Metaverse-Enabled Digital Twins for Business and Smart Cities: Toward A Human-Centered Framework for Digital Transformation

Rasem Qudaih[a*], Nicholas Caldwell[a], Imen Ben Salem[b], and A. Karthi[b]

[a]School of Business, Art, Social Sciences and Technology, University of Suffolk, Ipswich, Suffolk, United Kingdom
[b]College of Natural and Health Sciences, Zayed University, Abu Dhabi, United Arab Emirates
*E-mails: r.qudaih@uos.ac.uk

Keywords: Digital Twin, Metaverse, Extended Reality (XR), Smart Cities, Business Ecosystems, GIS, Human-Centered Decision-Making, Sustainability, Participatory Governance

Abstract

Digital Twin (DT) technologies are increasingly changing how businesses and cities model, assess, and enhance complex systems. Traditional DTs have served as static representations of tangible assets, providing monitoring and predictive functionalities. However, minimal stakeholder engagement and a focus on specific sectors have often limited their full potential. The rise of the metaverse, reinforced by Extended Reality (XR) technologies, presents a unique chance to evolve DTs into immersive, interactive, and human-centered platforms for collaborative decision-making. This integration allows stakeholders to visualize and engage with multidimensional data in real time, facilitating predictive analysis, scenario planning, and participatory governance. In business environments, DTs enhanced by the metaverse improve supply chain modelling, aid corporate strategy formulation, and foster innovation in customer experiences, ultimately increasing resilience and adaptability. In urban settings, they support smart infrastructure management, sustainability oversight, and collaborative planning by integrating IoT, Building Information Modeling (BIM), and geospatial data into engaging simulations. This research presents a conceptual framework that links business ecosystems and smart cities through a DT layer mediated by the metaverse, and GIS work for a GeoAI-enabled urban development system may address the political, societal, legal, and technical-instrumental challenges currently affecting cities and those expected in the foreseeable future. This framework, supported by enabling technologies and designed for inclusivity and scalability, illustrates a multidisciplinary approach to digital transformation applicable to both private and public sectors.

1. Introduction

Incorporating digital technologies has emerged as a key element in transforming organizations and urban environments. Industries such as manufacturing, healthcare, and smart city development increasingly use Digital Twin (DT) technologies to create real-time digital representations of physical objects. These technologies provide tools for predictive analysis, live monitoring, and process optimization; however, their use has generally been confined to technical specialists and specific fields (Qi Tao, 2018; Fuller et al., 2020). Simultaneously, Extended Reality (XR), cloud computing, and progressive visualization technologies have accompanied the metaverse as a new digital environment (Dwivedi et al., 2022). While XR is widely used in areas such as gaming, education, and training, its potential to improve collaborative decision-making in complex systems remains largely underexplored. This study argues that integrating digital twins, Geographic Information Systems (GIS), and the metaverse offers exciting prospects for human-centered, interdisciplinary digital transformation. By incorporating digital twins into immersive settings, decision-makers can engage collaboratively with data, simulate various scenarios, and develop more robust strategies for both business ecosystems and intelligent urban areas. This study reviews appropriate literature, highlights existing research gaps, and proposes an innovative conceptual framework to support this argument.

2. Literature Review

2.1 Digital Twins and Big Data

Combining digital twins and big data is essential for Industry 4.0 and advanced manufacturing. Digital twins offer real-time simulations of physical processes, establishing a feedback loop between the physical and virtual realms (Qi Tao, 2018). This technology has revolutionized industrial operations by enabling predictive maintenance, fault diagnosis, and lifecycle optimization, thereby enhancing efficiency and reducing costs. Big data analytics enhances digital twins by managing vast quantities of both structured and unstructured data produced during production and operations. This collaboration helps identify inefficiencies, forecast system behaviour, and enables more informed decision-making (Qi, Qi & Tao, 2018). Together, digital twins and big data foster more adaptable and resilient business practices while providing insights that can be applied to urban planning and governance.

Recent research highlights that although big data improves efficiency and understanding, digital twins offer immersive visualization and simulation features that overcome the shortcomings of traditional analytics. In contrast to dashboards that rely on static reports, digital twins offer three-dimensional, dynamic visualizations that can be integrated into XR and metaverse environments (Judijanto & Vandika, 2025). This capability is vital for decision support in manufacturing and smart city initiatives, as it allows stakeholders to validate outcomes and evaluate alternatives in a virtual context.

2.2. GeoAI GIS and Real-time GIS

Human-centered framework for smart cities that leverages the synergies between City Planning and the scientific disciplines of Big Data, Geographic Information Science and Systems, and Data Science which collectively constitute an emerging field known as Geospatial Artificial Intelligence (GeoAI) to accomplish four broad policy goals: 1) to improve the effectiveness of urban services and functions; 2) to tackle urgent societal, ecological, and economic issues that could affect urban systems at various levels, and 3) to aid in generating spatial data, information, and insights regarding human-environment interactions (Mortaheb and Jankowski., 2023). With advances in geospatial technologies, information and communications technologies (ICTs), and computational power, the smart city has gained traction in political, industrial, governmental, and academic domains.

To achieve the overarching goals of human-centered smart cities, we should focus on conceptual and empirical assessments of how the smart city might leverage synergies between city planning and three technological domains: Big Data, Geographic Information Science and Systems, and Data Sciences. These domains together form an emerging field called Geospatial Artificial Intelligence (GeoAI). The GeoAI could leverage various methodological and technical tools offered by Geographic Information Science and Systems, including big data, artificial intelligence, and sophisticated computational infrastructure and procedures. This section describes GIScience tools and analytical frameworks that could guide a GeoAI-based strategy for smart city planning, design, management, analysis, and simulation.

Recent developments in computational techniques, such as Artificial Intelligence (AI) and Deep Learning, have enabled the collection, processing, evaluation, and visualization of big data (Razavi, 2021). The scientific discipline of data science is also experiencing an upsurge as a result of these discoveries. Furthermore, the rapid development of big data applications has been enabled by the expanded availability of computational infrastructure, such as cloud computing platforms. (Gahegan, 2020). Geospatial Artificial Intelligence (GeoAI), an interdisciplinary field of spatial analysis, has recently emerged at the intersection of GIScience/GIS and the three aforementioned technological revolutions. GeoAI is a technological solution for geospatial problems that require substantial data and processing power (Mortaheb & Jankowski, 2023). The empirical, theoretical, and computational paradigms that have, up till now, successively defined the development of scientific inquiry signal a new stage of data-intensive investigation (Gahegan, 2020). In contrast to the data-driven approach, the top-down methodology simulates real-world entities and draws conclusions using deductive reasoning and prior knowledge, also referred to as domain knowledge, as well as pre-existing logical rules and constraints (Batty et al., 2013; Mortaheb & Jankowski, 2023).

Several studies have combined sustainability principles with GeoAI to address significant urban issues and enhance planning practices. Land utilization planning, for example, is an important component in city planning, with major consequences for the financial system (energy consumption and infrastructure costs), the community (public health and the urban atmosphere), and the environment (natural resource depletion, agricultural land conversion, and pollution) (Lord et al., 2015; Mortaheb & Jankowski, 2023).

https://doi.org/10.5194/isprs-archives-XLVIII-4-W18-2025-273-2026 | © Author(s) 2026. CC BY 4.0 License.

2.3. Digital Twins in Smart Cities and the Role of GIS

DTs are increasingly applied in urban environments to simulate transport systems, infrastructure resilience, and energy efficiency. Projects such as Virtual Singapore integrate more than 5,000 geospatial datasets into a dynamic 3D city model for disaster preparedness, planning, and sustainability. Helsinki 3D City applies DTs for climate adaptation, while Shanghai Urban DT integrates AI with real-time traffic and energy forecasting (Batty, 2018; Ketzler et al., 2020).

A critical enabling technology for smart city DTs is Geographic Information Systems (GIS), which integrates and visualizes geospatial data layers including transport networks, land use, environmental hazards, and demographics. GIS ensures spatial accuracy and context-awareness in DT platforms, linking IoT data and BIM models into comprehensive urban simulations. By embedding GIS in immersive metaverse environments, DTs evolve from static digital replicas into interactive spatial decision-support tools, enhancing citizen participation and transparency in governance.

2.4. Digital Twins in Business Ecosystems

Beyond manufacturing, DTs have expanded into business ecosystems, particularly in supply chain management, corporate strategy, and customer experience. For example, Siemens and IBM have demonstrated how DTs can model supply chain resilience, evaluate "what-if" scenarios, and enhance agility in the face of uncertainty (Fuller et al., 2020). DTs are also being used to simulate consumer interactions, product adoption, and retail site selection, often in combination with GIS to optimize logistics and spatial distribution (Bhati et al., 2025). Despite their potential, these applications remain fragmented, with little integration into urban-scale DTs or participatory decision-making.

2.5. The Metaverse and Participatory Governance

The metaverse, powered by XR technologies, offers immersive environments for collaborative interaction with complex data (Dwivedi et al., 2022). In urban planning, XR and VR tools have been applied to participatory design, making geospatial data and urban models more accessible to non-experts (Portman et al., 2015). In business, metaverse-based DTs have been explored for virtual prototyping and interactive training. However, integration across city and business DTs is limited, and opportunities for cross-sectoral decision-making remain underexplored. Embedding DTs and GIS within XR environments would create shared, spatially grounded platforms where stakeholders collaboratively engage with real-time data.

2.6. Ethical and Social Challenges

The convergence of DTs, GIS, and metaverse technologies raises challenges for data privacy, interoperability, and inclusivity. Without careful governance, these technologies risk reinforcing inequalities, favoring wealthy cities and corporations (Zallio & Clarkson, 2023; Ruhlandt, 2018). Ethical design and human-centered standards (ISO 9241-210; Sæbø et al., 2011) are essential to ensure transparency, accessibility, and trust in metaverse-enabled DTs.

2.7. Research Gap

Despite progress in DTs for manufacturing, smart cities, business ecosystems, and growing research on XR/metaverse applications, no integrative framework unites business ecosystems and smart cities through a metaverse-enabled DT layer enriched by GIS.

Current studies remain limited, focusing on technical optimization or immersive interaction. This paper addresses this gap by proposing a human-centered, cross-disciplinary framework. Table 1 summarizes previous research on DTs, big data, metaverse/XR, and governance, highlighting the fragmentation between industrial, urban, and immersive approaches.

Area	Focus of Previous Work	Gap Identified	Relevance to This Study
Digital Twins in Industry	Manufacturing optimization, predictive maintenance, lifecycle control (Qi & Tao, 2018)	Limited integration across business and city systems; expert-centric use.	Motivates a cross-sector framework that connects enterprise DTs with urban DTs
DTs in Smart Cities (with GIS)	Energy, mobility, infrastructure, climate resilience; GIS-based 3D	Technocratic implementations with weak participato	Supports adding metaverse/XR for inclusive, human-

	city models (Batty, 2018; Ketzler et al., 2020)	ry/immersive engagement	centered decision-making
Big Data + DT	Analytics over large, heterogeneous data; closed-loop optimization (Qi & Tao, 2018)	Data-centric dashboards; limited interactive/embodied exploration	Justifies moving from static analytics to immersive scenario planning
Metaverse/XR	Education, entertainment, urban planning (Portman et al., 2015; Mystakidis, 2022)	Rare integration with DTs and GIS for governance	Our framework embeds DT+GIS models in the metaverse to support collaborative decision-making.
GeoAI GIS	Geospatial GIS-based urban and human-centered framework development	Datasets based on time frames and real-time access	Remote sensing and geospatial parameters associated with the Digital Twins metaverse and Big Data.
Governance / Ethics	Privacy, interoperability, digital divide (Zallio, & Clarkson, 2023; Ruhlandt, 2018)	Lack of human-centered standards and inclusive access	We anchor the framework in human-centered design (ISO 9241-210)

Table 1. Previous research on DTs, big data, metaverse/XR, and governance.

As shown in Figure 1, existing research addresses digital twins, big data analytics, and metaverse environments separately, but their integration into a unified, human-centered framework for business ecosystems and smart cities remains unexplored. This gap motivates the conceptual framework proposed in Section 3.

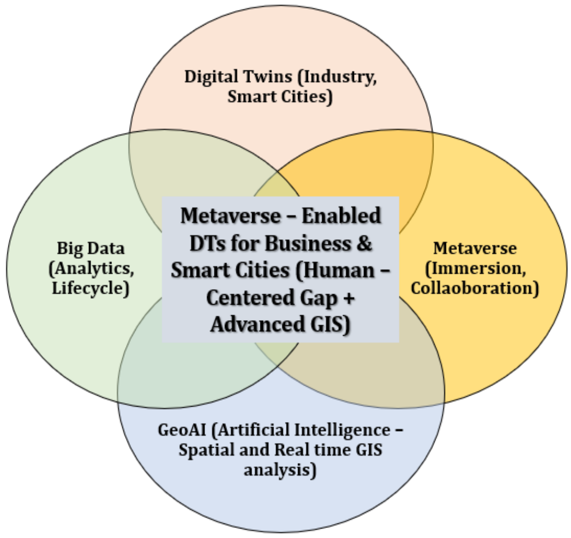

Figure 1. Literature Gap Map: Positioning This Study.

3. Conceptual Framework

The proposed framework is founded on the intersection of digital twins, geographic information systems (GIS), and immersive metaverse environments. Historically, digital twins have been viewed primarily as technical tools for oversight and improvement; however, when combined with spatial analytics and extended reality (XR) technologies, they become inclusive, human-centered platforms. As shown in Figure 2, the framework consists of three interconnected layers, each enhancing the overall ability to facilitate collaborative decision-making and build resilience. At the foundational level, the Digital Twin Layer brings together diverse data sources. Internet of Things (IoT) devices monitor real-time sensor data from various aspects of business operations and urban settings, including supply chain activities and traffic patterns. Building Information Modeling (BIM) provides essential structural and engineering details for infrastructure and urban development. GIS introduces a vital spatial component, merging land-use, environmental, and demographic information to contextualize business and urban processes. The Metaverse Immersive Layer advances these simulations into three-dimensional, interactive spaces. By leveraging XR technologies, stakeholders can engage with digital twins as static dashboards and dynamic, embodied experiences. Research on participatory planning indicates that immersive visualization significantly improves non-experts' understanding of complex geospatial information (Portman et al., 2015), suggesting that positioning digital twins within the metaverse can greatly enhance access and inclusivity.

The SDSS approaches have faced both opportunities and challenges due to the growth of big data and geo-intelligence. Using big data sources like smartphones, smart card transactions, and the Internet of Things has steadily prompted academics to move away from small datasets. GeoAI is founded on two methodological threads: the knowledge-based, top-down strategy and a bottom-up, data-centered paradigm. The latter is an inductive approach that largely relies on Machine Learning (ML) techniques (Mortaheb & Jankowski, 2023). Because it can both uncover hidden patterns in large data and generate predictions, it has become the standard paradigm in GeoAI. Deep Learning models, including Convolutional Neural Networks (CNNs), are at the forefront of machine learning. They have become well-liked for their accurate projections and strong feature extraction (Janowicz et al., 2020; Razavi, 2021).

The integration of GIS with modelling systems to support the design and assessment of decision alternatives has emerged as one of the prime applications of GIScience in the scheduling, strategy, and supervision of smart cities, leading to the progress of a widespread of tools known as Planning Support Systems (PSS) or Spatial Decision Support Systems (SDSS) (Keenan & Jankowski, 2019). GIS and DSS work together to create dynamic decision support systems that rely on open knowledge networks, crowdsourced and authoritative data, and inference techniques enabled by AI (Keenan & Jankowski, 2019).

Furthermore, GeoAI enables the transition from real-time optimization models to smart-city optimization. Potential topics for study under the new framework involve creating a computational method to effectively solve a large "p-median" problem using parallel high-performance computers (Mu & Tong, 2020; Mortaheb & Jankowski, 2023), utilizing both knowledge-based and data-driven approaches to plan an evacuation route during a natural disaster event based on smart mobile phone location data, and combining data derived spatial based machine learning techniques, to generate time-sensitive routes to avoid poor air quality while traveling in urban areas (Yin et al., 2020).

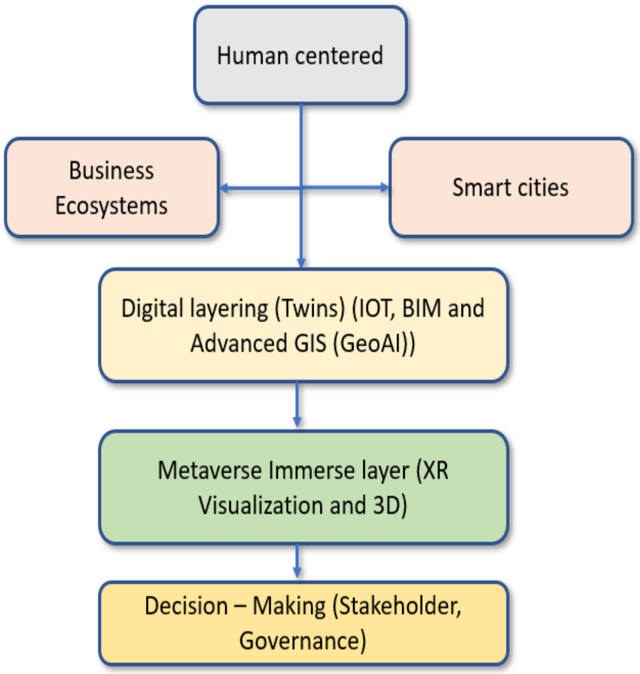

Figure 2. Conceptual Framework Diagram

The Human-Centered Decision Layer places the framework within participatory governance and business strategy. Stakeholders, including city residents, urban planners, corporate executives, and supply chain collaborators, actively use immersive simulations to evaluate policies, strategies, or contingency plans. This layer transitions digital twin applications from a centralized approach to a more collective decision-making process by facilitating real-time interactions among multiple stakeholders.

4. Applications

The proposed framework shows significant promise for utilization in both business ecosystems and smart cities, areas that have historically pursued digital transformation separately. The illustration in Figure 3 shows how IoT, BIM, GeoAI with GIS, and XR contribute to an immersive metaverse environment, enabling stakeholders to engage with urban and business systems in real time. This visualization not only highlights the technical integration of these enabling technologies but also underscores the human-centered focus of the approach. DTs have been widely used in business ecosystems for predictive maintenance, supply chain optimization, and corporate strategy modeling (Fuller et al., 2020; Bhati et al., 2025). The framework enhances these applications by embedding them in immersive XR environments. For instance, we can combine IoT-enabled logistics data, visualized through

GIS, with BIM-based warehouse or factory models to create an interactive supply chain twin. Within the metaverse, managers and suppliers can collaboratively simulate disruptions, such as port closures or raw-material shortages, and test alternative sourcing strategies in real time. Research on supply chain DTs has shown that immersive visualization improves operational agility and stakeholder engagement, fostering resilience in complex networks (Qi & Tao, 2018; Dwivedi et al., 2022).

In the context of smart cities, DTs are increasingly used for urban energy monitoring, infrastructure planning, and mobility management (Batty, 2018; Ketzler et al., 2020). Projects like Virtual Singapore and Helsinki 3D City showcase the integration of BIM and GIS datasets into city-scale digital twins for planning and climate adaptation. However, these applications often cater primarily to policymakers and technical experts. The metaverse embeds DTs, democratizing access and transforming them into participatory governance platforms. Research indicates that XR-based participatory planning enhances citizen trust and understanding of urban policies (Portman et al., 2015; Ruhlandt, 2018). By placing GIS-based data layers into immersive settings, residents and city planners can collaboratively assess scenarios such as traffic management policies, flood resilience strategies, or renewable energy implementation.

Furthermore, the framework supports applications spanning multiple domains. A notable example is emergency response, where IoT hazard sensors can identify environmental threats, GIS can provide spatial context for these risks, and BIM can reveal vulnerable infrastructure. An immersive simulation enables first responders, city leaders, and logistics providers to collaboratively coordinate adaptive strategies. Similarly, climate adaptation planning benefits from amalgamating environmental monitoring and XR visualization, as shown in recent studies focused on urban resilience planning using geospatial twins (Qi & Tao, 2018; Judijanto & Vandika, 2025). A proposed paradigm for addressing the complex geospatial issues that smart cities face is GeoAI. In fact, a hybrid strategy that integrates both inductive and deductive reasoning and is informed by theory is necessary, given the complexity of smart city problems. GeoAI could leverage a wide range of methodological and technical tools that Geographic Information Science and Systems offer, in addition to big data, artificial intelligence, and sophisticated computational infrastructure and procedures (Mortaheb & Jankowski, 2023). These applications exemplify the framework's value in optimization, inclusivity, transparency, and resilience. Thus, the framework depicted in Figure 3 highlights both a technical and sociotechnical transformation. By reconceptualizing digital twins as inclusive, immersive environments enriched by GIS, IoT, and BIM data, the model redefines DTs as platforms for collective resilience within both business and urban settings.

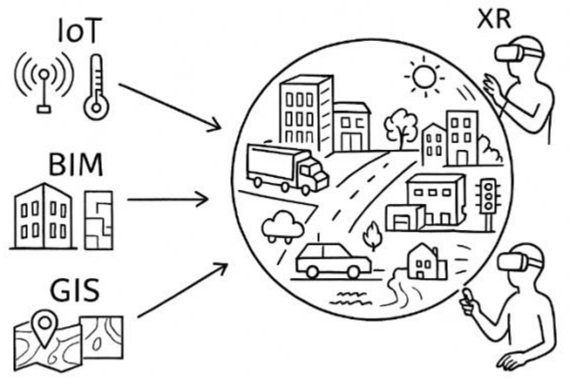

Figure 3. Application Scenarios of a Metaverse-Mediated Digital Twin Framework integrating IoT, BIM, GIS (GEOAI), and XR for business ecosystems and smart cities.

5. Discussion and Future Directions

Integrating digital twins, geographic information systems (GIS), and metaverse technologies is a timely response to the growing demand for cohesive, participatory methods in digital transformation. Research has typically evaluated digital twins based on their technical efficiency, predictive accuracy, and lifecycle cost savings (Qi Tao, 2018; Fuller et al., 2020). While these insights are valuable, they often prioritize expert users and overlook broader stakeholder involvement. The conceptual framework proposed in this study builds upon this existing research by focusing on human-centered, cross-sector decision-making while explicitly incorporating geospatial intelligence and immersive visualization. This aligns with current discussions surrounding digital governance, resilience, and sustainability in business and urban settings (Dwivedi et al., 2022; Ruhlandt, 2018).

A key question moving forward is how to test this framework in practical scenarios. Transport planning presents a promising avenue within the realm of smart cities. Integrating IoT-driven traffic sensors, BIM for infrastructure, and GIS mobility information could create a digital twin, experienced through XR. Pilot initiatives of this nature would allow assessments of technical feasibility and of participatory outcomes, such as increased citizen trust, greater inclusivity, and the legitimacy of policies. Evidence from participatory GIS and XR-based urban planning indicates that immersive visualizations can boost citizen involvement and enhance transparency in governance (Portman et al., 2015; Sb et al., 2011). Expanding these methods into digital twins mediated by the metaverse would significantly advance the development of inclusive urban governance.

The proposed framework could also enhance supply chain resilience in business ecosystems, a critical issue highlighted by the global disruptions caused by the COVID-19 pandemic (Ivanov & Dolgui, 2020). Digital twins are currently utilized to model disruptions and improve responsiveness (Ivanov, 2021; Bhati et al., 2025). However, integrating these models into immersive environments enhanced by GIS would facilitate quicker, more collaborative responses among managers, suppliers, and partners. Comparative analyses of dashboard-oriented approaches against immersive digital twin environments would provide empirical evidence of this enhanced value, especially in collective problem-solving and strategic risk-sharing. Future investigations must also address the impact of emerging technologies. Geo Artificial intelligence (AI) can enhance predictive analytics and scenario modeling with spatial aspects, along with blockchain technology, enabling secure and transparent data exchange across organizational and urban boundaries (Tao et al., 2019; Zallio & Clarkson, 2023). Additionally, edge computing and 5G networks could improve responsiveness and support near-real-time immersive interactions (Dwivedi et al., 2022). Together, these factors point toward the development of advanced cyber-physical-social systems that could break down the barriers between business operations and city functionality.

Nonetheless, ethical, social, and policy issues require careful consideration. Without equitable access and digital literacy, such systems risk reproducing or deepening social inequalities (Ruhlandt, 2018; Zallio & Clarkson, 2022). Metaverse-mediated DTs must therefore be created using human-centered principles (ISO 9241-210) and in accordance with the Sustainable Development Goals, particularly SDGs 9 (Industry, Innovation, and Infrastructure) and 11 (Sustainable Cities and Communities). Embedding these values into technical frameworks ensures that innovation contributes to efficiency, resilience, fairness, transparency, and accountability.

6. Conclusion

This paper presents a conceptual model that merges digital twins with the metaverse to facilitate digital transformation within business ecosystems and smart cities. The Human-Centered Decision Layer places the framework within participatory governance and business strategy. Stakeholders, including city residents, urban planners, corporate executives, and supply chain collaborators, actively engage with immersive simulations to evaluate policies, strategies, or contingency plans. This layer transitions digital twin applications from a centralized approach to a more collective decision-making process by facilitating real-time interactions among multiple stakeholders.

Utilizing insights from studies on digital twins, big data, Advanced geographic information systems (GeoAI GIS), the socio-political, normative, ethical, and technical-instrumental challenges that current and future cities face can all be addressed by a geoAI-powered urban design paradigm (Mortaheb & Jankowski, 2023). which extends to extended reality (XR) and participatory governance, the framework illustrates how immersive environments can enhance predictive analytics, foster collaborative decision-making, and bolster strategic resilience. The model is crafted to be both scalable and inclusive, laying the groundwork for interdisciplinary digital transformation that promotes business innovation alongside sustainable urban growth. The future development of metaverse-enabled digital twins will rely on thorough validation via pilot projects, the integration with cutting-edge technologies, and a persistent focus on ethical design. This framework promotes inclusive digital transformation by connecting business ecosystems with smart cities and anchoring decision-making in geospatial, immersive environments. It is a basis for constructing scalable, participatory, resilient sociotechnical systems.

Acknowledgements

The author would like to thank The School of Business, Art, Social Sciences and Technology, University of Suffolk, Ipswich, Suffolk, United Kingdom, for providing the facilities to conduct the research.

References

Batty, M. (2018). Digital twins. Environment and Planning B: Urban Analytics and City Science, 45(5), 817–820.

Ruhlandt, R. W. S. (2018). The governance of smart cities: A systematic literature review. Cities, 81, 1-23.

Dwivedi, Y. K., Hughes, L., Baabdullah, A. M., Ribeiro-Navarrete, S., Giannakis, M., Al-Debei, M. M., ... & Wamba, S. F. (2022). Metaverse beyond the hype: Multidisciplinary perspectives on emerging challenges, opportunities, and agenda for research, practice and policy. International journal of information management, 66, 102542.

Fuller, A., Fan, Z., Day, C., & Barlow, C. (2020). Digital twin: Enabling technologies, challenges and open research. IEEE Access, 8, 108952–108971.

Ivanov, D. (2021). Supply chain viability and the COVID-19 pandemic: A conceptual and formal generalisation of four major adaptation strategies. International Journal of Production Research, 59(12), 3535–3552.

Ivanov, D., & Dolgui, A. (2020). Viability of intertwined supply networks: Extending the supply chain resilience angles towards survivability. International Journal of Production Research, 58(10), 2904–2915.

Ketzler, B., Naserentin, V., Latino, F., Zangelidis, C., Thuvander, L., & Logg, A. (2020). Digital twins for cities: A state of the art review. Built environment, 46(4), 547-573.

Judijanto, L., & Vandika, A. Y. (2025). Research Advancements in Digital Twin Technology for Smart Manufacturing. The Eastasouth Journal of Information System and Computer Science, 2(03), 205-218.

Mystakidis, S. (2022). Metaverse. Encyclopedia, 2(1), 486–497.

Portman, M. E., Natapov, A., & Fisher-Gewirtzman, D. (2015). To go where no man has gone before: Virtual reality in architecture, landscape architecture and environmental planning. Landscape and Urban Planning, 142, 38–48.

Qi, Q., & Tao, F. (2018). Digital twin and big data towards smart manufacturing and Industry 4.0: 360-degree comparison. IEEE Access, 6, 3585–3593.

Bhati, M., Goerlandt, F., & Pelot, R. (2025). Digital twin development towards integration into blue economy: A bibliometric analysis. Ocean Engineering, 317, 119781.

Wang, P., & Luo, M. (2021). A digital twin-based big data virtual and real fusion learning reference framework supported by industrial internet towards smart manufacturing. Journal of manufacturing systems, 58, 16-32.

Sæbø, Ø., Rose, J., & Flak, L. S. (2011). The shape of eParticipation: Characterizing an emerging research area. Government Information Quarterly, 25(3), 400–428.

Zallio, M., & Clarkson, P. J. (2023). The ethics of the metaverse and digital, virtual and immersive environments: Metavethics. In The future of metaverse in the virtual era and physical world (pp. 93-103). Cham: Springer International Publishing.

Qi, Q., & Tao, F. (2018). Digital twin and big data towards smart manufacturing and industry 4.0: 360-degree comparison. Ieee Access, 6, 3585-3593.

Mortaheb Reza, Jankowski Piotr., 2023. Smart city re-imagined: City planning and GeoAI in the age of big data. Journal of Urban Management, 12, 4–15.

Razavi, S. (2021). Deep learning, explained: Fundamentals, explainability, and bridgeability to process-based modelling. Environmental Modelling & Software, 144, Article 105159.

Gahegan, M. (2020). Fourth paradigm GIScience? Prospects for automated discovery and explanation from data. International Journal of Geographical Information Science, 34(1), 1–21.

Batty, M. (2013). Big data, smart cities and city planning. Dialogues in Human Geography, 3(3), 274–279.

Lord, S., Fr_emond, M., Bilgin, R., & Gerber, P. (2015). Growth modelling and the management of urban sprawl: Questioning the performance of sustainable planning policies. Planning Theory & Practice, 16(3), 385–406.

Janowicz, K., Gao, S., Grant, M. K., Hu, Y., & Bhaduri, B. (2020). GeoAI: Spatially explicit artificial intelligence techniques for geographic knowledge discovery and beyond. International Journal of Geographical Information Science, 34(4), 625–636.

Razavi, S. (2021). Deep learning, explained: Fundamentals, explainability, and bridgeability to process-based modelling. Environmental Modelling & Software, 144, Article 105159.

Keenan, P. B., & Jankowski, P. (2019). Spatial decision support systems: Three decades on. Decision Support Systems, 116, 64–76.

Mu, W., & Tong, D. (2020). On solving large p-median problems. Environment and Planning B: Urban Analytics and City Science, 47(6), 981–996.