface as an a priori hypothesis detached from empirically driven modes of knowledge generation. This is not to cast doubt on the theorisation of urban peripheries, but rather to reframe the epistemological ambiguity as a lack of understanding of the embedded socio-spatial and political forces that mediate the outcome of urban and rural spaces.

Recognising this complexity demands that the peri-urban be operationalised in ways that are responsive to, rather than abstracted from, the empirical conditions in which it is encountered. In this sense, the peri-urban serves as a crucial lens through which a conceptual typology can be developed, one enriched by empiricism and attentive to urban difference. Operationalising the peri-urban here is extended as a means to bridge the lacuna that often exists between imported theory and empirical conditions within the scholarship of southern cities (Lawhon & Truelove, 2020). This mirrors Ghertner's (2015) cautionary critique that while gentrification as an analytic assists in identifying outcomes such as rising rent and market-induced displacement as global phenomena, it fails to chart the more fundamental interactions of land privatisation, the often contradictory actions of the state, and the overlapping socio-political dynamics of residents. Likewise, peri-urbanisation risks labouring at a generalised model that misses the fundamental dynamics occurring at the interface of rural and urban systems. Scholarship has therefore proposed positioning the peri-urban as an umbrella concept that works with empiricism to compose polyvocal and variegated processes, directed by a lens that makes legible the fragmentary, the multiple, and the particular (Follmann, 2022).

It is from this position that scholars have called for a "peri-urban turn" that re-engages peri-urban areas as a settlement typology composed as a dynamic assembly at multiple scales (Rajendran et al., 2024). From one distance it is critical to account for the relationships and reciprocities of peri-urban spaces amongst

increasingly planetary flows of resources, capital, people, and knowledge (Brenner & Katsikis, 2020), while simultaneously incorporating a granular "place-based" conceptualisation that emphasises peri-urban areas as a dynamic matrix for everyday life, identity, and social occurrence (Rajendran et al., 2024, p. 10). Drawing from formative debates on comparative urbanisms, the trajectory of this peri-urban turn aligns with the necessity to think across contexts so as to engage processes and outcomes that are at once diverse, featuring specific historical and socio-spatial dynamics, and differentiated, interconnected iterations within circuitries of urbanisation and globalisation (Robinson, 2023, pp. 4–5).

Within recent years, academic, artistic, and creative voices have borne witness to peri-urban spaces by centralising human storytelling and local worlds amongst the flows and circuits of the planetary (Beelen & Ganesan, 2016; Jayaraman et al., 2025). Within this growing body of thought and praxis, this article maintains that there is an opportunity to enhance this dual-lens of place and flow by integrating participatory, walking-based, and sensorial modes of place-based action with digital tools that widen the field of comparison. The article discusses the application of smartphone-based 3D reconstruction, popularly termed 3D scanning, to produce mobile digital objects that tilt the gaze towards the materials, objects, and landscapes of peri-urban spaces while additionally enabling the commingling of realities through web-based platforms. While non-specialist 3D scanning has been discussed as a tool for recording and surveying the built environment for heritage conservation (Tait et al., 2016) and citizen science in data-scarce contexts (Chmielewski et al., 2019), there remains little scholarship on the technology's capacity for generating embodied engagements with landscapes or as a component within ethnographic or walking methods, akin to other lens-based technologies such as photography or film.

This article turns to two peri-urban spaces at the edges of Hsinchu City, Taiwan and Chennai, India (see Figure 1), selected for their specialised positions within a critical supply chain of consumer smartphones, in which advanced components produced in the former by the world leader of fabrication (Taiwan Semiconductor Manufacturing Corporation [TSMC]) are assembled into finished products in the latter by the world leader in electronics manufacturing (Foxconn). In addition to this nodal connection, the sites exemplify a mode of peri-urbanisation particular to techno-industrialism in which factory enclaves are governed through what Ong (2011) identifies as a rule of exception, a flexible instrument of sovereign practice that holds them materially, economically, and territorially apart from the functioning of their surrounding regions. This separation is compounded by an ordering process in which the enclaves' role within planetary networks of high-tech production is elevated above the needs and realities of nearby residents and settlements. Read together, these conditions align the two sites with scholarship of the hinterland, an additional mode of peri-urbanisation generated through insistent logics that strategically bypass the coordinates, realities, and imaginaries of the everyday city (Arabindoo, 2020; Rajan, 2019). Tracing this interplay of exceptional rule and bypass through the emergence of functioning of both techno-industrial landscapes draws into focus the obscured encounters and practices of everyday life composed around and within the enclave.

It is here that the article proposes participatory 3D scanning as a means of engaging this peri-urban tension by discussing the method as a walking-based and sensorial encounter, situating smartphone photogrammetry alongside adjacent lens-based approaches. This discussion is proceeded by detailing two 3D scanning workshops conducted outside of Chennai and Hsinchu City that operationalise this proposition, leading to the production of the Techno-Urban Atlas (https://www.latentspace.com/TUA.html), a web-based platform built for composing and comparing participant outputs. The article then reports on the

workshop results through the emergent theme of inexorability, read in relation to concepts of exception and bypass, before turning to what 3D scanning methods offer to comparative work across peri-urban contexts.



Figure 1. Geographical locations of the two case study areas. Source: Adapted from Google Earth (Google, 2026).

2. Asian Techno-Industrial Hinterlands

As the global reliance on technology intensifies through the dispersion of precision technologies into myriad dimensions of human life, high-tech supply chains have become both extraordinarily complex and a matter of intense state competition (So, 2006). Miller (2022) declares the 21st century has emerged as an epoch in which the military and economic security of nations depend on access to one of the industry's few chokepoints, occupied by a handful of companies. This is especially relevant within Asian urban systems, already considered the factory of the world (Zreik, 2024), where state-led initiatives in collaboration with multinational companies have sought to capitalise on the high-tech sectors of a fourth industrial revolution (Miah et al., 2024), increasing the intensity and pace of urban expansion.

The contemporary high-tech production sectors can be divided into capital-intensive fabrication and labour-intensive assembly (Hao & Bu, 2022). This division is replicated territorially through the offshoring of production stages within supply chains where demands can be met with greater supply, forming constellations of global processes that converge into final products. Peri-urban areas across Asia, already key sites for transnational non-digital industries due to proximity to both urban and rural workforces, cheaper land, and often weaker governance regimes (Gururani & Kennedy, 2021), have witnessed novel modes of development and governance as the high-tech era has intensified the urgency and investment of industrial transformation. Where scholarship conceived of the peri-urban as a territory, process, or interface mediating rural and urban systems, the techno-industrial configurations more accurately align with the conceptualisation of hinterlands (Arabindoo, 2020), in which strategically state-constituted enclaves at the edges of cities are staged as territories of frictionless optimisation and distribution within criss-crossing

networks of industrial forms equally configured to smooth the global movement and processing of goods. This quality of unfettered movement is sustained by a logic of bypass, in which existing social, territorial, legal, and ecological realities are rendered through extrastatecraft (Easterling, 2014) as inconvenient frictions to be circumvented and subverted. Bypass is at once understood as a material deviation in which physical infrastructure is built to prioritise certain forms of movement over others (Arabindoo, 2020, pp. 217–218), and as an instrument of marginalisation which encloses and subordinates the claims and narratives of hinterland residents (Rajan, 2019).

In this regard, techno-industrial enclaves are best understood not as passive entities upon which flows of global processes organically converge, but as products of what Ong (2011, pp. 206–207) terms the rule of exception, through which state actors exercise political flexibility for economic and political ends. Spaces become sites of variegated governance and political exception that facilitate the "hyperbuilding" of two intractably global constructions: the mechanisms of economic capture and a geopolitical profile of national emergence (Ong, 2011). The techno-industrial hinterland locates this process through a protocol of geographical, economic, and ideological bypass oriented towards the geopolitical and economic aspirations of state actors while marginalising adjacent settlements and residents. The following subsections detail the emergence of two industrial enclaves within the peri-urban areas of Hsinchu City and Chennai as two distinct hinterlands oriented towards techno-industrialism, each enacting unique practices of bypass and exception.

2.1. The Hsinchu Science Park

The centre of Taiwan's techno-industrial industry is the Hsinchu Science Park (HSP), situated in the island's northwest. The HSP is built across nearly 10 square kilometres overlapping the administrative bodies of Hsinchu City (primarily urban) and Hsinchu County (primarily rural; see Figure 2). The genesis of the park can be traced to the establishment of the first Export Processing Zone in 1966 in the southern city of Kaohsiung, as the Kuomintang government sought to shift the focus of Taiwan's newly reconstituted economy from agriculture towards industry. The periphery of Kaohsiung was selected as an attractive location within which the enclave could fit into the existing urban infrastructure, including airport and shipping nodes, while drawing from the nearby cheap labour (Wong & Chu, 1984).

Two years later, emboldened by the success of the Export Processing Zone, the then Minister of Economic Affairs, Kuo-ting Li, proposed a research park in the Hsinchu region. Although the proposal initially failed to gain traction, it resurfaced in the 1970s in response to increasing international competition in manufacturing, rising labour costs, and geopolitical fallout from worsening relations with the US and derecognition by the UN (van Hoesel, 2003). An area at the edges of Hsinchu City and Hsinchu County was selected for its proximity to the Industrial Technology Research Institute, and Chiao Tung and Tsing Hua Universities, replicating the agglomeration pattern observed by government officials in the US's Silicon Valley between research institutions such as Stanford University and private sector ventures.

While Silicon Valley would emerge as the model prima facie, the Kuomintang government pursued a strong state-planning regime more reminiscent of the Kaohsiung Export Processing Zone than the softer touch practiced in California (Hsu, 2018b). The result was a hybrid entity combining the suburban entrepreneurial imaginary of the US West Coast with the enclave governance model of a free-port. This spacious and

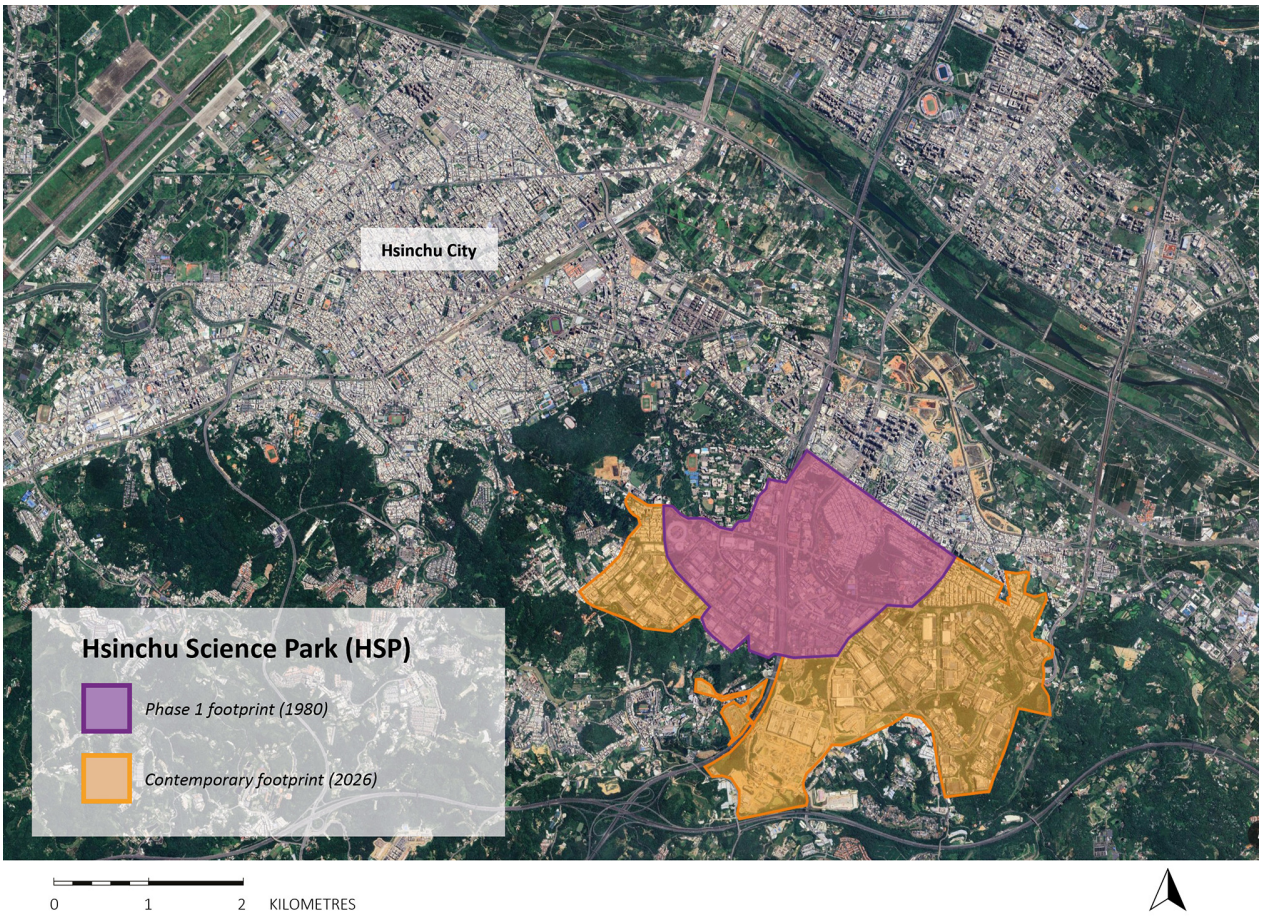


Figure 2. Hsinchu region with growth of HSP. Source: Adapted from Google Earth (Google, 2026), and data from International Demonstration Irrigation Processing Center (2026).

cosmopolitan landscape of bungalows and glass factories stood in visual contrast to the dense urban landscape of Hsinchu City and the traditionally rural Hakka villages of Hsinchu County. The territorial distinction was enhanced through material, economic, and regulatory means by the construction of perimeter walls and controlled access gates requiring special permits (Hsu, 2018a, p. 492). Additionally, a separate administrative entity subject to the National Science and Technology Council, unaffiliated with the governments of Hsinchu City or County, was created to oversee the park (So, 2006, p. 70), precluding local governments from directly sharing in its wealth creation.

The HSP entered a new era in the mid-1980s with the emergence of the integrated circuit (IC) sector as semiconductors increasingly became vital components of everyday technologies. Although United Microelectronics Corporation was the first semiconductor company established in the HSP, it was TSMC's rise as the world leader of IC fabrication that cemented the park's trajectory. Over subsequent decades, as the digital revolution brought the popularisation of personal computing, a near-global proliferation of smartphones, followed by the AI boom, the high-tech output of the HSP has come to take on a rhetoric of both economic miracle and salvation. As Taiwan's IC sector revenue is expected to total 270.7 billion USD (Taiwan Semiconductor Industry Association, 2026), the industry has additionally strategically positioned Taiwan amidst the US–China "Techno-Cold War," gaining the moniker the "silicon shield" (Lin et al., 2025).

This narrative of national redemption is an insistent presence within multiple levels of state functioning. In an address marking his first year in office, President Lai evoked Taiwan as "the world's silicon island" (Office of the President, 2025), totalising the imaginary of the HSP to a national scale. At a local level, the transformative power of this techno-industrial imaginary emerges through an enduring pattern of prioritisation over nearby rural and urban systems. National security, industrial urgency, and global competitiveness converge into an exceptional status that justifies the differentiation of the park, bypassing surrounding socio-ecological realities. Kollar (2026) describes how mandated fallowing of agricultural lands has become routine for rural farmers in surrounding counties as water resources are diverted to the HSP, with Taiwan's hydrological systems configured as mechanisms of techno-statecraft that legitimate exceptions and consolidate a spatial order centred on high-tech accumulation.

The position of the HSP as an instrument of marginalisation within the surrounding social configurations is distilled by the comments of former Hsinchu City mayor, Jen-chien Tsai, who satirised the area as a "technology colony" (So, 2006, p. 77). The comments reinforce a disarticulation that is observed by Wang (2023) in a study of the segregated mnemonic geographies of "old-timers," lifetime residents of the Hsinchu region, and the "newcomer" skilled workers employed within the HSP. The study notes that the HSP's ascendancy initiated a regional identity shift from historic city to technopole, creating a contested psychic landscape that hardened the social and economic divisions between the groups into an uneasy status quo. This was exacerbated by development plans oriented towards "globally influenced city expansion and improvement" (Wang, 2023, p. 258) that failed to generate inclusion between resident groups. Read alongside its economic, territorial, and material differentiation, these social rifts ground the HSP's functioning within an optimisation or bypass of local identity and memory, ordered against a capacity to smooth the planetary passage of commodities and state narrative.

2.2. Sunguvarchatram and State Industries Promotion Corporation of Tamil Nadu Sriperumbudur

Tracking the configurations of Chennai's urban edges, Gajendran (2016) distinguishes three phases: the colonial, the post-independence, and the post-neoliberal. Within the post-independence period, as part of a wider pattern of subnational state management of industrialisation, the State Industries Promotion Corporation of Tamil Nadu (SIPCOT) was created in 1972 to financially produce and administratively support industrial corridors. Through mechanisms such as tax holidays, credit entities, and import facilities, alongside a system of licensing, state entities held strong influence over the physical location of medium and large-scale industrial projects (Kennedy, 2007, p. 318). With the transition to neoliberalism in the 1990s, competition to attract lucrative international partnerships ramped up amongst individual Indian states, marking a period of deregulation, privatisation, and removal of administrative controls (Chandrasekhar, 2010). As the economy "opened up" at a national and state level, the role of the Tamil Nadu government was reconfigured into one of competitive gatekeeping, enacted increasingly through public-private partnerships with a "who's who" of transnational companies. The neo-liberalisation of state industrial planning had spatial ramifications, upending the prohibition of industrial estates within 50 kilometres of metropolitan areas due to concerns over pollution, saturation of urban infrastructure, and migration from rural areas. As controls loosened, SIPCOT corridors emerged in areas 30 and 40 kilometres outside Chennai, representing a shift towards state-driven anticipation of private demand for agglomerated growth pole configurations around the city's logistics and infrastructural networks (Kennedy, 2007).

The manufacturing plants of the 1990s provided an administrative rubric and territorial footprint for the intensification of SIPCOT parks in the 2000s, resulting in the formation of four key hinterlands ranging in focus from logistics hubs, power stations, watershed capture, and IT services parks (Woiwode et al., 2024). Economically and geographically central within this arrangement of hinterlands is the Chennai-Bengaluru Industrial Corridor, a mixed-sector strip extending west containing early SIPCOT parks, such as Ranipet, and some of the largest, including Oragadam. The emergence of this industrial formation, argue Homm and Bohle (2012), stems from two development strategies: a comprehensive IT policy produced by the state government in 2002, and the formalisation of existing incentive structures into territorialised Special Economic Zones (SEZs). Approved in 2012 and brought under SIPCOT's remit, the SEZ's standardised exceptional fiscal packages of tax and tariff relief into duty-free enclaves while minimising regulation. Fundamental to this incentive structure is exceptional access to water and electrical services, prioritising industrial consumers over everyday residents (Homm & Bohle, 2012, p. 292), further disarticulating the hinterland from its surroundings.

Within the Chennai-Bengaluru Industrial Corridor, this exceptional arrangement of economic and resource incentives encountered the digital revolution, ushering in techno-industrial actors including Samsung, Dell, and Nokia, all of which established operations in a SIPCOT park and SEZ outside of the small town of Sriperumbudur. Nokia set up the world's largest mobile handset manufacturing plant in January 2006, bringing suppliers such as Foxconn, a manufacturing and assembly company which dominates the offshore labour-intensive side of Taiwan's consumer electronics industry, complementing the "at-home" capital-intensive suppliers such as TSMC (Hao & Bu, 2022). By 2014, with the shuttering of Nokia's Sriperumbudur operations, Foxconn, now firmly the world leader in electronic manufacturing, was preparing to exit Tamil Nadu. By 2017, the geopolitical landscape had shifted, and the Tamil Nadu government sought to capitalise on Taiwanese companies looking to diversify manufacturing away from China (Venugopalan & Misra, 2025). Building on the existing SIPCOT framework and SEZ mechanisms, 49 acres were earmarked for Foxconn factories to begin iPhone production deeper into the Chennai-Bengaluru Industrial Corridor, next to the village of Sunguvarchatram (see Figure 3). For a community listing a population of 4,000 in 2011 (Directorate of Census Operations Tamil Nadu, 2011), the emergence and subsequent expansion of the Foxconn plant to 180 acres has been transformative. As the state seeks to deepen networks of world-class urban infrastructure, deploying what Goldman (2021) characterises as "a spectacular imaginary on *what could be*" (p. 6, emphasis in original), Sunguvarchatram faces the construction of a pending 5,746-acre greenfield airport 10 kilometres away and an incoming four-lane Bengaluru-Chennai Expressway less than a kilometre to the north.

In the present moment, the socio-spatial order of Sunguvarchatram is reconfigured by the sustained status quo of exceptional and parallel governance projected from the SIPCOT factories, rendering the village an afterthought against the functioning of the plant. The region faces ecological difficulties ranging from pollution associated with industrial effluents and vehicular emissions (Sundarrajan & Velmurugan, 2016) to continued strains on groundwater from the needs of SIPCOT factories (Gajendran, 2016). To service the labour needs of the factories, fragmented housing and transportation have shifted Sunguvarchatram towards absorbing workers, ferried to work every 8 hours at shift changes by a motorcade of employee shuttles. This housing question continues to usher in a wave of splintered land speculation as developers become key actors in a process of transforming agricultural land for urban real estate (Raman, 2016, p. 84). The public spaces of Sunguvarchatram have witnessed additional transformation as sites of protest and conflict spilling over from

nearby factories. As an attempt to become ever more attractive within an increasingly competitive global and intra-national field, Tamil Nadu reclassified SEZs as "public utility services," enabling strict parameters around de jure "legal" strike action for workers (Dutta, 2016, p. 45). This, in addition to highly securitised architectural mechanisms, has meant that labour disputes and organised protests are conducted within the public coordinates of Sunguvarchatram.

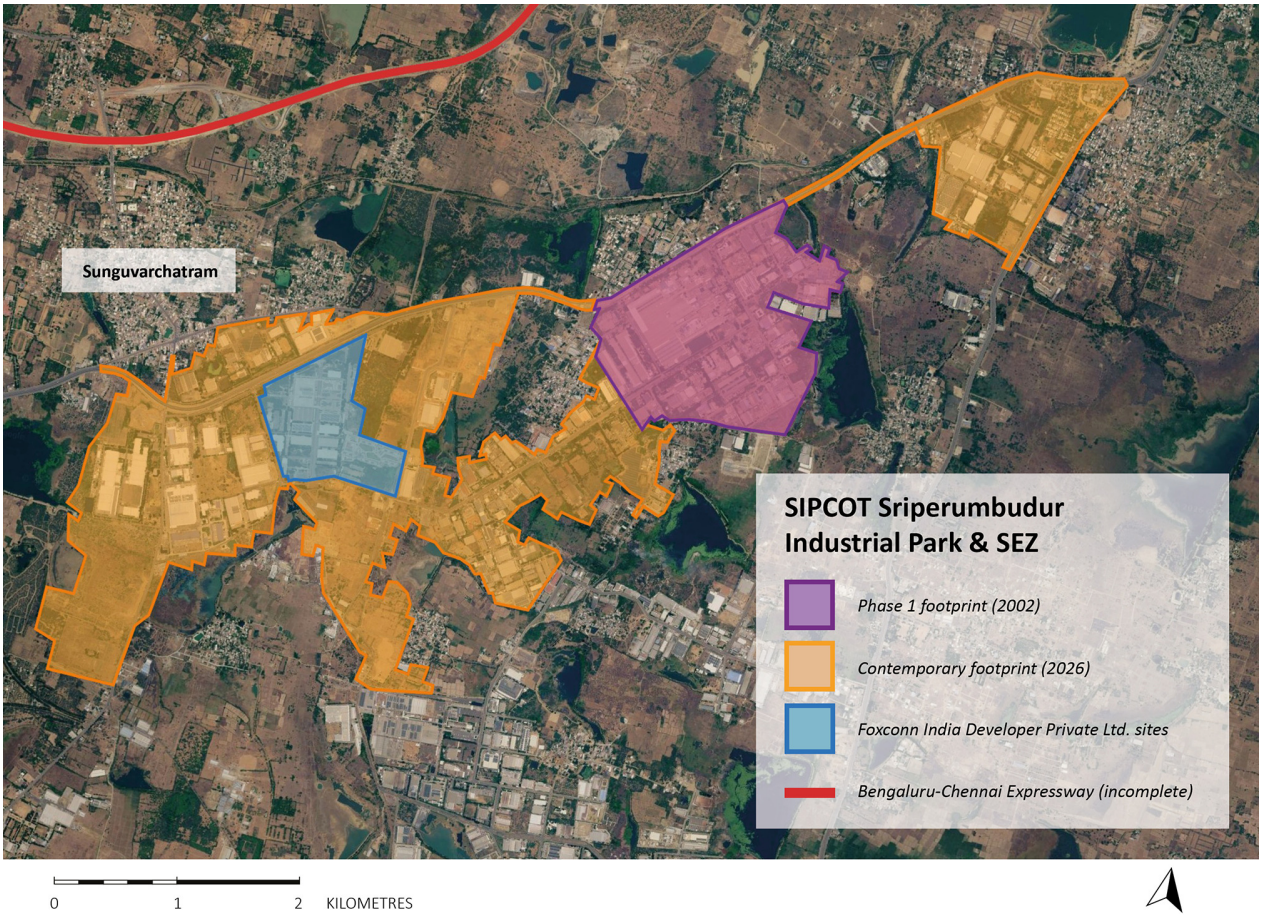


Figure 3. Sunguvarchatram region with growth of SIPCOT Sriperumbudur Industrial Park and SEZ. Source: Adapted from Google Earth (Google, 2026), and data from SIPCOT (2026).

3. Methods

Given the dense historical backdrops and layered present conditions of these two divergent hinterlands, the first step within the process of identifying relevant methods is assessing the mode of connection and comparison. Chen (2010, p. 215) maintains that understanding inter-Asian positions amidst modernisation is enhanced through ongoing processes that foster recognition of the similar pressures and trajectories experienced by, and impressed upon, others. Indeed, the connective tissue between these high-tech landscapes has become big news, gaining coverage in *The New York Times* (Travelli, 2024). Such accounts, however, predominantly compose contact at the register of the planetary, detailing the emergent economic, material, and corporate ties while upholding an empirical lacuna regarding the situated realities within which these flows converge. To comprehensively extend Chen's (2010) assertion into techno-urban hinterlands demands methods that foster comparison at two registers simultaneously: looking "upwards" as extended

modes of planetary movement constitute coordinated paths and nodes, and "below" where these processes are impressed and experienced within the geographies of ordinary life.

To engage this methodological concern, the study extends participatory smartphone 3D scanning employed at the interface of walking-based and sensorial reflection as an avenue towards outcomes that diversify frames of reference and multiply moments of contact between subjectivities. 3D scanning encompasses a range of techniques for generating 3D models from real-world subjects, including laser scanning, structured-light scanning, and photogrammetry. In contrast to the former modes of scanning, which require more specialised equipment, photogrammetry generates 3D models from 2D photographic data taken by a camera on the ground (terrestrially) or mounted to an aircraft or drone (aerially). Contemporary digital photogrammetry pipelines typically use a minimum of 20 photographs to be processed by cloud-based structure-from-motion (SfM) algorithms, which plot 3D points by locating homologous features across image data (Cascarano et al., 2025). Wilken and Thomas (2022) argue that photogrammetry's recent automation and increased availability via smartphone applications have opened up this technology, once monopolised by state cartographic organisations. From this perspective, 3D scanning can be seen to be maintaining a participatory moment in which access to the technology brings new opportunities of representation into urban research (Tait et al., 2016).

Much of the existing research regarding participatory photogrammetry presents aerial mapping as a countermapping technology which may unsettle the relations of power inscribed within cartography projects (Fish, 2020). Scholarship has yet to rigorously discuss the "on-the-ground" perspectives of terrestrial scanning. In absentia, this study looks to neighbouring lens-based practices to guide the discussion of embodied encounters with urban space. Notably, Cheng (2014) maintains that photographing spaces on foot brings our bodies into conversation with the environments it moves through by affected attraction (and distraction) to its ordinary socio-material components. The camera becomes a device that invigorates the relationship between the bodily senses, materials, and rhythms that frequently lie dormant within our daily encounters with a city, constituting a sensorial encounter that includes seeing, hearing, and feeling (Cheng, 2014, pp. 212–213). For Cheng (2014, p. 217), this perspective renders the act of photographing "from below" a generative and inventive praxis, one attuned to the felt presences and absences of the global as it inhabits the mundane objects and marginal spaces of the streetscape, presenting a means of sensing and feeling our way into alternative configurations of the planetary and the local. This article aligns terrestrial 3D scanning within this position, understanding the practice of smartphone photogrammetry as a walking-based encounter that likewise draws our perspective to the material and sensorial traces that constitute everyday urban life amongst the *felt* presence or absence unfolding of global flows that are always unfolding within the local sense of place (Massey, 1994).

3.1. Workshops and Website

In the Spring and Summer of 2024, two workshops were conducted in Chennai and Hsinchu City with the support of local stakeholder institutions: the Chennai Photo Biennale and the Hsinchu City Art Site of Railway Warehouse, respectively. A call for participants was disseminated in advance through each institution's networks, drawing a diverse group of local students and professionals alongside artists, activists, and architects (20 participants in Chennai and 15 in Hsinchu City). Each workshop followed a two-day multimodal structure. The first day provided technical training with a 3D scanning application on

participants' smartphones, pairing lecture-based overviews with hands-on practice in pairs (see Figure 4). In an effort to encourage participants to connect 3D scanning to sensorial reflection, the sessions drew from Arnold's (2019, p. 2) assertion that sensory ethnography, lens-based practices, and walking cooperate to become "not only a study of the city but also a study of the experience of the city," by accompanying technical learning with group worksheets prompting participants to direct their attention to what was experienced at the location of their scan. The workshops employed Polycam, a terrestrial 3D scanning application that creates high-quality 3D models via a photogrammetry pipeline that integrates analysis of images captured with a smartphone's camera with positioning data through an SfM algorithm (Cascarano et al., 2025, p. 215). The Polycam application was additionally selected for its free access, ease of use, and compatibility across iOS and Android platforms (see Table 1).



Figure 4. Participants practising 3D scanning in pairs in Hsinchu City.

The second day opened with a walking-sensing-scanning session along a pre-planned route through public areas of Sunguvarchatram and Hsinchu. Each route took participants through community areas near factory sites while avoiding entrance into dedicated industrial spaces. These routes were selected both because the industrial sites are highly securitised zones that restrict public access, and for the explicit aim of engaging with context-specific transformations occurring within everyday spaces that sit outside the exceptional status conferred on their techno-industrial neighbours. Participants operated in pairs for safety and technical support. Each pair received an information sheet with a route map and schedule, enabling self-determination of paths and timings, as well as a worksheet to structure their experiences, senses, and thoughts. The worksheet provided question and response sections encouraging participants to connect 3D scanning activities to wider socio-political ("What forces of transformation are at work?"), agentic ("What attracted you to this location?"), and sensorial contexts ("What do you hear, smell, feel, and think at this location?"). Upon completing the on-site session, the workshop relocated to a workspace where participants shared one 3D model. During this concluding session, participants cross-referenced their notes with their scans, framing their understanding of the encountered landscapes through personal affect and experience.

Table 1. List of smartphone devices and versions of Polycam used.

Smartphone Device	Polycam Version
Chennai Workshop—May 2024	
Apple iPhone 14 Pro Max	3.4.8 (iOS)
Apple iPhone 14 Pro	3.4.8 (iOS)
Apple iPhone 11 Pro	3.4.8 (iOS)
Apple iPhone 13	3.4.8 (iOS)
Apple iPhone 12 Pro	3.4.8 (iOS)
Apple iPhone 15 Pro	3.4.8 (iOS)
Hsinchu Workshop—July 2024	
Apple iPhone SE (3rd Generation)	3.5.3 (iOS)
Apple iPhone SE (2nd Generation)	3.5.3 (iOS)
Google Pixel 8	1.3.10 (Android)
Apple iPhone 15 Pro	3.5.3 (iOS)
Samsung Galaxy A15	1.3.10 (Android)
Apple iPhone 12	3.5.3 (iOS)
Apple iPhone 8	3.5.3 (iOS)
Apple iPhone 13	3.5.3 (iOS)

Unique to 3D objects, this later encounter enabled participants to intimately navigate the 3D space, developing and sharing their interest and motivations by panning and zooming in three dimensions.

Through the sharing of outputs, experiences, and reflections, parallel themes formed across the two research contexts. The nascent flow of symmetries and resonances, however, met friction against the difficulties of bringing the two sessions into closer dialogue due to geographical distance, language barriers, and participant scheduling. Through discussion with participants, it was decided that a website would be developed enabling workshop outputs to acquire thematic and digital proximity, while building on the walking-based dimension of the sessions by allowing users to navigate their own path through a web-based gallery of reflections and materials. In the proceeding months, a platform was built featuring workshop outputs in a gallery that could be navigated freely or sorted into thematic groupings (see Figure 5). Each image in the gallery led to a dedicated page featuring an interactive 3D model deployed using three.js and a short reflection written by the participant.

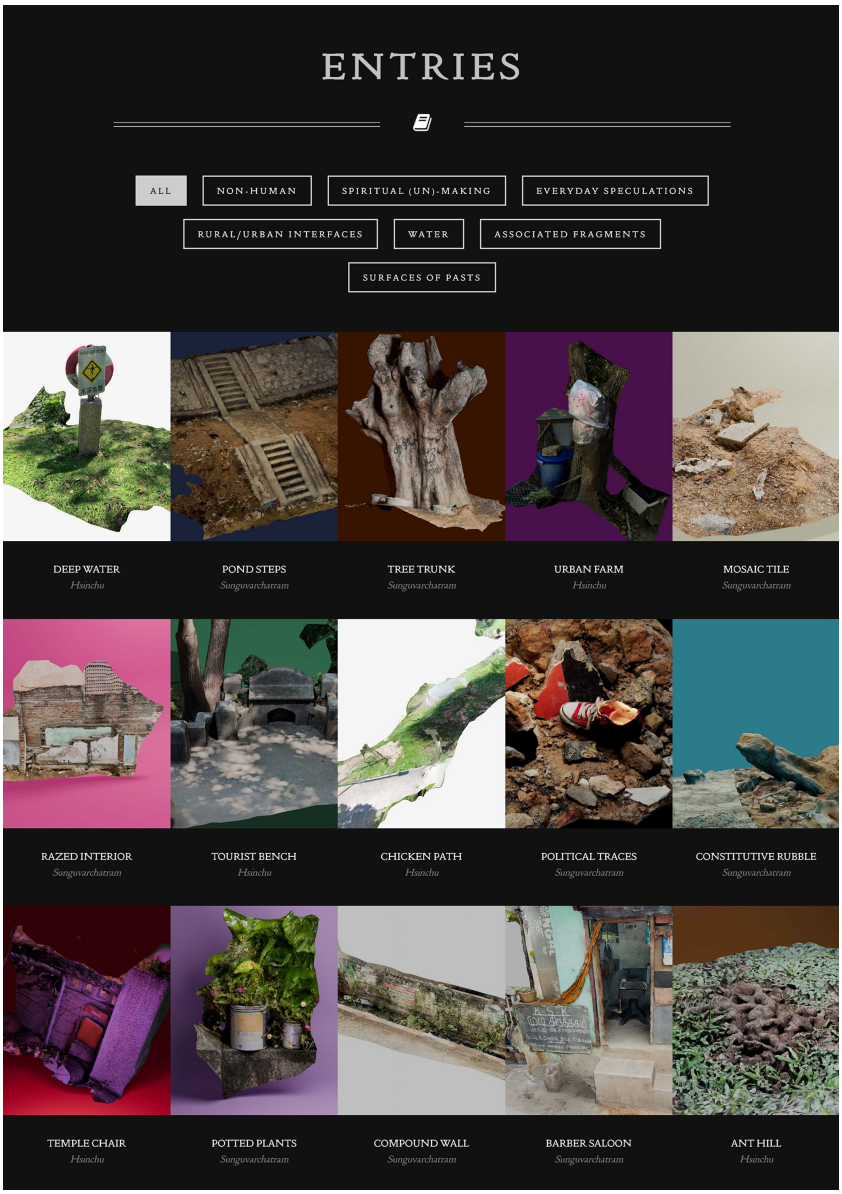


Figure 5. A screenshot of the Techno-Urban Atlas gallery with thematic groupings.

4. Results

Across both workshops, participants effectively used smartphone photogrammetry to record materials, bodies, objects, buildings, and landscapes. In both sessions, participants produced 3D objects and recorded sensorial observations expressing a felt tension between the regions as places composed through the quotidian practices of residents and the imposing logic of planetary flows associated with the tech industries. This tension rarely occurred through material juxtaposition within the same scan, instead registering to participants through the traces and residues indirectly associated with change and transformation. In the Hsinchu region, such tensions were predominantly sensed as a totalised urbanisation, with salience rising from extant non-industrial phenomena. While in Sunguvarchatram the tensions were sensed as ambient and fragmented, with the ordinariness of daily life looming under latent and uneven transformation associated with the expansion of the neighbouring industrial park.

In Sunguvarchatram, a central theme expressed by participants derived from feeling unsettled by the incomplete landscapes and debris remaining from ongoing transformations. This was exemplified by a participant who 3D scanned a half-demolished house, noting that its incomplete structure represented the violent interaction between the past and a developed and globalised future (Ruba; see Figure 6a). Another participant recorded fragments of a razed house in a pile of rubble, noting that something as concrete as a home could be removed and forgotten (Aaditya; see Figure 6c). Some participants felt hope from the perceived sense of community resilience to industrialisation, exemplified by a participant who 3D scanned a plant potted in a paint tin, feeling it represented new life growing precariously into the future (Ranjani; see Figure 6b). In Hsinchu, the feelings centred around surprise at finding extant human and natural phenomena that were perceived as disconnected from the artificial and totalised techno-industrial landscape. This feeling was located in anachoristic smells such as wet soil and cooking smells carried by the breeze and



Figure 6. Participant 3D scans relating to aspects of transformation: (a) Sunguvarchatram: Razed wall (*Ruba*); (b) Sunguvarchatram: Potted plants (*Ranjani*); (c) Sunguvarchatram: Mosaic tile (*Aaditya*); (d) Hsinchu: Anthill (*Chien*).

sounds such as the wind and birdsong. One participant concentrated on 3D scanning an anthill dug on an otherwise manicured and sterile lawn, a surprising and discordant presence within the abstracted space of the HSP (Chien; see Figure 6d).

A primary theme that emerged from the qualitative responses and 3D models was a texture of inexorability that extends from the totalising exceptionality of the techno-industrial hinterlands. As Follmann (2022) reminds us, an essential aspect of peri-urban regional variegations is a futurity that is spatially and temporally contingent upon forces that may never materialise. Analysis of the peri-urban must remain porous to the multiple and nonlinear processes of transformation that are *"not-always-transforming-into-urban"* (Follmann, 2022, p. 9, emphasis in original). Resonating with this point, inexorability perceived across the two sites manifested as questioning or identifying that non-industrial ordinary life was inevitably destined for reconfiguration. In Sunguvarchatram, this sentiment was evoked by reading everyday locations as on the cusp of loss or transformation. An outdated barber shop was read as a short-lived artefact surely to be lost with further development: "Such shops here will soon become a relic of the past with more branded shops of different sizes" (Anshul; see Figure 7a). Another participant was invited to 3D scan a cinema by its owner, who discussed how he was renovating in anticipation of new workers coming to the area. The participant reflected that "a decades-old traditional building renovated as speculation in the area grows. This reflects the broader changes happening in Sunguvarchatram due to the arrival of global capital. Even a small local region is connected by the world and economy" (Yuvan; see Figure 7b).

In Hsinchu, the notion of inexorability is expressed through the surprise of finding non-industrial practices persisting within the urban fabric. A group of participants was amazed to stumble upon a small unauthorised farm tucked amongst the backstreets, a practice found to be incongruent against the backdrop of the HSP. Here, a participant 3D scanned a developing fruit that had been carefully wrapped in a plastic bag, writing of it as a metaphor for such enduring irregularities: "This is an image of the city growing, yet not fully" (Yan-ze; see Figure 7c). Another participant found resonance with the HSP's own infrastructure as a "memento mori" of the techno-optimism that infuses the park: "A telephone booth built in the centre of the Hsinchu Science Park. Despite its sleek design, it has also become a fossil of a different time, and now out of place" (Yan-ling; see Figure 7d).

Across both workshops, the outputs converged on a shared relation to inexorability, registering the tension between planetary flow and place-based practice through a techno-industrialism that is grounded by a sense of totalizing reconfiguration. Through an embedded methodology that directed 3D scanning technologies "from below," the workshop outputs organised and expressed this sentiment into differing temporal orientations: In Sunguvarchatram, notions of place were unsettled by transformations perceived as emergent yet incomplete, whereas the Hsinchu region contained practices that were felt to have improbably remained.



Figure 7. Participant 3D scans relating to themes of inexorability: (a) Sunguvarchatram: Barber saloon (*Anshul*); (b) Sunguvarchatram: Cinema interior (*Yuvan*); (c) Hsinchu: Urban farm (*Yan-ze*); (d) Hsinchu: Phonebooth (*Yan-ling*).

5. Discussion

The following section reflects upon the topic of inexorable transformation emergent from the workshops in relation to two conceptual pairs, the rule of exception and hyperbuilding, and bypass and hinterlands, before reflecting on 3D methods in relation to existing lens-based methods and their potential for new framings of comparison and dissemination.

The theme of inexorability located across the workshops resituates our expectations of what exactly is being constructed within exceptional-ised landscapes of hinterlands in relation to futurity and the insistence by which it arrives. Returning to the rule of exception as the permissive foundation upon which the edifices of

global economic capture and state imaginary are (hyper)built, Ong (2011, p. 209) argues that the ultimate function is to secure the articulation of certain aspirations and expectations. The future, therefore, is restaged as an adamant guarantee of economic and state progress which is reflexively employed to justify further hyperbuilding and additional exceptional statuses. Read through this lens, participants encountered two sites in which an exceptional future is in comparative stages of emergence. Around the HSP, the rule of exception has been substantiated over five decades and totalised at a national scale, providing salience to materials, actors, practices, and objects that are perceived to have survived its consolidation. In Sunguvarchatram, where the techno-industrial assembly remains in varying states of arrival, a related logic is encountered as an anticipation of a future rendered as assured yet not fully constituted.

In composing the exceptional differentiation of the enclaves as a strategic technique of futurity retention, the workshop outputs open a lens to regard the hinterland's inscribed tensions between the local and the planetary as, in part, a variegated event of material and ideological construction. The totalising insistence of the techno-industrial landscape's inexorable future resonates as an additional mechanism by which hinterlands are spatially and epistemologically configured to bypass the unnetworked individuals who are externally rendered as frictions to be bypassed. The action of circumvention serves to marginalise the residents within the present as much as it facilitates the foreclosure of a right to futurity. This positions the methods and practices discussed within this article amongst Arabindoo's (2020, p. 220) urgent call for finding methods of visualisation that meaningfully compose the hinterland's "uneven capitalist development" and "unprecedented forms of creative destruction," as a pathway to digitally and sensorially bear witness to what remains outside of a supposedly inexorable presentation of a necessary future.

It is necessary here to raise certain challenges and opportunities that emerge from 3D scanning as a method. Rose (2014) argues that visual research methods must engage not only what visual materials represent, but their circulation and usage as communicational tools. Framing the 3D object as both a visual material and an instrument of visual research, the 3D object departs from other visual methods, namely photography, in two respects in relation to representation and circulation. First, unlike photography, which constructs a picture place through the relationship of foreground and background, photogrammetry models present subjects in isolation, detached from the spatial context that surrounds and contextualises the source object. This type of background data can be essential for representing socio-political contexts. Here we should consider the photograph of P. Kumar (see Jayaraman et al., 2025) in Chennai's Ennore Creek, where narrative is powerfully expressed by the juxtaposition of foregrounded fisherfolk and the backgrounded columns of the ecological catastrophe that is the Ennore Thermal Power Plant. To a degree, 3D objects may possess a self-contained juxtaposition with their subject matter, exemplified by the contrast between organic and anthropogenic materials (see Figure 6b). However, it is recommended that participatory 3D scanning take extra care to situate the isolated outputs amongst the richness of the environments that surround and inform them. Drawing again from Arnold (2019), the worksheets provided a useful means for participants to record personal experiences, strengthening the relationship between the 3D model and the unscannable encounters and feelings of being in the world.

Second, 3D objects gain new capacities to compose comparison as highly mobile fragments. In contrast to the photographic image, which presents representations within the framing device of a cropped border, outside of which the world presumably exists yet is not expressed, photogrammetry produces objects that exist in digital space as fragments, the only borders appearing at the edge of their own materiality. Unlike the more

complete photograph, the 3D object aligns with McFarlane's (2021) notion of the urban fragment, a disparate and disharmonious poetic entity that trades coherence for an ease of circulation between intersecting lines of thought. This fragmentary circulation underpins the Techno-Urban Atlas as an online arrangement that does not establish equivalence between the two hinterlands, but stages resonances between particular 3D objects, enabling a "looser form of juxtaposition" (McFarlane, 2021, p. xix) to proceed across multiple lines of comparison that are initiated by the user. This form of user-led comparison is guided by Chen's (2010, p. 212) assertion that emergent subjectivities, horizons, and perspectives may form through the processual contact of inter-Asian imaginaries, seeking to use the mechanics of the website to render for the user an open and navigable pathway to what Niranjana (2022, p. 106) terms the "other locations on the map."

6. Conclusion

This article has argued that peri-urban research scholarship requires frameworks capable of holding place-based and flow-based lenses in tension, a requirement that is as much methodological as it is conceptual. Approaching Sunguvarchatram/SIPCOT Sriperumbudur and the Hsinchu/HSP regions as techno-industrial hinterlands illuminates how such enclaves are sustained through a rule of exception (Ong, 2011) while bypassing the ordinary material and practised coordinates of the city (Arabindoo, 2020). Participatory smartphone photogrammetry is proposed as a potent means for encountering these conditions "from below" (Cheng, 2014), underpinned by two workshops within the regions that encouraged participants to position their 3D models within a broader sensorial landscape. The interaction of digital and embodied methods enabled the emergence of a comparative relationship to the inexorability of techno-industrial transformation through differing angles of fragmentation and totality. In detailing the workshops' secondary stage of building the Techno-Urban Atlas, the article has discussed how the outputs of 3D scanning methods, as both fragmented yet highly mobile digital objects, may circulate in web browsers to create novel modes of user-led and cross-context comparison and understanding.

Several matters for further action surface from the discussion of this fledgling and experimental methodology. Terrestrial scanning remains under-theorised against aerial mapping methods, beckoning further discussion as to what is afforded when technologies of 3D representation are at once opened up to the public and positioned towards everyday landscapes. This article has focused on the capacity for such methods and technologies to render the interfacing tensions of the planetary and the local within the unresolved epistemologies of the peri-urban. This author sees great potential in and eagerly encourages the deployment of integrated modes of digital and sensorial responses to additional urban contexts.

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Conflict of Interests

The author declares no conflict of interests.

Data Availability

All research data can be accessed at https://www.latentspace.com/TUA.html

LLMs Disclosure

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