



OPINION PAPER

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Shaping future sustainable cities with AI-powered urban informatics: Toward human-AI symbiosis

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Abstract

The rapid evolution of Artificial Intelligence (AI) has ushered in a transformative era for urban studies, moving beyond traditional analytical methods to advanced Deep Learning architectures, with Transformers model in the spotlight. Yet, unlike bioinformatics, which has successfully utilised AI to decode static biological systems, or cheminformatics, which optimises chemical synthesis, urban informatics grappled with human-centric complexity that encompass subjective perceptions, socio-political dynamics, and multifaceted challenges that defy deterministic solutions. To avoid techno-solutionist pitfalls, we convened an interdisciplinary group of scholars to explore AI-powered urban informatics and proposed a Human-AI Symbiosis framework to foster sustainable cities and advance urban research. This Opinion paper synthesises insights into four key research directions, focusing on the evolving landscape of urban informatics and its potential to drive innovation in sustainable cities, policy-making, and societal development.

Keyword Urban informatics; GIScience; Artificial intelligence; Sustainable cities

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1 Main

Cities have long been central to human history and civilisation, serving as hubs of culture, innovation, and economic growth (Glaeser, 2011). From the ancient city-states of Mesopotamia to the modern metropolises, they have shaped societies by driving advancements in commerce, governance, art, and science. However, rapid urbanisation has also brought about a series of pressing challenges (Jacobs, 1961), such as traffic congestion, public health crises, environmental degradation, and social inequalities (Almulhim et al., 2024). The complexity of these problems extends beyond the capabilities of any single discipline, necessitating interdisciplinary approaches like urban informatics to tackle the challenges using data and emerging technologies (Batty, 2013; Dong et al., 2024; Hu et al., 2023; Ye et al., 2025).

Urban informatics integrates spatial, behavioural, environmental, economic, and social data with computational techniques to enhance our understanding of urban systems (Batty, 2013; Foth, 2008a, 2008b; Hu et al., 2019; Shi, Goodchild, Batty, Kwan, & Zhang, 2021). However, unlike bioinformatics (Y. Liu et al., 2023) and cheminformatics (Saifi et al., 2024), which have seen significant breakthroughs in understanding biological systems and chemical properties through the AI revolution (e.g., AlphaFold and the synthesis route optimisation), the potential of urban informatics to reveal insights and solutions for urban challenges remains underexplored. While AI holds promise for modelling urban dynamics,

its effectiveness is limited by the inherent complexity and non-determinism of human behaviours and socio-political dynamics, which make urban system modelling particularly challenging.

Recognising that the advancement of AI is poised to fundamentally disrupt all scientific disciplines (Nelson et al., 2025) and to avoid techno-solutionist pitfalls, we convened a diverse group of scholars at different career stages, drawing expertise from a variety of fields including GIScience (Claramunt & Dube, 2023; Gao, 2020), urban planning, architecture, urban studies, computer science, and engineering, and identified several critical challenges in developing AI-powered urban informatics. Through intensive discussions, we propose *Human-AI Symbiosis*, a framework where AI and humans collaborate iteratively to co-create adaptive, equitable solutions, as depicted in Fig. 1.

This framework responds to critiques of “techno – solutionism” by positioning AI not as a standalone fix but as a partner in navigating urban complexity. It emphasises a model of mutual enhancement, i.e., AI augments human creativity and judgment, while human insights refine AI models to align with ethical, cultural, and contextual priorities; meanwhile, communities actively shape AI tools through participatory design, ensuring solutions addressing marginalised voices rather than perpetuating biases.

Four research agendas emerged from interdisciplinary dialogue guided by the Human–AI Symbiosis framework

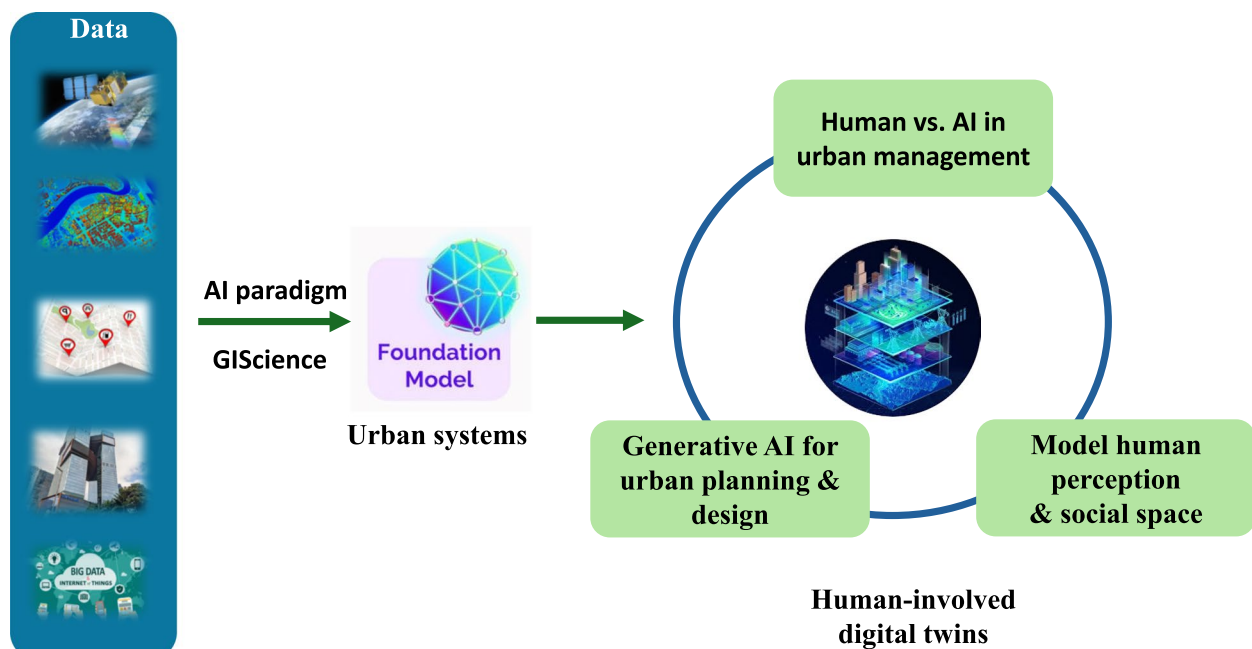


Figure. 1 Human-AI Symbiosis framework for urban sustainable development

(Fig. 1). Each agenda reflects a distinct but interrelated dimension of this symbiosis—ranging from system-level modelling to human-centred design and governance. Rather than following a rigid taxonomy, the fourfold research agendas reflect the multifaceted nature of urban challenges and the complementary roles that AI can play in addressing them.

1. Adopting AI paradigms to model urban systems:

We aim to transform urban informatics through multiple complementary AI approaches: unified data representations and advanced tokenisation mechanisms for efficient processing; context aware representation learning that integrates multi-modal data across domains. This improves the simulation and prediction of urban dynamics such as traffic flow, energy consumption, and social behaviour. The integrative approach potentially contributes to comprehensive “World Models” that can simulate complex urban dynamics while accounting for local nuances and variability.

2. Modelling human Perception and social space:

Urban informatics must transcend traditional physical space modelling by integrating multi-modal language models capable of analysing human perception data, thereby transforming digital twins into dynamic systems that simulate how environmental changes influence social behaviours, community cohesion, and sense of place. This requires leveraging advancements in artificial intelligence to synthesise theories of human cognition, psychology, and social behaviour, with a focus on understanding how perception shapes spatial experiences and social interactions within urban environments.

3. Developing Generative AI for responsible urban planning and design:

Urban planning and design requires Generative AI to have interpretable and explainable tools that provide explainable insights into feature importance, biases and reasoning behind decisions, while ensuring equitable benefits across society to prevent exacerbating urban inequalities and protecting individual rights through thoughtful regulation and multifaceted approaches.

4. Enhancing human roles in urban management:

Urban informatics should advance human-AI collaboration through open digital twin platforms, interdisciplinary education, and participatory frameworks to mitigate technological alienation and ensure AI augments—not replaces—human decision-making in fostering responsive, resilient cities. This requires integrating AI tools to enhance the capacities of urban planners, policymakers, and local governments via data-driven insights, while embedding

human oversight and ethical governance as foundational principles in the design and deployment of AI systems.

We hope this agenda will spark broader discussions to fully embrace the transformative potential of AI and digital technologies in urban studies.

2 Adopting AI Paradigms to Model Urban Systems

Urban systems are dynamic ecosystems shaped by interactions across economic, environmental, and social dimensions. In the past decade, Geographic Information Science (GIScience), including geographic information system, remote sensing, and digital twin technologies have been foundational to urban informatics (D. Li, Yu, & Shao, 2021; Longley, Goodchild, Maguire, & Rhind, 2015; Shi et al., 2021). Recent AI applications in GIScience have further improved tasks in urban informatics like feature identification and mobility prediction, but they often fall short in addressing the intricate contextual challenges posed by urban systems (Claramunt & Dube, 2023; Janowicz et al., 2020; Pappalardo et al., 2023). The gap underscores the need for domain-specific AI innovations and a shift toward unified frameworks inspired by the success of large language models (LLMs) to model urban complexities effectively.

A critical shift to this AI paradigm lies in developing unified data representations that integrate multi-source and multi-modal data, such as satellite imagery, mobility data, and socio-economic indicators, into a single modeling framework to provide scalable insights across various urban contexts and adapt to spatial and temporal dynamics. Under the current AI framework like Transformers, advanced tokenisation mechanisms are essential to preserve spatial and temporal integrity when encoding urban data into discrete, learnable units. For example, how can we tokenise road networks while maintaining their topological structure or capturing the temporal variations of traffic patterns? Additionally, data source diversity must be prioritised within the development of generative AI, as models trained on limited or uniform datasets risks overlooking critical variations in urban environments.

Furthermore, to gain insights from transportation, energy, and environmental systems to inform one another, urban informatics should support context-aware representation learning (Baheti & Gill, 2011; Huang et al., 2024; P. Liu & Biljecki, 2022; Mai, Li, & Lao, 2023; Mazumder, Enslin, & Blaabjerg, 2021). The notion of context, whether social, cultural, or environmental, often remains underrepresented in current AI models. Without context, generative AI fails to capture the full complexity of geographical data. Joint-Embedding Predictive Architectures (JEPA) (Assran et al., 2023; LeCun, 2022)

offer a promising approach to address this limitation through their hierarchical abstraction capabilities and self-supervised learning mechanisms that can better capture contextual relationships without relying on hand-crafted data augmentations. This architectural approach enables the discovery of hidden relationships between built environments and human activities or between local and global factors. Eventually, such advanced representation learning capabilities could enable more sophisticated simulation of urban evolution, such as predicting the impacts of infrastructure changes or the effects of climate events on urban systems.

In summary, adopting AI paradigms will transform urban informatics by providing tools to advance our understanding and management of modern cities. And drawing on the principles of large language models, urban informatics has the potential to contribute to the realisation of the “World Model” (Assran et al., 2023; Ha & Schmidhuber, 2018; LeCun, 2022; Mai et al., 2024).

3 Modelling human perception and social space

Urban spaces are shaped by an intricate interplay between physical and social dimensions (Cresswell, 2009; Fu, 2022; Hull et al., 1994; Tuan, 1979). While extensive work has modelled urban physical space, such as digital twins or City Information Models (CIM), representation on social space remains underexplored, which embodies the relationships, interactions, and shared meanings that people create within these environments (Fox & Wolf, 2024; Jang et al., 2024). Accurate and semantic analysis of human natural language, image, and video data has been rather unfeasible due to their non-deterministic nature, until recent breakthroughs in multi-modal capable large language models (OpenAI et al., 2024). Integrating physical, emotional, and social data will enable urban informatics to develop models that simulate or generate spaces that are both functional and meaningful, fostering stronger community connections and more inclusive urban solutions. This integration would necessitate the development of innovative model architectures, such as the JEPa design, which have been proposed by leading researchers to effectively accommodate these diverse data elements and identify meaningful patterns across physical and social dimensions.

This research direction can significantly enhance the capabilities of digital twins in urban environments by incorporating human perceptions, emotional connections, and subjective experiences following principles of GIScience. Digital twins could evolve from static replicas into dynamic, context-aware systems capable of simulating how environmental changes (e.g., new infrastructure or cultural events) impact social behaviour, community cohesion, and the “sense of place”—the unique qualities

that give a location its identity and meaning for individuals and communities (Jang et al., 2024). For example, an advanced digital twin, generally understood as a simulation process that integrates physical models, sensors, and historical operational data (D. Li et al., 2021), can simulate how neighbourhood changes and broader structural city dynamics influence social interactions, community attachment, and mobility patterns (Caldarelli et al., 2023; Chu et al., 2024; F. Zhang, Zhou, Ratti, & Liu, 2019). This, in turn, offers deeper insights into how the environment shapes people’s behaviour, attitudes, and sense of place, which is central to human-centred urban systems (Goodchild et al., 2024; Ye et al., 2023).

By embedding both physical and social dimensions into urban informatics, this research agenda holds great promise to develop urban spaces that are not only efficient but also emotionally resonant, aligning with community needs and values.

4 Developing generative AI for responsible urban planning and design

AI-enhanced digital twins allow urban planners to reveal patterns, trends, and potential issues overlooked by traditional methods (Annaswamy et al., 2016; Yeh, 2024). As Professor Batty pointed out, however, the aim of AI in an urban context is inventing future urban forms rather than just analysing or predicting them (Batty, 2013, 2024a). Beyond generating text, image, audio, video, or survey responses (Aher, Arriaga, & Kalai, 2023), AI has inspired cartographers to automate production (Kang et al., 2024; Y. Zhang et al., 2024) and researchers to synthesise individual trajectories, which will offer transformative possibilities for responsible urban planning and design (Kapp, Hansmeyer, & Mihaljević, 2023; X. Li et al., 2024; K. Liu et al., 2024).

Although generative design shows great promise, it also has potential pitfalls that must be addressed (Cugurullo et al., 2024; Jiang et al., 2024). A major concern is that AI models are often criticised as “black boxes”, which lack transparency for policymakers and planners to understand how each feature contributes to the model’s overall performance. Therefore, developing interpretable tools to provide explainable insights is crucial to highlight feature importance and biases, utilising diagnostic metrics and visual summaries. Beyond mere interpretability (understanding which features influence outcomes), GIScience-driven AI systems for urban planning require explainability—the ability to articulate the reasoning process behind specific recommendations. Without such GIScience-based comprehensive explanations, even models with high interpretability can fail to provide decision-makers with the causal understanding necessary for confident implementation. This transparency is

crucial for AI-driven policymaking and design, ensuring trust, accountability, and compliance with ethical and regulatory standards.

Second, generative design should ensure that the potential designs can benefit all members of society equitably from an algorithm perspective (Cao, Gao, & Qiu, 2023; Fox & Wolf, 2024), to avoid gender and racial biases that are exhibited in LLMs (Fang et al., 2024). There is a risk of exacerbating existing urban inequalities if spatial inequality, digital divides, and shifts in power dynamics within urban environments are not prioritised (Isagah & Ben Dhaou, 2024). Additionally, concerns around privacy, data security, and surveillance require thoughtful regulation to protect individual rights (Janowicz, 2023).

To support responsible AI use in urban planning, we emphasise the need for fairness, transparency, and sensitivity to social impacts. Drawing on (Shaw, Ye, Goodchild, & Sui, 2024), we underscore the importance of addressing data access and privacy consent, particularly as urban datasets increasingly incorporate personal and location-based information. This calls for broader evaluation criteria that go beyond technical performance to include ethical and societal considerations. Addressing these caveats carefully is essential for the responsible urban planning and design using generative AI. This research agenda calls for a multifaceted approach for the public good while minimising unintended consequences that could negatively impact vulnerable populations. Scholars in urban informatics must ethically recognise the boundaries and potential harms associated with the implementation of new models and algorithms. They should actively engage with policymakers, civil society, and affected communities to co-develop safeguards, including legal frameworks that protect civil rights and prevent discrimination (Jobin, Ienca, & Vayena, 2019), and guarantees equitable access to the benefits of AI-driven spatial design.

5 Enhancing human roles in urban management

AI technologies should augment, rather than replace, human insights in an urban context. Societal impact studies are needed to understand how AI will shape social structures, economic opportunities, and individual privacy. As AI increasingly influences urban planning, public policy, and resource management, the human role in decision-making must remain central; otherwise, there is a risk of handing over our society to machines and living under the rule of various visible and invisible machines. This concern represents a potential acceleration of what critical theorists have long identified as technological alienation (Heidegger, 1977; Marcuse, 1964)—where the pursuit of algorithmic efficiency and quantifiable metrics distances citizens from meaningful urban participation

and governance. As AI systems optimise for measurable outcomes, we risk rapidly advancing toward urban futures that are technically 'efficient' but fundamentally dehumanised.

"Putting the human in the loop" (Batty, 2024b) should be at the centre of urban informatics, particularly through the use of open digital twin platforms that will encourage not only expert knowledge but also public interaction and participation (Chen et al., 2023). By embedding human dynamics into data-driven modelling, we strengthen the connection between AI systems and real-world urban experiences (Shaw et al., 2024). This will foster environments that prioritise not only technological enhancement but also human well-being and social cohesion. The human-AI collaboration will ensure that diverse community needs and perspectives are actively included in decision-making, facilitating proactive interventions and providing nuanced insights into complex urban dynamics. This open nature will enhance our interaction with urban spaces, ultimately leading to the development of more human-centred, responsive, and resilient cities.

To prepare future generations for an AI-driven world, urban informatics education must evolve alongside research. Interdisciplinary curricula should integrate not only computer science, data science, and AI to develop new platforms for real-time collaboration, creating open-source repositories for geospatial datasets and GeoAI foundation models (Cao et al., 2023), but also geography, urban studies, sociology, economics, and critical thinking (Caros & Zhao, 2024; Kandlhofer, Steinbauer, Hirschmugl-Gaisch, & Huber, 2016) to emphasise sustainable practices and address real-world urban challenges. Urban informatics can offer a holistic approach that ensures students are equipped with both the technical skills and the broader societal understanding needed to navigate the complexities of future cities.

6 Conclusion

The Opinion paper has illuminated a transformative vision for the future of urban informatics, where Human-AI Symbiosis ensures technology and humanity evolve together. By prioritising mutual learning over automation, the four key research agendas are defined as: adopting AI paradigms, modelling human perception, using generative AI responsibly, and enhancing human roles, which collectively paint a picture of a field poised for significant advancement. These topics not only promise technical innovations but also emphasise the critical need to consider human factors, ethical implications, and societal impacts while avoiding the technological alienation. It is also important to note that these four research agendas are neither parallel nor independent. Instead, they are deeply interconnected, working

in synergy within the Human-AI Symbiosis framework. Together, they contribute to the shared goal of making cities more sustainable and the evolving landscape of urban informatics by addressing various facets of urban development—ranging from data-driven insights and human experiences to technological integration and societal impacts. This convergence is essential for fostering smart, resilient, and inclusive urban environments. As we progress, the academic community must remain vigilant and proactive, guiding these innovations with rigorous research, interdisciplinary collaboration, and a commitment to responsible development. By remaining adaptable and forward-thinking, we can tackle complex urban challenges, shaping cities that are sustainable, equitable, and human-centred (Yue et al., 2022).

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Authors' contributions

Conceptualization and discussion: all authors; Discussion coordinating: Yang Yue; Manuscript drafting: Yang Yue, Guanyu Yan, Tian Lan, and Christophe Claramunt; Visualization: Yang Yue; Manuscript revision: Yang Yue, Guanyu Yan, Tian Lan, and Christophe Claramunt; Final version editing and auditing: all authors.

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