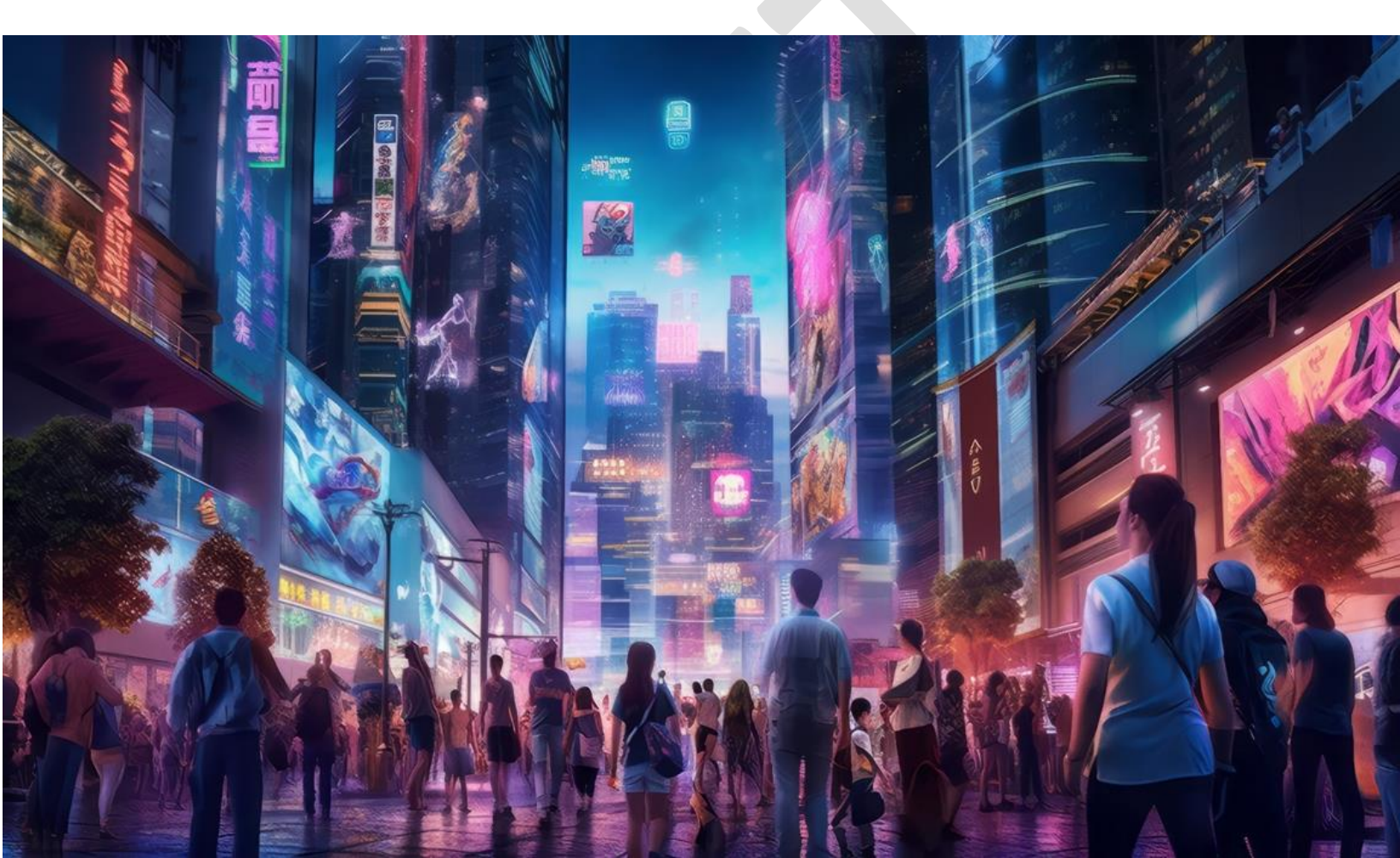


DRAFT Global Digital Citiverse Framework



Global Initiative on Virtual Worlds and AI - Discovering the Citiverse

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Foreword

This publication was developed within the framework of the [Global Initiative on Virtual Worlds and AI – Discovering the Citiverse](#), which is a global multistakeholder platform launched by the International Telecommunication Union (ITU), the United Nations International Computing Centre (UNICC), and Digital Dubai, and supported by more than 70 international partners.

The Initiative aims to shape a future where AI-powered virtual worlds are inclusive, trusted, and interoperable. By connecting people, cities, and technologies, it empowers meaningful progress through AI-powered virtual worlds.

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The publication was authored by Akhilesh Nirapure (UNICC), Samad Sepasgozar (UNSW Sydney), Taisha Fabricius (Esri), Mouna Kenoui (Centre for Development of Advanced Technologies, CDTA), Saeed Khalfan Aldhaheeri (University of Dubai), Xuesong Michael Zhai (College of Education, Zhejiang University), Martin Brynskov (Open & Agile Smart Cities & Communities, OASC), Harmen Van Sprang (Sharing Cities Alliance and Future Society Lab), Andrea Stazi (San Raffaele University of Rome and National University of Singapore), Dieter Uckelmann (Hochschule für Technik Stuttgart), Junseob Lee (Electronics and Telecommunications Research Institute, ETRI), Abdelhameed Mohamed (Engineering Consultants Group, ECG), Zhihan Lyu (Xidian University), Mohamed Mohsen (Engineering Consultants Group, ECG), Raza Jafri (MetaWorldX), Mariana de La Roche Wills (BlackVogel), Mat Yarger (Demia), Luiza Rey (Fio Legal), Fabio Budris Klaz (SAIA - Black Vogel Consulting), Tonia Damvakeraki (HBI Consulting), Asa Dahlborn (BlackVogel), Fabiana Di Porto (University of Rome Unitelma Sapienza), Marco Fontana (Polytechnic University of Milan), Clara Pezuela (ITI), Christoph Paul Runde (Virtual Dimension Center, VDC), Prasanna Lal Das (Digital Advisor), Tracey Follows (Futuremade Ltd and University of Staffordshire), Antonio Jara (Libelium), Pilar Orero (Universitat Autònoma de Barcelona), Michael Mulquin (Open & Agile Smart Cities & Communities (OASC).

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Disclaimers

The opinions expressed in this publication are those of the authors and do not necessarily represent the views of their respective organizations, Executive Committee members or Steering Committee members of the Initiative. The findings presented in this report are based on a comprehensive review of existing literature and voluntary written contributions submitted by a diverse range of stakeholders.

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Acronyms

AI	Artificial Intelligence
AI/ML	Artificial Intelligence / Machine Learning
AIDC	Automatic Identification and Data Capture
AIoT	Artificial intelligence of Things
AR	Augmented Reality
BIM	Building Information Modelling
CDBB	Centre for Digital Built Britain
DID	Decentralized Identifier

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DPI	Digital Public Infrastructure
DT	Digital Twin
eMBB	Enhanced Mobile Broadband
FGMV	Focus Group on MetaVerse
Gen AI	Generative Artificial Intelligence
GDP	Gross Domestic Product
GDPR	General Data Protection Regulation
GIS	Geographic Information System
GML	Geographic Markup Language
glTF	Graphics Library Transmission Format
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
ICT	Information and Communication Technology
IFC	Industry Foundation Classes
IMT	International Mobile Telecommunications
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
ITU	International Telecommunication Union
ITU-T	International Telecommunication Union — Telecommunication Standardization Sector
ITU-R	International Telecommunication Union — Radiocommunication Sector
JTC	Joint Technical Committee
LoRaWAN	Long Range Wide Area Network
LPWAN	Low Power Wide Area Network
mMTC	Massive Machine-Type Communications
MR	Mixed Reality
MV	Metaverse

NB-IoT	Narrowband Internet of Things
NDTp	National Digital Twin programme (UK)
NFC	Near Field Communication
NGN	Next Generation Networks
NGSI-LD	Next Generation Service Interface — Linked Data
OGC	Open Geospatial Consortium
QoS	Quality of Service
RFID	Radio Frequency Identification
RTLS	Real-Time Location Systems
SDG	Sustainable Development Goal
SDO	Standardization Development Organization
SME	Small and Medium-sized Enterprise
SSN	Semantic Sensor Network
UN	United Nations
URLLC	Ultra-Reliable Low Latency Communications
VC	Verifiable Credential
VR	Virtual Reality
W3C	World Wide Web Consortium
WHO	World Health Organization
XR	eXtended Reality

Executive summary

For decades, cities have sought to address urban challenges such as mobility, climate resilience, inclusion, and housing through fragmented, one-size-fits-all approaches. While well-intentioned, these methods often produced disconnected systems and uneven progress. As cities grew more interdependent, a new paradigm is needed – one that connects the physical, social, and digital dimensions of urban life.

Digital innovation has brought this paradigm within reach. What began as isolated “smart city” projects – data dashboards, connected sensors, and e-governance tools – has evolved into a holistic vision for urban collaboration: the *citiverse*. This vision integrates artificial intelligence (AI), digital twins, AR/VR, and blockchain to create adaptive, inclusive, and trusted digital ecosystems.

The Global Initiative on Virtual Worlds and AI – Discovering the Citiverse, launched by the International Telecommunication Union (ITU), the United Nations International Computing Centre (UNICC), and Digital Dubai with more than 60 partners, turns that vision into coordinated global action. It aligns closely with two UN-wide efforts: the Global Digital Compact (GDC), which defines *what* the digital future must be – open, safe, inclusive, and human-centred; and UN2.0, which defines *how* the UN system will deliver it – through agility, integration, and impact. The Citiverse Initiative provides *with what*: practical frameworks and mechanisms that help cities translate global commitments into tangible, locally relevant solutions.

Within this structure, Track 7 – Emerging Technologies delivers the Global Digital Citiverse Framework, a living, non-prescriptive reference developed through global collaboration. Rather than dictating how to act, it guides implementers toward the most relevant standards, tools, and technologies for their local contexts. Above all, it upholds the UN principle that no city is left behind – whether large or small, advanced or at an early digital stage – ensuring that the benefits of innovation are accessible to all.

Guiding themes

The Framework is organized around three guiding themes:

- **Section 1:** Why? – the imperative for transformation and the value of technology in addressing urban challenges.
- **Section 2:** What? – the foundational elements needed to build a trusted, interoperable, and people-centred citiverse.
- **Section 3:** How? – practical pathways for experimentation, prototyping, and implementation through sandbox environments.

Together, these themes take cities on a journey from understanding the imperative to building foundations and applying solutions.

Why it matters

Cities face increasing complexity – from climate adaptation and resource management to equitable service delivery. Emerging technologies offer transformative potential but require shared principles, open standards, and trusted pathways for adoption. The Initiative provides a global platform for coordination, and the Framework equips cities with credible guidance to adopt technology responsibly, inclusively, and efficiently.

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What the framework delivers

It consolidates global knowledge into a practical reference for cities worldwide and offers:

- **A curated** collection of standards, tools, and models for applying emerging technologies.
- **Guidance** on introducing AI, AR/VR, digital twins, and blockchain responsibly into city systems.
- **A living resource** that evolves with evidence and technological progress, supporting advanced and early-stage cities.

By connecting local ambition with global standards, the Framework helps municipalities build trust, safeguard rights, and promote innovation aligned with the Sustainable Development Goals (SDGs).

What comes next

Building on Track 7's knowledge base, **Track 9 – Sandbox Experiment Facility** will enable cities to test and refine technologies in controlled environments before scaling. This iterative cycle – *knowledge* → *application* → *evidence* – ensures that the Framework remains relevant, adaptive, and grounded in real-world experience.

Call to Action

Leaders are encouraged to:

- **Adopt and adapt** the Global Digital Civerse Framework within their local contexts.
- **Participate** in sandbox experiments (Track 9) to test solutions safely before scaling.
- **Collaborate** across borders and sectors to share learning and accelerate innovation.
- **Contribute** to global standards and open frameworks to ensure equitable progress for all cities.

In essence, the **Global Digital Compact** defines *the vision*, **UN2.0** enables *the delivery*, and the **Civerse Initiative** – through the Global Digital Civerse Framework (Track 7) and the Sandbox Experiment Facility (Track 9) – translates that vision into *action*. Together, they chart a path toward a responsible, inclusive, and evidence-based digital future where no city is left behind.

1 Vision and rationale of the citiverse

Digital technologies are increasingly being integrated into cities, allowing for virtual activities and, when possible, merging virtual and physical spaces. The advances of intelligence systems may impact how we improve the living environments and the shared operating systems for cities using an open, AI-augmented digital fabric that mirrors the physical world in real time. This is supposed to let citizens, planners, governors, administrators, and machines co-create better urban futures. This document intends to discuss how, by fusing interoperable digital twins and virtual technologies with immersive interfaces. The citiverse turns static maps into responsive, multiscale simulations, dynamic and predictive tools for the future generation of cities. This chapter presents a visionary overview of the citiverse, defines it from a technological perspective, and explains its rationale. The chapter emphasizes the convergence technologies that underpin the framework and the transformative potential of emerging technologies. This chapter is an opening, which orients and facilitates the discussions in the chapters that follow.

1.1 Vision and objectives

Cities today are at the crossroads of several overlapping changes. More than half of the global population now lives in urban areas and this is predicted to exceed 70 per cent by 2050¹. Cities are also the engines of the global economy, generating more than 80 per cent of global GDP². Their dense ecosystems foster innovation, cultural exchange, and opportunity. However, cities are also subject to significant pressures from the very factors that give them their vibrancy such as population growth, economic concentration, and technological integration.

Urbanization is accelerating the demand for housing, mobility, energy, and essential services, often outpacing the ability of current infrastructure and governance systems to adapt. Climate change makes this strain even worse. Cities contribute more than 70 per cent of global CO₂ emissions³, and 99 per cent of urban residents breathe air that exceeds WHO pollution thresholds⁴. From heatwaves and rising sea levels to floods and resource scarcity, cities are increasingly vulnerable to environmental shocks. These risks are unequally distributed, affecting underserved communities the most.

To address the pressing challenges of urbanization, citizen engagement, climate change, and digital transformation, citiverse could be a potential solution. The vision of this report is to provide a framework that fosters a future in which the citiverse becomes an inclusive, sustainable, and citizen-centric ecosystem, a seamless convergence of physical and digital worlds that empowers municipalities, policymakers, urban planners, and inhabitants to co-create adaptive, resilient, sustainable, inclusive, and innovative cities.

The aim of this report is to present an enhanced, detailed, and policy-relevant citiverse framework that provides municipalities, urban governance stakeholders, planners, and executives with a structured pathway to transform cities and address grand urban challenges. Building on existing concepts of digital and virtual cities, this framework advances them by integrating a wide spectrum of tools, technologies, standards, and use cases. It is designed to be informative at governance and executive levels, enabling cities to adopt emerging technologies such as AR, VR, IoT, digital twins, and AI, in a way that is ethically grounded, technically feasible, inclusive, and globally informed.

Table 1 Objectives of the present document and corresponding chapters

Objectives	Overall chapters
Articulate the vision, purpose, and relevant technologies to support the citiverse as a framework for addressing complex urban challenges and guiding future-ready city administrations.	Vision and Rationale of the Citiverse
Map the key challenges facing cities and identify where emerging technologies can create transformative impacts (economic, social, ecological).	Urban Challenges and Technology Impact Zones
Define principles, safeguards, and governance models that ensure the ethical, secure, and responsible use of data within the citiverse.	Data Governance and Ethical Stewardship
Describe the digital architecture, platforms, and enabling technologies that underpin the citiverse, ensuring robustness, scalability, and sustainability.	Technical Backbone
Explore standards, benchmarks, and frameworks that ensure seamless integration and interoperability across systems, platforms, and cities.	Interoperability Standards
Assess readiness factors such as connectivity, digital infrastructure, and institutional capacity that determine how cities can adopt and scale citiverse technologies.	Infrastructure and Technology Readiness
Explore how citiverse tools can enhance citizen participation, inclusivity, and accessibility, so ensuring that digital transformation benefits all residents.	Citizen Experience and Inclusion
Showcase global examples and case studies that illustrate successful applications of emerging technologies, extracting lessons and key metrics to guide future adoption.	Pilot Case Studies and Global Lessons
Provide guidance for municipalities to design and configure sandbox environments, enabling safe experimentation, iterative testing, and prototyping of citiverse solutions before full-scale deployment.	Sandbox Environments and Prototyping Ecosystems

While technology often becomes the core of discussions on future cities, especially when cities are perceived as inefficient and in need of smarter solutions, significant challenges remain regarding the applicability of emerging technologies at the city level. For example, including fragmented data infrastructure, siloed systems, and digital although economic growth is significant, it remains unevenly distributed, perpetuating civic alienation, spatial segregation, and exclusion from planning processes. Fragmentation is emerging as a critical obstacle, as diverse platforms, standards, and infrastructures risk creating silos rather than fostering interoperability and collective progress. Even though economic growth is significant, it is still not distributed

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evenly, which perpetuates civic alienation, spatial segregation, and exclusion from planning procedures. Optimization is not enough to meet these convergent challenges; transformation is required.

At the same time, a unique technological window has opened. An unparalleled opportunity is presented by the development and expanding accessibility of immersive technologies, including Extended Reality (XR), spatial computing, and AI-driven simulation, as well as the global movement to create inclusive Digital Public Infrastructures (DPIs). Real-time responsiveness is made possible by cloud and edge computing, decentralized identity systems are altering trust and data sovereignty, and XR hardware is getting cheaper.

Beyond just being places for entertainment, virtual worlds are also evolving into spaces for civic participation, collaboration, and service provision. Because of this shift, it is not only possible but also necessary to reconsider how cities support interactions and engagements of their citizens online. While smart cities and urban digital twins have delivered meaningful progress, they often prioritize institutional efficiency and system optimization over inclusive governance and citizen participation. Smart cities tend to prioritize operational efficiency. Digital twins enhance system simulation and infrastructure management. And yet both often fall short in engaging the people who live in, shape, and are affected by the city. They may overlook the social, local knowledge, and civic participation that shape the everyday reality of urban residents.

What is needed now is a paradigm shift-, from systems built for people, to systems co-created with people.

1.2 Definitions and rationale

Two key definitions of the citiverse were proposed in the FGMV-34 Report (06/2024) - ITU⁵, while the broader concept of the metaverse was previously introduced in the FGMV-20 Report (12/2023) - ITU⁶. Citiverse is sometimes referred to as the metaverse for cities⁵. From another perspective, citiverse is supposed to prioritize a human-centred approach and promote Sustainable Development Goals (SDGs) and principles. Citiverse is also known as a specified version of metaverse for cities prioritizing a human-centred approach and promoting sustainable development⁵. Metaverse is referred to an integrative ecosystem of virtual worlds offering immersive experiences to users, that modifies pre-existing and creates new value from economic, environmental, social and cultural perspectives⁶. A metaverse is virtual and augmented, which represents, or associates with physical objects or environments.

⁷ Designed to be inclusive, accessible, and sustainable facilitating innovation, civic participation, and the integration of urban systems. This definition primarily emphasizes how technology is being used to develop or empower the city and professionals to accomplish certain objectives, such as empowering the city and anticipating the achievement of certain objectives, like inclusivity or sustainability. However, another definition provided by the European Commission⁸ highlights new services or practices as the inherent outcome of using a Citiverse. Citiverse, in this definition, refers to interconnected spaces, and citizens are known as actors who are represented by avatars:

The citiverse is also defined as a series of interconnected and distributed hybrid and virtual worlds representing, and synchronized with, their physical counterparts. Based on this definition, it offers new (administrative, economic, social, policy-making, and cultural) virtual goods, services, and capabilities to city and community actors (e.g., citizens) represented as digital avatars Inspired by ISO/IEC 23005-1:2020 and IEEE 2888 standards and Zare and Jalali⁹.

An extended definition is presented by Anthopoulos et al.¹⁰, which adopts ITU's definition of the citiverse, describing it as the application of the metaverse within urban contexts.

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Citiverse is seen as a metaverse subset that is associated with a particular physical urban system. It is a large-scale interconnected data-driven system, which supports digital urbanism by facilitating the augmentation of urban spaces and urban operations. Citiverse grounds on the potential of metaverse and Smart City digital twinning, which utilize emerging ICT (*e.g.*, AI, IoT, Blockchain, language technologies, digital twin and virtual or mixed reality technologies).

Cities can create a more diverse, inclusive, interactive, and sustainable social space for their residents by implementing the concept of citiverse. Moreover, citiverse is expected to encompass all the main aspects of a given physical city, while providing a virtual space where inhabitants can create “avatars” to interact, communicate, and access education, transportation, health care, tourism and public services¹⁰.

In the context of urban applications, the citiverse can be considered as an immersive, interoperable digital urban ecosystem composed of interconnected and synchronized virtual worlds that reflect and augment real-world urban environments. It integrates a wide range of technologies, including Extended Reality (XR), Digital Twins, Artificial Intelligence (AI), the Internet of Things (IoT), and Blockchain, to provide city administrators, urban planners, and citizens with new tools for participatory governance, real-time simulation, and digital service delivery. This ecosystem enables inclusive, data-driven decision-making, fosters civic engagement, and supports sustainable, resilient urban development.

The present framework adopts a native inclusive citiverse concept. An inclusive citiverse is a digital or hybrid urban ecosystem blending smart city technologies, virtual environments, and civic life for all its citizens. This chapter provides a high-level overview of the basic concepts and principles to secure a native, inclusive citiverse in which no citizen is left behind. Planning an inclusive citiverse requires the involvement of a diverse collaborative group of stakeholders. The final objective is to raise awareness of the importance of designing an accessible and inclusive citiverse by design - and not as an afterthought. The chapter allows the introduction of overall concepts that support developing an ecosystem where accessibility and inclusion are primary drivers of innovation, and key factors for the improvement of citizen satisfaction and quality of life.

In short, the citiverse represents an integrative framework covering an open, standard-driven, sovereign digital infrastructure that significantly strengthens resilience, supports innovation, and secures autonomy. By design, it ensures that cities can integrate advanced technologies such as AI-native networking and innovative green infrastructures, without being trapped in outdated proprietary systems.

What sets the citiverse apart is not only its technological advances, but also its capacity to reshape governance, participation, and digital culture. It reframes cities as living, co-created ecosystems, where inclusivity, accessibility, and sustainability are core principles, in line with the SDGs and the UN’s “leave no one behind.” Digital accessibility includes multilingual services, immersive XR designed for people with disabilities, and equitable participation in planning and service delivery.

The following table summarizes some of the main ideas of this broader civic vision by contrasting trends with the more limited approaches of Smart Cities and Urban Digital Twins. The citiverse is not meant to take the place of digital twins or smart cities. Instead, it enhances their strengths through inclusive engagement, participatory governance, and socio-technical integration. As a result, city-making becomes transparent, flexible, and collaboratively developed with its residents, creating room for creativity, discussion, and experimentation.

Table 2 Overall differentiation or distinctions among Smart Cities and Urban Digital Twins concepts and the citiverse framework

Dimension of comparison	Smart cities	Urban digital twins	Citiverse framework
Core Logic	Optimize city services through data and ICT	Simulate, monitor, and optimize urban systems in real time	Transform governance, participation, and urban life via immersive, interoperable ecosystems
Main Tools	IoT, sensors, analytics	GIS, BIM, simulation, DT platforms	XR (AR/VR/MR), AI, DT, IoT, Blockchain, Cloud/Edge, open standards
Focus	Efficiency, infrastructure, service delivery	Operational resilience, scenario modelling, asset management	Human-centred co-creation, inclusivity, digital culture, sustainability
Governance	Often vendor-driven, fragmented	Technocratic, expert-led	Participatory, transparent, standards-based, sovereignty-oriented
Role of inhabitants	Service user, data provider	Mostly observer, sometimes consulted	Active co-creator and civic agent, with inclusive and accessible engagement
Limitations	Siloed, risk of vendor lock-in, weak inclusivity	Narrow scope, limited public engagement	Integrates social, ecological, institutional transformation with technology, ensures no one is left behind, but yet the adoption rate needs to be increased.

At its core, Smart Cities and Digital Twins may focus on efficiency and simulation; the citiverse tends to advance toward an inclusive, standards-based ecosystem that ensures equal access for all.

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1.2.1 The citiverse as a potential solution

The citiverse responds to urban challenges with a bold new approach. It is a human-centered, immersive, and interoperable urban ecosystem that also integrates XR, Digital Twins, AI, IoT and Blockchain, enabling trusted digital identity, secure data sharing, and decentralized governance. This shared digital layer allows citizens, planners, and decision-makers to interact, simulate, and co-design urban life collaboratively and in real time.

At its heart, the citiverse is more than a technological shift. It marks a transformation in how cities are governed, experienced, and shaped, placing collective intelligence and civic agency at the heart of urban innovation. It empowers cities to function as dynamic, sensing, and evolving systems, responsive to the voices, needs, and aspirations of all.

In a world marked by increasing complexity, compounding crises, and eroding public trust, the citiverse offers a hopeful and actionable way forward. It enables future cities to become more resilient, inclusive, and agile-not as a distant vision, but as a global initiative that begins now.

1.2.2 Convergence of technologies supporting the citiverse framework

The citiverse is grounded in a set of foundational technologies that together enable real-time sensing, simulation, intelligence, and trust at the city scale. AI provides the analytical and decision-making engine; the IoT supplies real-time sensor data streams; digital twins function as the living mirror of the city; blockchain guarantees provenance, trust, and secure transactions; and mixed reality bridges the real and the virtual, allowing city actors to interact with complex information in intuitive, spatially anchored ways. Formalized by ITU, ISO/IEC, and relevant standards bodies, these definitions ensure consistency and international applicability. Together, the convergence of these technologies offers capabilities that constitute the technical substrate for governance, planning, and citizen engagement within the citiverse.

Convergence, in the context of emerging technologies, refers to the integration and amalgamation of multiple tools into unified systems that enhance efficiency, usefulness, and acceptance by improving compatibility, interoperability, connectivity, trust, and accessibility¹¹. Climate technologies such as AIoT-enabled (Artificial Intelligence of Things) digital twins, already demonstrate how convergence can reduce greenhouse gas emissions while optimizing building performance and energy use. Resilient technologies, which are often used to sustain remote operations, show how convergence ensures continuity of essential services during times of disruption, even though issues of complexity, safety, and reliability remain¹¹. More broadly, convergence of technologies represent a novel shift away from siloed, single-purpose tools toward integrated systems where autonomous platforms, IoT/Web of Things, and human-machine interfaces can operate seamlessly. While challenges around interoperability, workforce skills, and readiness persists, convergence provides the foundation for innovation and transformation¹¹. For the citiverse, this notion of convergence is essential. The rationale is that without uniting fragmented digital tools into interoperable ecosystems, the citiverse cannot achieve its ambition of accessibility, successful performance, inclusivity, resilience, and sustainability. Instead, convergence ensures that diverse technologies, from AI and digital twins to AR/VR and AIoT function together as a holistic ecosystem, enabling cities to become more adaptive, citizen-centred, and future-ready.

Rather than investing in fragmented smart city pilots, citiverse offers city governors, leaders and planners a unifying digital infrastructure that promotes interoperability, data sovereignty, and cross-sector collaboration. This shift – from siloed digital systems to integrated, citizen-facing environments – marks a strategic evolution in public sector digital transformation, thereby enabling cities to operate more coherently, inclusively, and

effectively.

The following table gives a summary of a few fundamental technologies that are aligned with the convergence of technologies supporting the citiverse framework¹².

Table 3. Selected technologies to support the Citiverse framework.

Table 3 Enabling technologies to support the citiverse framework

Enabling technology	Definition
Artificial intelligence (AI)	Computerized system that uses cognition to understand information and solve problems. ITU-T M.3080
eXtended Reality (XR)	An environment containing real or virtual components or a combination thereof, where the variable X serves as a placeholder for any form of new environment (<i>e.g.</i> , augmented, assisted, mixed, virtual, or diminished reality). ITU-T P.1320
Digital Twin (DT)	Digital representation of an object of interest. NOTE - A digital twin may require different capabilities (<i>e.g.</i> , synchronization, real-time support) according to the specific domain of application. ITU-T Y.4600
Internet of things (IoT)	A global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies. ITU-T Y.4000
Blockchain	A type of distributed ledger that is composed of digitally recorded data arranged as a successively growing chain of blocks, with each block cryptographically linked and hardened against tampering and revision. ITU-T X.1400

The *Urban Brief: Digital Twins for Cities 2025*¹³ defines digital twins as dynamic, data-driven virtual replicas of urban environments that integrate live, static, and historical information to monitor, simulate, and optimize city systems. However, there are some characteristics conceptually presumed to define a digital twin such as a two-way data flow between the physical object and the digital counterpart, as differentiated from a digital shadow in a scholarly paper focusing on elucidating a paradigm shift to expedite a smart, sustainable built environment¹⁴.

The Urban Brief descriptions of 3D modelling, interactive visualization, and even the use of avatars in Curitiba's case study (Brazil) imply that elements of virtuality are central to how city digital twins are built and experienced¹³. These are examples that highlight that immersive and visual dimensions closely tied to virtual reality are essential for making complex data accessible, enabling citizens and stakeholders to interact with lifelike models of urban infrastructure, and fostering participatory urban planning. In this sense, the brief

underscores how digital twins rely not only on data and AI but also on virtual representations to bridge the gap between abstract analytics and tangible city realities.

While the digital twins and associated technologies form the computational and infrastructural backbone, immersive technologies especially are those that most directly shape citizen and civil servant experience within the citiverse. Building on Milgram and Kishino's¹⁵ reality-virtuality continuum, Recommendation ITU-T P.1320 "Quality of experience assessment of extended reality meetings"¹⁶ distinguish between VR, AR, MR, and XR.

These immersive modalities define how actors perceive, engage, and co-create within digital urban environments. In practice, this may mean that a civil servant accesses a city's Digital Twin through VR for scenario simulations, while a citizen uses AR overlays to access mobility or energy consumption data in real time. XR serves as the umbrella framework, encapsulating the dynamic interplay of all immersive modes.

Beyond the core and immersive domains, the citiverse may benefit from additional enabling paradigms that ensure scalability, interoperability, and resilience. Concepts such as Metaverse (MV), Generative AI (Gen AI), and Spatial Computing define the broader theoretical and practical landscape of the citiverse, extending its impact beyond the digital replication of cities into realms of content creation, multimodal interaction, and human-machine collaboration.

At the infrastructure level, cloud computing and edge computing are essential to managing the immense data throughput and latency-sensitive interactions of city-scale immersive systems. Meanwhile, interoperability ensures that heterogeneous systems – from IoT devices to governance platforms – can communicate seamlessly using open standards. This tier of concepts ensures that the citiverse is not only a technically feasible construct but also a sustainable, evolvable, and standards-aligned ecosystem.

1.2.3 Beyond technology: The citiverse as a strategic urban transformation

While emerging technologies are central to the citiverse framework, it is far more than a technical undertaking, it is supposed that the framework marks a profound societal and institutional shift. The citiverse framework supports cities to move beyond conventional digitization or basic smart cities and embrace a new urban paradigm: one that redefines civic participation, safeguards public digital space, and empowers collective agency.

It challenges traditional governance models to become more transparent, adaptive, and accountable, embedding ethics, equity, and inclusion as core design imperatives rather than afterthoughts. This transformation is not merely about deploying XR headsets or building digital twins; it is about rebuilding trust between inhabitants and institutions, closing the digital divide, and ensuring that technology is aligned with the broader collective urban interest.

Citiverse introduces a shared spatial interface where city officials, planners, and residents can collaboratively visualize, simulate, and co-create urban policies, services, and futures, within governance ecosystems that are fair, responsible, and grounded in values of ethical leadership, civic oversight, and collaborative decision-making.

Crucially, the citiverse moves beyond the Smart City narrative and the technical focus of traditional urban digital twins. It proposes a new kind of digital infrastructure, interactive, participatory, and purpose-driven, enabling cities to become more inclusive, resilient, and responsive in the face of complex, accelerating change.

1.2.4 Why advanced technologies matter for cities

As cities face escalating challenges, emerging advanced technologies may serve as key enablers of transformation. Their value lies not in novelty alone but in their ability to help urban administrations anticipate needs, simulate futures, manage complex systems in real time, and engage citizens in more inclusive and participatory ways.

As mentioned before, citiverse provides a cohesive digital ecosystem where emerging technologies – including AI, immersive technologies (AR/VR/MR), digital twins, the IoT, cloud and edge computing, and blockchain – converge to support governance, planning, and public service delivery. Yet, for these technologies to interoperate meaningfully, they must be grounded in a shared spatial foundation.

This is where Geographic Information Systems (GIS) play a central role, providing the spatial framework that underpins the citiverse. It anchors real-time inputs from IoT, immersive simulations from XR, and predictive analytics from AI within a unified geographic context, ensuring all data and interactions are precisely geolocated and contextually understood.

At the building and infrastructure scale, Building Information Modelling (BIM) data integrates seamlessly into this spatial layer, linking detailed asset information with the broader geospatial model. The key consideration of using BIM is its interoperability and compatibility¹⁷. Aligning BIM models (often in IFC format) to city-wide coordinate systems, and applying interoperability standards such as CityGML and InfraGML, allows the citiverse to connect IoT sensor streams to specific components, enable immersive XR-based design reviews, and run predictive simulations for energy performance, structural health, and environmental impacts. The result is a multiresolution urban information model that supports operational management and long-term strategic planning.

This spatial foundation aligns with open standards such as IndoorGML for indoor navigation, the ISO 191xx series for geospatial metadata and data quality, and related OGC/ISO specifications that ensure data interoperability, portability, and re-use. Cities like Rotterdam and Singapore already use such frameworks to simulate urban flows, monitor infrastructure, and enhance resilience. Citiverse takes these capabilities further, integrating them into a real-time, immersive, and interoperable system-of-systems.

Emerging technologies function across multiple interconnected layers within the citiverse architecture: from infrastructure enablers such as cloud-native architectures, edge computing, and blockchain – which ensure scalability, security and interoperability – to experience mediators like XR interfaces, generative AI, and intelligent avatars that shape how citizens and officials interact with digital environments.

More than isolated digital tools, these technologies serve as enablers of responsive and intelligent urban systems. They allow municipalities to anticipate citizen needs, optimize infrastructure in real time, simulate urban development scenarios, and design more inclusive and transparent planning processes.

1.2.5 How the citiverse meets core municipal needs

By integrating emerging technologies into a cohesive spatial and technical framework, the citiverse enables cities to address pressing urban challenges through:

- **Spatial Decision-Making and Analysis:** The citiverse leverages GIS and immersive environments to allow urban planners, engineers, and citizens to co-design infrastructure. By overlaying real-time and historical

data within a spatial context, they can simulate the impact of policies and infrastructure changes geospatially before implementation.

- **Resilience and Scenario Planning:** AI and Digital Twins model complex urban systems, helping city leaders test future conditions – climate, economic shocks, migration – before they occur.
- **Real-Time Monitoring and Responsiveness:** IoT and edge computing deliver continuous data from the physical world. These data are integrated seamlessly into the citiverse's GIS foundation, so enabling dynamic urban management, from pinpointing traffic congestion and optimizing energy grids to orchestrating an emergency response in real time.
- **Transparent and Participatory Governance:** Blockchain and decentralized identities empower secure, auditable civic engagement, voting, and participatory budgeting.
- **Scalability and Interoperability:** Cloud-native infrastructure ensures scalability across city departments while adhering to open standards and interoperability protocols.
- **Data Governance and Sovereignty:** The citiverse supports responsible data stewardship frameworks that protect citizen privacy while enabling valuable insight across city operations.

For city administrations, embracing emerging technologies through the citiverse is not about adopting digital trends — it is about modernizing the institutional and technological backbone of public administration itself. It enables cities to govern with foresight, operate with efficiency, and engage with legitimacy. As citizens increasingly demand responsive, transparent, and inclusive urban services, the citiverse provides a future-ready foundation that meets those expectations.

Ultimately, the citiverse empowers municipalities to transition from siloed digital initiatives toward holistic digital governance, where immersive, intelligent, and interconnected technologies support cities not only in solving today's urban challenges but also in shaping tomorrow's sustainable, inclusive, and resilient urban futures.

1.2.6 The transformative potential of emerging technologies in the citiverse

Citiverse enables structural changes that go far beyond optimization. Its impact can be organized across three transformation dimensions: economic, social, and ecological.

Economics

The citiverse fosters entirely new urban economies, going far beyond cost-efficiency. Crucially, citiverse drives future-proof employment: from AI modelling, 3D spatial computing, and XR content design, to digital heritage curation and cross-domain system integration. For example, Seoul's Metaverse Seoul [18] has already created jobs in XR development and municipal service delivery, demonstrating that cities can become digital employers, not only regulators or service providers. SMEs, in turn, gain access to interoperable DT and XR platforms, powering new urban innovation chains in mobility, logistics, and energy. In this sense, the citiverse is more than an efficient tool; it is the foundation of resilient, innovation-driven economies, aligned with Europe's Digital Decade and the UN SDGs.

Social

The citiverse redefines citizenship in the digital age. It enables immersive consultation platforms such as virtual town halls and participatory budgeting XR simulations, where citizens can explore policy trade-offs in 3D, thereby reinforcing trust, legitimacy, and transparency. Beyond governance, the citiverse can be used to extend classrooms into interactive urban laboratories, where learners engage with history, ecological systems, and civic data in dynamic ways. Initiatives like the EELISA Metaverse for Sustainability¹⁸ illustrate how XR strengthens community-based learning and knowledge exchange across borders. Health and well-being can also be another impact of citiverse. For example, rehabilitation through XR, immersive mindfulness spaces, and interactive ecological environments directly enhances quality of life in urban contexts. Above all, citiverse is a contract for inclusion. With affordable access models, multilingual XR, and AI-driven accessibility (voice commands, automated translation, adaptive interfaces), it ensures nobody is left behind -empowering elderly, disabled, or marginalized groups to participate actively in the digital society.

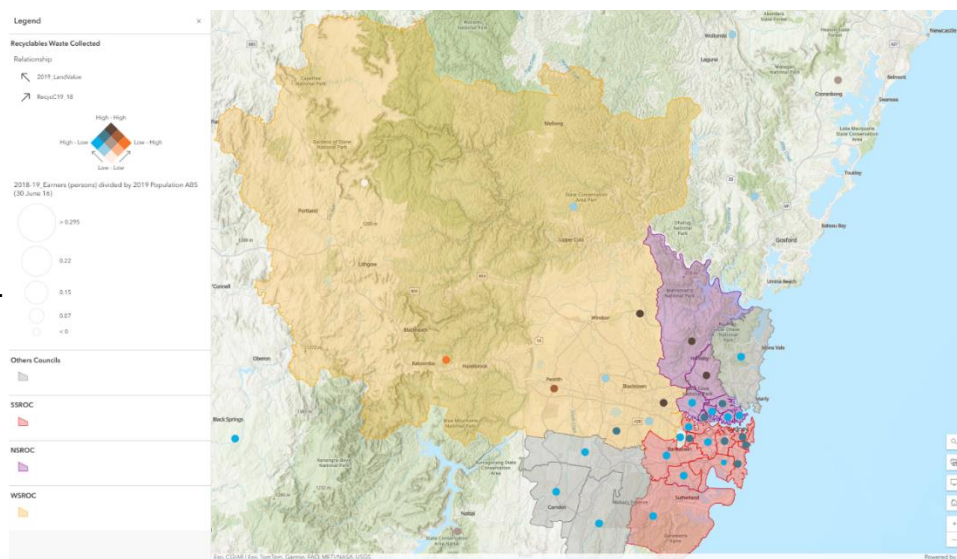
Ecological

The ecological potential of the citiverse goes beyond incremental sustainability. By interlinking Digital Twins, AI forecasting, and IoT sensing, cities gain the capacity to simulate climate-resilient futures with unprecedented granularity. The citiverse contributes directly to SDG 11 by enhancing spatial planning, resilience, citizen participation, and urban sustainability, while also supporting other key SDGs such as SDG 9 (innovation and infrastructure), SDG 13 (climate action), and SDG 7 (clean energy)- through intelligent energy optimization, climate scenario simulations, and infrastructure efficiency. Furthermore, citiverse creates new avenues for addressing poverty (SDG 1) and inequality (SDG 10) by improving service accessibility and enabling digital inclusion. Its alignment with global cooperation efforts (SDG 17) is exemplified through the UN Citiverse Challenge and other multilateral platforms that encourage co-creation among cities, technology partners, and citizens. The technological upgrade offered by citiverse is a multidimensional transformation strategy that enables municipalities to rethink how they govern, plan, and serve, accelerating progress toward greener, smarter, and more equitable urban futures¹⁹.

Furthermore, a wide range of SDGs, including SDG1, SDG3, SDG4, SDG8, SDG9, SDG10, SDG11, SDG12, SDG13, SDG16 and SDG17, can be achieved with the help of the Citiverse use cases mapped in the Citiverse Use Case Taxonomy, developed under the Global Initiative on Virtual Worlds and AI – *Discovering the Citiverse*¹⁸.

Several practices have demonstrated the value of advanced technologies in support of the SDGs, which can further support the idea of using citiverse to help achieve the SDGs at the national level. For example, in Singapore¹⁸, AI-enhanced evacuation DTs reduce emissions during crisis mobility scenarios. Another example is Tallinn, the Green Twins initiative¹⁸ uses XR to visualize biodiversity corridors and green strategies in line with the EU Green Deal²⁰.

Figure 1. Screenshot from ArcGIS Online showing the jurisdictions of Sydney's councils and regional organisations of councils (SSROC, NSROC, WSROC) and the waste tonnage of recycled collected waste. (Courtesy: Simon Xu and Sara Shirowzhan)²¹



Urban waste is being estimated using GIS and visualized on a dashboard in a recent practice that enables practitioners and decision-makers to monitor trends in the stream of recyclable, residual, and organic waste in urban waste management²¹. For example, Figure 1 shows a screenshot of an application based on ArcGIS Online showing the jurisdictions of Sydney's councils and regional organizations of councils (SSROC, NSROC, WSROC). The map uses colour density to represent the combined variation of two metrics: the average land value of each local government area (LGA) and the waste tonnage of collected recycled waste.

Equally transformative is ecological literacy. For example, XR allows citizens to experience sea-level rise, urban heat islands, or flood risks through embodied simulations, strengthening collective awareness and political will.

2 Urban Challenges & Technology Impact Zones

In an era in which cities are the epicentres of innovation and complexity, understanding the array of urban challenges, from climate resilience and mobility to public health and service delivery, is essential. This chapter dives into those core systemic challenges, revealing through use cases based on cities how citiverse technologies offer powerful, integrated tools for transformation.

Importantly, the challenges presented here are mostly aligned with the thematic areas in the [Citiverse Use Case Taxonomy](#), developed under the [Global Initiative on Virtual Worlds and AI](#). Similarly, most of the presented use cases are crosschecked with the [Citiverse Use Case Taxonomy](#), ensuring they are grounded in real-world relevance and tested under rigorous maturity, risk, and stakeholder evaluations. Linking challenges, technologies, and validated use cases creates a cohesive roadmap, helping cities visualize how the citiverse can deliver on vision and impact.

2.1 Climate change adaptation planning for infrastructure systems resilience

Challenge:

Cities worldwide face increasing flood risks -from riverine surge to extreme rainfall and sea-level rise. Aging drainage infrastructure, urban heat island effects, soil imperviousness, and inadequate green buffering make many cities vulnerable. Flood events carry enormous human, environmental, and economic costs, particularly in low-lying, dense coastal urban centres. According to IPCC, by 2050, eight times as many city dwellers could be exposed to higher temperatures and 800 million more people could be at risk from the impacts of rising seas and storm surges. Cities must reconfigure in a way that cultivates resilience.

Tech Impact Zones – digital twins (DT) + AI:

Digital twins built from high-resolution 3D city models, continuous IoT streams, and hydrological data empower real-time flood simulation and scenario forecasting. The UK's Climate Resilience Demonstrator (CReDo) is a digital twin project that uses connected data to enhance climate change adaptation and resilience. Focusing on the impact of flooding on energy, water, and telecom networks, it unites major infrastructure providers to improve resilience planning, incident response, and recovery. Nottingham City Council has developed an advanced 3D digital twin to support more efficient, transparent and inclusive urban planning. Built on geospatial and planning data, and enhanced through XR visualization, the platform allows planners and citizens to explore future developments in immersive 3D, supporting scenario analysis and stakeholder engagement.

Also, cities like Lisbon employ digital twin platforms to forecast 100-year rainfall designs and optimize investments in infrastructure (e.g., tunnels, wetlands), saving an estimated hundreds of millions over decades (Geospatial World)

2.2 Transport & mobility optimization

Challenge:

Rapid urbanization strains existing mobility systems. Traffic congestion, GHG emission linked to transport system, poor signal coordination, accident hotspots, lack of real-time visibility into micro-mobility flows, and siloed data among agencies all conspire to impede safe, equitable transport access. Estimates suggest that urban areas are responsible for 70per cent of global CO₂ emissions, with transport and buildings being among

the largest contributors (IPCC 2022)²².

Tech Impact Zones – DT + AI+IOT:

Modern mobility DTs assimilate streaming feeds from traffic sensors, public transport, micromobility apps, and weather data. Seoul's Smart Traffic Management System uses a digital twin powered by AI and more than 5 000 sensors to monitor and control traffic in real time. By predicting and managing conditions, it reduces congestion, improves safety, optimizes signal timings, and aids emergency responses. The system has already cut travel times by 25 per cent in pilot areas and is now being expanded citywide. Madrid is using AI and digital twins to modernize its public transport, with a focus on smarter bus scheduling. The city's transport authority optimizes routes and deployment based on demand, traffic, and environmental data, thereby reducing delays, improving efficiency, and enhancing the passenger experience. AI predicts ridership surges, enabling timely adjustments that cut costs and support sustainability goals. Singapore has built a city-wide digital twin to simulate disaster scenarios and enhance evacuation planning. Developed by the Urban Redevelopment Authority and Housing & Development Board with GovTech and A*STAR, this real-time, hyper-realistic model helps officials visualize and coordinate responses to floods, fires, and terrorist threats. It is especially effective in managing emergencies in dense urban areas with complex transport systems.

Tech Impact Zones — AR+VR:

Boston and the Massachusetts Bay Transportation Authority are using immersive VR to boost public engagement and promote equity in transit planning. By combining GIS, urban simulation, and VR headsets, residents can explore proposed bus, subway, and pedestrian upgrades in 3D. This approach deepens understanding and ensures designs that serve all communities better, especially those often underrepresented. London is integrating augmented reality into its Mobility-as-a-Service platforms to improve city navigation. Citymapper tested an AR prototype that overlays routes onto the real world via smartphones or AR glasses, helping users navigate more easily and confidently. The aim is to make travel seamless, inclusive, and engaging, especially for tourists and those with accessibility needs.

Tech Impact Zones – Drones + AI

Autonomous drone delivery services like Manna Aero in Dublin (carrying ~4 kg loads over ~3 km), reduce delivery time and emissions by more than 70 per cent and slash costs by more than 90 per cent vs. traditional trucks (theguardian.com)²³.

2.3 City administration, services and public participation

Challenge:

City administrations face mounting pressure to deliver efficient and transparent services amid rising citizen expectations for timely responsiveness, personalized engagement, and digital access. Traditional, siloed service delivery such as permit processing, infrastructure maintenance, and public feedback, often leads to inefficiencies and citizen frustration. Furthermore, the expanding digital literacy of citizens means they increasingly expect immersive, informative, and easy-to-navigate digital government interactions. Modernizing municipal operations to meet these expectations – while ensuring equity, engagement, trust, and co-creation – remains a pivotal challenge for a citiverse.

Tech Impact Zones – DT + AR+VR+AI+ XR Immersion :

Patras, Greece, is creating an Urban Resilience Digital Twin that blends real-time data with citizen feedback to guide city planning. By mapping public sentiment and identifying priority areas, the city can address issues faster, strengthen community engagement, build trust, and boost overall urban resilience. San Diego is piloting VR and AI-powered training to onboard public sector employees. Interactive simulations cover scenarios from emergency response to public engagement, with AI tutors providing personalized guidance. This approach boosts retention, builds confidence, speeds up onboarding, and lowers training costs compared to traditional methods. Copenhagen, Denmark, is advancing its smart city vision with a digital twin developed in partnership with Cisco and Tele Danmark Communications. Spanning a 7-mile area, it integrates data from infrastructure such as lighting, parking, and waste management into a single, scalable platform. Real-time monitoring helps optimize operations, cut costs, and enhance services, while supporting economic growth, sustainability, and quality of life for residents.

Seoul's Metaverse "Seoul Platform" is the world's first city-run public metaverse, offering citizens virtual access to town halls, official consultations, and public services without physical barriers. Combining XR, AI, and metaverse technologies, it promotes inclusive, participatory governance and sets a global standard for citiverse innovation.

Tech Impact Zones – Blockchain:

Dubai's Roads and Transport Authority (RTA) is exploring blockchain to transform vehicle registration, replacing lengthy, paper-based steps with secure digital records for each car. This speeds up the process, enables instant ownership transfers and reduces fraud risks. For the booming used car market, blockchain offers buyers a transparent, tamper-proof record of a vehicle's history, including service, accident, and ownership details – helping them avoid hidden issues. Sellers benefit from added credibility, while buyers gain confidence in their purchase, fostering a more efficient and trustworthy automotive marketplace (autotraders.ae)²⁴.

2.4 Infrastructure asset mapping, management & inspection

Challenge:

Maintenance of urban structures and public utilities such as underground pipes, bridges, tunnels, roads and power lines is expensive, hazardous, and often reactive. Failures can cause safety incidents and service disruptions, especially when physical inspections are delayed or incomplete.

Tech Impact Zones – DT + AR/VR+AI+IOT:

Digital twins can be used to create an interactive digital map of underground pipes and cables spanning private sector utilities. City and urban planners can use this DT platform to issue maintenance permits more efficiently, identify safety issues, and plan new infrastructure projects. The Geospatial commission in the UK is building a digital twin of underground pipes and cables – the National Underground Asset Register (NUAR) – to improve the efficiency and safety of buried infrastructure by providing a secure way to access data from more than 600 public and private sector asset owners. The first phase covered London and Northeast England, with a further roll out to all of England and Wales.

Tech Impact Zones - drones + AI-enabled vision:

Autonomous drone fleets equipped with high-resolution cameras and thermal/LiDAR sensors inspect hard-to-reach areas like bridge underdecks or elevated pipelines. In China's PipeChina pilot, DJI drones executed pre-programmed 190-point waypoint plans over pipeline suspension bridges, enabling automated bridge inspection by capturing consistent visual data and detecting surface defects that triggered alerts for engineers, dramatically increasing inspection frequency and reducing human risk (enterprise-insights)²⁵.

2.5 Public safety, health & disaster resilience

Challenge:

Cities are increasingly confronting the compounded threats of emergencies, health crises, and chronic environmental stressors such as extreme heat, poor air quality, disease outbreaks and infrastructure failures, which strain public health systems and emergency preparedness. Moreover, many cities lack integrated systems that fuse meteorological, health, and infrastructural data, resulting in delayed early-warning insights and reactive response strategies that put lives and livelihoods at risk.

Cities must be ready to anticipate, model, and respond rapidly to emergencies, disease outbreaks, and safety incidents, with heterogeneous populations, evolving mitigation measures, and fragile healthcare systems. Strengthening urban resilience in these areas, requires proactive, multisectoral coordination, community engagement, and equitable resource distribution to ensure that no one is left behind in times of crisis undrr.org.

Tech Impact Zones – DT + VR + AI + IoT:

Singapore's National Research Foundation has created a digital twin that combines IoT sensor data and environmental insights into a 3D city model. Used by emergency teams to simulate floods, plan evacuations, and allocate resources, it cut response times during the 2023 monsoon season. The platform has since expanded to support disease tracking and health resource management, enhancing the city's overall resilience. In Australia, Energy Queensland has combined its Advanced Distribution Management Solution with its Geographic Information System to create a network digital twin of its power grid. This unified, accurate model reflects the grid's real-time and operational state, enabling scenario planning and simulations without disrupting critical services, while providing a single, consistent source of truth across the organization. Also, INTERPOL is piloting the use of metaverse technology to create digital twins of crime scenes, preserving them exactly as they were for ongoing analysis. These virtual replicas ensure accurate documentation, aid in evidence review, and help train field personnel. They also allow juries to virtually tour scenes, providing valuable spatial context that can support more informed deliberations.

Tech Impact Zones - drones:

As demonstrated by Zipline's operations, an American company that designs, manufactures, and operates delivery drones to deliver vaccines, medical kits or test samples directly within many cities around the world, bypassing traffic bottlenecks and enabling rapid response, even in high density settings. As of September 2021, more than 75 percent of blood deliveries in Rwanda outside of Kigali use Zipline drones. (Wikipedia²⁶).

2.6 Urban energy resilience & sustainability

Challenge:

Cities worldwide are under mounting pressure to rapidly decarbonize energy systems while ensuring reliable supply, especially amid climate-driven shocks like heatwaves, storms and infrastructure stress. Urban areas consume the majority of global energy and are projected to grow significantly, further challenging energy security and amplifying greenhouse gas emissions. Therefore, achieving urban energy resilience demands integrated solutions, merging urban design, renewable integration, smart energy management, and inclusive infrastructures to build sustainable, equitable, and future-ready cities.

Technology Impact Zones – DT + AI:

Power outages due to bad weather are rising in the U.S. as the effects of climate change intensify. Utilities are adopting DTs for real-time modelling of energy networks. For instance, Neara's 3D digital twin platform enables utilities to simulate wind or vegetation impact on power lines and proactively schedule vegetation trimming and prioritize repairs (TIME)²⁷. Similarly, Twin2Share is validating DT based management of local Renewable Energy Communities (RECs) to balance load, storage, and forecast solar output (klimateutralstadt)²⁸. In Sweden's Malmö district of Hyllie, a pioneering energy system combines renewable sources—such as biogas, solar, and waste heat—with thermal management systems (E.ON's "ectogrid" and "ectocloud") that optimize energy flows to manage supply and demand effectively (The Guardian)²⁹.

Technology Impact Zones - blockchain:

Platforms like Brooklyn Microgrid (via Exergy) support local peer to peer energy trading, cryptographically validating transactions between prosumers and consumers peer to peer, reducing grid load and creating local resilience (Brooklyn Microgrid³⁰).

2.7 Further application examples

Furthermore, technologies like digital twins, AI, AR/VR, Blockchain, drones, and IoT can address urban challenges, expanding beyond the above-mentioned use cases.

Digital Twins can go beyond flood simulation and public engagement to include zoning and land-use analysis, allowing urban planners to simulate development impacts before construction for more sustainable design.

AI and machine learning, in addition to disaster planning and disease tracking, can be used for predictive policing by analysing crime data, and for analysing real-time data from air quality sensors to predict pollution and issue health alerts.

Blockchain, while discussed for vehicle registration, also has applications in secure voting and identity management, offering tamper-proof digital identities for citizens and transparent management of public funds.

AR/VR, beyond transit planning and navigation, can be used for virtual tourism and historical preservation, creating AR experiences that overlay historical information on landmarks and allowing exploration of historical buildings via VR.

Finally, drones and IoT, in addition to inspecting power lines, can perform real-time structural health monitoring of bridges and tunnels, using cameras and embedded sensors to proactively identify potential

failures.

2.8 Conclusion

Cities today face interconnected challenges spanning climate resilience, mobility, public health, energy sustainability, and citizen engagement. Citiverse technologies such as digital twins, AI, AR/VR, blockchain, IoT, and drones, are proving transformative by enabling real-time data integration, predictive modelling, immersive engagement, and secure transactions. These solutions not only improve efficiency, safety, and sustainability but also foster transparency, inclusivity, and trust between governments and citizens. By turning complex urban systems into connected, interactive models, cities can move from reactive problem-solving to proactive, evidence-based planning, creating more resilient and future-ready urban environments. The citiverse approach demonstrates how linking validated use cases to specific challenges offers a scalable roadmap for impactful innovation.

Suggestions for city administrators and policymakers

- 1) **Conduct holistic needs assessments** – Identify priority urban challenges through stakeholder engagement, ensuring solutions address both systemic issues and local needs.
- 2) **Evaluate technology readiness and risks** – Use structured frameworks to assess maturity, integration feasibility, cybersecurity, and ethical considerations before adoption.
- 3) **Start with pilot programs** – Implement small-scale pilots to validate impact, refine solutions, and build stakeholder buy-in before full-scale deployment.
- 4) **Vision and goal setting** – Create a clear, citizen-centric vision with measurable goals aligned to local priorities and globally recognised frameworks (e.g., SDGs, Recommendation ITU-T Y.4903 : Key performance indicators for smart sustainable cities to assess the achievement of sustainable development goals).
- 5) **Develop scalable implementation plans** – Align technology rollouts with long-term city strategies, budgets, and sustainability goals, enabling adaptation as needs evolve.
- 6) **Promote data governance and interoperability** – Establish policies for secure, standardized, and shared data exchange to maximize the value of integrated platforms.
- 7) **Ensure inclusivity and equity** – Design solutions that are accessible to all communities, prioritizing underrepresented and vulnerable populations.
- 8) **Develop scalable implementation plans** – Align technology rollouts with long-term city strategies, budgets, and sustainability goals, enabling adaptation as needs.

3 Data governance & ethical stewardship

In today's data-driven urban environments, city administrators face the dual challenge of leveraging data and emerging technologies for public good while upholding privacy, rights, accountability, and trust. The citiverse is an area in which this is particularly important as by its very nature it is built around the individual, providing them with personalized information, guidance and services and offering them opportunities to participate in planning on issues in which they have personal stake.

This chapter is about establishing rules and practices that ensure that data are used responsibly, transparently, and in line with societal values. It examines key pillars of ethical data practice – *privacy-by-design, data sovereignty, consent models, and AI transparency* – drawing from leading global frameworks and emerging standards. It provides a policy-oriented overview of how cities can embed ethical principles into their digital initiatives and concludes with actionable recommendations for policymakers.

3.1 Privacy by design

Privacy by Design (PbD) is an approach to system and policy design that embeds privacy and data protection from the outset, rather than as an afterthought. PbD rests on seven foundational principles³¹:

1. Being proactive (not reactive) in anticipating privacy risks.
2. Making privacy the default setting.
3. Embedding privacy into design.
4. Achieving full functionality (no false trade-offs between privacy and utility).
5. Ensuring end-to-end security of data.
6. Maintaining visibility and transparency of data practices.
7. Keeping a user-centric focus.

In practice, this means that any new city technology or service, from smart traffic systems to citizen portals, should be built with strong privacy safeguards by default. If an individual does nothing, their privacy should still be protected by the system's design. For example, applications should collect only the minimum data needed (data minimization) and anonymize or pseudonymize personal data wherever possible.

Privacy by Design has been globally recognized and codified in regulations. The EU's *General Data Protection Regulation (GDPR)*³² explicitly mandates "data protection by design and by default," requiring organizations to implement appropriate technical and organizational measures (like data minimization and encryption) from the early development stage. This concept is now standard practice in modern data protection laws around the world. For city policymakers, adopting PbD means integrating privacy impact assessments and risk mitigation into project planning. It also means training city IT staff and vendors on privacy principles, so that any smart city initiative, whether it's deploying closed-circuit television (CCTV) with AI analytics or a city health app, considers privacy implications at every step. Embracing Privacy by Design helps build public trust by demonstrating that the city proactively safeguards citizens' personal information rather than reacting to breaches or scandals after the fact.

3.2 Data sovereignty and localization

Data sovereignty refers to the idea that data are subject to the laws and governance structures of the jurisdiction in which they are collected – and more broadly, that individuals and communities should have control over their own data. In a smart city context, data sovereignty is about *empowering citizens with control over their data in increasingly digital urban environments*. Cities today deploy IoT sensors, cameras, and digital services that generate vast amounts of data about residents and urban activity. Ethical stewardship demands that these data be managed in ways that respect local values and autonomy. Practically, this can mean ensuring that city data are stored in local or national data centres subject to local privacy laws, rather than in foreign jurisdictions with different regulations. It also means cities setting rules on data sharing: who has access to municipal data, whether third-party tech vendors can re-use city data, and how to prevent unwarranted surveillance or exploitation of citizen information.

Globally, concerns about sovereignty have led to data localization measures and stricter cross-border data transfer rules. For instance, the European GDPR places tight conditions on transferring personal data outside the EU, effectively asserting European data sovereignty by ensuring that EU data stay protected under EU standards even when moved abroad. Many countries are enacting similar requirements to keep certain sensitive data (like health or government data) on local servers. City leaders should be aware of these legal frameworks and also of the ethical expectation that citizens' data are treated as a public trust, not a commodity. Initiatives like the Cities Coalition for Digital Rights³³ (launched by cities like Amsterdam and Barcelona) explicitly include data sovereignty as a core principle, affirming that cities should retain control over municipal data and ensure it's used for public benefit. Notably, Barcelona's 2018 "Manifesto in favor of technological sovereignty and digital rights for cities"³⁴ established core values of digital governance – including *technological and data sovereignty, citizen digital rights, interoperability, participatory governance, transparency and privacy*. This means cities committing to own and govern their data (rather than ceding all control to private tech companies), and to do so in a way that upholds citizens' rights and privacy.

Achieving data sovereignty at city level involves policy and technical measures. Policymakers should institute clear data governance frameworks that define how data are collected, stored, and shared across city departments and with external partners. Breaking down data silos while maintaining oversight is crucial – data should not be locked up by individual departments or vendors in ways that city authorities or the public cannot oversee. Contracts with cloud providers or smart city platform vendors should include provisions aligning with local data protection laws and clarifying data ownership (e.g., the city retains ownership of data and controls its use). Furthermore, to truly empower citizens, some cities are exploring models like personal data stores or trusts, where residents can access, review, and even choose to share or withhold their personal data collected by city systems.

3.3 Consent models and user rights

Traditional privacy frameworks worldwide place consent at their core: individuals should have a say in how their personal data are used. However, obtaining meaningful consent in a smart city can be challenging – data are often collected passively (sensors, cameras) or in bulk, and residents may not even know it. Thus, city data governance must innovate beyond the consent forms' checkbox to more citizen-centric models. At minimum, informed consent should be sought whenever feasible, with clear and accessible explanations of which data are collected and for what purpose. For city services that require citizens to provide personal information (for example, signing up for a municipal digital ID or a transit app), *opt-in consent* with granular controls is ideal – letting people choose which data they wish to share and allowing them to withdraw consent easily. Consent

models should follow local standards, whenever available, or the GDPR standard of being *freely given, specific, informed, and unambiguous*, avoiding any coercive or overly broad consent requests.

That said, not all urban data processing will have a traditional consent opportunity (nobody clicks “I agree” for a traffic camera). In such cases, ethical stewardship demands strong alternative protections: strict purpose limitation (data collected for traffic management is not repurposed for commercial advertising, for instance), anonymization of individuals in datasets, and open communication about city data practices. Transparency is key, even if implicit consent is assumed for certain public interest data collections, citizens should be informed via public notices, city websites and consultations about which data are being gathered in their community. Leading privacy frameworks emphasize that individuals should retain rights over their data even after collection. Under laws like GDPR, data subjects have rights to access their data, correct inaccuracies, request deletion (“right to be forgotten”), and object to certain processing. City administrations should establish processes to honor these rights. For example, if a citizen wants to know what city services know about them (e.g., CCTV footage or smart energy meter data), there should be an accessible way to request that information. City data policies should also consider vulnerable groups and digital inclusion – ensuring consent and privacy notices are provided in multiple languages and formats, and that no group is left in the dark about how their data are used.

In exploring innovative consent models, some global initiatives are worth noting. The concept of data trusts has emerged as a way to manage consent and data sharing on a community level: an independent entity holds data on behalf of citizens and makes decisions in their collective interest (for example, a city might place mobility data into a trust that approves only beneficial uses of that data). Additionally, the notion of “*personal data empowerment*” (championed by movements like MyData³⁵ in Europe and globally) suggests giving individuals portable copies of their data and tools to manage permissions centrally. While still nascent, these approaches signal a shift from one-time consent transactions to ongoing user control. For city policymakers, the immediate step is to ensure all data initiatives adhere to high standards of notice and consent where applicable, embed privacy settings that citizens can control, and uphold the principle that people own their personal data. By treating consent not as a legal formality but as an ethos of user autonomy, cities can strengthen public trust and engagement in digital services.

3.4 AI transparency and accountability

As cities adopt artificial intelligence, from algorithms that optimize traffic flow to AI systems aiding in policing, or service delivery, so transparency and accountability become paramount. *AI transparency* means that decisions or actions taken by automated systems should be explainable and open to scrutiny. Citizens have a right to know when an algorithm is being used in city services and how it affects them.

For example, if a city uses an AI system to determine eligibility for social housing or to route emergency services, the criteria and logic of that system should be transparent. This does not necessarily mean exposing source code, but it does mean providing understandable explanations for AI-driven decisions and making information about the data and objectives of the AI public. The UNESCO *Recommendation on the Ethics of AI* (2021)³⁶ explicitly includes “Transparency and Explainability” as a foundational principle, stating that stakeholders should be informed when they are interacting with AI and be given *understandable explanations* of outcomes that significantly affect them. Likewise, the OECD AI Principles (2019)³⁷ underscore that AI actors should commit to transparency and responsible disclosure to ensure AI systems are understandable and challengeable.

Transparency is closely tied to accountability – the idea that there must be a human answerable for how an AI system operates. Algorithms cannot be a black box immune from oversight; city authorities deploying AI must ensure mechanisms to audit systems, correct errors or biases, and provide recourse for citizens who feel harmed by automated decisions. Global ethical standards universally stress accountability. OECD’s principles list accountability as a core value, calling for AI actors to be accountable for proper functioning of AI in line with the above principles. UNESCO similarly mandates “*Responsibility and Accountability*”, meaning clear roles such that ultimate responsibility lies with people, not machines. In practice, for a city this could mean requiring vendors of AI systems to provide audit logs and fairness testing results or establishing an internal review board that evaluates algorithmic tools before and during deployment. Some pioneering cities and governments have even created algorithm registries – public lists of AI systems in use along with information about their purpose, data, and impact assessments – to enhance transparency.

A critical aspect of AI accountability is addressing biases and ensuring fairness. Without careful governance, AI systems can inadvertently perpetuate discrimination – for instance, facial recognition misidentifying minorities or predictive policing tools over-targeting certain neighborhoods. Ethical stewardship requires rigorous bias testing and inclusive design. Many frameworks (such as the EU’s *Ethics Guidelines for Trustworthy AI* and IEEE’s initiatives) highlight non-discrimination as a key principle and call for *algorithmic impact assessments* to detect and mitigate bias before systems are rolled out. City policymakers should mandate such assessments for high-stakes AI (e.g., in law enforcement or social services) and involve external experts or community representatives in reviewing potential impacts. Additionally, maintaining a level of human oversight over AI decisions is considered best practice – for example, GDPR gives individuals the right not to be subject solely to automated decisions that have significant effects, insisting on human review in those cases. Human oversight and the ability to appeal AI-driven decisions create accountability by ensuring that algorithms do not have the final say on matters of citizens’ rights or benefits.

3.5 Global frameworks and emerging standards

City administrators do not have to start from scratch when establishing data governance and AI ethics policies, a number of international frameworks and standards now exist to provide guidance, reflecting a growing global consensus on ethical digital practices. These include:

- The *UNESCO Recommendation on the Ethics of Artificial Intelligence*, announced in November 2021 and endorsed by all 193 member states of UNESCO, this Recommendation articulates core values, principles, and policy action areas for ethical AI. Its values include respect for human rights, environmental sustainability, inclusiveness, and peace. It sets out ten principles – among them, “*Fairness and Non-Discrimination*,” “*Privacy and Data Protection*,” “*Transparency and Explainability*,” “*Human Oversight*,” and “*Accountability*” – which align closely with the topics discussed above. Uniquely, UNESCO’s framework goes beyond principles to recommend concrete actions for governments such as conducting ethical impact assessments, promoting AI literacy, and even banning AI applications that conflict with fundamental rights (it explicitly calls for a ban on AI systems for social scoring or mass surveillance). For city leaders, UNESCO’s Recommendation provides a high-level blueprint that can be translated into local policies ensuring that AI deployments in urban settings uphold human dignity and democratic values.
- The *OECD AI Principles*, adopted in 2019 and updated in 2024, which were also endorsed by the G20 nations. These principles promote the use of AI that is innovative, trustworthy, and respects human rights and democratic values. They enumerate five broad value-based principles: (1) inclusive growth, sustainable development and well-being; (2) human-centred values and fairness (which explicitly includes

respect for privacy and civil liberties); (3) transparency and explainability; (4) robustness, security and safety; and (5) accountability. The OECD guidance also provides recommendations for policymakers such as investing in R&D for trustworthy AI, fostering an enabling governance environment, building human capacity, and international cooperation in AI oversight. For a city government, aligning with OECD AI Principles might mean evaluating city AI projects against these criteria (e.g., is an algorithm fair and inclusive? Is it secure and reliably safe? Are we being transparent about it?). Because OECD's principles have global legitimacy and have informed national AI strategies, they can serve as a common language for cities to collaborate and share best practices in AI governance.

Crucially, data protection and privacy frameworks underpin ethical data use. The EU's GDPR, enacted in 2018, has set a de-facto global benchmark for privacy law. GDPR's influence is seen in the wave of privacy legislation worldwide (from California's CCPA to laws in Brazil, India, and others) that echo its provisions. Key GDPR principles – lawfulness, fairness, transparency, purpose limitation, data minimization, accuracy, storage limitation, integrity/confidentiality, and accountability³⁸ – have become *the foundation of modern data governance*. For example, GDPR requires that any processing of personal data have a clear legal basis (such as consent or public interest), and that individuals have enforceable rights over their data. City administrators in jurisdictions with GDPR-like laws must ensure compliance, but even elsewhere, embracing these principles is considered best practice. GDPR also introduced the requirement for Data Protection Officers (DPOs) in public bodies and privacy impact assessments for high-risk processing – measures that cities globally are adopting to strengthen internal oversight of data projects. Ultimately, GDPR's ethos is “privacy by default” and user empowerment, which dovetails with the ethical stewardship goals discussed in this chapter. Beyond frameworks, there are emerging technical standards that cities should be aware of as they professionalize data governance.

As the United Nations specialized agency for information and communication technologies, ITU plays a key role in developing international standards that enable trusted, secure, and interoperable digital ecosystems. ITU's work in areas such as data governance, artificial intelligence, digital twins, and smart sustainable cities provides an essential foundation for cities advancing toward the Citiverse. Relevant ITU-T Recommendations — including those under Study Group 20 on Internet of Things (IoT), Smart Sustainable Cities, and Digital Twins — offer guidance on topics such as interoperability (e.g., Recommendations ITU-T Y.4900 series), data sharing mechanisms, and AI ethics and governance. Together, these standards help ensure that emerging digital infrastructures remain people-centric, secure, and interoperable across jurisdictions.

Minimal Interoperability Mechanisms (MIMs) as described in Recommendation ITU-T Y.4505³⁹ provides sets of basic requirements and tools to enable effective data sharing and use. The MIM on Personal Data Management aims to support the provision of services that will enable citizens to be able to manage data about themselves easily so that it can enable outcomes they want, for themselves and for their community, while not compromising on privacy. It contains a list of key capabilities that cover the key issues that need to be addressed:

1. Individuals should be provided with information regarding what data about themselves is available, stored, shared, and so on by the providers of the applications and/or services they use. (Here “individuals” covers all people that live or work or visit a city or community and all their different roles within that community.)
2. Information regarding how data about an individual is being, or will be, used should be provided to them in a clear, understandable and unambiguous way.

3. Individuals should be able to have confidence that data about them is processed appropriately to safeguard privacy and to a high degree of security
4. Individuals should be able to request changes to, or deletion of, part or all data about themselves that is available, stored, shared, etc. by the provider of the applications and/or services using that data. The providers would need to comply with these requests unless there were legally justifiable reasons not to do so. For instance, an individual cannot expect information regarding their age or any other key factual piece of information to be changed so as to be incorrect, specifically in a way that will affect their eligibility for services. Also, GDPR, as an example, limits data subject right to data portability and right to be forgotten to a narrow subset of the 6 legal bases of processing (consent and entering a contract).
5. Individuals should be able to access and transfer data about themselves {or produced by themselves} through many different channels
6. Individuals should only be required to share information about themselves that is strictly needed for the delivery of a particular service or event. This requires that service providers should explain the reasons for all requests for information and should indicate what information is mandatory for accessing the service and what is optional, along with the consequences for not responding to requests for optional information. For instance, additional e-mail addresses or phone numbers may be asked for as back-up to enable access to the content should the provided e-mail address stop working. They are not strictly needed for access to the service, but their absence creates additional risks.
7. Individuals should be able to indicate under which circumstances what data about themselves (or produced by themselves) is 'available to be used' by which parties and for what purposes through a 'permission arrangement'. For instance, an individual might give permission for their location data to be used for the city administration in order to better understand travel patterns for public transport planning purposes.
8. Individuals should be able to grant consent to providers of applications and/or services, be they governmental or businesses, to access data that provides evidence for their eligibility for those applications/services, from those agencies that hold that evidence, to enable them to access these applications and/or services easily. This could potentially be handled via a trusted third party.
9. Individuals should be able to give permission for data about themselves to be combined in ways that enable services to which they are entitled to be offered proactively to them, including at the time they need it. For instance, to be made aware of services they might be eligible for, or to share information with relevant agencies related to life events such as moving home, leaving education, and so on.
10. Individuals should have a reliable and authoritative way to check that data about themselves (or produced by themselves) is used in strict compliance with the permissions they have granted
11. Individuals should have access to a central point where they can decide on how data about themselves (or produced by themselves) can be used and shared and when and for how long, and where they could find out all the uses for which they have consented that data about them could be used, and where they could review, change or delete their consents. One way to enable this is to provide individuals with a central repository where all data about themselves could be stored and managed.
12. Individuals can choose the operator they wish to manage data about themselves (or produced by

themselves) and move from operator to operator.

13. Individuals can roam with their data between cities, regionally, nationally and internationally.

Another significant development is the new ISO/IEC 42001 (2023)⁴⁰ standard – the first international standard for AI management systems. ISO/IEC 42001 provides a structured approach for organizations to govern AI ethically and responsibly. It sets out requirements for establishing an AI management system covering aspects like data protection, risk management, transparency, and human oversight in AI operations. Organizations (including city agencies or departments) can seek certification to ISO 42001 to signal that they adhere to recognized best practices in AI governance. The standard is flexible and risk-based – it calls on organizations to *identify and mitigate AI-related risks* (from data misuse to lack of explainability) and to continually improve their AI processes. For a city, adopting ISO 42001 could mean instituting formal policies for AI project management, conducting regular ethics and risk assessments, and being ready for external audits of AI systems. The fact that ISO 42001 is certifiable is noteworthy – it provides external accountability and trust signals to stakeholders that an entity meets a high bar for ethical AI.

Another influential body is the Institute of Electrical and Electronics Engineers (IEEE), which through its *Ethically Aligned Design* (EAD)⁴¹ initiative and the P7000 series of standards has been driving the translation of ethical principles into concrete engineering guidelines. IEEE's *Ethically Aligned Design* document outlines key principles for autonomous and intelligent systems, emphasizing *human well-being as the primary success metric, transparency, accountability, and prevention of bias*. It highlights concepts like “*data agency*” – individuals’ control over their personal data – and calls for embedding ethical considerations throughout the AI system lifecycle. Building on this, IEEE has developed specific standards (the 7000-series⁴¹) addressing issues such as algorithmic transparency (IEEE 7001), data privacy processes (IEEE 7002), algorithmic bias mitigation (IEEE 7003), and others. For example, IEEE 7001 provides guidelines to ensure autonomous systems can *assess and explain their actions to users*, directly tackling the transparency challenge. While these IEEE standards are voluntary, they offer granular advice that city IT departments and vendors can use when designing or procuring AI systems – effectively operationalizing high-level ethics into technical requirements. By referencing or requiring compliance with such standards in RFPs and city projects, policymakers can ensure that ethical principles are not just aspirational statements but built into the technology.⁴²

Work continues to identify the mechanisms that public authorities and others can put in place to implement these key principles.

Suggestions for city administrators and policymakers

City leaders should take proactive steps to institutionalize data governance and ethical technology practices. Below are key suggestions to ensure privacy, transparency, and accountability in the “Global Digital Citiverse”:

- **Establish a comprehensive data governance policy:** Develop a city-wide data governance framework or charter aligned with international principles (UNESCO, OECD, GDPR, ITU). This policy should define roles (e.g., designate a Chief Data Officer or Data Protection Officer), set standards for data handling across all departments, and commit the city to *privacy, fairness, and transparency by design* in all digital projects. Incorporate the core values from global frameworks – such as human rights, inclusivity, and sustainability – as guiding pillars of your city’s digital strategy.
- **Implement privacy-by-design in city projects:** Integrate privacy considerations into every stage of project development. Require that new smart city initiatives or IT systems undergo a privacy impact

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assessment at inception. Follow the PbD principles (e.g., data minimization, secure data lifecycle, user-centric design) and document how each project addresses them. Make “privacy by default” a standard clause in vendor contracts – meaning solutions deployed in the city must have strong privacy protections turned on by default, without needing manual enablement by users. Encourage innovation in privacy-enhancing technologies (like anonymization, differential privacy for data analytics) to enable useful data insights without compromising individual privacy.

- **Strengthen data sovereignty and security:** Ensure that city data, especially personal or sensitive data of residents, is stored and processed in compliance with local laws and community expectations. Negotiate with cloud providers for data residency (e.g., keep data on servers within national territory or jurisdictions with equivalent privacy safeguards). Retain ownership and control over municipal data; avoid arrangements that grant vendors unchecked access or rights to re-use city data. Where feasible, explore building or joining *trusted data platforms* in the public sector domain (for instance, national or regional government clouds) to reduce dependency on foreign infrastructures. Enhancing cybersecurity is also part of sovereignty – invest in robust security measures (encryption, access controls, monitoring) to protect city datasets from breaches, as data sovereignty means little if the data are not secure from unauthorized exploitation.
- **Adopt clear consent and engagement practices:** Make transparency and citizen consent cornerstones of all data collection efforts. Provide *clear public notices* about surveillance technologies (e.g., signage for CCTV with AI analytics, website disclosures for data-tracking in city apps). Wherever personal data are directly collected from citizens, use consent forms or interfaces that are easy to understand, avoiding jargon and informing individuals of their rights. Implement dashboards or portals where residents can manage their consents and privacy settings for various city services – giving them a degree of ongoing control. Recognize that consent is not a one-time checkbox: establish processes to periodically re-evaluate and refresh consents (particularly for prolonged data uses) and to inform citizens of any significant changes in data use. Additionally, actively engage the public in dialogue about new technologies – hold community consultations or ethics panels when introducing, for instance, facial recognition in public spaces, to gauge comfort levels and incorporate public values in deciding how or whether to proceed.
- **Ensure AI transparency and oversight:**
 - 1) Create an *algorithm registry* or publicly accessible list of AI systems employed by the city, including their purpose, the type of data they use, and measures in place to prevent bias or errors.
 - 2) Internally, establish an AI Ethics Review Board or designate an existing oversight committee (including legal, technical, and community representatives) to vet significant AI deployments. This board should review algorithmic impact assessments (e.g., evaluating potential biases, impacts on different demographic groups,) and make recommendations to improve system design or to halt projects that pose undue risks.
 - 3) Introduce policies that require a human-in-the-loop for critical decisions – for instance, if an AI flags individuals for security reasons or determines eligibility for benefits, a human official should review and have the authority to overturn unjust or inexplicable outcomes.
 - 4) Regular audits of AI systems should be mandated (possibly by independent third parties or academic partners) to verify that they remain compliant with fairness, accuracy, and privacy standards over

time.

- **Build capacity and foster ethical culture:** Invest in training programmes for city staff and contractors on data ethics, privacy law compliance, and AI bias awareness. The people implementing and managing smart city technologies need to be well-versed in these issues. Consider partnering with universities or international organizations to develop capacity-building workshops. Simultaneously, cultivate a culture of ethical reflection in city agencies: encourage reporting and discussion of ethical concerns, and empower officials (for example, the DPO or CIO) to pause or modify projects on ethical grounds. Reward departments or teams that excel in citizen data stewardship (through recognition or incentives for innovative privacy features or transparency initiatives). By making ethics part of performance considerations, the administration signals its seriousness about these values.
- **Collaborate and share best practices:** City administrators should not work in isolation – they should join networks and coalitions focused on digital rights and smart city ethics. Sharing experiences through forums and initiatives like the [Global Initiative on Virtual Worlds and AI – Discovering the Citiverse](#), *OECD Smart Cities Toolkit* or the Cities Coalition for Digital Rights allows municipalities to learn from each other's successes and mistakes. Advocate at the national level for laws and resources that support city-level data governance (e.g., push for clear legal frameworks on AI in government, or funding for privacy-respecting smart infrastructure). Internationally, engage in standardization efforts or pilot projects (for example, a city could volunteer to pilot an international standard implementation in the public sector context, helping to refine how that standard applies to governments). By cooperating across cities and countries, policymakers can help develop interoperable ethical standards – making it easier for technology providers to meet requirements and for citizens to enjoy consistent protections.
- **Monitor, evaluate, and iterate:** Ethical data governance is not a one-off task but an ongoing process. Set up metrics and indicators to track how well the city is doing – for instance, the number of privacy impact assessments conducted, response times to data subject requests, diversity metrics in algorithmic outcomes, or citizen satisfaction/trust levels regarding data use (perhaps measured through surveys). Publicly report on these indicators to maintain accountability. Use audits and public feedback to continuously update policies: if gaps or new risks are identified (such as a new type of AI technology the policy did not foresee), be ready to revise guidelines accordingly. Keep abreast of emerging technologies (e.g., generative AI, new sensors) and proactively study their implications for privacy and ethics in the city context. An agile, learning-oriented governance approach will enable the city to adapt and uphold ethical stewardship amid rapid technological change.

By implementing these recommendations, city administrators and policymakers can operationalize the principles of data governance and ethical stewardship. The outcome will be a “Digital Citiverse” that harnesses data and AI for innovation and efficiency *without* compromising the values, rights, and trust of the people it serves. In a world of smart cities, those cities that lead on ethical data practices will not only avoid pitfalls but also distinguish themselves as trusted digital cities – places where citizens confidently engage with technology, knowing that their privacy is respected and their well-being is the foremost priority.

4 Technical backbone

This chapter, titled “Technical backbone”, provides the technological guidance required for implementing the citiverse framework within city operations. It is directed primarily toward city administrators and public policy implementers seeking to harness the power of advanced technology in governance and urban management.

The core objective of this chapter is to outline, phase by phase, the infrastructure components, data ecosystems, and digital enablers that constitute the technological backbone of citiverse. Each phase builds upon the previous to form a cohesive, lifecycle-based system that transitions from sensing, data management and connectivity to integrated decision-making and immersive operational control.

4.1 Scientific methodology

The content and structure of this chapter follow a scientifically grounded approach that aligns with systems engineering approach based on ISO/IEC/IEEE 15288, which defines the lifecycle processes for system development, deployment, and management⁴³.

Given that this document is primarily intended for city administration, the classification of the citiverse technical backbone phases is structured from the perspective of municipal engagement and responsibilities. The framework is divided into three phases, each addressing a fundamental question. These phases are:

- Phase 1: City Assets and Connectivity
- Phase 2: Data Aggregation and Processing Hubs
- Phase 3: Citiverse in Operation

The fundamental question that each phase addresses is introduced in the below table:

Table 4 Fundamental Questions

Phase number	Phase name	Fundamental question
1	City Assets and Connectivity	What physical assets, connectivity infrastructure, and data standards must be deployed across the city to enable real-time sensing and seamless data integration?
2	Data Aggregation and Processing Hubs	What data management infrastructure, processing capabilities, and analytical tools should be established to transform raw data into actionable intelligence?
3	Citiverse in Operation	What operational platforms, visualization tools, and governance mechanisms are required to monitor, manage, and optimize city functions in real-time?

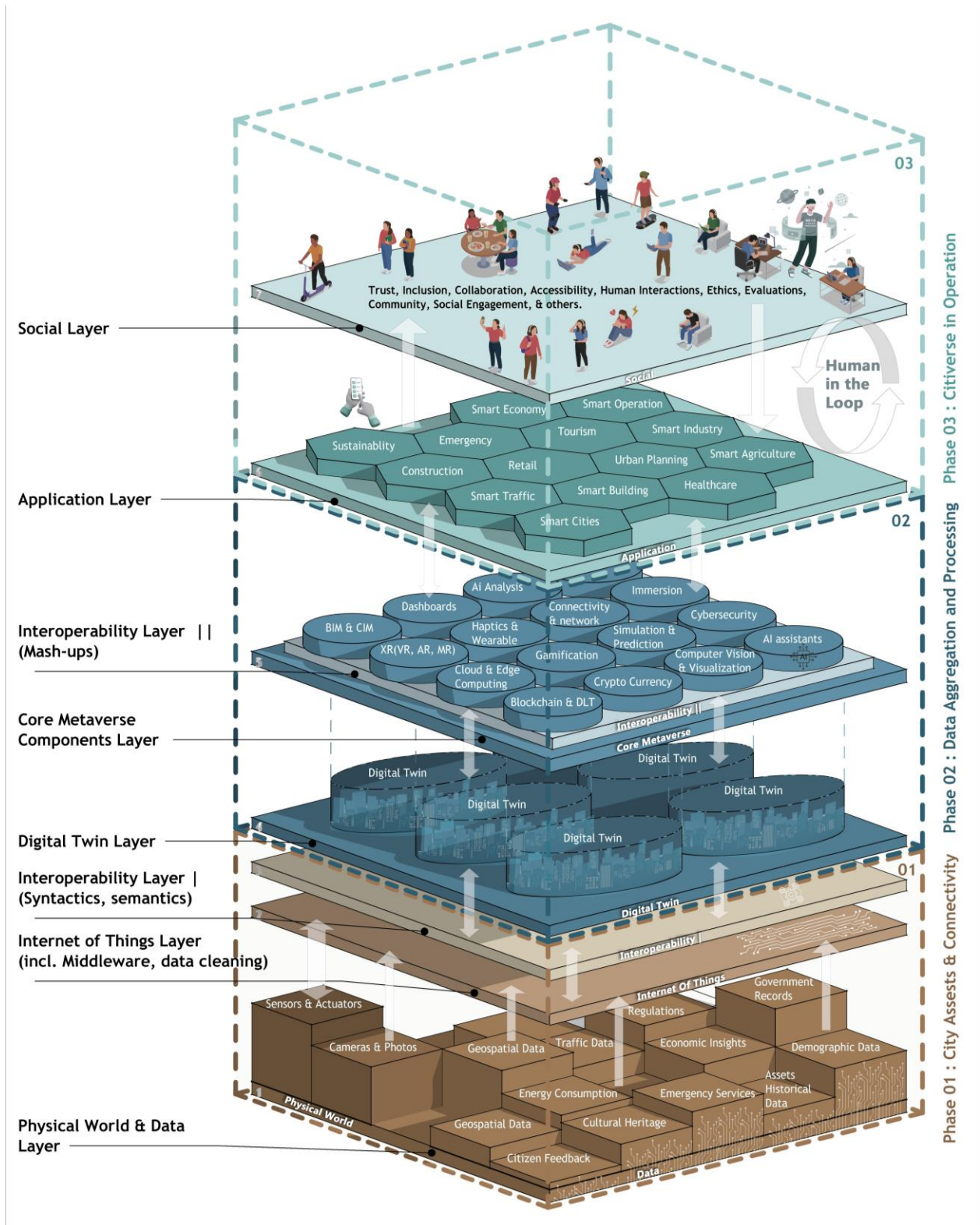
These three phases include the technical citiverse framework which can be grouped in seven logical layers⁴⁴⁴⁵⁴⁶:

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- The physical world and data layer ensures connection to real-world artefacts (e.g., garbage-bin sensors) and data sources (e.g., GIS-data, infrastructure data).
- The Internet of things (IoT) layer ensures the connection of real-world sensed data and other data sources and contains middleware-components managing edge-devices, data cleaning and simple filtering.
- The interoperability layer I adds structure (syntactics) and meaning (semantics) to data for automated data processing. However, more than 80 per cent of all data are unstructured.
- Digital twins address specific fields of applications.
- The core metaverse component layer adds core technologies such as improved extended reality (XR) visualisations, AI-integration, blockchain and functionalities such as simulation and prediction. The contained interoperability layer II allows mashups of different digital twins, as well as structured and unstructured data to be interpreted by humans and AI assistants.
- The application layer finally addresses the diverse application fields for cities including smart traffic, emergency management, smart building management and urban planning as well as culture and tourism applications.
- However, technology should not be seen in an isolated view, but in regard to the social stakeholders in the city. Thus, a seventh, social layer should be considered focussing on topics such as trust, ethics and social engagement.

The figure below depicts the alignment between the three phases of the citiverse technical backbone outlined in this chapter and the seven logical layers of the citiverse framework.

Figure 2 Technical backbone phases and logical layers



4.2 Chapter structure

This chapter is organized into three sequential phases, each encompassing specific layers within the citiverse technical framework:

Phase 1: City Assets and Connectivity

This focuses on evaluating the city's basic infrastructure and its readiness for digital technology. It involves mapping and assessing physical assets. It also evaluates digital connectivity, which includes broadband access, IoT devices, and network systems. Additionally, it checks how well existing systems work together and share data. This sets the stage for smart technologies and urban developments. This phase makes sure the city has the necessary infrastructure and connectivity to support sustainable growth and digital change.

Phase 2: Data aggregation and processing hubs

This addresses the systems that collect, store, analyse, and interpret data including data centres, AI/ML platforms, and data governance frameworks.

Phase 3: Citiverse in operation

This envisions the real-time, immersive operational layer powered by digital twin, XR dashboards, and closed-loop decision systems.

Each phase includes three standard subsections:

- 1) **Overview:** Providing a technical and conceptual background.
- 2) **Technical suggestions:** It serves as a concise, tabulated conclusion directed to city administrations. It summarizes each recommendation, its appropriate application context, and an example of a related standard or framework. It should be noted that every recommendation is linked to multiple standards and frameworks; however, the reference mentioned with each recommendation is provided as a representative example only. For broader coverage, collective references such as the *Landscape of Internet of Things (IoT) Standards*⁴⁷ can be consulted.
- 3) **Explanation of the technical suggestions:** Offering a detailed narrative of each suggestion backed up with related references and case studies.
- 4) A dedicated section outlines the cross-references between selected suggestions and the use cases identified in the [Citiverse Use Case Taxonomy, developed under the Global Initiative on Virtual Worlds and AI – Discovering the Citiverse](#).
- 5) The final section presents overarching conclusions and strategic considerations for implementation.

It is to be noted that before starting the Citiverse implementation, each city should review and evaluate its current digital infrastructure. This helps to understand what systems already exist, what can be reused, and what needs improvement or replacement.

By knowing the strengths and gaps in the existing digital ecosystem, cities can avoid duplicating efforts, make better

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use of past investments, and plan for smooth integration with the Citiverse. This evaluation also helps identify which systems can connect through common standards and APIs, ensuring that the Citiverse will work well with the city's existing technologies and future upgrades.

4.3 Phase 1: City Assets and Connectivity

4.3.1 Overview

A smart city is rooted in its physical infrastructure: the tangible assets that form the foundation for digital transformation. These assets range from roads, bridges, and buildings to public lighting, utilities, and environmental monitoring stations. The ability to connect these assets through digital technologies is what initiates the transition from traditional to smart urban management.

Connectivity plays a crucial role in enabling real-time data exchange between physical infrastructure and digital platforms. This involves a spectrum of technologies, from wired fibre-optic networks to wireless protocols like LoRaWAN, NB-IoT, 5G, and satellite communication. The selection of appropriate connectivity solutions depends on the asset type, data requirements, geographic coverage, and integration potential.

In this phase, the digital transformation is primarily in the form of digital shadows: digital representations of physical objects that capture static or real-time data. These shadows are precursors to full-fledged digital twins and are essential for setting up monitoring, diagnostics, and performance analysis.

From a systems engineering perspective, this phase aligns with the early phases of the ISO/IEC/IEEE 15288⁴⁸ lifecycle: Stakeholder requirements definition, system requirements analysis, and architectural design. It ensures that city infrastructure is not only digitized but also structured in a way that supports scalable and interoperable integration in later stages.

4.3.2 Technical Suggestions of Phase 1

Table 5 Phase 1 Technical Suggestions

No.	Suggestion	When to be used	Example of related standard/framework
1	Digital Mapping of City Assets	During city asset inventory and early planning phases	ISO 19115 Geographic Information - Metadata
2	Implement Auto-ID and QR/NFC tagging for urban furniture and utility systems	When labelling and tracking physical infrastructure elements	ISO/IEC 15459 Information technology - Automatic identification and data capture techniques - Unique identification <u>Recommendation ITU-T Y.4811 Reference framework of converged service for</u>

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			<u>identification and authentication for IoT devices in a decentralized environment</u>
3	Utilize photogrammetry and 3D city modelling for urban asset digitization	For creating accurate digital basemaps and integrating physical assets into the citiverse	ISO 19130-1 Geographic information - Imagery sensor models for geopositioning - Part 1: Fundamentals
4	Establish fibre-optic backbone connectivity for public buildings and command centres	For backbone infrastructure connecting critical institutions	Recommendation ITU-T G.652 Characteristics of single-mode optical fibre and cable
5	Establish redundancy and failover mechanisms for critical asset connectivity to ensure service continuity	During deployment of connectivity for critical infrastructure and during periodic upgrades	Recommendation ITU-T Y.1271 Framework on network requirements and capabilities to support emergency telecommunications over evolving circuit-switched and packet-switched networks
6	Integrate NB-IoT for utility metering	For smart metering and utility telemetry	3GPP Release 13 NB-IoT Specifications
7	Deploy LoRaWAN networks for wide-area environmental sensing	For low-bandwidth sensor applications requiring long-range, low-power data transmission in distributed urban assets	Recommendation ITU-T Y.4480 - Low power wide area networking (LPWAN) technologies for IoT applications
8	Use 5G for high-bandwidth, low latency infrastructure	For real-time systems like traffic control and surveillance	ITU-R M.2083 IMT Vision - Framework and overall objectives of the future development of IMT for 2020 and beyond
9	Design asset registration and monitoring workflows to align with city digital twin strategy	When preparing foundational layers for digital twin integration	ISO 55002 Asset management - Management systems - Guidelines for the application of ISO 55001
10	Establish semantic and syntactic	When integrating	W3C Semantic Sensor

interoperability frameworks using standardized ontologies and data models	heterogeneous urban systems and digital twins to enable consistent data exchange, interpretation, and cross-domain applications	Network (SSN) Ontology
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4.3.3 Explanation of Phase 1 Suggestions

This section provides an in-depth explanation of the suggestions outlined in the previous table. Each suggestion is analysed in terms of its function, relevance to city operations, and how it integrates into the broader citiverse strategy. Illustrative examples and global case studies are included where applicable to demonstrate feasibility and impact.

Suggestion 1: Digital mapping of city assets

Digital mapping of critical infrastructure is the foundation of a smart city's technical backbone. By creating accurate, high-resolution geospatial datasets of physical assets such as roads, utilities, power grids, water networks, emergency facilities, and public buildings, city administrations can establish a single source of truth for asset location, attributes, and condition, thereby enabling interoperability across departments and different partners and supporting resilience planning⁴⁹.

One of the related standards is the ISO 19115, which provides a consistent metadata framework for describing spatial datasets, ensuring that information about data content, quality, condition and other characteristics is standardized. This improves data discovery, exchange, and integration across systems⁵⁰.

One of the related case studies is Helsinki which uses ISO-aligned geospatial standards, including CityGML, to maintain a detailed 3D city model that supports urban planning, utilities management, and disaster preparedness⁵¹. Another case study is Amsterdam which provides standardized, open geospatial datasets including thematic maps for urban development, sustainability, traffic, and infrastructure via its official interactive map portal, supporting evidence-based planning and real-time decision making⁵².

Suggestion 2: Implement Auto-ID such as QR/NFC tagging for smart city elements

Applying Auto-ID technologies such as RFID, QR codes, and NFC tags assigns each asset a unique, machine-readable identity. When scanned, these identifiers link to comprehensive digital records containing maintenance histories, specifications, and geospatial metadata. This approach streamlines field operations, facilitates integration into digital twin ecosystems, and improves asset lifecycle management across departments and partner organizations. By enabling precise and efficient tracking, Auto-ID supports better planning, operational efficiency, and resilience in smart city infrastructure⁵³.

One of the related standards is the ISO/IEC 15459, which provides a global framework for unique identification in automatic identification and data capture (AIDC) systems. It defines how items – including assets, locations, and products – can be assigned unique identifiers that are machine-readable and interoperable across systems. Applying ISO/IEC 15459 to urban assets ensures that QR or NFC tags are standardized and globally recognizable, avoiding duplication or conflicts in identification schemes. This not only improves the efficiency of municipal asset management but also ensures interoperability across departments and with external stakeholders (e.g., contractors, technology providers and regional authorities). In the context of smart cities, compliance with ISO/IEC 15459

guarantees scalability and integration across diverse infrastructure monitoring systems⁵⁴.

One of the related case studies is Barcelona, which has adopted RFID tagging for public infrastructure and urban furniture to improve inventory accuracy, optimize maintenance workflows, and integrate asset data with citywide management platforms. This initiative demonstrates the practical benefits of standardized Auto-ID implementation, reducing operational inefficiencies while enabling data-driven decision-making across multiple municipal departments⁵⁵.

Suggestion 3: Utilize photogrammetry and 3D city modelling for urban asset digitization

Employing photogrammetry for large-scale 3D mapping enables cities to generate precise, up-to-date digital representations of their built environment. By converting aerial and terrestrial imagery into georeferenced 3D point clouds and meshes, photogrammetry provides critical input for digital twins, urban planning, and infrastructure monitoring. This approach ensures a cost-effective and scalable means of capturing reality, particularly for rapidly growing urban areas⁵⁶.

One of the related standards is ISO 19130-1, which specifies the metadata and sensor models required to transform photogrammetric imagery into accurate spatial coordinates. This standard provides the interoperability framework for ensuring that photogrammetry-derived datasets can be consistently integrated into geographic information systems (GIS) and city digital twins⁵⁷.

One of the related case studies is the Helsinki 3D+ project, where the City of Helsinki developed a city-scale 3D model using aerial photogrammetry and laser scanning. The digital twin integrates photogrammetry-derived reality meshes with semantic models in CityGML, supporting applications such as solar energy potential analysis, noise mapping, and urban planning simulations. This initiative demonstrates how photogrammetry serves as a critical foundation for smart city digital twins⁵⁸.

Suggestion 4: Establish fibre-optic backbone connectivity for public buildings and command centres

Establishing a fibre-optic backbone is essential for smart cities, as it provides the high bandwidth, low latency, and resilience required to connect critical institutions such as hospitals, government facilities, schools, and command centres. Fibre networks ensure secure and seamless communication across departments and enable advanced applications like telemedicine, video surveillance, and e-government platforms. By serving as the foundation for digital service delivery, fibre backbones support scalability, reliability, and long-term sustainability in urban digital transformation⁵⁹.

One of the related standards is ITU-T G.652, which provides the technical foundation for most globally deployed single-mode optical fibre. It defines key parameters such as attenuation, dispersion, and operating wavelength ranges, ensuring robust and efficient long-distance transmission. Adhering to these standard guarantees interoperability across equipment vendors and network operators, allowing cities to build future-proof backbones that can seamlessly integrate with existing and emerging communication systems. By aligning with G.652, municipalities ensure their investments deliver high reliability, scalability, and compatibility with advanced technologies⁶⁰.

One of the related case studies is Qatar which has implemented a nationwide fibre-optic backbone under the Qatar National Broadband Network (QNBN) initiative, launched in 2011 to provide ultra-high-speed connectivity across the country. The programme established an extensive fibre backbone connecting government ministries, public service facilities, hospitals, and municipal command centres. This infrastructure has enabled the integration of smart applications such as e-government services, intelligent transport systems, and emergency response platforms. By ensuring redundancy and secure connectivity for critical institutions, the QNBN project has become a cornerstone

of Qatar's smart city transformation, supporting initiatives such as Lusail Smart City and the nationwide Hukoomi e-government portal⁶¹.

Suggestion 5: Establish redundancy and failover mechanisms for critical asset connectivity to ensure service continuity

For smart cities, ensuring uninterrupted connectivity to critical infrastructure – such as hospitals, emergency response centres, and power grids – is paramount. Network failures, cyberattacks or physical disruptions can cause severe operational downtime, threatening public safety and economic stability. By establishing redundancy and failover mechanisms, municipalities can guarantee that if a primary communication channel or system fails, backup systems seamlessly take over. These measures enhance resilience, minimize service disruptions, and safeguard continuity of essential urban functions⁶².

One of the related frameworks is Recommendation ITU-T Y.1271 “Framework(s) on network requirements and capabilities to support emergency telecommunications over evolving circuit-switched and packet-switched networks”, which establishes a security framework for Next Generation Networks (NGN) with a focus on ensuring availability, integrity, and resilience of critical communication infrastructures. The framework emphasizes the implementation of redundancy, failover, and survivability mechanisms within network design to mitigate service disruptions caused by hardware failures, cyber incidents, or natural hazards. By addressing continuity of service as a core requirement, Recommendation ITU-T Y.1271 provides guiding principles for building reliable and secure connectivity infrastructures that support smart city operations and digital twin environments.

One of the related case studies is the city of Stockholm, in Sweden, which has implemented a dual-layer fibre backbone for its municipal critical assets, including hospitals, emergency services, and command centres. The network uses redundant ring topologies with automatic failover to ensure continuous connectivity if one fibre route is disrupted by construction work, natural disasters, or technical faults. Each critical facility is connected to at least two separate fibre paths, enabling seamless rerouting of data traffic without service interruption. This redundancy model has been vital for safeguarding critical communications such as emergency dispatch and hospital information systems, demonstrating how urban infrastructures can maintain connectivity resilience through built-in failover mechanisms⁶³.

Suggestion 6: Integrate NB-IoT (LPWAN) for utility metering

NB-IoT (Narrowband Internet of things) is a Low-Power Wide-Area Network (LPWAN) technology standardized by the 3rd Generation Partnership Project (3GPP) in Release 13, designed to enable efficient, long-range communication for IoT devices with minimal power consumption. In utility metering, NB-IoT supports real-time telemetry, remote monitoring, and predictive maintenance by transmitting small packets of data over existing cellular infrastructure. Its deep indoor coverage and low operational costs make it particularly suitable for static smart city assets such as water, electricity and gas meters. Integrating NB-IoT into municipal infrastructure enhances resource management, enables early anomaly detection, and reduces manual inspection costs⁶⁴.

One of the related standards is the 3GPP Release 13 standard, which provides the technical specifications for NB-IoT, ensuring interoperability, reliability and scalability across different vendors and service providers. It defines the radio interface, network architecture, and operational parameters required to deliver low-power, wide-area connectivity, making it an ideal framework for large-scale urban IoT deployments. Compliance with this standard helps ensure that deployed devices and systems can integrate seamlessly into existing mobile networks while meeting performance and coverage requirements⁶⁵.

One of the related case studies is China's smart metering rollout using NB-IoT technology, where utilities have deployed NB-IoT-connected smart water and gas meters that enable real-time data collection, improved network reliability and remote meter reading. These implementations have significantly reduced operational costs and enhanced service efficiency, particularly in locales where meters are located in hard-to-reach areas⁶⁶.

Suggestion 7: Deploy LoRaWAN networks for wide-area environmental sensing

Deploying LoRaWAN (Long Range Wide Area Network) for wide-area environmental sensing enables cities to gather real-time data from distributed sensors. The technology is optimized for low-bandwidth applications requiring long-range connectivity, low power consumption, and reliable transmission of small data packets⁶⁷. This makes it highly suitable for monitoring environmental parameters such as air quality, noise levels, soil moisture, and urban microclimates. By adopting LoRaWAN for distributed sensing, municipalities can enhance decision-making for environmental sustainability, public health, and climate resilience while minimizing infrastructure costs⁶⁸.

One of the related standards is Recommendation ITU-T Y.4480, which provides a framework for low power wide area networking (LPWAN) technologies for IoT applications. This standard defines reference architecture, functional capabilities, and interoperability guidelines, ensuring that LoRaWAN deployments follow a harmonized approach across different vendors and cities⁶⁹.

One of the related case studies is in the United Kingdom the Thames Valley Berkshire Smart City Cluster project provides a strong example of using LoRaWAN wireless connectivity for resilient urban monitoring. Funded through the UK Government's Local Growth Fund and coordinated by Reading Borough Council with regional partners, the project rolled out a large-scale IoT network covering Reading, Wokingham, Bracknell, and West Berkshire. The LoRaWAN infrastructure supported applications such as flood sensors, air quality monitors, smart lighting, and assisted-living devices. By ensuring low-power, wide-area coverage across mixed urban and rural contexts, the initiative highlighted how resilient wireless connectivity can complement fibre networks in enabling cost-effective and scalable smart city services⁷⁰.

Suggestion 8: Use 5G for high-bandwidth, low-latency infrastructure.

The deployment of 5G infrastructure provides cities with high-bandwidth and ultra-low latency capabilities, enabling advanced digital services across urban systems. Unlike previous generations, 5G supports massive machine-type communication (mMTC) and enhanced mobile broadband (eMBB), allowing simultaneous connection of millions of IoT devices with reliable performance. For city administrations, this means the ability to implement real-time services such as intelligent traffic management, smart surveillance, and remote healthcare delivery. The recommendation to adopt 5G infrastructure is, therefore, essential for building resilient, data-driven, and responsive urban environments⁷¹.

One of the related standards is Suggestion ITU-R M.2083 "IMT Vision - Framework and overall objectives of the future development of IMT for 2020 and beyond", which defines the IMT-2020 vision, setting the performance requirements and use cases for 5G technologies. It emphasizes three key capability areas: enhanced mobile broadband (eMBB); ultra-reliable low latency communications (URLLC); and massive machine-type communications (mMTC). These categories directly align with urban infrastructure needs where real-time responsiveness, scalability, and reliability are critical. By following this standard, cities can ensure that their 5G deployments comply with internationally harmonized guidelines, ensuring interoperability and future-proofing investments in smart infrastructure⁷².

One of the related case studies is Barcelona, which has piloted high-bandwidth, low-latency infrastructure to strengthen urban systems such as traffic control and public safety monitoring. The city's initiatives demonstrate how

5G technologies can be leveraged to balance sustainability objectives with emerging security requirements, while enhancing responsiveness and resilience in urban governance. This case provides a strong benchmark for municipalities seeking to integrate advanced connectivity into data-driven and efficient urban operations⁷³.

Suggestion 9: Design asset registration and monitoring workflows to align with city digital twin strategy

Designing asset registration and monitoring workflows is essential for ensuring that physical and digital assets are systematically documented, tracked and integrated into the city's digital twin strategy. This structured approach creates a single source of truth for asset metadata, locations, and operational states, while real-time monitoring ensures the twin remains synchronized with the physical city. Such integration enhances predictive maintenance, resource optimization, and resilience in urban infrastructure management⁷⁴.

One of the related standards is ISO 55002, which provides detailed guidance on implementing asset management systems, covering lifecycle management, data governance and performance evaluation. By applying ISO 55002, city administrations can align asset registration and monitoring workflows with international best practices, ensuring data accuracy, consistency, and accountability within their digital twin strategies⁷⁵.

One of the related case studies is the UK National Digital Twin Programme (NDTp), led by the Centre for Digital Built Britain (CDBB). The programme developed standardized asset information models and monitoring workflows to connect infrastructure owners, utilities, and city administrations into a federated digital twin environment. Through consistent registration of asset data and real-time monitoring, the NDTp has demonstrated how urban-scale digital twins can support infrastructure resilience, predictive maintenance, and more informed governance⁷⁶.

Suggestion 10: Establish semantic and syntactic interoperability frameworks using standardized ontologies and data models

Adopting a unified smart city ontology is essential to ensure semantic and syntactic interoperability across diverse systems, platforms and data sources. Ontologies provide a structured representation of knowledge domains, enabling different stakeholders and technologies to share a common understanding of terms, relationships and processes. By establishing a shared ontology, cities can reduce ambiguity, align heterogeneous datasets and facilitate integration across domains such as energy, mobility, infrastructure, and citizen services. This enhances the scalability of the citiverse and ensures that data exchanged between systems retains their intended meaning, even in complex multistakeholder environments⁷⁷.

One of the related frameworks is the W3C Semantic Sensor Network (SSN) Ontology and its lightweight extension SOSA (Sensor, Observation, Sample, and Actuator), which provides a formalized framework for describing sensors, observations, and the relationships between sensing devices and the data they generate. By adopting SSN/SOSA, cities can ensure that sensor data are semantically consistent and interoperable across platforms, enabling smoother integration into digital twins and the citiverse. The ontology facilitates alignment of heterogeneous IoT data streams with urban knowledge models, ensuring accurate interpretation and automated reasoning within interoperable smart city ecosystems⁷⁸.

One of the related case studies is the SmartSantander testbed IN Santander, Spain, which deployed a wide array of sensors across the city and implemented semantic interoperability by mapping sensor data to standardized frameworks such as the W3C SSN/SOSA ontology. This allowed seamless integration of heterogeneous IoT data covering domains such as mobility, environment, and infrastructure enabling cross-domain analytics, improved service coordination, and a scalable IoT ecosystem for the city⁷⁹.

4.4 Phase 2: Data aggregation and processing hubs

4.4.1 Overview

Once city assets are digitally connected, the next crucial step is to manage the influx of data generated from diverse sources across the urban environment. This phase focuses on the infrastructure, platforms, and governance mechanisms required to aggregate, store, analyse, and convert raw data into actionable insights. It forms the central nervous system of the citiverse, enabling intelligence and automation.

The core components of this phase include:

- **Data centres:** Serving as the digital backbone where collected data are processed and stored. This can range from traditional centralized data centres to edge and cloud-based architectures.
- **AI and ML integration:** Advanced analytics and prediction models that transform data into foresight, facilitating proactive, and optimized city operations.
- **Data governance frameworks:** Policies, standards, and protocols to ensure data privacy, interoperability, access control, and ethical usage.
- **Digital twin foundations:** This is when the digital twin begins to take shape, as aggregated, structured, and processed data are used to simulate real-time city conditions, forecast trends, and power virtual urban environments.

From a systems engineering perspective, this phase corresponds with the implementation, integration, and verification phases as outlined in ISO/IEC/IEEE 15288⁸⁰. At this point, the city transitions from raw data acquisition to knowledge production, laying the groundwork for intelligent digital twins in phase 3.

4.5 Technical Suggestions of Phase 2

Table 6 Phase 2 Technical Suggestions

No.	Suggestion	When to be used	Example of related standard/framework
11	Develop scalable hybrid cloud-edge data centre architecture to manage high-volume, latency-sensitive urban data streams	When handling diverse, large-scale datasets requiring centralized and distributed processing	ISO/IEC 22123-3 Information technology - Cloud computing - Reference architecture
12	Implement robust data quality management and master data governance processes	When ensuring accuracy, consistency, and reliability of aggregated datasets	ISO/IEC 38505-1 Information technology - Governance of data - Part 1: Application of ISO/IEC 38500 to the governance of data

13	Integrate AI/ML platforms for predictive analytics, anomaly detection, and automated decision support	When real-time data analysis, predictive modelling, and anomaly detection are required to optimize urban services and governance, anticipate incidents, and enable automated decision making	ISO/IEC 5339 Artificial intelligence - Guidelines for AI applications
14	Implement unified data lake/warehouse layers with near real-time ingestion pipelines	During initial hub deployment to consolidate multisource city data for analytics and decision making	ISO/IEC 20547-3 Information technology - Big data reference architecture - Part 3: Reference architecture
15	Establish open APIs and adopt interoperability standards for cross-platform data sharing	When interoperability across diverse city platforms and systems is essential to avoid data silos and ensure seamless integration	<u>Recommendation ITU-T Y.4505 Minimal interoperability mechanisms for smart and sustainable cities and communities</u>
16	Define and enforce citywide data governance frameworks covering ownership, privacy, and ethical use	From the outset of data platform implementation	ISO/IEC 38500 Information Technology - Governance of IT for the Organization
17	Deploy federated learning and privacy-preserving analytics for sensitive or distributed datasets	When multiple entities need to collaborate without sharing raw data	ISO/IEC 27701 Security techniques - Extension to ISO/IEC 27001 and ISO/IEC 27002 for privacy information management - Requirements and guidelines
18	Define digital twin data structures, interfaces, and synchronization methods	When preparing operational twin environments and simulation readiness	Recommendation ITU-T Y.4224 - Requirements for digital twin federation in smart cities and communities
19	Integrate BIM, CIM, GIS, IoT, and operational data streams into a unified visualization and analytics platform	For cross-domain planning, simulation, and monitoring	ISO/IEC 30182 Smart city concept model - Guidance for establishing a model for data interoperability
20	Implement blockchain-based data integrity and provenance mechanisms for critical city	When there is a need to ensure tamper-proof, verifiable records of transactions, asset identities, or	Recommendation ITU-T Y.4464 Framework of blockchain of things as

datasets

historical data changes.

decentralized service
platform

4.6 Explanation of Phase 2 Suggestions

Suggestion 11: Develop scalable hybrid cloud-edge data centre architecture to manage high-volume latency-sensitive, urban data streams

Managing high-volume, latency-sensitive urban data streams requires an architecture that balances centralized computing power with distributed processing closer to data sources. Hybrid cloud-edge data centre models address this challenge by combining the scalability and storage capacity of centralized cloud systems with the responsiveness of edge computing nodes. This setup reduces latency for real-time applications such as traffic control, emergency response, and environmental monitoring, while still allowing large-scale analytics and storage in centralized facilities⁸¹.

One of the related standards is the ISO/IEC 22123-3, which provides a structured cloud computing reference architecture. It defines the roles, functional components, and interactions required to design and manage cloud systems in a way that ensures interoperability, scalability, and secure data exchange. This framework is particularly relevant for city-scale deployments where multiple cloud and edge nodes must be integrated to manage diverse and rapidly changing urban data streams⁸².

One of the related case studies is Singapore, where the Smart Nation Sensor Platform enables lampposts retrofitted as sensor nodes to collect real-time data such as air quality, noise levels, and footfall and support situational awareness in urban planning and public safety. The Smart Nation Operation Centre (SNOC) ensures continuous operation by providing 24/7 monitoring and incident response, allowing critical services to remain functional even during disruptions. This hybrid edge-cloud model consistently improves responsiveness and resilience in city-wide applications⁸³.

Suggestion 12: Implement robust data quality management and master data governance processes

Implementing robust data quality management frameworks ensures that urban platforms maintain the accuracy, consistency and reliability of aggregated datasets. By enforcing validation rules, continuous monitoring and standardized metadata practices, cities can prevent errors, enhance trust in analytics, and enable more effective decision-making across critical domains such as mobility, energy and public safety⁸⁴.

One of the related standards is ISO/IEC 38505-1, which extends the principles of IT governance to the domain of data, providing a framework for assigning accountability, defining responsibilities, and establishing policies to ensure data are managed as a valuable asset. For city administrations, adopting ISO/IEC 38505-1 strengthens master data governance, ensures data quality across domains, and supports consistent decision-making within urban platforms⁸⁵.

One of the related case studies is the United Kingdom's National Underground Asset Register (NUAR), which harmonizes master data from hundreds of asset owners into a single platform. NUAR's standardized data model and governance processes are designed to improve dataset consistency and completeness, enhance metadata availability, and raise overall data quality thereby supporting safer, faster street works and more reliable city operations⁸⁶.

Suggestion 13: Integrate AI and ML platforms for predictive analytics, anomaly detection, and

automated decision support

The integration of artificial intelligence (AI) and machine learning (ML) platforms into city operations and governance enables proactive and adaptive decision-making. Predictive analytics can anticipate traffic congestion, equipment failures, or energy demand spikes before they occur. Anomaly detection improves resilience by identifying irregular patterns such as water leakage, air quality deterioration, or cyber intrusions. Automated decision support then allows city managers to take timely action, thereby reducing human error and improving service delivery⁸⁷.

One of the related standards is ISO/IEC 5339, which provides practical guidance for applying AI technologies across domains, focusing on governance, transparency and the implementation of best practices. It is particularly relevant for ensuring that AI and ML platforms used for anomaly detection and predictive analytics in cities follow trustworthy and standardized approaches⁸⁸.

One of the related case studies is in Helsinki, Finland, where the city has applied AI-driven predictive analytics to optimize public transport operations. By analysing passenger flows, weather conditions, and traffic patterns, the system forecasts demand and adjusts bus and tram schedules dynamically. This reduces congestion, improves service reliability, and enhances commuter satisfaction. The project highlights how AI and ML platforms, when responsibly integrated, can transform city operations by enabling proactive interventions rather than reactive responses⁸⁹.

Suggestion 14: Implement unified data lake/warehouse layers with near real-time ingestion pipeline

Unified data lake/warehouse layers are essential for consolidating diverse city data for example, transportation, utilities, environmental monitoring, and civic services – into a cohesive platform. By breaking down silos, cities can employ advanced analytics for improved planning, service delivery, and crisis management, thereby enhancing governance and operational efficiency⁹⁰.

One of the related standards is the ISO/IEC 20547-3, which provides a structured framework for implementing scalable big data systems such as data lakes and warehouses. It defines essential components for data ingestion, storage, processing, and analytics, so ensuring interoperability across diverse platforms. For municipalities, adhering to this standard means deploying robust, interoperable data layer solutions that support large-scale, real-time urban analytics⁹¹.

One of the related case studies is the Amsterdam Innovation ArenA (AIA), which uses a dedicated data lake to capture and integrate diverse datasets – including Wi-Fi location, solar panel generation, and video camera streams – for real-time innovation testing and analytics. This unified dataset approach has enabled collaborative experimentation in a living lab environment, showcasing how hybrid data infrastructures can spur agile smart city development and robust urban analytics⁹².

Suggestion 15: Establish open APIs and adopt interoperability standards for cross-platform data sharing

Open APIs are fundamental for enabling seamless integration across diverse urban data systems from transportation and utilities to governance and citizen services. By implementing standardized, well-documented APIs, cities avoid siloed infrastructures and vendor lock-in, thus encouraging innovation, scalability, and agile service development by both public authorities and private stakeholders⁹³.

One of the related frameworks is Recommendation ITU-T Y.4505 “Minimal interoperability mechanisms for smart

and sustainable cities and communities”, which provide lightweight, vendor-neutral enablers such as APIs and data models that support cities in achieving global interoperability⁹⁴.

One of the related case studies is the Nordic Institute for Interoperability Solutions (NIIS), which manages the X-Road data exchange platform used in Estonia and Finland. This federation allows both countries to securely share data and services across borders while maintaining national autonomy and compliance with privacy regulations. The initiative demonstrates how a standardized interoperability framework can enable seamless, secure, and scalable cross-border digital services, reduce administrative burdens and foster trust between governments and citizens⁹⁵.

Suggestion 16: Define and enforce citywide data governance frameworks covering ownership, privacy, and ethical use

Defining and enforcing citywide data governance frameworks ensures urban data are handled responsibly across departments, agencies, and external partners covering the entire data lifecycle from collection to disposal. Effective governance safeguards ownership, privacy, and ethical use, fostering public trust while enabling reliable, secure, and strategic data-driven decision making⁹⁶.

One of the related standards is ISO/IEC 38500, which provides updated governance principles for the effective, efficient, and ethical use of IT within organizations⁹⁷.

One of the related case studies is the European Union’s *Living-in.EU initiative*, which promotes a common framework for data governance and digital transformation in cities. By adopting a shared approach to ethical principles, interoperability and transparency, the initiative has enabled participating cities to better coordinate their digital strategies while safeguarding citizen trust⁹⁸.

Suggestion 17: Deploy federated learning and privacy-preserving analytics for sensitive or distributed datasets

Federated learning and privacy-preserving analytics let multiple city entities (e.g., health, transport, utilities) train models on decentralized data without moving or pooling raw records. This reduces legal and security risk while still enabling forecasting, anomaly detection and joint insights across departments. Techniques such as secure aggregation and differential privacy further limit disclosure, making analytics feasible where centralization is impractical or prohibited⁹⁹.

One of the related standards is ISO/IEC 27701, which specifies the requirements for a Privacy Information Management System (PIMS) and extends ISO/IEC 27001 and ISO/IEC 27002 with privacy-specific controls and guidance on data subject rights. This standard strengthens governance in federated learning environments by embedding privacy-by-design principles, ensuring that data sharing and analytics respect individual privacy while maintaining robustness, accountability and regulatory compliance¹⁰⁰.

One of the related case studies is the European project DECODE (Decentralised Citizen Owned Data Ecosystem), implemented in Barcelona and Amsterdam. The initiative explored how cities can enable privacy-preserving data sharing for urban services, using distributed ledger technologies and advanced privacy techniques to give residents more control over their personal information. The project showed how municipalities can balance data-driven innovation with citizen trust and GDPR compliance, making it a pioneering example of federated and privacy-aware city data governance¹⁰¹.

Suggestion 18: Define digital twin data structures, interfaces, and synchronization methods.

Digital twin data structures, interfaces, and synchronization methods are essential for creating coherent and interoperable digital replicas of urban systems. By defining standardized data formats and synchronization protocols, city administrations ensure that digital twins across operational domains (such as mobility, utilities and urban planning) can be integrated and maintained effectively enhancing situational awareness and enabling cross-sector collaboration¹⁰².

One of the related standards is ITU-T Y.4224, which specifies requirements for digital twin frameworks in smart cities, ensuring standardized approaches to data synchronization, semantic interoperability and system scalability¹⁰³.

One of the related case studies is Virtual Singapore, a high-resolution, data-rich 3D digital twin of the entire city-state that incorporates real-time data on buildings, infrastructure, population movements, and environmental conditions. Urban planners, researchers and agencies use the platform to simulate scenarios such as infrastructure projects, flood responses or traffic flow management, so enabling data-driven policymaking for sustainable development and resilience¹⁰⁴.

Suggestion 19: Integrate BIM, CIM, GIS, IoT, and operational data streams into a unified visualization and analytics platform.

Integrating BIM, CIM, GIS, IoT, and operational data into a unified visualization and analytics platform enables cross-domain planning, simulation, and monitoring. By harmonizing building-level semantics with city-scale geospatial context and live telemetry, planners can see interdependencies, test scenarios, and operate services more efficiently and safely¹⁰⁵.

One of the related standards is ISO/IEC 30182, which provides a standardized framework for organizing and categorizing the diverse data domains of a city to facilitate integration and interoperability. It establishes a conceptual model that defines key entities, and their attributes and relationships across domains such as transport, energy, environment, governance, and infrastructure. By applying this structured ontology, city authorities and platform providers can align heterogeneous datasets – including BIM, GIS, IoT, and operational records – under a common reference architecture. This ensures that data streams from different systems can be mapped consistently, enabling unified visualization, analytics, and decision-making within smart city platforms¹⁰⁶.

One of the related case studies is Rotterdam's Digital Twin, which integrates BIM/GIS base data with live city information to optimize operations such as emergency response, waste collection, and traffic management. The platform combines real-time sensor streams with 3D city models to support decision-making and scenario analysis across departments¹⁰⁷.

Suggestion 20: Implement blockchain-based data integrity and provenance mechanisms for critical city datasets

Implementing blockchain-based data integrity and provenance mechanisms enhances trust and verifiability in smart city datasets. These technologies provide tamper-proof, auditable records of data transactions across multiple platforms, minimizing risks of manipulation, loss of authenticity, or unauthorized changes in critical city datasets¹⁰⁸.

One of the related standards is Recommendation ITU-T Y.4464 "Framework of blockchain of things as decentralized service platform", which defines how blockchain technologies can support decentralized trust, secure data transactions, and interoperability across IoT-based infrastructures. This ensures that city-scale ecosystems relying on connected devices can achieve verifiable and tamper-resistant data exchanges¹⁰⁹.

One of the related case studies is the City of Dubai's "Dubai Blockchain Strategy", launched in 2016, which aims to make Dubai the world's first blockchain-powered government. By implementing blockchain across urban operations, Dubai has enhanced the security, efficiency, and transparency of its data systems, reducing paperwork, preventing fraud, and enabling more reliable data exchange across government and private sector entities. This case demonstrates how blockchain can strengthen urban data governance and streamline city administration¹¹⁰.

4.7 Phase 3: Citiverse in operation

4.7.1 Overview

The final phase of the technical backbone focuses on operationalizing the citiverse through immersive platforms, real-time dashboards, closed-loop decision-making systems, and comprehensive digital twin deployments. At this point, the digital infrastructure established in phases 1 and 2 converges into a unified smart city command and governance environment.

This phase enables decision makers, city operators, and even citizens, to interact with the urban environment in a multidimensional, interactive format. It integrates data streams, AI-driven analysis, and spatial intelligence into control systems that can visualize, predict and respond to dynamic urban conditions.

From a systems engineering perspective, this aligns with the validation, operation, and maintenance processes in the ISO/IEC/IEEE 15288¹¹¹ lifecycle. It also sets the groundwork for continuous feedback loops that inform planning, optimize services and promote adaptive governance.

4.7.2 Technical Suggestion of Phase 3

Table 7 Phase 3 Technical Suggestions

No.	Suggestion	When to be used	Example of related standard/framework
21	Ensure open data publishing with privacy safeguards	When releasing city datasets for transparency, innovation, and third-party application development	ISO/IEC 27556 Information security, cybersecurity and privacy protection - User-centric privacy preferences management framework
22	Deploy cybersecurity incident response protocols for citywide applications	When safeguarding urban systems from cyberattacks or breaches is a priority	ISO/IEC 27035-1 Information technology - Information security incident management - Principles and Process
23	Ensure visualization platforms are accessible, multilingual, and compliant with universal design	When designing interfaces for inclusivity and accessibility	ISO 9241-210 Ergonomics of human-system interaction - Human-centred design for interactive systems
24	Deploy centralized and	For integrating key metrics	<u>Recommendation ITU-T</u>

	federated urban dashboards for decision makers	across city departments	<u>Y.4903: Key performance indicators for smart sustainable cities to assess the achievement of sustainable development goals</u>
25	Integrate extended reality (XR) interfaces into city command centres	When enabling immersive urban visualization for operators	ISO/IEC 18039 Information technology - Computer graphics, image processing and environmental data representation - Mixed and augmented reality (MAR) reference model
26	Enable AI-based control systems for energy, mobility, and emergency services	For fully automated service delivery and resilience management	ISO/IEC 42001 AI Management Systems
27	Establish training simulators using digital twins for emergency and infrastructure management	For preparedness planning and skills development	IEEE 1278.1 IEEE Standard for distributed interactive simulation - Application protocols
28	Conduct continuous performance audits using AI-powered operational KPIs	For ongoing optimization of services and transparency	ISO 37123 Sustainable cities and communities - Indicators for resilient cities
29	Launch citizen-facing apps and web platforms linked to citiverse infrastructure	For public engagement, participatory governance, and feedback	Web Content Accessibility Guidelines (WCAG) 2.2
30	Implement real-time feedback loops between digital twins and city operators	For autonomous decision-making and performance optimization	OGC SensorThings API Part 2: Tasking

4.7.3 Explanation of Phase 3 Suggestions

Suggestion 21: Ensure open data publishing with privacy safeguards

Open data publishing is a cornerstone of transparent and innovative smart city governance, enabling third parties to build applications, conduct research and drive new services. However, releasing city datasets without proper safeguards can expose sensitive personal or organizational information, so undermining trust and creating legal risks. Therefore, municipalities must establish strong privacy-preserving mechanisms such as data anonymization, pseudonymization, and aggregation before publishing datasets for public use¹¹².

One of the related standards is ISO/IEC 27556, which specifies a model in which personally identifiable information (PII) is managed according to user preferences, enabling cities to build open data platforms that respect individual privacy, expressly manage consent, and operate with transparency by default¹¹³.

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One of the related case studies is the European Union's Open Data Portal, which makes thousands of datasets publicly accessible while implementing strict privacy and anonymization policies. The initiative enables innovation and transparency by supporting start-ups, researchers and policymakers, while ensuring compliance with the General Data Protection Regulation (GDPR). By applying privacy-by-design principles, the EU demonstrates how cities and regions can release valuable data responsibly¹¹⁴.

Suggestion 22: Deploy cybersecurity incident response protocols for citywide applications.

Deploying cybersecurity incident response protocols for citywide applications ensures that urban digital infrastructure can withstand, detect, and recover from malicious cyberattacks or system breaches. Cities rely on interconnected platforms spanning transport, energy, health and public safety, making them high-value targets. A well-structured response programme minimizes disruption, safeguards sensitive data, and coordinates recovery actions across agencies protecting citizen trust and service continuity¹¹⁵.

One of the related standards is the ISO/IEC 27035-1, which outlines a structured approach to prepare for, detect, report assess, and respond to security incidents in a way that is applicable to any organization. It ensures citywide applications follow a unified, internationally recognized incident management process, thereby enhancing resilience, consistency, and response efficiency across urban digital systems¹¹⁶.

One of the related case studies is Singapore's Cybersecurity Programme for Critical Information Infrastructure (CII), where the Cyber Security Agency (CSA) coordinates incident handling protocols across essential urban sectors like energy, transport, and health care. The programme defines clear escalation chains, mandatory incident reporting procedures, and joint response drills effectively safeguarding urban systems from amplified cyber threats and ensuring resilience across government and private infrastructures¹¹⁷.

Suggestion 23: Ensure visualization platforms are accessible, multilingual, and compliant with universal design

Ensuring visualization platforms are accessible, multilingual, and compliant with universal design is essential for inclusive urban engagement. By implementing universally designed interfaces that support multiple languages and cater to users with diverse abilities, cities can empower broader citizen participation, enhance transparency, and ensure equitable access to information and services¹¹⁸.

One of the related standards is ISO 9241-210, which establishes requirements and principles for integrating human-centred design throughout the lifecycle of interactive systems. It emphasizes usability, accessibility and satisfaction for a diverse range of users, including those with varying physical, cognitive, and linguistic abilities. By following ISO 9241-210, cities can ensure that digital platforms support equitable access, adapt to multilingual contexts, and comply with universal design principles¹¹⁹.

One of the related case studies is the Barcelona City Council's Smart City platform, which integrates multilingual interfaces and accessibility features to ensure that all residents can access urban dashboards and public data services. The city applied WCAG compliance, language localization, and universal design to its visualization tools, thereby fostering digital inclusivity. This approach demonstrates how accessibility and multilingualism can be embedded in urban visualization systems to create equitable digital experiences¹²⁰.

Suggestion 24: Deploy centralized and federated urban dashboards for decision makers

Centralized and federated urban dashboards provide city decision makers with a unified view of critical

indicators across departments, enabling data-driven governance. These dashboards consolidate diverse datasets from mobility, energy, environment, health and safety domains into an integrated interface that facilitates monitoring, coordination, and proactive decision-making. By offering high-level strategic views and granular operational details, dashboards enhance transparency, improve situational awareness, and support efficient resource allocation¹²¹.

Recommendation ITU-T Y.4903, which defines key performance indicators (KPIs) for smart sustainable cities to assess the achievement of the Sustainable Development Goals (SDGs), provides a globally recognized framework for structuring such dashboards. Implemented under the United for Smart Sustainable Cities (U4SSC) initiative—a UN platform supported by 20 UN entities—this Recommendation has been applied in more than 250 cities worldwide. It supports cities in measuring and visualizing their progress toward sustainability, resilience, and inclusiveness¹²².

By integrating Y.4903 into centralized and federated dashboard systems, cities can ensure consistency, interoperability, and comparability of data across departments and domains. This enables evidence-based governance, fosters international benchmarking, and aligns local actions with global sustainability objectives such as the SDGs.

Suggestion 25: Integrate extended reality (XR) interfaces into city command centres

Extended reality (XR) – encompassing augmented, virtual, and mixed reality – is increasingly leveraged in urban command centres to enhance situational awareness. By overlaying live data onto physical environments or immersive 3D models, XR tools help urban managers better understand complex conditions like traffic congestion or emergency incidents, supporting faster and more coordinated response actions¹²³.

One of the related standards is ISO/IEC 18039, which defines a reference model for mixed and augmented reality (MAR), including concepts, components, and generalized system architecture. Applying this model helps cities specify interoperable XR solutions, align interfaces and data flows, and integrate immersive applications consistently into command-centre environments¹²⁴.

One of the related case studies is RescueAR in Japan which is an Augmented Reality system designed specifically for UAV-supported emergency and search-and-rescue operations. RescueAR enables real-time geotagged scene visualization, fostering intuitive information sharing and collaboration between Remote Operators (ROs) and On-Site Operators (OSOs). Through this context-aware AR overlay, response teams gain clearer spatial cognition, improved situational awareness and more effective metacognitive coordination during high-stakes rescue missions. In experimental evaluations involving law enforcement officers, RescueAR demonstrated a significant improvement in interpreting dynamic scenes and coordinating team actions. Its design illustrates how XR systems can directly support emergency decision-making workflows¹²⁵.

Suggestion 26: Enable AI-based control systems for energy, mobility, and emergency services.

AI-based control systems are increasingly enabling real-time automation across critical urban operations such as managing flexible energy demand, optimizing traffic flow, and coordinating emergency response. By leveraging continuous data streams and machine learning algorithms, these systems help cities dynamically allocate resources, proactively manage disruptions, and improve overall resilience and responsiveness across services¹²⁶.

One of the related standards is ISO/IEC 42001, which provides requirements and guidance for establishing,

implementing, maintaining, and continually improving an AI management system¹²⁷.

One of the related case studies is Pittsburgh's SURTRAC adaptive traffic-signal system, which applies artificial intelligence to optimize signal timings in real-time across urban intersections. The system supports a continuous feedback loop between live traffic conditions and automated control, improving throughput and reducing delays illustrating how AI-based control can enhance city operations in time-critical mobility scenarios¹²⁸.

Suggestion 27: Establish training simulators using digital twins for emergency and infrastructure management.

Training simulators powered by digital twins enable immersive rehearsal of urban disaster scenarios – such as evacuation routes during floods or infrastructure failures – by mirroring real systems and data in virtual environments. These platforms prepare emergency responders and city staff by practising coordination and testing response strategies under realistic, controlled conditions, resulting in better preparedness and more effective crisis management¹²⁹.

One of the relevant standards is IEEE 1278.1, which establishes rules for interoperability across simulators, ensuring that multiple training systems can exchange data seamlessly during collaborative exercises. For urban applications, adherence to IEEE 1278.1 guarantees that digital twin simulators used by emergency services, transport authorities, and utility operators can function in an integrated and coordinated training environment¹³⁰.

One of the related case studies is in the United Kingdom, as the city of Glasgow has piloted a digital twin-based training environment as part of the GBP 24 million Smart Resilience Project funded under the UK Innovate programme. The system creates a real-time virtual model of the city's infrastructure – covering transport, energy, and water networks – enabling emergency planners to simulate disruptions such as flooding, power outages, or large-scale accidents. City operators and first responders use the platform for scenario-based training, testing decision-making processes and coordination strategies without real-world risks. The digital twin has enhanced Glasgow's ability to prepare for crises, reduce response times, and improve cross-agency collaboration¹³¹.

Suggestion 28: Conduct continuous performance audits using AI-powered operational KPIs

This suggestion highlights the importance of using artificial intelligence to enable continuous, automated performance audits of urban infrastructure and city operations. By defining and monitoring operational key performance indicators (KPIs) across energy, water, mobility, and digital services, AI systems can benchmark performance, detect inefficiencies, and identify early deviations from expected behaviour. This approach ensures a proactive shift from traditional, periodic audits to a real-time, data-driven monitoring framework that strengthens resilience, improves transparency, and supports evidence-based governance¹³².

One of the related standards is ISO 37123, which establishes a set of standardized metrics to evaluate and monitor the resilience of urban systems. It provides guidance for measuring a city's ability to withstand, adapt to, and recover from disruptive events, including natural hazards, infrastructure failures, and socio-economic shocks. The standard complements ISO 37120 by focusing specifically on resilience-related indicators such as continuity of essential services, redundancy of critical infrastructure, and emergency preparedness. By adopting ISO 37123, municipalities can conduct systematic performance assessments, benchmark resilience

levels against other cities, and integrate continuous audit results into their long-term urban planning and risk management strategies¹³³.

One of the related case studies is the city of Toronto, Canada, which has embedded continuous performance auditing into its Resilience Strategy. The municipality uses standardized indicators to monitor infrastructure resilience, community vulnerability, and emergency preparedness, with insights published through its open-data dashboards and annual resilience reporting. This structured audit process ensures ongoing performance assessments and helps Toronto adapt urban systems in response to climate change, social inequities, and governance challenges-strengthening transparency and fostering integrated resilience planning¹³⁴.

Suggestion 29: Launch citizen-facing apps and web platforms linked to citiverse infrastructure

Citizen-facing apps and web platforms significantly enhance urban governance by enabling real-time feedback, improved service transparency, and direct participation. These tools empower residents to report issues, engage in policy discussions, and contribute to decision-making, fostering trust and accountability between government and communities¹³⁵.

One of the related standards is Web Content Accessibility Guidelines (WCAG) 2.2, which ensures that digital platforms and applications are accessible to all citizens, including people with disabilities, thereby promoting inclusivity and equal access to city services¹³⁶.

One of the related case studies is Barcelona's Decidim platform, an open-source citizen participation system that allows residents to propose, debate, and vote on urban projects. Decidim demonstrates how citizen-facing apps can successfully connect communities with municipal decision-making processes, enhancing accountability and participatory governance¹³⁷.

Suggestion 30: Implement real-time feedback loops between digital twins and city operators.

Real-time feedback loops between digital twins and city operators ensure that simulations remain continuously aligned with evolving urban conditions. By integrating live sensor data, these systems enable dynamic calibration and immediate response – such as rerouting traffic, adjusting energy distribution, or reallocating emergency services – thus facilitating proactive, data-informed decision-making in critical situations¹³⁸.

One of the related standards is the OGC SensorThings API Part 2: Tasking, which provides an open and standardized way to integrate sensing, actuation, and control into digital twin ecosystems. This specification defines how tasking capabilities can be added to IoT-enabled systems, allowing digital twins to not only monitor but also instruct and optimize urban assets in real-time. By aligning city operations with SensorThings API, municipalities ensure interoperability and scalability of feedback-enabled smart services¹³⁹.

One of the related case studies is the Port of Corpus Christi's OPTICS system in Texas. OPTICS uses an AI-powered, real-time digital twin of the port to enhance operational safety and response. By integrating live vessel tracking, environmental data, and predictive simulations, the system supports rapid decision-making and emergency response planning. This demonstrates how digital twins with real-time feedback can significantly improve operational resilience in high stakes environments⁹⁹.

4.8 Cross References to Citiverse Use Case Taxonomy

The Citiverse Use Case Taxonomy presents a set of use cases spanning multiple thematic areas. This section of

the chapter establishes cross-references between some of the recommendations outlined in Phases 1, 2 and 3 and the corresponding use cases identified under Track 8.

- 1 A relevant use case linked to Suggestion 1 (Digital Mapping of City Assets) is (Digital Underground Asset Mapping). This use case falls within the thematic area of (Urban Planning, Placemaking, and Infrastructure) and is categorized under Horizon 1.
- 2 A relevant use case linked to Suggestion 9 (Design asset registration and monitoring workflows to align with city digital twin strategy) is (Built Environment Lifecycle & Material Reuse). This use case falls within the thematic area of (Urban Planning, Placemaking, and Infrastructure) and is categorized under Horizon 2.
- 3 Two relevant use cases linked to Suggestion 13 (Integrate AI and ML platforms for predictive analytics, anomaly detection, and automated decision support). The first use case is (Predictive Transit Scheduling) which falls within the thematic area of (Transport and Mobility) and is categorized under Horizon 1. The second use case is (Predictive Transit Scheduling) which falls within the thematic area of (Transport and Mobility) and is categorized under Horizon 1.
- 4 Two relevant use cases linked to Suggestion 24 (Enable AI-based control systems for energy, mobility, and emergency services). The first use case is (Immersive Operational Command and Control) which falls within the thematic area of (Public Safety, Health & Disaster Resilience) and is categorized under Horizon 1. The second use case is (Emergency Response Real-Time Facilitation) which falls within the thematic area of (Public Safety, Health & Disaster Resilience) and is categorized under Horizon 2.
- 5 Four relevant use cases linked to Suggestion 27 (Launch citizen-facing apps and web platforms linked to citiverse infrastructure). The first use case is (Virtual Urban Placemaking) which falls within the thematic area of (Urban Planning, Placemaking & Infrastructure) and is categorized under Horizon 1. The second use case is (XR Mobility Planning) which falls within the thematic area of (Transport and Mobility) and is categorized under Horizon 2. The third use case is (Virtual Town Halls) which falls within the thematic area of (City Administration and Public Participation) and is categorized under Horizon 2. The fourth use case is (Citizen Sentiment Mapping) which falls within the thematic area of (City Administration and Public Participation) and is categorized under Horizon 2.
- 6 A relevant use case linked to Suggestion 29 (Deploy cybersecurity incident response protocols for citywide applications) is (Cyberthreat Simulation for Critical Infrastructure). This use case falls within the thematic area of (Public Safety, Health & Disaster Resilience) and is categorized under Horizon 2.

4.9 Conclusions

The development of a robust Technical Backbone is fundamental to the realization of the citiverse vision. Across the three phases outlined in this chapter, a clear trajectory emerges: from the digitization of physical assets, through structured data aggregation, to the establishment of an integrated operational environment. Together, these phases define a lifecycle-driven pathway that enables cities to progress from fragmented data environments toward holistic, real-time, and human-centred governance.

Phase 1 established the prerequisites for digital transformation by mapping and connecting physical infrastructure, embedding identification mechanisms, and deploying resilient connectivity networks. This foundational layer ensured that city assets could be reliably sensed, tracked, and integrated into broader digital

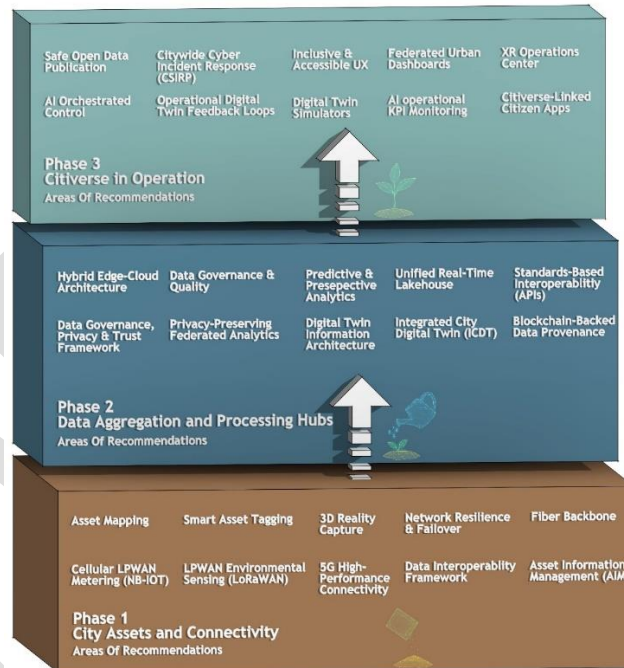
ecosystems.

Phase 2 translated raw sensing into intelligence by consolidating data within hybrid cloud-edge architectures, applying AI/ML for predictive analytics, and enforcing governance mechanisms to guarantee interoperability, trust, and ethical data use. At this stage, the digital twin transitioned from static models toward dynamic, federated systems capable of simulating and informing complex urban processes.

Phase 3 operationalized the citiverse as a multidimensional, immersive decision environment. Here, the convergence of digital twins, XR platforms, and closed-loop control mechanisms created real-time governance capabilities, enabling city administrators to anticipate challenges, optimize resources, and engage stakeholders transparently and inclusively.

The following figure provides a visual overview of the key areas covered by the suggestions in each phase.

Figure 3 Key areas covered by the suggestions



Equally important is the cross-referencing of some suggestions with Citiverse Use Cases Taxonomy, which anchors the technical backbone to concrete, real-world urban applications. By linking some recommendation across Phases 1, 2 and 3 to thematic use cases ranging from urban planning and infrastructure monitoring to mobility, energy, and citizen engagement, this chapter ensures that abstract technical guidance is directly translatable into operational scenarios. This alignment strengthens the practicality of the citiverse framework by providing city administrators with a clear line of sight from standards and infrastructure design to tangible outcomes in service delivery, sustainability and quality of life.

Across all three phases, a recurring theme has been the alignment of technical progress with internationally recognized standards and frameworks. Referencing ISO, ITU-T, IEC, W3C, and other bodies ensures that the citiverse framework remains interoperable, scalable, and globally relevant. Equally, the integration of real-

world case studies demonstrates that these recommendations are not abstract aspirations, but actionable measures already validated in practice.

Finally, it is important to emphasize that the citiverse cannot be reduced to a technological project alone; its ultimate success depends on embedding this backbone within a governance ecosystem that prioritizes trust, ethics, inclusivity and long-term resilience. By doing so, cities can ensure that the citiverse serves as more than a digital infrastructure: it becomes a civic platform that empowers administrations, communities and businesses to co-create sustainable and adaptive futures.

In conclusion, the Technical Backbone described in this chapter provides a roadmap and a practical toolkit for city leaders. It demonstrates how systems engineering principles, layered architectures, and global standards converge into a coherent, future-ready model of urban governance. The pathway is incremental yet transformative: as cities progress through the three phases, they lay the groundwork for a citiverse that is technically sound, socially trusted, and strategically aligned with the evolving challenges of the 21st century.

5 Landscape of Citiverse Standards

In the citiverse, physical and digital worlds converge providing inclusive and sustainable services (such as representation, analysis, decision-making, prediction, simulation, visualization) to citizens and city stakeholders through the real-time interaction with digital objects and immersive experiences. Such convergence and interaction require clear, widely adopted standards to ensure interoperability across technologies, seamless communication between systems, and trust in human-machine collaboration. Standards provide a common framework that guarantees compatibility, reliability, and security, while also safeguarding ethical and human-centred principles. Without them, the citiverse risks fragmentation, inefficiency, and exclusion, so undermining its potential as a unified and sustainable urban ecosystem.

In this chapter, we focus on the essential international standards that can be used by public entities all over the world, including the Global South, to implement citiverse technologies. To do so, we first illustrate all the existing standards that are needed to implement a citiverse by municipalities; then, we select, from among them, those standards that can be readily used by any city of the Global South (typically: those that are open source and free of charge). This is needed to ensure inclusivity and allow also cities with extremely limited resources to afford and implement a viable citiverse.

This chapter proceeds as follows: after reviewing existing reports and databases that collect standards for mature citiverses (5.2), we select and classify the standards relevant to building the essential blocks of a citiverse (inclusivity) based on the recommendations included in chapter 4 (5.3), focusing also on ethics and inclusion (5.4), and the interoperability among technologies (5.5). Finally, we focus on the standards that can be readily used by any city of the Global South (5.6).

5.1 Sources and classification

There are already several databases and reports that collect and classify citiverse standards. For this chapter, we resort to two main sources of information: the first one is the Virtual Dimension Center (VDC) XR & Metaverse Standards Register¹⁴⁰, a worldwide, publicly-accessible, and searchable database for standards, specifications, recommendations, guidelines, working groups and standards developing organizations (SDOs) on eXtended Reality and Metaverse topics. Our second source is the StandICT.eu Technical Working Group (TWG) Report of CitiVerse: Standardisation Landscape for CitiVerse (2023)¹⁴¹, which provides an overview and links to existing standard databases.

Additional tools and resources that can be considered include: the Metaverse Standards Forum (MSF)¹⁴²: a collaborative initiative bringing together organizations to develop interoperability standards for an open and inclusive metaverse; as well as the Open Metaverse Interoperability Group (OMI Group)¹⁴³: an open-source community working on protocols for metaverse interoperability, including identity, social graphs, and 3D content sharing.

5.2 Consolidated overview of citiverse standards

Drawing from the mentioned existing reports and databases, in the following paragraphs, we present the categories of essential standards necessary to implement citiverse, allocating them in the three fundamental phases identified in Chapter 4: City Assets and Connectivity (5.3.1), Data Aggregation and Processing Hubs (5.3.2), and citiverse in Operation (5.3.3).

5.2.1 Phase 1 - City assets and connectivity

The first phase of the citiverse, as described in Chapter 4, requires robust communication infrastructures and trusted digital frameworks to connect physical city assets with their digital counterparts. Hence, other than the examples of standards mentioned in Chapter 4 (relative to: (1) geographical mapping of the existing assets and (2) connectivity of the information into the citiverse), two groups of standards are relevant to implement this phase: a. Telecom standards, and b. IoT and trustworthiness enhancing standards.

Table 8 Standards for Phase 1 (City assets and connectivity)

City assets and connectivity types of standards	Function	Examples	Explanation
a. Telecom standards	Provide the foundation for mobile and broadband networks, ensuring that immersive applications such as augmented reality (AR) and mixed reality (MR), can operate at scale.	3rd Generation Partnership Project (3GPP) 5G Media Action Group (5G-MAG)	Aims at standardizing mobile technologies, including GSM (2G), UMTS (3G), LTE (4G), and 5G NR. 3GPP specifications, especially Release 15 and later, supporting XR applications with low-latency and high-reliability requirements, which are critical for immersive experiences Promotes the deployment of media technologies using 5G networks and the global Internet, enabling access to immersive content on mobile devices.
b. IoT and trustworthiness enhancing standards	Ensure that connected devices and sensors – the nervous system of the citiverse – are	<u>Recommendations on ITU-T Y.4100: Common requirements of</u>	<u>Recommendation ITU-T Y.4100 provides the common requirements of the IoT.</u> <u>Recommendation ITU-T Y.4101 provides requirements for IoT devices used for operation</u>

designed with reliability, resilience, and security in mind. Together, these standards establish the essential technical and trust layers for linking urban assets to the citiverse.

the Internet of things

Recommendation ITU-T Y.4101:

Common requirements and capabilities of a gateway for Internet of things applications

Recommendation ITU-T Y.4103:

Common requirements for Internet of things (IoT) applications

of IoT applications in the context of disaster in addition to the common requirements of IoT in ITU-T Y.4102. It also provides requirements for the operation of IoT applications during disaster.

Recommendation ITU-T Y.4103 includes the common requirements for Internet of things (IoT) applications enabling advanced services by interconnecting (physical and virtual) things based on, existing and evolving, interoperable information and communication technologies.

The requirements defined in this Recommendation are general requirements, and can therefore be applied to many kinds of IoT applications regardless of their types and characteristics.

ISO/IEC 30141
IoT Reference
Architecture

Defines a high-level reference architecture for IoT systems, identifying abstract functions, structures, and interactions between IoT systems, users, and the physical environment. It supports scalability, interoperability, and alignment with business and societal values in smart city ecosystems.

ISO/IEC TS
30149
Trustworthiness
Principles for
IoT

This technical specification sets out principles for IoT trustworthiness. It provides guidance on ensuring reliability, safety, security, privacy, and resilience in IoT deployments. These principles are critical in urban citiverse contexts where device networks underpin essential services.

OGC Sensor &
Geospatial Web
APIs

A suite of interfaces – SensorThings (sensor data), WFS/WMS (vector & map layers), GeoSPARQL (semantic spatial queries), GeoPose (camera pose) – that standardize access to geospatial and IoT data.

ISO 23247

Provides a layered digital-twin architecture with

	functional views and information exchange specs.
W3C Web of Things (WoT)	Defines a Thing Description (TD) JSON-LD model, binding templates, and scripting APIs enabling seamless, protocol-agnostic communication among heterogeneous IoT devices.

[Reference for detailed standards: VDC's XR & Metaverse Standards Register; TWG Report on citiverse \(esp. paras 4.2 Connectivity and 4.4 Platform\).](#)

Phase 2 - Data aggregation and processing hubs

As discussed in chapter 4 (specifically the examples of standards for Phase 2), once connectivity and data flows are established, Phase 2 requires a coherent framework to aggregate, model, and process information from multiple city systems. While interoperability standards are addressed in section 5.4, below here we focus on (c) visualization and interaction, as well as (d) data governance and processing ones.

Table 9 Standards needed in Phase 2 (Data aggregation and processing hubs)

Data aggregation and processing hubs standards (Phase 2)	Function	Examples	Explanation
Phase 3	Recommendation ITU-T Y.4812 Interoperability of IoT devices' identity across metaverse platforms	ITU	This Recommendation describes identity interoperability for IoT devices across metaverse platforms, and provides relevant technical features, functional requirements and reference frameworks.
c. Visualization and interaction standards	Provide lightweight formats for 3D content, optimized for mobile and browser-first experiences	glTF WebXR ARML 2.0	An open standard for the efficient transmission of 3D assets (the so called "JPEG of 3D).\" Widely supported, it enables sharing and rendering of 3D content across platforms. An API that allows immersive experiences to run directly in web browsers, eliminating the need for specialized hardware or software. A standard XML/JSON-based markup language with

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		(OGC)	ECMAScript bindings to define augmented objects, their appearances, anchors, and event behaviours in AR scenes
		NGSI-LD (ETSI)	A JSON-LD/RDF-based Linked Data API standard for sending real-time contextual information (e.g., sensor readings, events, entity states) between systems.
d. Data governance and processing standards	Provide principles for managing, controlling, and governing large-scale urban datasets.	IEEE P2957	Big Data Governance - Provides governance frameworks for managing big data, ensuring quality, accountability, and compliance. Supports transparency and control of aggregated urban data in citiverse hubs.
	Ensure that data from diverse domains can be visualized, analysed, and re-used effectively through efficient and accountable governing systems, enabling the citiverse to serve as a living, responsive digital ecosystem.	IEC SRD 63273 (Parts 1 & 2) – City Information Modelling (CIM)	Defines CIM requirements based on stakeholder use cases and links to SDGs (UN Sustainable Development Goals). It formalizes digital methods for managing urban systems and planning processes in aggregated city hubs.

[Reference for detailed standards: TWG Report on citiverse⁹, Information \(4.3\).](#)

Phase 3 – Citiverse in operation

Based on Chapter 4 (especially the examples of standards for phase 3 related to: (i) management of the operating aspects of the citiverse; (ii) data accessibility, privacy, and security; (iii) training and auditing the system; (iv) deploying an interface for the public), the operational phase of the citiverse requires a strong focus on ethics, governance (that goes beyond the data governance requirements of phase 2), and user protection.

Table 10 Standards needed in Phase 3 (Citiverse in operation)

Citiverse in operation standards (Phase 3)	Function	Examples	Explanation
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e. AI trustworthiness	Ensuring trustworthy AI in citiverse services.	IEEE P2863 – Governance of AI	Introduces governance criteria for artificial intelligence (AI), covering transparency, accountability, and bias minimization
		ISO/IEC 42001	Specifies requirements for an AI management system, ensuring organizational processes support ethical, safe, and well-governed AI deployment.
	Enabling seamless cross-domain interactions and transactions in the citiverse.	IEEE P2874	Defines the Spatial Web Protocol to secure interoperable, semantic connections between devices, platforms, and users.
		ITU FG-MV Technical Report on Challenges to achieving trustworthy metaverse	This Technical Report presents key concepts, challenges and a reference model for a trustworthy metaverse including standardization landscape and roadmap.
f. Cybersecurity	Evaluating cybersecurity	ITU FG-MV Technical Report on The essential components of trusted data use in building a trustworthy metaverse	This Technical Report outlines the essential groundwork needed to understand the symbiotic relationship that facilitates the use of trusted data in establishing and maintaining a trustworthy metaverse.
		ISO/IEC AWI TS 27115 – Cybersecurity Evaluation of Complex Systems	Provides methods for evaluating the security of complex, interconnected systems, protecting digital twins and IoT infrastructures.
		ITU FG-MV Technical Report on Cyber risks, threats, and harms in the metaverse	It provides an overview of this emerging digital realm and its potential, highlighting its transformative nature. It also analyses and documents the specific cybersecurity risks, threats, and potential harms associated with the metaverse.

[Reference for detailed standards: TWG Report on citiverse, Information \(4.3\)](#)

and People Centric (5.1).

5.3 Ethics standards in citiverse

In this Section we focus on categories of standards specifically aimed at addressing ethical and inclusivity aspects of the citiverse. Further reference for ethical and inclusive standards apt for a Global South citiverse is provided in Section 6.

5.3.1 Digital ethics

The standards described in this section focus on responsible, fair, transparent, and human-rights-aligned development and deployment of digital technologies.

Table 11 below describes the relevant categories of standards concerning digital ethics, providing the essential information regarding them and connecting them to the relevant phases of citiverse implementation, as identified in chapter 4.

Table 11 Digital Ethics standards

Target (connection with citiverse development phases)	Title	Source	Notes
Phases 1, 2 and 3	IEEE Standards for the Metaverse	IEEE	Series of standards focused on emerging technologies such as metaverse, AI, blockchain, cloud computing, and more
Phases 1, 2 and 3	ITU FG-MV Technical Report on Guidelines for consideration of ethical issues in standards that build confidence and security in the metaverse	ITU	This Technical Report provides a set of guidelines that address ethical aspects in the establishment of standards for engagement within the metaverse.
Phases 2 and 3	OASIS Consortium Metaverse Safety Standards	OASIS Consortium	Frameworks for safety, privacy, inclusion, governance, and moderation structures – including executive roles for immersive platforms
Phase 3	Metaverse Standards Forum (MSF) – Ethical	MSF	Focus on reviewing and synthesizing the various ethical approaches proposed for the Metaverse, identifying areas of consensus, and addressing

	Principles		contentious issues
Phases 2 and 3	UNESCO Recommendation on the Ethics of Artificial Intelligence	UNESCO	Adopted by 194 UNESCO member states
Phases 2 and 3	OECD AI Principles	OECD	Adopted by OECD members plus approximately 70 other countries
Phases 1, 2 and 3	IEEE 7000-series Standards	IEEE	Voluntary adoption
Phases 1, 2 and 3	Toronto Declaration: Protecting Human Rights in Machine Learning	Amnesty International and Access Now	Mostly adopted by the CSO sector so far
Phases 1, 2 and 3	UN High-Level Panel on Digital Cooperation: Values and Principles for Digital Age	UN Secretary General Office - UNCTAD	Reference document

5.3.2 Digital inclusion

The standards described in this section focus on access, accessibility, affordability, digital skills and rights-based inclusion in the digital world.

Table 12 below describes the relevant categories of principles concerning digital inclusion, providing the essential information regarding them and connecting them to the relevant phases of citiverse implementation, as identified in chapter 4. Unique reference for each principle is hyperlinked under the “Source” column. Standards related to Digital inclusion are further detailed in Table 13.

Table 12 Digital Inclusion standards - Principles

Target (connection with citiverse development	Title	Source	Notes
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phases)

Phase 3	ITU FGMV-15 – Metaverse Accessibility Guidelines	ITU	Guidelines to evaluate metaverse platforms for the SDG principles of diversity, equity, and inclusion in terms of digital transformation.
Phase 3	ITU FGMV-03 Digital Inclusion Guidelines	ITU	Guidelines that aim to ensure that everyone has equal and equitable use of ICT products and services.
Phase 3	UNESCO Internet Universality ROAM-X Principles	UNESCO	Tool, with accompanying indicators, to measure “internet universality.”
Phase 3	EN 301 549 (EU Accessibility Standard)	ETSI (European Telecommunication Standards Institute)	Standards to measure the accessibility of websites, electronic documents and non-web software.
Phase 2 and 3	ISO 30071-1: Web Accessibility Process Standard	ISO	Guidelines for building and maintaining ICT systems (including products and services) that are accessible to diverse users.
Phase 2 and 3	CARE Principles for Indigenous Data Governance	Global Indigenous Data Alliance (GIDA)	Focus on the role of data in advancing Indigenous innovation and self-determination. These principles complement the existing FAIR principles .
All three phases	African Declaration on Internet Rights and Freedoms (AfDec)	AfDec Coalition	Pan-African initiative to promote human rights standards and principles of openness in Internet policy formulation and implementation on the continent.

Table below considers Digital Ethics and Digital Inclusion standards specific for the implementation of Phase 3 (Citiverse in Operation).

Table 13 Digital Ethics and Digital Inclusion standards for Phase 3

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Citiverse in operation (Phase 3)	Function	Examples	Explanation
g. Safety, ethical, and privacy enhancement	Establish safety, ethical, and privacy principles for extended reality applications, ensuring that immersive experiences respect human rights and local cultural norms.	IEEE P7016 – Ethical XR	Establishes requirements for ethical, inclusive, and safe XR applications, protecting user rights in immersive environments.
		XR Safety Initiative Framework (XRSI)	Provides global guidelines for XR safety, privacy, and ethics, addressing identity, data protection, and safeguarding vulnerable groups.
h. User data privacy & identity	Embedding privacy protections from the earliest design stages, ensuring consumer trust and protection in citiverse operations.		
		ISO/IEC 24760 Identity Management Framework	Defines trusted processes for handling digital identity across platforms, enabling trusted citizen identification across citiverse platforms.
		W3C Decentralized Identifiers (DIDs) & Verifiable Credentials (VCs)	Represent self-controlled digital identities, and VCs allow digitally signed proof of attributes (e.g., age, citizenship) that can be verified independently.



5.4 Interoperability standards mapped with technology backbone

As highlighted in the Technical Backbone (chapter 4), the development of a citiverse includes plenty of technologies and infrastructures. The city administrations may struggle with the selection and combination of all these technologies to reach full interoperability amongst them and with their legacy systems in the city.

Reaching interoperability is not trivial and requires addressing different dimensions. Interoperability needs to be addressed at four different levels: (a) legal, (b) organizational, (c) semantic and (d) technical. When two organizations or systems need to interoperate, they must: align their legal and contractual frameworks;

coordinate governance mechanisms and processes; share a common vocabulary of terms and meanings; and use compatible interfaces and data models to effectively interact. In the citiverse context, all these dimensions require attention, however, this chapter will focus on interoperability at the technical level (d).

Standards are the way to reach technical interoperability. Section 5.3 above lists the main international standards that administrators should follow to develop the citiverse in their city, according to the development phases stated in Chapter 4. The standards are technical norms developed by consensus, accessible for use, published by a recognized entity and of voluntary compliance. The alignment of standards is a challenging activity, which requires the consensus of the stakeholders in a certain domain in adopting the same or compatible standards for implementing functionality; and in some cases, the intervention of intermediaries who map the various standards that need to cohabit.

Chapter 4, Technical Backbone, provides a set of recommendations, divided per phase, to build technically a citiverse, and specifies the set of core technologies which are required to implement each recommendation. In the table below (Table 7), we have collected the essential list of standards to address each of the phases and the guidelines to reach interoperability amongst them, following the recommended standards in section 5.3. Other related standards are mentioned in Chapter 4, but this table refers to the ones which are more specific and essential for the citiverse purpose.

Table 14 Main recommended standards per citiverse phase and interoperability recommendations

Phases		Recommended standards	Interoperability recommendations
City assets and Connectivity (Phase 1)	3GPP	- Build the network of devices across the city following existing standards for IoT architecture (ISO/IEC 30141), ensuring the proper security level (ISO/IEC TS 30149). - Mapping various protocols and payloads from IoT devices to a common standard like W3C JSON-LD. - Describe all datasets with an enrich metadata standard (i.e., ISO 19115 or OGC for geographical data) which allows cataloguing, publishing and discovering them efficiently. - Deploy mobile and Internet connectivity across the city by following 3GPP which standardize different mobile technologies to work together.	
	ISO 19115 Geographic Information – Metadata		
	ISO/IEC 30141 IoT Reference Architecture		
	ISO/IEC TS 30149 Trustworthiness Principles for IoT		
	OGC Sensor & Geospatial Web APIs		
	ISO 23247 – Digital Twin architecture		
	W3C Web of Things (JSON-LD)		
<u>Recommendations ITU-T Y.4000-Y.4999 series</u>			

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Data aggregation and processing hubs (Phase 2)	GITF (3D)	- Establish the semantic interoperability schema for all the aggregated data in the digital twin of the city following the specification in ISO/IEC 30182. It will require defining the common vocabulary and data models and normalizing the raw data to the common language. - Define a common set of APIs to integrate all data collected from city infrastructure. There are various standards depending on the type of data to integrate (i.e., NGSI-LD for real-time contextual information, gITF for 3D content, ARML for augmented objects, WebXR for immersive experiences, ISO 29481-3:2022 for BIM, OpenXR for mixed reality assets). - Define and establish a data governance model for all the data aggregated at city level using the frameworks recommended by IEEE P2957 or ISO/IEC 38505-1 - Design and develop the Digital Twin of the city relying on ISO 23247 which provides a reference architecture. In some cases, a city may need to federate various digital twins, follow then ITU-T Y.4224 for collecting the requirements of the federation. - Consolidate the overall information about the city in a City Information Modelling following IEC SRD 63273 specifications. - Follow emerging initiatives like the Minimal Interoperability Mechanisms (MIMs) promoted by the Open and Agile Smart Cities association and under standardization process in ITU. They are working in an interoperable citiverse. - Use the recommendations in ISO/TR 23262:2021 to ensure the interoperability between GIS and BIM, if needed.
	WebXR API	
	ARML 2.0 - Markup language	
	ETSI NGSI-LD API	
	IEEE P2957 Big Data Governance	
	IEC SRD 63273 (CIM)	
	ISO/IEC 38505-1 Governance of data	
	Recommendation ITU-T Y.4505 Minimal interoperability mechanisms for smart and sustainable cities and communities	
	ITU-T Y.4224 Requirements for digital twin federation	
	ISO/IEC 30182 Smart city concept model	
	ISO/TR 23262:2021 GIS and BIM interoperability	

Recommendations ITU-T
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Citiverse in Operation (Phase 3)	IEEE P7016 – Ethical XR Safety Initiative Framework (XRSI)	Follow Ethical (IEEE P7016) and Privacy (ISO 31700-1) by Design approaches in all the developments and processes in the citiverse to ensure that from the city infrastructure deployment, through the
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IEEE P2863 – Governance of AI

ISO/IEC 42001
Requirements AI
management system

IEEE P2874 – Spatial Web Protocol

ISO/IEC AWI TS 27115 –
Cybersecurity Evaluation of
Complex Systems

ISO 31700-1 – Privacy by
Design for Consumer
Goods and Services

ISO/IEC 24760 Identity
Management Framework

W3C Decentralized
Identifiers (DIDs&VCs)

Recommendations ITU-T
Y.4000-Y.4999 series

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digital representation of the city towards the immersive experience in the virtual world, the ethical and privacy concerns are embedded from the design phase in the citiverse solution. This will provide homogeneity to the overall scenario, fostering interoperability aspect.

- Set up an interoperable identity framework (**ISO/IEC 24760**) to allow the integration of citiverse users' identities under the same standard. The current trend in distributed environments like citiverse is the use of **W3C Decentralize Identifiers and Verifiable Credentials** for self-controlled digital identities.

5.5 Key standards to consider for a citiverse apt for the Global South (inclusivity)

The standards identified above serve to implement a fully-functioning and fully operational citiverse, as it would appear at its maturity. However, it is important to adapt the citiverse concept for the Global South and create minimum requirements (building blocks) for a viable and comprehensive citiverse.

Strategies to be considered to build a civic-focused, locally grounded citiverse are the following:

- 1) **Leverage Existing Infrastructure:** Utilize widely available technologies such as mobile networks and devices, to ensure accessibility.
- 2) **Promote Local Innovation:** Encourage local developers and entrepreneurs to create solutions tailored to regional needs, fostering economic growth and relevance.
- 3) **Ensure Inclusivity:** Design platforms that are accessible to individuals with varying levels of digital literacy and physical abilities.
- 4) **Foster Public-Private Partnerships:** Collaborate with governments, NGOs, and private sector entities to pool resources and expertise.
- 5) **Implement Ethical Frameworks:** Establish guidelines that protect user data, ensure privacy, and promote equitable access to digital services.

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5.5.1 Recommendations and related standards to tailor a citiverse for the Global South

By aligning with ITU's mission and vision (Citiverse Framework), and tailoring strategies to the unique contexts of the Global South, we can develop citiverse implementations that are viable and transformative, even if they are not fully deployed at their potential.

As shown in Table 8 below, to attain a citiverse that is viable for Global South, the following standards and recommendations are to be considered. (1) Telecom Standards like 3GPP and 5G-MAG may ensure reliable connectivity by leveraging existing infrastructure. (2) Existing open formats and APIs such as glTF, OpenXR and WebXR may guarantee interoperability and reduce development costs. (3) Collaborate with organizations like ITU may help develop standards that make the citiverse accessible to all. (4) Participating in collaborative open ecosystems and forums like the MSF and OMI Group may help shape shared standards. (5) Following IEEE P7016 and XRSI guidelines may help create ethical and secure virtual environments ensuring safety and inclusion.

Table 15 Key standards and recommendations for an inclusive citiverse apt for the Global South

Category	Recommendation	Examples of viable standards	Explanation
Telecom infrastructure standards	1. Leverage Existing Connectivity Infrastructure	3GPP (3rd Generation Partnership Project)	Standardizing mobile technologies including GSM (2G), UMTS (3G), LTE (4G), and 5G NR. 3GPP specifications, especially Release 15 and later, support XR applications with low-latency and high-reliability requirements, which are critical for immersive experiences
	Utilize widely available technologies such as mobile networks and devices, to ensure accessibility.	5G Media Action Group (5G-MAG)	Promotes the deployment of media technologies using 5G networks and the global Internet, enabling access to immersive content on mobile devices.
Interoperability and Accessibility	2. Ensure Inclusivity: Design platforms that are accessible to individuals with varying levels of digital literacy and physical abilities.	glTF (GL Transmission Format)	An open standard for the efficient transmission of 3D assets (the so called "JPEG of 3D)." Widely supported, it enables sharing and rendering of 3D content across platforms.
		OpenXR:	A standardized API that enables the development of XR applications interoperable across different devices and platforms, reducing fragmentation and development costs.
		WebXR:	An API that allows immersive experiences to run

			directly in web browsers, eliminating the need for specialized hardware or software.
Collaborative initiatives	3. Promote Local Innovation and accessibility: Encourage local developers and entrepreneurs to create solutions tailored to regional needs, fostering economic growth and relevance		Collaborate with organizations like ITU to develop standards that make the citiverse accessible to all.
Open ecosystems and forums	4. Foster Public-Private Partnerships: Collaborate with governments, NGOs, and private sector entities to pool resources and expertise.		Participate in forums like the MSF and OMI Group to help shape shared standards.
Security, Privacy, and Ethics	5. Implement Ethical Frameworks: Establish guidelines that protect user data, ensure privacy, and promote equitable access to digital services.	IEEE P7016: XRSI (XR Safety Initiative)	A standard for the ethical design and operation of metaverse systems, ensuring XR technologies adhere to core ethical principles. An organization that promotes privacy, safety, and ethics in XR experiences, offering guidelines and best practices for safe and inclusive virtual environments.

5.5.2 Assessment of recommendations and related standards to tailor a citiverse for the Global South

Table 16 below briefly acknowledges if and why the identified standards are essential to attain a citiverse apt for the Global South.

Table 16 Workability of identified standards to establish a Global South Citiverse

Category	Standard	Apt for Global South Citiverse?	Why?
1. Telecom standards	3GPP, 5G-MAG	⚠ Partially	Useful for infrastructure planning but should be subordinated to civic priorities like access equity, not bandwidth maximization.
2. Interoperability and accessibility	glTF, OpenXR, WebXR	☑ Yes	Essential for enabling cross-device, low-bandwidth 3D visualization– key in low-resource settings. WebXR especially supports browser-first experiences, perfect for mobile-first regions.
3. Collaborative initiatives	ITU	☑ Yes	ITU's focus on accessibility and sustainability aligns closely with citiverse values.
4. Open ecosystem	MSR, OMI Group	☑ Mostly	While "metaverse"-oriented, these groups offer open models and tools for civic tech re-use.
5. Security, privacy, and ethics	IEEE P7016, XRSI	☑ Yes	Ensures civic tech is safe, ethical, and respects rights and local norms.

These standards are **necessary but not sufficient**. As synthesized in Table 17 below, to be truly apt for a Global South Citiverse, the following existing standards/initiatives could also be considered:

Table 17 - Further standards needed to ensure civic engagement in Global South Citiverse

Category	Standard needed	Why?
6. Civic ontologies & urban Standards	ISO 37120	Sustainable cities indicators
	CityGML or GeoJSON	Urban modelling and GIS integration
	INSPIRE Directive (EU)	Public spatial data infrastructure
7. Open data &	OpenAPI, GraphQL:	For civic services/APIs.

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participation standards	DCAT, CKAN:	for managing civic datasets
	Decidim or CONSUL:	Open-source platforms for participatory democracy

5.5.3 Next steps: What further standards are needed to tailor a Citiverse for the Global South

In perspective, more standards need to be developed (Table 18) to also ensure that (a) Cultural sovereignty and digital rights, as well as (b) Education and capacity-building tools are granted for Citiverses in the Global South.

Table 18 Additional concerns and corresponding standards needed to build Global South Citiverse

Category	Typology of Standard needed
a. Cultural sovereignty and digital rights	a.1 Local content licensing frameworks a.2 Data sovereignty standards for Global South governance (e.g., African Union's Data Policy Framework)
b. Education and capacity-building tools	b.1 Localization toolkits b.2 Open-source XR dev toolchains that run on low-end hardware

5.6 Conclusion and suggestions

Cities should adopt international standards with flexibility, tailoring them to local capabilities and contexts while embedding ethical, inclusive and governance principles alongside technical interoperability. In doing so, municipalities can ensure the citiverse becomes a tool for equity, trust, and sustainable urban transformation.

In the following we summarize a possible workflow for municipalities that intend to build a citiverse

Suggestion 1 Create an online spreadsheet with the standards you need

- 1 Polish, clean and agree on final collection
- 2 Create an online page with the collection
- 3 Include a public form to collect feedback/input

Suggestion 2 Strategy, methods and tools for implementing a suitable governance structure for the citiverse ecosystem it is meant for

Strategy:

- 1 What is your ecosystem? What is your ambition/vision for it? How does your organization relate itself to this Citiverse ecosystem?

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- 2 Importance of (different levels of) trust within a citiverse ecosystem
- 3 What kind of cooperation (e.g., public, private, ppp, commons, etc.), who is responsible for what?
- 4 What kind of form of governance (e.g., Governance Board) is required, also considering the (lack of) rules and regulations?
- 5 What is the composition and mandate?
- 6 What are the main issues to be addressed?
- 7 Is your architecture/digital infrastructure interoperable (open standards) for all participants within (and outside) your citiverse ecosystem?
- 8 What is the ethical framework you need to base the system in your local context? (adaptation of ethics and inclusivity standards)

Methods & Tools: refer to example use cases identified in Track 8 (e.g., the “Open Urban platform Rotterdam”).

6 Infrastructure & technology readiness

As cities across the globe embrace digital transformation, the successful deployment of City Digital Twins (CDTs) and citiverse experiences hinges on robust infrastructure and technological readiness. This chapter offers a comprehensive consolidation of engineering guidance, equipping stakeholders with essential frameworks, reference architectures and practical toolkits to move from experimental pilots to scalable, production-ready solutions. Emphasising the interplay between compute layers, next-generation networks, and privacy-preserving AI, the following content lays out actionable strategies, maturity models and technical blueprints—ensuring that city-wide digital environments are not only immersive and interoperable, but also resilient, secure, and aligned with international benchmarks for smart urban development.

By emphasising the need for adaptability and alignment with up-to-date hardware specifications, this guidance ensures that technical recommendations remain relevant and actionable throughout the planning and implementation phases of city-wide digital transformation. Stakeholders are encouraged to continually verify vendor requirements to maintain infrastructure reliability and future-proof their City Digital Twin initiatives.

6.1 Why “infrastructure & tech readiness” decides city digital twins’ success

Cities are moving from pilots to production-scale City Digital Twins (CDTs) and citiverse experiences that blend geospatial reality, operational data and immersive 3D. Delivering this at city scale requires a continuum of compute (edge → cloud →, eventually, quantum accelerators), resilient next-gen networks (5G-Advanced/early 6G and mesh), IoT that feeds trustworthy data, and privacy-preserving AI such as federated learning (FL). This chapter provides: (1) an engineering blueprint across these layers and (2) a Readiness, Maturity & Diagnostic Toolkit aligned to U4SSC and NYU CETI.

Reference architecture: The SENSE Verse EU slides present a data-space-centric stack with OASC/NGSI-LD, OGC services, identity/clearing (Gaia-X), and Unity/Web front-ends – a strong template for operated CDTs (see “SENSE – Proposed integration architecture, D2.2”).

6.2 The Edge–Cloud–Quantum continuum for cities

Edge: Ruggedized x86/ARM nodes at junction boxes, lampposts, depots, and control rooms perform low-latency tasks – video analytics, traffic optimization, sensor fusion. Expose secure APIs (NGSI-LD, OGC) and push events rather than raw streams to save bandwidth.

Cloud/HPC: Ingest, long-term storage, model training (ML/physics), and heavy 3D processing (photogrammetry meshing, tiling, USD scene composition) run in cloud/HPC. SENSE dataspace components – connectors, identity issuers, clearing house, participant agents – enable trust, usage control, and governance across providers.

Quantum (near-term): Prepare optimization workflows (grid, routing, scheduling) so classical solvers can later be swapped for quantum/quantum-inspired back ends without re-plumbing.

Design pattern: Treat the continuum as three execution classes:

- Realtime/interactive (edge): ms latency; stream → feature detection → event.
- Near-real time (cloud): seconds to minutes; data assimilation, map tiling, micro-simulations.
- Batch/strategic (HPC/quantum): hours to days; long-horizon planning and what-if scenarios.

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6.3 Next-gen networks (5G-Advanced/6G), mesh, and IoT

5G-Advanced/6G trajectory brings higher reliability, sub-10 ms latencies, and integrated sensing/communications. Design applications to adapt to heterogeneous links (LPWAN for meters, 5G for video, Wi-Fi/mesh for venues) and degrade gracefully (edge inference when backhaul drops).

Mesh for venues & districts: Festivals, stadiums and waterfronts benefit from self-healing mesh nodes (Wi-Fi 6/7 or private 5G small cells) to keep AR/VR and visitor analytics online. SENSE use cases (Kiel tourism/emergency training; Cartagena traffic/environment/planning) illustrate such needs.

IoT and data formats: Adopt Recommendation ITU-T Y.4502 and OGC services; normalize 3D assets (FBX/OBJ/GLTF→GLB) and rasters (GeoTIFF → GeoPNG) for web delivery.

6.4 Data spaces, identity, and pipelines (SENSE Verse EU as a reference)

A city data space ensures discoverability, trust, usage control, and monetization. The SENSE architecture shows providers of static files (media/3D/models/shapfiles) and dynamic feeds (IoT platforms, GIS) linked via a dataspace connector enforcing policies. Identity issuers and Gaia-X clearing houses perform conformity/identity checks; participant agents handle contracting, logging, payment, registry, and governance.

At the UI layer, SENSE plans Unity for HMD/PC/Mobile and a web stack (e.g., Mapbox).

Web-native 3D sandbox: It outlines a pure-browser twin that relies on client GPU acceleration (Chrome/Edge) and can load GeoJSON, 3D Tiles, and imagery by URL.

6.5 Engines & viewers: when to use Omniverse, Unreal, Unity, Cesium, Godot, deck.gl

Omniverse (USD-first, multitool collaboration): Best for USD pipelines, large-model interoperability, and engineering fidelity; RTX GPUs are the norm.

Unreal Engine (UE5): High-end real-time with Lumen/Nanite; ideal for ops centres, training, VR.

Unity: Versatile for cross-platform field apps, HMD/PC/mobile, and serious games.

CesiumJS: Browser-native globe/3D Tiles; great for public visualizations and geospatial streaming.

Godot (+ 3D Tiles for Godot): Open-source engine that can stream photogrammetry/terrain/buildings using the plugin (requires Godot 4.1+).

deck.gl (vis.gl): High-performance WebGL2 toolkit for large-scale geospatial visualization in the browser.

6.5.1 Practical tech requirements (CPU/GPU/RAM) by platform

Omniverse Studio/Enterprise:

RTX GPU with ~24–48 GB VRAM for complex USD scenes (multiGPU for very heavy scenes); 12–24 CPU cores; 64–128 GB RAM; NVMe storage.

- Unreal (UE5): 8–16 CPU cores; 32 GB RAM; 8 GB+ VRAM DX12 GPU; fast NVMe.

- Unity: 8–16 CPU cores; 16–32 GB RAM; mid/high-range GPU.
- Godot + 3D Tiles: Godot 4.1+; modern GPU; 16–32 GB RAM.
- CesiumJS / deck.gl (browser): Any WebGL2-capable discrete GPU markedly improves frame rates for dense layers; ensure browser GPU acceleration is enabled.

City-scale back end (indicative T-shirt sizing):

- Pilot / single district (50–100 km², 10–50 sources): One GPU server (e.g., RTX A6000 48 GB) for rendering/tiling; 1–2 CPU nodes (32–64 vCPU, 128–256 GB RAM) for ETL/APIs; 50–100 TB object storage.
- City core (500–1,000 km², 100–500 sources): 2–4 GPU servers (48 GB VRAM each); 4–6 CPU nodes (64–128 vCPU, 256–512 GB RAM); 0.2–0.5 PB storage.
- Metro scale (multicity): GPU farm with auto-scaled render pods; CPU cluster 1000+ vCPU; ≥1 PB storage with lifecycle tiering.

Note: Always profile your assets (mesh density, textures, concurrency) and consult official vendor documentation for the latest requirements.

6.6 Blueprint: Readiness, maturity & diagnostic toolkit

This section provides a practical and comprehensive blueprint to design, build, and scale a citiverse, as a persistent, city-wide spatial computing environment that fuses geospatial reality, operational systems, and immersive 3D experiences for public value. Unlike generic treatments that foreground data exchanges, this chapter keeps a laser focus on the citiverse itself: the experience architecture, spatial data and 3D pipelines, real-time operations, edge–cloud compute, next-generation networks, IoT sensing, engines and viewers, security and digital ethics, service operations, and a readiness/maturity toolkit aligned to U4SSC and NYU CETI benchmarks. Where helpful, indicative hardware “T-shirt sizes” and platform runbooks are provided; these are engineering guidelines for city-scale projects and should be validated against current vendor documentation.

The citiverse is the city’s persistent digital reality: a living, spatially anchored environment where decision-makers, operators, citizens, and businesses interact with the same city in synchronized 2D/3D/XR views. It is not a “project” but an operational capability, which is fed by sensors and systems, rendered with modern 3D engines, and governed by clear service levels and ethics. Its purpose is to produce joint situational awareness, what-if planning, and citizen experiences that reinforce trust and inclusion.

The citiverse differs from a conventional city digital twin in two respects. First, it treats experience delivery (control rooms, field XR, public web) as a first-class architectural concern. Second, it designs compute, networks, and data lifecycles around interaction latencies and scene complexity, rather than around purely back-office integration.

6.6.1 Design principles

- 1) Outcome-anchored: each module in the stack must trace to concrete civic outcomes and KPIs (e.g., U4SSC).
- 2) Experience-first: start from target interactions – situational awareness, training, citizen wayfinding –

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and flow backward to data and infrastructure.

- 3) Open, portable, web-capable: prefer open scene formats (e.g., USD, glTF), stream-able 3D (e.g., 3D Tiles), and browser delivery for reach.
- 4) Compute continuum by latency class: map workloads to edge (ms), cloud (s–min), and HPC/strategic (hrs–days); keep pipelines event-driven.
- 5) Resilient networks: design for heterogeneous links (5G-Advanced/early 6G, Wi-Fi 6/7 mesh, LPWAN) and graceful degradation.
- 6) Security and digital ethics by design: protect people, places, and processes; minimize data movement; Favour privacy-preserving analytics.

6.6.2 The Citiverse reference stack (Experience-centric)

Experience Layer: Control rooms, field XR (HMD/mobile), and citizen-facing web viewers deliver the same authoritative city scenes at different fidelities and latencies. Engines such as Omniverse, Unreal, Unity, CesiumJS, Godot, and deck.gl are selected per channel (Section 9).

Spatial & 3D Foundations: A maintained city base (terrain, imagery, buildings, interiors) with level-of-detail rules, tiling, and coordinate system discipline. Workflows from BIM/CAD/photogrammetry to USD/glTF/3D Tiles are automated to ensure repeatability.

Real-Time Context & Sensing: IoT and city systems push events and state changes to scene layers; edge nodes perform feature extraction to reduce bandwidth. Where analytics require privacy, federated learning runs at the edge.

Compute Continuum: Edge for interactive inference and safety loops; cloud/HPC for tiling, assimilation, training; strategic back ends for batch “what-if” planning and, later, quantum-ready optimization slots.

Network Fabric: 5G-Advanced/early-6G for mobile video/XR; Wi-Fi 6/7 mesh for venues and waterfronts; LPWAN for meters; private 5G where needed; each application specifies its uplink/downlink and jitter budgets.

6.6.3 Twelve-step implementation playbook for any city to deploy a citiverse initiative

Step 1 – Vision, use-cases, and value narrative

Identify three anchor use-cases spanning (i) operational efficiency (e.g., multimodal traffic), (ii) public safety/resilience (e.g., flood rehearsal), and (iii) citizen experience (e.g., inclusive wayfinding). For each, define the interaction target (e.g., 60 fps VR training; <1 s alarm overlay), user roles, and measurable outcomes. This ensures subsequent technical choices serve a coherent experience portfolio.

Deliverables: Use-case briefs; interaction budgets; success KPIs (mapped to U4SSC/CETI).

Risks: over-broad scope; unclear ownership.

Step 2 – Experience architecture and channels

Specify channels (Ops Centre, Field XR, Public Web) and their constraints – scene complexity, concurrency, device class. Decide the primary engines per channel (e.g., Unreal for ops, Unity for field apps, CesiumJS for web) and define content equivalence rules so all channels reference the same authoritative layers.

Deliverables: Experience matrix; device personas; accessibility criteria.

Risks: channel divergence; duplicated scene assets.

Step 3 – Spatial data & 3D pipelines

Design the authoring-to-delivery pipeline: ingestion (BIM/CAD/FBX/OBJ), decimation and texturing, coordinate alignment, USD/glTF normalization and 3D Tiles tiling for the web. Establish LOD policies and asset governance (versioning, metadata, responsible release). Automate photogrammetry/meshing jobs in cloud/HPC as needed.

Deliverables: Pipeline diagrams; LOD policy; content registry.

Risks: inconsistent coordinates; uncontrolled file growth.

Step 4 – Real-time city layers

Instrument traffic, environment, utilities, and events as overlay layers with clear symbology, update rates, and caching rules. Favour event-driven updates rather than raw streams; only transmit features and state deltas. Align update frequencies to interaction budgets for each channel.

Deliverables: Layer catalogue; update SLAs; cache/TTL design.

Risks: oversharing raw feeds; latency spikes.

Step 5 – IoT sensing & edge analytics

Inventory devices; attach digital device passports (security, calibration, maintenance). Use secure boot/TPM and OTA patching. Push feature extraction (e.g., person/vehicle counts, anomaly flags) to edge nodes to reduce bandwidth and improve resilience. When individual-level data are sensitive, adopt federated learning to train models without centralizing raw data.

Deliverables: Device registry; edge inference playbook; FL governance note.

Risks: unmanaged firmware; model drift; privacy blind spots.

Step 6 – Edge compute patterns

Deploy ruggedized x86/ARM nodes at junction boxes, lampposts, depots, and control rooms. Treat edge workloads as a first-class tier: ms-latency inference, traffic optimization, sensor fusion. Enforce API gateways at the edge; prefer push events over streams; ensure graceful offline behaviour.

Deliverables: Edge node BOM; container images; local failover modes.

Risks: thermal limits; unmanaged sprawl.

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Step 7 – Network fabric engineering

Plan for heterogeneous links: LPWAN for meters; 5G-Advanced/early-6G for video and XR; Wi-Fi 6/7 mesh for districts/venues. For events (festivals, waterfronts), use self-healing mesh and mobile cells. Design per-use-case uplink budgets and jitter envelopes; build in degraded modes (edge-only inference) when backhaul fails.

Deliverables: Radio design and SLAs; venue mesh kits; fallback playbook.

Risks: uplink starvation for XR; unmanaged interference.

Step 8 – Cloud/HPC & the strategic tier

Use cloud/HPC for ingest, long-term storage, model training, and heavy 3D processing (photogrammetry, meshing, tiling, USD composition). Reserve batch/strategic windows for long-horizon planning and “what-if” scenarios; keep the pipeline quantum-ready for optimization workloads that may later benefit from quantum/quantum-inspired back ends.

Deliverables: Lakehouse & object storage plan; training/tiling jobs; batch windows.

Risks: uncontrolled egress costs; under-sizing for tiling.

Step 9 – Engines & viewers: Selection and sizing

Select engines by use-case/channel (Table 1) and provision authoring/viewer hardware accordingly. For example: Omniverse for USD-centric collaboration, Unreal for high-fidelity ops centres and VR training, Unity for cross-platform field apps, CesiumJS for browser delivery of 3D Tiles, Godot (with 3D Tiles) for open-source city apps, and deck.gl for large-scale web geo-visualization. Typical authoring and viewer specifications are summarized in Table 2.

Deliverables: Engine portfolio; authoring workstations; viewer device profiles.

Risks: over-indexing on a single engine; insufficient GPU VRAM.

Step 10 – Security, privacy, and digital ethics

Adopt a privacy-by-design posture: minimize data movement; use edge redaction and federated learning for sensitive analytics; implement proportional retention and auditable access. Conduct data protection impact assessments (DPIA) for citizen-facing experiences and XR capture. Security controls include device identity, code signing, secure boot, segmentation, and continuous posture assessment.

Deliverables: DPIA templates; security baselines; audit logging.

Risks: inference leakage; “function creep” in public spaces.

Step 11 – Service operations (SRE for the citiverse)

Operate the citiverse as a 24/7 service with service-level objectives for latency, frame-rate, data freshness, and availability. Establish content operations (scene QA, LOD governance), release trains (quarterly capability drops), and green-ops (GPU scheduling, storage tiering). Build observability (telemetry, synthetic probes) and

playbooks for incident and change management.

Deliverables: SLOs; runbooks; content QA gates; cost/energy dashboards.

Risks: content debt; runaway storage; opaque costs.

Step 12 – Readiness, maturity, and diagnostic toolkit

Run a structured self-assessment across seven domains: Spatial/3D Foundations; Real-Time Layers; IoT & Edge; Networks; Cloud/HPC; Engines & Delivery; Security & Operations. Each domain has 8–12 capability checks, a 0–5 maturity scale, and evidence-of-practice examples. Scores map to Readiness Gates:

- Gate A – Pilot: domain average ≥ 2.5 ; basic channel demo live.
- Gate B – Scale: average ≥ 3.5 ; automated pipelines and SLOs in place.
- Gate C – Federate: average ≥ 4.2 ; city-wide coverage and cross-domain interoperability.

The toolkit tags each capability to U4SSC KPIs (e.g., accessibility, environmental monitoring) and NYU CETI pillars to keep investments tied to outcomes and to benchmark against peer cities.

Deliverables: Scoresheet; radar charts; 12–24-month roadmap; quarterly gap closures.

Risks: scoring without evidence; over-ambitious timelines.

6.7 Annex 1: Platform-specific runbooks:

- Omniverse: Stand up Nucleus; align content to USD; size RTX GPUs per workload; use connectors for BIM/CAD/GIS; stream to thin clients.
- Unreal: Equip authors with 32 GB RAM and 8 GB+ VRAM GPUs; use World Partition; integrate NGSI-LD/OGC.
- Unity: Target cross-platform delivery; plan 16–32 GB RAM for CDT projects; export GLB for web as needed; mind request-based pricing for certain map SDKs.
- CesiumJS & deck.gl: Ensure WebGL2-capable browsers; performance tuning via layer choice, tile resolution, and client GPU memory budgeting.
- Godot + 3D Tiles: Use Godot 4.1+ with the plugin to stream photogrammetry/terrain/buildings; good for open-source city apps and education.
- Webnative sandbox: Deploy a noinstall, codetweakable twin for planners; load GeoJSON/3D Tiles/imagery via URLs; requires client GPU acceleration in Chrome/Edge.

Platform Comparison Table

Platform	Primary use in a city CDT	Rendering mode	Typical authoring	Viewer HW	Ecosystem highlights
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HW					
Omniverse	USD collaboration, industrial/AEC twins; physics	Native (RTX), server streaming	RTX GPU ~24–48 GB VRAM; 12–24 cores; 64–128 GB RAM; NVMe	Thin clients via streamed sessions; or workstation	USD pipeline, Nucleus, connectors
Unreal (UE5)	High-fidelity real-time, ops centres, VR training	Native	8–16 cores; 32 GB RAM; 8 GB+ VRAM; NVMe	Gaming-class PC/HMD	Lumen/Nanite, enterprise plugins
Unity	Cross-platform city apps; HMD/PC/mobile; serious games	Native	8–16 cores; 16–32 GB RAM; mid/high GPU	Broad incl. mobiles	Large asset store; C#/DOTS
CesiumJS	Planet-scale geospatial + 3D Tiles	Browser (WebGL)	Modest; tiles authored server-side	WebGL-capable browser; discrete GPU recommended	Open 3D Tiles, ion ecosystem
Godot + 3D Tiles	Open-source runtime with streamed reality content	Native	Godot 4.1+; modern GPU; 16–32 GB RAM	Mid-range PC	3D Tiles plugin; growing CDT fit
deck.gl	Massive web geovis & analytics layers	Browser (WebGL2)	N/A (web dev)	WebGL2 browser; HW acceleration on	Layer stack (Hexagon/Tile/Trips) ; WebGPU emerging

6.8 Examples of size scalability based on the size.

- Pilot / single district (50–100 km², 10–50 sources): ~1 GPU server (e.g., 48 GB VRAM) for rendering/tiling; 1–2 CPU nodes (32–64 vCPU, 128–256 GB RAM) for ETL/APIs; 50–100 TB object storage.
- City core (500–1,000 km², 100–500 sources): 2–4 GPU servers (48 GB VRAM each); 4–6 CPU nodes (64–128 vCPU, 256–512 GB RAM); 0.2–0.5 PB storage.
- Metro scale (multicity): auto-scaled render pods; CPU cluster 1000+ vCPU; ≥ 1 PB storage with lifecycle tiering.

Always profile assets (mesh density, textures, concurrency) and confirm against current vendor guidance.

6.9 Conclusion: Paving the way for inclusive and resilient digital cities

In summary, the path to successful city-scale digital transformation hinges on a holistic approach to infrastructure and technology readiness. By adopting robust engineering blueprints, reference architectures, and tailored maturity toolkits, cities can confidently transition from isolated pilots to resilient, immersive citiverse environments. This journey demands continual adaptation to evolving hardware and network standards, a steadfast commitment to security and digital ethics, and a clear focus on outcome-driven experiences for all stakeholders. Ultimately, the citiverse represents not just a technological leap, but an operational evolution – empowering cities to deliver trusted, inclusive, and future-proof digital services that enhance urban life and foster civic collaboration.

7 Citizen Experience & Inclusion

An inclusive native citiverse planning is not just about who can build it, but about who should shape it. Planning requires a coalition: participatory, interdisciplinary, and community-first. Urban planners and architects interpret spatial justice, city infrastructure, and human-centred design to translate physical urban needs into virtual environments and hybrid spaces. Civic Tech Experts and digital designers build the accessible digital interfaces and experiences. Their role is to ensure the citiverse is usable, interoperable and accessible. They have to take into consideration existing guidelines and requirements [b-W3C] to ensure an accessible environment, also considering requirements related to user representation. Policy makers and local government officials need to draft mandates to create and regulate inclusive public spaces and digital rights by establishing frameworks for digital inclusion, privacy, data governance and equitable access. IT provides an infrastructure which is the technology backbone needed to build with digital inclusion as a human right in mind, not just scale or profit. Civil society organizations and advocacy groups are the voices of those often left out. Following the principle of “nothing about us without us” they should be part of the planning process from its inception, by defining requirements, and to monitor inclusion metrics, raise concerns, and co-create engagement strategies. Attention should be paid to vulnerable groups such as the aged, people with disabilities, low-income residents, immigrants, refugees, and people living alone.

Why a native inclusive citiverse planning

Building a native inclusive citiverse means creating by design a digital urban ecosystem that is equitable, participatory and representative of all citizens, not just the tech-savvy elite. It is the foundation for a just, ethical and future-ready digital society. A native inclusive citiverse ensures that marginalized and underrepresented communities are part of the digital urban life. Designing an inclusive citiverse avoids retrofitting inclusion later, which often results in tokenism or inadequate accessibility, something similar to an orthopaedic inclusivity that is obvious and expensive. An inclusive citiverse will help in bridging the digital divide, which is persistent in the physical city, at a time when most city services require digital interaction. Still many communities lack access to digital tools, services and infrastructure. A truly inclusive citiverse helps close this gap by designing digital environments that consider diverse languages, devices, literacy levels, abilities, and connectivity levels. An inclusive citiverse leads to resilience in governance, services, crisis response, and cultural preservation.

Taking diverse needs into consideration from the designing phase helps prevent bias in algorithms, surveillance systems, and virtual governance. It also ensures the ethical use of data and equitable access to AI-driven services in the digital city. Inclusion ensures the digital city reflects real-world diversity, not just a

technocratic vision of the future. An inclusive citiverse enhances citizen belonging and participation, and in turn the trust in digital governance, urban planning and cross-cultural collaboration.

User-centric design

User-centric design underpins the entire native inclusive citiverse by emphasising the principles of accessibility, usability, and inclusivity throughout the interaction design process. This involves proactively considering diverse user requirements such as sensory, cognitive, and motor abilities, from the earliest design stages. Adhering to established accessibility standards such as the Web Content Accessibility Guidelines (WCAG) ensures that the citiverse inclusive framework not only supports universal usability but also aligns with legal and ethical obligations toward digital inclusion.

7.1 The inhabitant

Virtual representation

The inhabitant is the foundational unit of the citiverse. It may be represented by an avatar, a hologram or data. Still the inhabitant is a human-centred presence shaping the ethical, inclusive, and sustainable future of digital cities. An inhabitant should be a digitally-empowered individual who participates actively in the social, cultural, economic, and governance dimensions of the virtual-urban ecosystem. Inhabitants are not passive consumers of services; they are co-creators, stakeholders, and rights-holders in a blended physical-digital civic environment. The fact that most inhabitants are not digitally empowered individuals means the digital ecosystem has to be enriched and be accessible.

Identity system approaches

Inclusive native citiverse planning is not just about who can build it, and who should shape it; it is also about who can participate in it. The social promise of an inclusive citiverse lies in its interactivity.

Unlike conventional smart cities, which largely collect and process data in the background, the citiverse at its best is designed as a two-way system where citizens, planners, and policymakers can collaborate in real time to shape and improve their shared environment. Extended reality tools allow people to “step into” virtual models of their city, test ideas, and see the potential impact of policies before they’re applied in the real world. But for this vision to work, the system needs to know who is participating and to ensure those participants have the right to be heard.

In this case, digital identity becomes essential. It is the key that lets a citizen move across different parts of the physical-virtual city, from immersive community meetings to accessing online services, without losing their ability to be recognized and trusted.

Alongside this sits the digital twin, a dynamic, data-driven model of the individual that can help personalize services and ensure planning decisions reflect real community needs. Without secure, citizen-controlled versions of both, the citiverse risks becoming a one-way mirror: systems can “see” people through the data they generate, but people cannot see, or influence, how they are represented. In short, true interactivity requires not just technology, but identity.

However, that identity system needs to be designed in a way that whilst offering visibility and transparency, is also privacy-protecting. Broadly speaking, three main models are available:

Centralized identity systems

Run by a single authority such as a national or local government agency. These are straightforward to administer and can integrate well with existing public services. However, they can also become single points of failure or control, raising concerns about surveillance of citizens and data misuse.

Federated identity systems

Where multiple trusted organisations (for example, government, banks, educational institutions) act as identity providers. These spread trust and responsibility across different entities, reducing centralized control, but can still create dependency on large institutional players. Whilst federated systems offer higher resilience, they still carry the risk of coordinated breaches, inconsistent or unequal access, and covert data sharing between providers that can erode trust.

Self-sovereign identity systems

Where individuals hold and control their own identity credentials, often using blockchain or similar technologies. This model maximizes personal control and privacy but requires greater digital literacy of all participants and robust infrastructure to manage securely.

Planners in the citiverse will likely need to combine these approaches, balancing trust, accessibility and citizen autonomy. Crucially, whichever model is chosen must work seamlessly with digital twins, virtual worlds, and immersive environments to ensure that policy decisions and service delivery reflect accurate data and individual rights.

7.2 Inclusive interactions in the Citiverse

To access the citiverse content presentation there should be a barrier free interaction to include navigational structures, interaction mechanisms, and the integration of assistive technologies. Addressing these challenges requires a systematic and standardized approach to interaction design that accommodates diverse user needs while remaining scalable across platforms and use cases.

The framework for inclusive citiverse interaction plays a critical role in promoting consistency, re-usability and inclusivity. Positioned between low-level services and high-level use cases, these frameworks define modular atomic interactions such as authentication, communication, and object manipulation, that can be combined flexibly to support a wide range of user goals.

By abstracting common interaction patterns and integrating accessibility and interoperability principles at their core, the framework enables developers to build inclusive applications without reinventing foundational elements. It also supports standardization efforts by providing a common vocabulary and structure for designing and evaluating virtual experiences. As such, the framework for inclusive citiverse Interaction is an essential building block in the effort to create equitable, sustainable, and user-centred virtual environments.

The primary objective of this framework is to provide a structured foundation for standardizing interactions within virtual worlds, emphasizing modularity, accessibility, and interoperability. Modularity ensures that interactions are re-usable and adaptable across various contexts, simplifying implementation and maintenance. Accessibility aims to guarantee equitable use of virtual environments by users with diverse abilities, addressing barriers from initial design stages. Interoperability facilitates seamless integration of

different technological components and services, allowing frameworks to function consistently across multiple virtual platforms and scenarios. To achieve these objectives, the framework comprises two core components: atomic interactions and support services.

Atomic interactions

Atomic interactions are fundamental interaction patterns, serving as re-usable building blocks essential for constructing complex user experiences in virtual worlds. By abstracting common tasks such as authentication, navigation, and communication, atomic interactions provide standardized protocols that can be applied consistently across diverse virtual environments, thereby simplifying development and promoting consistency and usability.

Atomic interactions in the citiverse: Authentication, role and permission management, navigation, proprioception, object manipulation, communication, consent management, environmental customisation, contextual help and guidance, feedback and interaction confirmation, and session persistence and state management.

Support services

Support services encompass the technological resources and capabilities that facilitate atomic interactions, enhancing their functionality and accessibility. Examples include subtitling services, real-time language translation, assistive navigation aids, and text-to-speech systems. By providing these enabling technologies, support services extend the functionality of atomic interactions, ensuring they meet diverse user needs and preferences.

The framework for interaction in the inclusive citiverse functions as an intermediary layer between abstract interaction models and concrete technical implementations. Atomic interactions such as authentication, communication, or object manipulation, depend on a variety of enabling services to operate effectively. These include but are not limited to identity management systems, real-time communication protocols, and accessibility tools (e.g., screen readers, speech recognition). By modularising these services, the framework ensures that interaction logic remains consistent while allowing services to be updated, replaced, or extended without disrupting the user experience. This separation of concerns supports scalability, technical flexibility, and platform independence.

Each atomic interaction in the framework is designed with explicit service dependencies. For example, authentication relies on services such as OAuth for secure token exchange, while communication may leverage WebRTC or RTP for real-time data transfer. Support services like haptic feedback engines or machine translation APIs further enhance these interactions. The framework therefore acts as an abstraction layer that binds user-facing functionality to underlying technical infrastructure in a standardized and re-usable way.

7.3 Tools for inclusive interaction in the citiverse

This section outlines key input and output interaction modalities - ranging from hand, face, and eye tracking to bio-signals and haptic feedback. Understanding these technologies is essential to building XR systems that enhance accessibility, inclusivity, and user engagement within virtual environments. It is highly recommended to have disabled people on board when extending the use of assistive technologies. People with disabilities have more expertise and creative hacks in re-adaptation and modification of assistive technologies.

Hand tracking - A system to detect and interpret hand poses, gestures and finger movements of the user in XR.

Hand-held controllers - Physical devices used to navigate and interact with XR environments via buttons and motion tracking.

Face tracking - Captures facial expressions to enable realistic avatar animation and emotion recognition.

Mouth and Lip tracking - Monitors movement around the lips and mouth for accurate speech representation and lip-sync in avatars.

Eye tracking - Tracks eye movements to enable gaze-based interaction, foveated rendering, and attention-based user interface elements in XR environments.

Feet tracking - Captures foot position and motion for locomotion and full-body presence in XR.

Full body tracking - Captures and maps the entire body's movement to enable realistic avatar representation and physical interactions in XR. Full-body tracking systems may use a combination of visual, inertial, thermal, and bio-signal inputs to achieve accurate motion representation across varied environments and use cases.

Voice based interactions - Allows users to control and interact with XR using speech.

Bio Signals based interaction - Uses physiological signals to interpret user states or enable control.

Brain Controlled Interfaces (BCIs) - Interfaces enabling direct control of XR using brain signals.

Neuromuscular Signals Uses subvocal muscle activity to silently communicate or interact.

Existing Assistive technology as an XR interface - Integrates already-in-use assistive devices into XR for accessible interaction.

Haptic feedback - Provides physical sensations to simulate touch, force, or texture in XR.

Spatialized Sound as information - Uses 3D audio cues to convey direction and context in virtual space.

7.4 Accessibility services

Accessibility services provide an alternative communication for users who cannot access or fully access audio or visual elements and for users who cannot fully understand standard language. Two key features need to be considered in virtual worlds, the first being **positioning**: access services need to be positioned in the virtual world. For instance, textual alternatives like subtitles (also called captions) need to be located on a certain area of the virtual sphere whereas audio description also need to be positioned on a certain location, i.e., the audio needs to come from a certain area of the virtual sphere. The second is **guiding mechanism**: a mechanism towards the focus of attention (speaker, virtual object, action, etc.) is needed to guide the user. For instance, if a person with hearing loss is navigating in the virtual world and someone is speaking in a location behind them, they would need a mechanism to guide them to the speaker. Examples of guiding mechanisms are arrows or radars. A light around an object could also be used as a guiding mechanism towards an object.

Additionally, the citiverse will ensure access through different input and output alternatives and facilitate user personalization to fulfil user needs. These alternative services are:

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Textual alternatives Text alternatives for audio can take different forms. Subtitles are instrumental for users who do not understand the language (interlingual subtitles) and for those who do understand the language but cannot hear it (intralingual subtitles). In this case subtitles – sometimes also called subtitles for the deaf and hard-of-hearing (SDH) – provide an alternative for speech and non-speech information such as character and language identification, paralinguistic elements, sound, silence and music. Similarly, transcripts are written alternatives to spoken words, sometimes including non-speech information and generally in the same language of the audio. For example, a user may need a transcript when they participate in a virtual meeting in a virtual world.

Audio alternatives There are different access services that provide audio alternatives to visual content, be they images or written text. Audio description provides an auditory alternative to visual content: audio description describes the visuals and supports those who cannot access the images. Audio description can be applied to static content (a work of art) or dynamic content (a video). For example, users with sight loss enjoying an art experience in a virtual world would benefit from an audio description of the works of art. They would also need an easy way to navigate to the place where the virtual exhibition is taking place and an audio description of the environment. Audio introductions provide an audio summary of the visual content before accessing it. Audio introductions complement audio descriptions. For example, a user may listen to an audio introduction describing the main features of a virtual world where a gaming experience will take place before entering this virtual world.

Visual content can sometimes be written text. For instance, content in a language A may be subtitled in language B for those who do not speak language A. However, some users may have difficulties seeing or reading the subtitles and on-screen text. Audio subtitles provide an audio version of subtitles and on-screen text for those who do not understand the source language and cannot read these visual textual elements. For example, a virtual world may feature an avatar speaking in Catalan with automatic subtitles in English. An English-speaking person with sight loss or with reading difficulties would not be able to access this content unless audio subtitles (also called spoken subtitles) are offered.

Visual gestural alternatives Sign language interpreting provides a visual gestural alternative to oral languages, benefitting users who cannot access the audio and understand sign language. Similarly, oral language interpreting may provide a spoken version of a sign language or another oral language. For instance, spoken content in English in a citiverse may be signed into American Sign Language. Similarly, a Catalan sign language speaker and a Catalan oral speaker may communicate through interpreting services.

Haptic alternatives Haptic alternatives may facilitate and enhance communication with users through vibrotactile features or by a change of temperature. For instance, haptic feedback may offer cues to a blind user so that navigation in the virtual world is easier. Deaf-blind users may use a Braille display to access visual information.

Easy-to-understand languages Easy-to-understand languages encompass different simplified language varieties that enhance comprehensibility, ranging from Easy Language (or Easy-to-Read or Easy Read) to Plain Language. Easy Language is the most simplified modality and is especially addressed to persons with comprehension difficulties for any reason. Plain Language is less simplified and is addressed to a broader user group, not necessarily with comprehension difficulties.

In the citiverse it would be good practice to offer instructions in Plain Language, providing also Easy Language alternatives. Similarly, it would be necessary to offer users an easy way to go to a safe place or allow them to

customize the environment in the virtual world in case they do not understand, or feel overwhelmed. For instance, a user may look for a more relaxed gaming experience in the virtual world, with easy navigation alternatives, a slower pace, Easy Language content and a shortcut that takes them to a safe space or adjusts the light or the noise. Easy-to-understand languages can also be applied to access services such as audio description, subtitling or sign language interpreting to create hybrid easy-to-understand access services.

7.5 Standards

Standardization in ICT for citiverse digital inclusiveness has primarily focused on accessibility for persons with disabilities. Since the late 1990s, various international standards have been developed to enhance the accessibility of ICT products and services, by Study Group 21 (SG21, formerly SG16) and Study Group 20 (SG20) of the International Telecommunication Union Telecommunication Standardization Sector (ITU-T), as well as Subcommittee 35 (SC35) under the Joint Technical Committee 1 (JTC1) of ISO/IEC, and World Wide Web Consortium (W3C).

ITU-T has issued recommendations on accessibility to telecommunication networks and services, while ISO/IEC JTC1 has developed accessibility standards across a wide range of IT domains, including hardware, software and the web, providing a reference framework for national adoption.

Although the World Wide Web Consortium (W3C) is not formally part of international standardisation development organisations (SDOs), it plays a crucial role in accessibility, especially web accessibility, which is the starting point and the most mature area of digital accessibility discourse.

W3C's Web Content Accessibility Guidelines (WCAG) have become the de facto international standard, recognized as ISO/IEC 40500 and adopted by numerous countries as national standards, forming a shared global framework for accessibility.

ITU-T

As a United Nations specialized agency for digital technologies, the International Telecommunication Union (ITU) has issued recommendations for ICT accessibility since the mid-2000s. Within ITU's Telecommunication Standardisation Sector (ITU-T), various study groups have developed standards for accessible communication services targeting persons with disabilities and older persons. In 2007, ITU-T approved its first comprehensive accessibility guideline: ITU-T Recommendation F.790, "Telecommunications accessibility guidelines for older persons and persons with disabilities". This document guides designing accessible communication devices, software, and services, serving as a global reference for telecom operators and manufacturers. It includes a wide range of requirements—from physical design of telephone terminals to software user interfaces and service procedures—forming the foundational framework for subsequent accessibility standards.

ITU has since expanded its scope to cover media accessibility and terminology. In 2015, ITU-T adopted Recommendation F.791, which defines standardized terms related to accessibility, disability and assistive technologies, aiming to support consistency among national standards developers. In the broadcasting and multimedia domain, Recommendation H.702 (2015) defines accessibility profiles for IPTV systems, including support for subtitles, sign language, and audio description; the 2020 revision updated technical requirements for delivering accessible content on modern IPTV platforms. Additional specifications include annexes to the H-series defining testing frameworks, and FSTP-AM (2015), a guideline on audiovisual conferencing accessibility.

Several standards targeting audiovisual impairments were issued in 2018. ITU-T Recommendation F.921 defines concepts and requirements for audio navigation systems for visually impaired individuals, applicable to indoor and outdoor environments. ITU-T F.930, on the other hand, specifies functional and procedural standards for multimedia telecommunication relay services such as remote sign language interpretation for individuals with hearing or speech disabilities. Other reports such as FSTP-ACC-RemPart (2015) on remote participation accessibility, have gained relevance during the pandemic and the era of increased virtual engagement.

ITU is also actively developing accessibility standards in emerging fields like smart cities, the Internet of things (IoT), and artificial intelligence. Recommendation Y.4204, issued by ITU-T Study Group 20 (IoT and Smart Sustainable Cities and Communities), outlines accessibility requirements for IoT-based services for persons with disabilities and the elderly. It presents various use cases—such as smart home devices, wearables, and environmental control systems—and categorizes design considerations by types of disabilities (visual, hearing, motor, and cognitive). In 2023, this was expanded into Recommendation Y.4219, which adds further guidance to enhance accessibility across broader IoT and smart city infrastructures. To ensure accessibility is integrated into all ICT standards, ITU-T has also adopted ISO/IEC Guide 71:2014 as ITU-T H. Suppl.17, which recommends incorporating accessibility considerations into all stages of standards development in cooperation with ISO and IEC.

ISO/IEC JTC 1

The ISO/IEC JTC 1 (Joint Technical Committee 1 on Information Technology) formulates international standards encompassing all domains of Information and Communication Technology (ICT) and has instituted accessibility standards in diverse sectors, including software, hardware, the web, education, and assistive technologies through its dedicated working groups. Among the early standards established in the late 2000s were guidelines for software accessibility and documents delineating the requirements of users with disabilities. For instance, ISO 9241-171:2008 serves as a standard that provides comprehensive guidelines to guarantee that software interfaces can be utilized efficiently and satisfactorily by persons with disabilities. It incorporates extensive recommendations such as providing alternative text for user interface elements, supporting keyboard navigation, and maintaining adequate contrast ratios.

Another example is ISO/IEC TR 29138-1:2009, a technical report that consolidates prevalent accessibility requirements for users with disabilities. This document offers an enumeration of comprehensive requirements across approximately 14 distinct areas, functioning as a reference for standards developers. The report underwent revision in 2018 to accommodate users' needs in the current technological landscape.

In the realm of web accessibility, JTC 1's most noteworthy achievement was the formalisation of W3C guidelines as international standards. In 2012, ISO/IEC JTC 1 published ISO/IEC 40500:2012, which serves as an exact adoption of the W3C Web Content Accessibility Guidelines (WCAG) 2.0. WCAG 2.0 comprises twelve guidelines along with detailed success criteria organized under four principles: Perceivable, Operable, Understandable, and Robust. By achieving the ISO/IEC 40500 status, these guidelines can be referenced more effectively as national standards worldwide. (Note: While W3C released WCAG 2.1 in 2018, the ISO version remains at 2.0 as of 2025, with expectations that WCAG 2.2 and subsequent versions will also be adopted as international standards.)

The interoperability of hardware and assistive technology interoperability has been a key concern for JTC 1. The ISO/IEC 29136:2012 standard, entitled "Accessibility of Personal Computer Hardware," establishes

methodologies for the design of hardware interfaces—such as keyboards, mice, and displays—to ensure accessibility for persons with disabilities (for instance, using Braille displays, tactile markers, force thresholds, and so so). The ISO/IEC 13066 series pertain to the compatibility between operating systems and assistive technologies (including screen readers and specialized mice). Part 1 (2011) delineates the requirements for interoperability, while the accompanying annexes offer environment-specific guidelines for Windows, Linux, and other systems.

Furthermore, the ISO/IEC 24751 series (2008–2013) has established standards for articulating individual accessibility preferences within personalized learning environments, thereby contributing to the definition of the concept of “AccessForAll” in the field of education.

Recently, standards have been developed in response to the emergence of artificial intelligence (AI) and the diversification of digital content. ISO/IEC 30071-1:2019 provides a comprehensive code of practice for incorporating accessibility considerations throughout the ICT product and service development process. It systematizes the approach by which development organisations can define accessibility objectives and effectively implement and verify them.

Other technical committees under the International Organisation for Standardisation (ISO) have also published related standards. For instance, ISO 21801-1:2020, entitled “Cognitive Accessibility Guidelines,” delineates principles for the design of products and services intended for users with cognitive disabilities, making it a significant reference in AI-based service design. Additionally, the International Electrotechnical Commission (IEC) has released IEC 63008:2020, which specifies methods for testing accessibility in household appliances. This aims to improve the usability of smart home and Internet of things (IoT) devices for persons with disabilities.

Efforts have also been undertaken to incorporate accessibility considerations into the standardization process itself. ISO/IEC and ITU have collaboratively published ISO/IEC Guide 71:2014, titled “Guide for addressing accessibility in standards.” This guide provides practical recommendations to standard developers regarding the systematic incorporation of the needs of persons with disabilities, older populations, children, and others into all standards. It advocates for strategies and objectives concerning accessibility, including the principle to “consider universal access from the outset of design.” Consequently, due to the dissemination of this guide, a greater number of new ISO and ITU standards now encompass accessibility clauses, thereby reinforcing the global trend towards digital inclusion through standardization.

W3C

W3C launched the Web Accessibility Initiative (WAI) in 1997, continuing to develop standards aimed at enhancing accessibility and inclusiveness for people with disabilities. Early on, it established foundational guidelines such as WCAG 1.0 (1999), ATAG 1.0 (2000), and UAAG 1.0 (2002), which set principles for web content, authoring tools and user agents (browsers). In 2008, W3C adopted WCAG 2.0 as a formal recommendation, restructuring the guidelines, and later updated them with ATAG 2.0 and UAAG 2.0 in 2015. WCAG 2.1 (2018) addressed mobile environments and the needs of users with cognitive, learning, and low-vision disabilities, while WCAG 2.2, released in 2023, further expanded the success criteria.

In parallel, the WAI-ARIA (Accessible Rich Internet Applications) specification evolved to support dynamic web content—initially released as version 1.0 in 2014, updated to 1.1 in 2017, and again to 1.2 in 2023. W3C is also developing WCAG 3.0, a next-generation set of guidelines intended to encompass not only web content but also

applications, authoring tools, publishing, and other digital technologies within a more inclusive framework.

WCAG 2.2, published in October 2023, added 9 new success criteria to the existing WCAG 2.1 framework, strengthening accessibility for users with cognitive impairments, low vision and those who rely on keyboard navigation. Notable additions include clearer focus indicators, alternatives to drag-and-drop actions, minimum touch target sizes and simplified authentication methods. These enhancements maintain backward compatibility while improving support for mobile and modern interfaces.

Meanwhile, WCAG 3.0 remains in draft form and proposes a fundamental shift from binary pass/fail criteria toward a more flexible, tiered conformance model (Bronze, Silver, Gold). It expands the scope to cover a broader range of digital content, including applications, PDFs, and IoT devices. WCAG 3.0 emphasises user-centred accessibility, technical neutrality, and measurable outcomes, aiming to improve inclusiveness and real-world effectiveness.

Global digital identity standards are evolving, focusing on interoperability, security, and user control, driven by organizations like the International Organization for Standardization ([ISO](#)) which develops identity-proofing standards (e.g., ISO/IEC 29003), and the World Wide Web Consortium ([W3C](#)) which develops open standards like Decentralized Identifiers ([DIDs](#)).

7.6 Regulatory framework

UN Sustainable Development Goals (SDGs), especially SDG 11 (Sustainable Cities and Communities) and SDG 10 (Reduced Inequalities) and the UN CRPD.

In 2006, the United Nations convention on the rights of persons with disabilities (CRPD) came into force. The CRPD is one of the nine core international human rights treaties, and it includes 33 articles covering all the areas of life. By 2016, 161 out of 193 United Nations Member States had ratified the CRPD, this is more than 80 per cent of countries [b-UN OHCHR]. Once a country ratifies, it is legally bound to implement the core 33 articles and must report on its progress in writing to the United Nations periodically. CRPD recognizes the importance of access to communication in Article 9 where it states:

“To enable persons with disabilities to live independently and participate fully in all aspects of life, States Parties shall take appropriate measures to ensure persons with disabilities access, on an equal basis with others, to the physical environment, to transportation, to information and communications, including information and communications technologies and systems, and to other facilities and services open or provided to the public, both in urban and in rural areas.”

Two examples of legislation [b-DREDF] related to IT development and disabilities are the United States of America (USA) and the European Union (EU). In the US, the Twenty-First Century Communications And and Video Accessibility Act (CVAA) was signed by President Barack Obama on 8 October, 2010. The CVAA makes sure that accessibility laws enacted in the 1980s and 1990s are brought up to date with 21st century technologies, including new digital, broadband, and mobile innovations. Another example is in the European Union (EU), comprising 27 Member States. The EU is not a nation state but rather an alliance of nations. Each individual EU country maintains its own relationship with the UN as an independent party. For issues of media accessibility, the EU collectively engages as a party, thereby influencing all 27 Member States.

Three pieces of legislation have been the result of the CRPD adoption in the EU. These three pieces have taken the form of a directive, which is legally binding, meaning that the EU member states have an obligation to apply

the content of the act. In chronological order the first is the audiovisual media service directive (AVMSD) Directive 2010/13/EU of the European Parliament and of the Council of 10 March 2010 on the coordination of certain provisions of audiovisual media services. This directive created an EU-wide legal framework to coordinate national legislation on all audiovisual media, whether traditional TV broadcasting or on-demand services platforms working in the EU such as Netflix, Amazon Prime Video, Apple and HBO. The directive covers different aspects of audiovisual media such as the prohibition of hate speech and discrimination based on disability and other grounds, commercial information on TV programmes, protection of minors, independence of the national regulatory bodies that monitor audiovisual services, and the promotion of European audiovisual productions. The directive established legal requirements to advance accessibility of audiovisual media for persons with disabilities. In 2018, the EU updated AVMSD with stronger requirements for accessibility. In light of the evolving market realities, the Directive (EU) 2018/1808 of the European Parliament and of the Council, dated 14 November 2018, modifies Directive 2010/13/EU [b-EU AVMSD]. This directive pertains to the coordination of certain provisions established by law, regulation, or administrative action in Member States concerning the provision of audiovisual media services (audiovisual media services directive), commonly known as the audiovisual media services directive.

The second directive is the web accessibility directive (EU) 2016/2102 of the European Parliament and the Council of 26 October 2016 [b-EU WAD]. This directive covers the accessibility of the websites and mobile applications of public sector bodies. It forces public sector bodies such as municipalities, schools, health services and transport information, to make their websites and mobile applications accessible to people with disabilities. The Directive requires websites and applications (APPS) of public sector institutions to meet specific technical requirements set out in web accessibility standards such as W3C, and it also mentions a limited number of exceptions for example, the accessibility of the interaction with media player, and the media player itself. The directive requires:

- An accessibility statement for each website and mobile application.
- A feedback mechanism so that users can flag accessibility problems or request access to inaccessible content.
- Regular monitoring and reporting of results of public sector websites and applications by Member States.

The third piece of EU legislation is Directive (EU) 2019/882 of the European Parliament of the Council of 17 April 2019 that concerns, whichi accessibility requirements of products and services European accessibility act [b-EU EAA]. This law seeks to make products and services in the EU more accessible for people with disabilities. Some examples include smartphones, tablets, computers, TV and its content, e-books, online shopping websites, self-service terminals, delivery of transport service information, including real-time travel information, consumer banking services, and so on. There is a marked difference in this directive from the previous two accessibility directives, namely, the extension to public and private sector organizations, who are required to monitor the accessibility of their respective websites, mobile applications and media content. In addition to this requirement, organizations are required to provide an accessibility statement to a central authority in their respective countries. The EAA since 20 June 2025 is in force and mandatory.

Almost all countries in the world have signed and ratified the CRPD leading to several national actions, i.e., to draft legislation to support CRPD, to develop standards to provide requirements, specifications, guidelines to fulfil the national legislation, and finally to report to the United Nations.

7.7 Use cases

Lessons from Estonia and Helsinki

Estonia's e-ID proves that secure, universal digital identity can give every citizen recognized access to services, from voting to health care, with minimal friction.

Helsinki's MyData framework and digital twin show how citizen-controlled data and immersive planning tools can turn that access into real influence. Together, they form a roadmap for a citiverse that is participatory, inclusive, and technically accessible, where people are visible in the system and active in shaping it.

7.8 Conclusion

In conclusion, the development of an inclusive native citiverse is essential for creating a digital urban ecosystem that is equitable, participatory, and representative of all citizens. By involving a diverse coalition of urban planners, architects, civic tech experts, policymakers, and community advocates, we can ensure that the citiverse is designed with accessibility, usability and inclusivity at its core. This approach not only bridges the digital divide but also fosters resilience in governance, services, and cultural preservation. By prioritizing user-centric design and considering diverse needs from the outset, we can prevent biases and ensure ethical use of data, ultimately enhancing citizen participation and trust in digital governance. The inclusive citiverse is not just a vision for the future; it is a necessary foundation for a just, ethical and future-ready digital society.

8 Pilot case studies & global lessons

Chapter 8 highlights practical pilot use cases that demonstrate how digital twin technology and immersive virtual world platforms can solve real challenges cities face today. The goal of this chapter is to present replicable, high-impact case studies that cities around the world can learn from and scale—leveraging these experiences to inform their journey into the citiverse [22]. Each use case is mapped to IDC's three-tier Horizon Framework, which classifies urban technologies based on maturity: Horizon 1 (deployed), Horizon 2 (early pilot), and Horizon 3 (discovery phase).

8.1 Use Case 1: Aurora, Canada – Civic engagement and transparency

Horizon category: Horizon 1

Urban challenge:

Aurora faced limited citizen participation, poor transparency in local governance, and misalignment between citizen needs and public service delivery.

Solution summary:

MetaWorldX developed a Citizen Engagement Digital Twin platform that integrated GIS, real-time IoT feedback, and a mobile-first UI. Citizens could report issues, participate in public polls, and track project progress via a centralized platform.

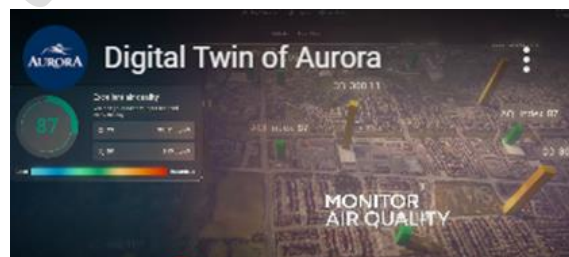
Infrastructure requirements:

- Integration with GIS systems and city dashboards
- Mobile and web-based citizen interface
- Feedback API with IoT and service request tracking

Global lessons:

- Even small municipalities can deploy high-impact digital twins with limited infrastructure
- Transparent digital feedback loops improve trust and civic participation
- A low-barrier platform design maximizes inclusivity

Figure 4 Aurora City Digital Twin – Citizen Facing



<https://metaworldx.com/project/aurora/>

<https://www.aurora.ca/business-and-development/auroras-digital-twin/>

8.2 Use case 2: NEOM, Saudi Arabia – Public safety and command & control

Horizon category: Horizon 2 → Horizon 3

Urban challenge:

NEOM required an intelligent safety system for its C2 Centre to manage physical security, emergency simulation, and command workflows at scale. Traditional surveillance lacked predictive and integrated capabilities.

Solution summary:

MetaWorldX implemented a Public Safety Digital Twin featuring 3D visualizations of the command centre, IoT sensor integration, and AI-powered scenario simulations (e.g., rogue ship intrusion, fire evacuation). Systems included PSIM, access control, and real-time dashboards for security operators.

Infrastructure requirements:

- High-fidelity 3D virtual environment of the C2 Centre
- Integration with access control, PSIM, and VMS systems
- AI models for threat simulation and emergency response planning

Global lessons:

- Safety operations benefit significantly from integrated digital twins with real-time and predictive capabilities.
- Urban resilience can be enhanced with simulation-based response frameworks.
- Complex infrastructure requires cross-system interoperability for maximum impact.

Figure 5 NEOM Public Safety



8.3 Cross-cutting Horizon 1 use cases

In addition to the MetaWorldX Case Studies, other Horizon 1 use cases provide immediate, scalable benefits that cities can implement today:

- 1) **Digital Underground Asset Mapping:** Cities can digitally map underground infrastructure (e.g., pipes, cables) for safer construction, planning, and permitting. Example: UK's NUAR project improved efficiency and reduced accidents during digs.
- 2) **Smart Waste Management and Recycling:** A city-wide digital twin tracks waste output, optimizes collection, and promotes recycling. Example: Copenhagen's Cisco-powered digital twin enhanced urban operations.
- 3) **XR-Enabled Fieldworkers:** Frontline workers equipped with AR/VR tools can visualize assets, follow checklists, and connect with remote experts. Example: Vienna's BRISE project combines BIM and AR for digital inspections.
- 4) **Urban Air Quality Monitoring:** Digital twins fed by IoT sensor networks visualize and predict air pollution levels. Example: BINUS University in Jakarta integrates sensor data with real-time visualization.
- 5) **Traffic Optimization and Simulation:** AI-fed digital twins' model real-time road activity to reduce congestion and emissions. Sensor fusion from traffic cameras, connected vehicles, and road infrastructure fuels these simulations.

8.4 Use Case 3: Granada, Spain – Alhambra Living Lab: Heritage Conservation & Visitor Experience

Horizon Category: Horizon 1 → Horizon 2

Urban challenge:

Preserve a UNESCO heritage site under high visitor pressure while improving accessibility and interpretation for diverse audiences, and maintaining environmental comfort and structural health across palaces, gardens, and access areas.

Solution summary:

The Alhambra Living Lab deploys a standards-based 3D Digital Twin that fuses real-time IoT (crowd flows, air/noise, parking, structural and soil conditions) with analytics dashboards and an immersive 3D viewer. A multilingual LLM assistant (LLaMa) personalizes routes, audioguides, and educational content and explains simulation results. The platform is FIWARE-based (NGSI-LD) with data-space connectors and operates as secured SaaS; it is aligned with the EU Local Digital Twin Toolbox and EDIC for sustainability and cost-effective operations.

Infrastructure requirements aligned with the blueprint:

- **IoT sensing network (560 devices):** 30 Wi-Fi/BLE crowd-counting Smart Spot units; 10 Smart Spot Air for air quality & noise; 500 NB-IoT parking sensors; 10 Libelium ONE indoor nodes for structural

monitoring; 10 Libelium ONE soil probes for gardens.

- **3D capture & visualization:** Photogrammetry (camera provided) to generate the 3D model; Unreal-based renderer and Eagle 3D Stream for web access and XR; BIM-ready indoor/outdoor navigation.
- **Dashboards & analytics:** Grafana BI dashboards; real-time and historical views; overlays of sensor layers on the 3D model.
- **AI & assistants:** LLM/Generative AI (LLaMa) for multilingual, age-appropriate content, interactive tours, and explanation of model outputs.
- **Data & standards:** FIWARE Context Broker (NGSI-LD/NGSIV2), OpenAPI, GAIA-X, DCAT-AP, ENI; connectors to data spaces/SmartDataModels (MiM1 / MIM2 / MIM3).
- **Cloud & security:** SaaS on OVHcloud with ENS Alto; pentesting (MyCloudDoor) and accessibility audits; ISO/UNE compliance.
- **Existing systems integration:** Interactive map & audio guide APIs; SIALH and RIA repositories; use of on-site Wi-Fi to extend IoT coverage.
- **Capacity building:** Training and technology transfer with the University of Granada; onsite and online sessions in Granada/Sevilla.

8.5 Global lessons:

- **Open, EU-aligned stack reduces lock-in and TCO:** FIWARE/GAIA-X standards and EDIC support enable long-term maintenance, shared infrastructure, and up-to-date components.
- **From monitoring to prediction:** Built-in models (e.g., CHIMERE, MUNICH, Street-Canyon) turn sensing into actionable simulations for air quality and comfort.
- **Interpretation at scale with LLMs:** A domain-tuned assistant broadens accessibility (language, age, expertise) and helps stakeholders understand twin outputs.
- **Security and compliance matter for heritage sites:** ENS Alto, ISO and pen-testing practices are feasible within culture-tourism contexts.
- **Upskilling local team's anchors sustainability:** Structured documentation and hands-on training foster autonomy beyond the initial deployment.

8.6 Conclusion: A Blueprint for the Global Citiverse

The examples from Aurora and NEOM illustrate the spectrum of what is possible – from simple, citizen-focused platforms to integrated public safety systems with predictive simulation. Supplemented by mature Horizon 1 applications like underground asset mapping and XR-enabled inspections, these use cases form a growing body of knowledge that cities can replicate and scale. By capturing these insights in Chapter 8, we aim to equip cities globally with practical, field-tested strategies to enter the citiverse – one use case at a time.

9 Sandbox Environments & Prototyping Ecosystems

In the evolving landscape of the citiverse, sandbox environments serve as foundational pillars for innovation, policy development and inclusive experimentation. These are not merely any digital simulations, but structured ecosystems that replicate urban dynamics to enable safe, scalable, and responsible testing of new technologies, regulatory models, and civic participation mechanisms.

Sandbox environments are digitally simulated, policy-enabled frameworks that allow governments, start-ups, researchers, policymakers, industry partners, and citizens to co-create, validate, and refine innovative solutions in a controlled, feedback-rich setting. Much like flight simulators used to train pilots before real-world deployment, these testbeds reduce risk while enhancing readiness. They combine digital twins, synthetic or anonymized real-world data, and programmable rules to create virtual cities that can be explored without physical or regulatory disruption.

The value of sandboxes within the citiverse lies in their ability to accelerate discovery while safeguarding public trust. They allow for rapid prototyping of digital tools, new governance models, and participatory mechanisms, particularly in areas like urban planning, AI for public services, immersive citizen engagement and digital identity systems. For cities facing increased complexity, interdependence, and public scrutiny, sandboxes become a strategic asset, not a luxury.

The citiverse sandboxes should be developed on flexible technology stacks, utilizing platforms such as Unity, Unreal Engine, NVIDIA Omniverse, Cesium, and open-source frameworks depending on project needs. These platforms are cloud-native or hybrid, allowing for scalable deployment while addressing latency-sensitive simulations. Hosting environments can be deployed on leading cloud platforms such as AWS, Azure, or European sovereign clouds like GAIA-X, depending on local data sovereignty needs. Spatial data infrastructures, including GIS systems, IoT telemetry, transportation models, and synthetic demographics, power the realism of these digital twins.

AI and machine learning tools play a central role within the sandbox, not just in creating intelligent agents or automating services, but also in forecasting, optimization, and behavioural modelling. Simulated chatbots for permitting, AI-powered traffic models, or energy grid optimizations are tested safely, enabling cities to understand the benefits and potential harms before implementation. Ethical considerations such as algorithmic bias, surveillance risks, and explainability, must be integrated into sandbox protocols and evaluation tools.

Beyond the technical layer, sandboxes are anchored in standards and governance principles. Interoperability frameworks based on ITU-T Recommendations (e.g., Y.4208, Y.4505), CityGML, IFC, OpenAPI, JSON-LD, and other open standards such as NGSI-LD, EPCIS/GS1, and OGC APIs ensure that these environments are not isolated experiments but integrable parts of broader digital ecosystems. Ontology-driven design ensures semantic interoperability across domains like energy, mobility and public health.

Ethical and inclusive governance is embedded in the sandbox architecture. Data privacy, user consent, and digital identity frameworks are not afterthoughts; they are core to the design. Decentralized Identifiers and verifiable credentials offer secure and user-centric identity management.

Digital identity is extended not only to citizens but also to urban assets such as smart lighting, mobility hubs, or environmental sensors, ensuring secure authentication and interaction within the virtual twin. GDPR compliance, behavioural transparency, and zero-trust cybersecurity models further ensure trustworthiness.

Participation rules and inclusion principles guide how these environments operate. They are designed to be open to local governments, industry partners, civil society actors, and citizens, with special emphasis on involving underrepresented groups such as youth, women, and marginalized communities. Through co-creation workshops, gamified simulations, and feedback loops, these environments foster equitable innovation. Beyond testing, sandboxes serve as capacity-building platforms, offering training modules, documentation, and city-to-city learning exchanges to strengthen digital competencies across urban teams.

A sandbox is therefore more than a test site; it is a programmable layer of urban governance. Legal sandbox frameworks allow regulators to issue time-bound exemptions for testing experimental technologies under supervised conditions. This creates room for policy innovation: governments can test new models of data governance, welfare distribution, zoning, or urban AI without locking into long-term risk. Sandbox environments increasingly incorporate RegTech solutions, dashboards, algorithmic compliance checks, and automated audit tools, to monitor regulatory performance in real time.

The infrastructure of a citiverse sandbox is built with care. From digital twin platforms like Bentley iTwin, Dassault 3DEXPERIENCE, or open-source equivalents, to CI/CD pipelines, containerized architecture orchestrated with Kubernetes, and observability layers powered by tools such as Grafana and Prometheus, the system is agile and robust. Sandbox-specific APIs and SDKs enable developers to contribute, iterate and scale their solutions. Developer ecosystems are supported through public APIs, testing datasets, and sandbox SDK toolkits.

Security and compliance are non-negotiable. Federated identity systems, encrypted communications, automated audit trails, and sandbox isolation protocols ensure that participants can operate safely, while maintaining accountability. Governance structures such as sandbox councils or public oversight boards, add another layer of ethical review.

Depending on the use case, sandboxes may be accessed via desktop interfaces, mobile devices, or immersive headsets such as Meta Quest or HTC Vive, and are optimized for high-speed 5G and edge network connectivity.

The [Global Initiative on Virtual Worlds and AI](#) is already piloting sandbox environments in several cities, particularly in the Global South. These testbeds focus on locally relevant challenges, climate adaptation, civic tech, decentralized identity, and are designed to run on minimal infrastructure, often with offline capabilities. In doing so, they democratize access to cutting-edge innovation tools. Sandboxes also support climate resilience planning, including urban heat island mapping, flood risk simulation, and energy grid stress testing under climate extremes.

Case studies such as Virtual Singapore illustrate the potential of city-scale sandboxes. There, detailed urban simulations support public planning and private sector experimentation, showing how data-rich environments can be the backbone of smart, collaborative city building.

Singapore also offers a compelling model for policy experimentation through its Monetary Authority of Singapore (MAS) regulatory sandbox. While focused on fintech, this framework serves as inspiration for urban applications such as testing zoning algorithms, AI-based hiring tools, or decentralized utility billing systems in a time-bound, supervised environment.

Sandbox environments are typically led by municipal innovation departments, national digital authorities, or UN agencies in collaboration with academic and industry partners.

To move from prototype to policy, cities can embed sandboxes into their long-term innovation infrastructure. This includes graduation pathways for successful experiments, documentation aligned with international standards, and funding mechanisms such as public-private partnerships or mission-oriented accelerators. To ensure meaningful outcomes, sandboxes should align with measurable KPIs such as SDG indicators, Net Zero impact metrics, or citizen satisfaction indexes, bridging experimentation with strategic city goals.

9.1 Use case integration: From vision to real-world prototypes

The Horizon Framework developed under the Global Initiative on Virtual Worlds and AI, categorizing digital transformation initiatives as Horizon 1 (deployed), Horizon 2 (early pilot), and Horizon 3 (discovery phase), provides a useful structure for understanding the maturity and scalability of sandbox-based innovations. Chapter 8 outlined global case studies mapped to this framework, offering practical insights that inform the development and operationalization of citiverse sandbox environments.

These examples not only demonstrate how sandbox-based prototypes can evolve into live deployments, but also highlight the foundational role of interoperability, inclusion and regulatory foresight. Together, they shape a growing library of replicable digital twin solutions that cities can adapt based on their own infrastructure and priorities.

The principles described above are already being tested in pioneering use cases across the world. For instance:

- Digital Underground Asset Mapping (UK): A digital twin of underground pipes and cables enables safer infrastructure planning and coordination across stakeholders, as demonstrated in the UK's National Underground Asset Register (NUAR). This project is projected to save more than GBP 400 million annually through efficiency and safety improvements.
- XR-Enabled Urban Planning (Nottingham): XR and immersive digital twins allow citizens and planners to explore future urban developments. Nottingham's 3D planning platform has unlocked billions in investment through better planning workflows and stakeholder engagement.
- Air Quality Monitoring and Prediction (Jakarta): BINUS University is piloting a digital twin for urban air quality, integrating sensor data and MR environments to visualize and simulate pollution interventions.
- Smart Waste Management (Copenhagen): A digital twin project integrates data across urban services including waste management, enabling optimized operations and environmental impact reduction.
- Immersive Operational Command & Control (Singapore): A national-scale digital twin supports crisis response, flood management, and public health coordination in real time.
- Cyberthreat Simulation for Critical Infrastructure (Australia): Immersive command environments simulate cascading infrastructure failures and threat scenarios, supporting risk mitigation and network resilience.
- Agentic Urban Environments (Project Sid): AI agents autonomously simulate urban interactions, enabling experimentation with city design, governance models, and civic behaviours.
- Civic Engagement Platforms (Aurora, Canada): A lightweight digital twin and citizen portal enhanced transparency and participatory governance at municipal scale.

These use cases exemplify how sandbox environments, paired with digital twin and metaverse technologies, can turn ambitious ideas into tested, scalable innovations. Their lessons form a living blueprint for cities seeking to enter and thrive in the citiverse.

9.2 Conclusion: Building trustworthy innovation in the citiverse

In conclusion, sandbox environments embody the meeting point between **bold ideas and responsible implementation**. Within the citiverse, they are not transient pilots but **enduring components of a living architecture**—spaces where futures are tested, refined, and scaled with trust.

The recommendations presented in this document constitute a **comprehensive framework for digital transformation**, yet they are not intended as a universal prescription. Each city's **vision, maturity, and strategic priorities** should guide the selection and adaptation of specific components, technologies, and standards.

To this end, cities are encouraged to undertake a **contextual scoping and tailoring exercise**—identifying the elements most relevant to their current phase of development, institutional capacity, and desired outcomes. For instance, a city beginning with a focused initiative such as citizen participation in service design may not require the full suite of data or real-time systems described herein, while a more mature city may advance toward integrated IoT, AI, and interoperability infrastructures.

By embedding innovation within **structured, inclusive, and ethical environments**, and by calibrating scope to local realities, the citiverse ensures that digital transformation remains **adaptive, equitable, and aligned with human needs, planetary boundaries, and democratic values**.

About the Global Initiative on Virtual Worlds and AI – *Discovering the Citiverse*

Launched by ITU, UNICC, and Digital Dubai, the [Global Initiative on Virtual Worlds and AI – Discovering the Citiverse](https://www.itu.int/metaverse/virtual-worlds/) is a multistakeholder platform dedicated to shaping the next generation of AI-powered virtual worlds¹⁴⁴.

These immersive digital environments are transforming how people live, learn, govern, and interact. The Initiative ensures that AI-powered virtual worlds evolve in ways that are inclusive, interoperable, and human-centric—and that they help deliver on the Pact for the Future and its Global Digital Compact.

Serving as a neutral and action-oriented platform, the Initiative brings together cities, governments, UN agencies, private sector companies, academia, and civil society to collaboratively shape the responsible development and deployment of these technologies.

The Initiative advances its mission through three strategic pillars, each supported by dedicated tracks that address the most urgent challenges and promising opportunities in AI-powered virtual worlds. This comprehensive structure enables the Initiative to deliver high-level global guidance and practical implementation in cities worldwide.

The Initiative is supported by more than 70 international partners.

For more information, please visit: <https://www.itu.int/metaverse/virtual-worlds/>.

Meet the Champions

Champions are entities that demonstrate leadership by providing financial contributions in support of the Initiative. This may include funding for events, challenges, research outputs, communication activities, trainings, travel grants, or other related efforts.



Meet the Founding Partners

Founding Partners are the organizations that launched the Initiative. They serve as the core convening entities and contribute to shaping its long-term vision. The Founding Partners are:



Meet the Supporters

Supporters are organizations that have expressed endorsement of the Initiative and actively participate in its activities. This includes, but is not limited to, participation in tracks, contribution of use cases, co-organization of events, provision of expertise, or public advocacy of the Initiative.



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¹⁴⁴ <https://www.itu.int/metaverse/virtual-worlds/>



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For more information,
please contact: virtualworlds@itu.int
Website: <https://www.itu.int/metaverse/virtual-worlds/>

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