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D2.1: SENSE Standards Register

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Executive Summary

The rapid convergence of digital technologies, encompassing digital twins, virtual, augmented, and mixed reality (VR, AR, MR), and the emerging of the metaverse, calls for coherent standardization to enable interoperability, security, and ethical governance across these interconnected domains. This deliverable provides a comprehensive overview and roadmap of relevant standards alike relevant standardisation activities useful for the SENSE project, aiming to foster harmonization in the development and deployment of next-generation immersive environments. The objective is to consolidate terminology, identify best practices for interoperability and security requirements, and outline the current state of VR, AR, and MR and metaverse standards, thereby enabling consistent and scalable implementations in digital twin and metaverse platforms within the SENSE project.

This deliverable D2,1 is a comprehensive document detailing the SENSE most relevant standards and that act as Standard Register. This deliverable will serve as a publicly accessible database mapping the landscape of SENSE-related standardization activities, providing insights into emerging standards, their categories, and their relevance to the SENSE project. This deliverable positions the SENSE standardization activities within this emerging complex ecosystem, addressing terminologies, data and identity frameworks, and the evolving landscape of immersive reality technologies. It further explores metaverse-related specifications, with a detailed focus on digital twin standards, virtual and augmented reality frameworks, and mixed reality specifications, before advancing into the architecture of metaverse city components and data-related standards for adoption and privacy.

The deliverable begins by introducing its purpose and structure, then positions SENSE within the broader standardisation context. It explores core Metaverse components and Digital Twin specifications, highlighting contributions from ISO, IEEE, W3C, and the Metaverse Standards Forum. Further sections examine standards for urban Metaverse environments, with emphasis on infrastructure and city data frameworks. This deliverable also addresses critical data-related standards covering privacy, sharing, and governance. This standards registry serves as a practical guide for understand then applying relevant standards to support the SENSE project's goals in building secure, interoperable smart city solutions.

The Chapter 1 introduces the scope and purpose of the Standards Registry, explaining its role within the SENSE project and outlining how the deliverable is structured for practical use by relevant partners. Chapter 2 situates the SENSE standardisation activities within the broader landscape by defining essential terminology and frameworks, with a focus on identity, data management, ethics, and operational requirements. Chapter 3 delves into the specification of Metaverse components, examining Digital Twin standards in depth and surveying contributions from major standardisation bodies such as ISO/IEC, IEEE, and the Metaverse Standards Forum. It explores how these components can serve as references within the SENSE context. Chapter 4 shifts focus to Metaverse city components, discussing infrastructure, frameworks, and data standards needed to build immersive, interoperable urban environments. Chapter 5 addresses critical data-related standards and their role in the adoption of Metaverse technologies. It explores aspects such as data sharing, privacy, and protection, presenting best practices and guidelines developed under the SENSE initiative to ensure secure and efficient data usage. Finally, Chapter 6 summarises the key insights and findings, offering a concise overview of the relevance and applicability of existing standards in advancing the SENSE vision. Chapter 7 provides a comprehensive list of references and resources to support further exploration and implementation.

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1 Introduction

The rapid evolution of digital technologies is reshaping how we interact with the physical and virtual worlds. In this transformative landscape, concepts such as Digital Twins, Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR), and the Metaverse have emerged as key enablers of next-generation applications across diverse sectors including smart cities, manufacturing, healthcare, and entertainment. However, the realization of the full potential of these technologies depends critically on establishing robust, interoperable, and widely adopted standards that can guide their development, integration, and operation.

The advancement of digital technologies over the past two decades has fundamentally transformed how humans engage with both the physical and virtual environments. With the advent of immersive technologies such as Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR)—collectively known as Extended Reality (XR)—our daily experiences are increasingly mediated by digital interfaces. These innovations not only redefine personal entertainment and communication but also influence industrial workflows, education, healthcare, urban development, and more. At the heart of this transformation lies the integration of physical and digital experiences through constructs such as Digital Twins and the emerging Metaverse.

Digital technologies have seamlessly blended into daily life, reshaping how we work, socialize, and access services. From virtual collaboration platforms in the workplace to AR navigation in smartphones and VR-based fitness applications, the boundary between the real and the virtual continues to blur. Digital Twins—virtual replicas of physical assets—are widely used in manufacturing, urban planning, and healthcare to monitor, simulate, and optimize real-world processes in real time. This convergence not only enhances operational efficiency but also enables predictive maintenance, improved design iterations, and immersive training environments.

The Metaverse—a persistent, interconnected digital environment that enables shared experiences across virtual and augmented realities—has emerged as a concept of profound significance. It envisions a digital ecosystem where individuals and organizations interact through avatars, digital objects, and spatial computing. Unlike isolated VR or AR applications, the Metaverse aims to offer continuity of identity, assets, and presence across multiple platforms.

To realize this vision, robust frameworks and standards are essential to ensure interoperability, security, and accessibility. Key requirements include standardized file formats for 3D assets, common communication protocols for real-time interaction, and mechanisms for identity and asset management across virtual spaces.

This deliverable is contextualized within the scope of Metaverse and Digital Twins frameworks to position the SENSE project approach in relation to the state of play of City Metaverse.

The SENSE initiative aims to address this pressing need by providing a comprehensive framework for standardization activities that underpin the complex ecosystems of Digital Twins and the Metaverse. This deliverable serves as a foundational deliverable that articulates the objectives, scope, and structure of the SENSE standardization approach, positioning it within the broader global standards landscape and highlighting its relevance to industry stakeholders, researchers, and policymakers.

1.1 Objective of the Deliverable

The objective of this deliverable is to collect both SENSE Digital Twin Standards and the SENSE City Meta Verse related standards, including references to existing technologies and their implementation work towards deploying the metaverse concept into City Software Infrastructures.

The primary objective of this deliverable is to present a systematic overview and critical analysis of current and emerging standards related to Digital Twins and the Metaverse, with a particular focus on interoperability, data governance, security, ethical considerations, and technology frameworks. By consolidating and mapping the diverse standardization efforts — spanning international bodies such as ISO/IEC, IEEE, and JTC 1, as well as industry consortia like the Metaverse Standards Forum — this deliverable seeks to identify gaps, alignments, and best practices that can inform the SENSE roadmap.

Specifically, this deliverable aims to:

- Define a clear taxonomy and terminology to harmonize communication across stakeholders involved in Digital Twin and Metaverse development.
- Detail the data frameworks and interoperability requirements essential for seamless integration of heterogeneous systems and platforms.
- Address identity, security, and privacy frameworks that are crucial to building trust and ensuring ethical operation within immersive environments.
- Review and analyze the state of play of VR, AR, and MR standards and their applicability to Metaverse implementations.
- Outline component and system-level Digital Twin specifications and their relevance to urban and industrial applications.
- Provide a structured overview of Metaverse city infrastructure, frameworks, and data components, highlighting applicable standards.
- Present best practices and user guides for data sharing, privacy, and protection aligned with SENSE principles.

Through these objectives, the deliverable lays the groundwork for a coordinated standardization strategy that facilitates interoperability, scalability, and sustainability of Metaverse and Digital Twin ecosystems.

1.2 Structure

The deliverable is structured as follows:

Chapter 1 Introduction:
This section provides the overall understanding and distribution of the Standards Registry deliverable, This section addresses the main objectives and goals of the deliverable within the context of the SENSE project and provides insights towards understanding the standardisation landscape, this section also explain the structure of the deliverable and how this can be used within the SENSE project by the relevant partners.

Chapter 2 Positioning Standardisation Activities into SENSE:
This section described the SENSE standardization activities within the current landscape by defining key terminology, outlining data and identity frameworks, and discussing ethical and operational requirements. It also reviews the current state of VR, AR, and MR standards as foundational technologies for the Metaverse.

Chapter 3 Metaverse Components Specification:
This section focuses on Metaverse specifications, detailing the various levels of Digital Twin standards and surveying relevant standards from prominent bodies such as ISO/IEC and IEEE, alongside consortium-driven initiatives like the Metaverse Standards Forum. This crucial section delves into the existing Metaverse Specifications of key components that potentially can be served as references within the SENSE project. It includes a comprehensive examination of the Digital Twin Standards, starting with a description that outlines Digital Twin purposes and roles, followed by a discussion of related Virtual Reality, Augmented Reality and Mixed reality standardisation work and literature in the Metaverse.

Chapter 4 Metaverse City Components Specifications:
This section addresses the specifications for Metaverse city components, including infrastructure, frameworks, and data management, providing descriptions and technology-specific standards essential for building and operating immersive urban environments. This section is dedicated to identifying technology-related standards that have demonstrated the practical application of the key components discussed earlier in the context of cities and urban environments. This sections focuses on related standards to City Frameworks and City Data.

Chapter 5 Data-Related and Adoption of Standards:
This section delves into data-related aspects critical to Metaverse adoption, such as data sharing, privacy, security, and protection. It presents prerequisites, best practices, and user guides developed under the SENSE initiative to promote secure and efficient data exchange. This section is instrumental in illustrating how the Digital Twin and Metaverse Data is can be used for implementing and use within the governance activities of the SENSE project. This section focuses on Data Sharing Standards, Data Privacy and Data protection along with its interfaces and how they interact with other Metaverse technologies and components form other Digital Twins and Metaverses.

Chapter 6 Conclusions:
The final section of the deliverable summarises the key findings, insights, and outcomes derived from the collection of standards analysis in relation with the SENSE Digital Twins and Metaverse. It provides a summary of the deliverable, touching on the standards relevance and the state of play for smart cities, as outlined along the deliverable.

Chapter 7 References:
The final section is a comprehensive collection of references and publications list where more information and details can be found. This section act as a data base of informative resources related to the SENSE objectives and technologies.

2 Positioning SENSE Standardization Activities

Digital technologies evolve rapidly, thus the lines between physical and virtual realities are increasingly blurred. This convergence is largely driven by immersive technologies such as Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), as well as data-rich constructs like Digital Twins. These technologies collectively form the backbone of what is now commonly referred to as the **Metaverse,** a persistent, shared, and interoperable digital environment where users, systems, and services interact across spatial and temporal boundaries.

2.1 Terminology, Definition and Taxonomy

The Metaverse is a persistent digital environment and is described by its use for effective development and governance of representing, including and generating more complex systems in a digital world, thus a clear and consistent terminology and taxonomy are essential.

A critical first step involves establishing a unified terminology and taxonomy to disambiguate the diverse concepts spanning digital twins, virtual environments, and metaverse applications. This promotes shared understanding across stakeholders and prevents semantic drift, which can hinder interoperability. SENSE advances this by synthesizing existing definitions into a clear hierarchical framework delineating entities, assets, and processes relevant to immersive technologies.

2.1.1 Foundational Definitions

To support a common understanding, it is important to distinguish between key terms, This is the terminology used by the SENSE consortium, it should follow the technology developments and align as much as possible with other standard terminology used in Digital Twin industry.:

- **Virtual Reality (VR):** A fully digital environment where users are immersed in a computer-generated space, typically using head-mounted displays and motion tracking.
- **Augmented Reality (AR):** A live view of the real world enhanced with digital elements, such as graphics or data overlays, often accessed via mobile devices or smart glasses.
- **Mixed Reality (MR):** A hybrid environment where digital and physical elements coexist and interact in real time, allowing users to manipulate and respond to both physical and virtual inputs.
- **Digital Twin:** A dynamic, virtual representation of a physical object, system, or process that enables simulation, monitoring, and real-time decision-making based on data collected from the real world.
- **Metaverse:** A collective, persistent digital space composed of interconnected virtual worlds, where users are represented through avatars and engage in interactive, often immersive, experiences.

2.1.2 Taxonomy in Context

The **Metaverse** represents an evolving digital ecosystem where users, systems, and content coexist and interact across immersive and persistent environments. To enable interoperability and structured development, it is essential to establish a **taxonomy**—a classification system that defines the layers, components, and interactions within the Metaverse.

The taxonomy helps align technology development with existing and emerging **standards** to ensure compatibility, scalability, and governance. The taxonomy of the terms in the foundational definitions section above is not only technical but also functional. XR technologies (VR, AR, MR) represent the interface layer, while Digital Twins form the informational core of the Metaverse, enabling synchronization between digital and physical systems. Understanding the taxonomy of Metaverse components helps in structuring standards and aligning development across sectors.

The Metaverse is composed of several interdependent layers, each representing a functional domains, This layered taxonomy enables modular and scalable development, allowing different stakeholders—developers, city planners, enterprises, and citizens—to participate in and build upon Metaverse environments using compatible tools and protocols.

- **Interface Layer (Human Interaction)**
  Encompasses XR devices and standards such as OpenXR and WebXR. This includes the devices and software that allow users to interact with virtual environments—such as VR headsets, AR glasses, haptic devices, and gesture controls. Standards here focus on interaction modalities and hardware-software integration.

- **Experience & Content Layer**
  This layer encompasses 3D environments, digital avatars, spatial audio, and animations. Content must be portable, lightweight, and renderable across devices. This is where models, simulations, and interactive scenarios reside.

- **Representation Layer (Data Models & Digital Twins)**
  Includes formats like glTF, USD (Universal Scene Description), and X3D for rendering and transmitting digital content . Digital Twins, as real-time digital counterparts of physical entities, form the foundation of this layer. They enable synchronization between real-world processes and virtual environments through data exchange and semantic models.

- **Data, Synchronisation & Interoperability Layer**
  Covers standards for real-time data interaction, including Digital Twin protocols and interoperability frameworks such as ISO 23247. Involves identity management, security, ethics, and data privacy, with contributions from W3C, IEEE, and ISO. This layer enables systems to work together through APIs, protocols, and communication standards. It supports cross-platform operability and seamless experience transitions across platforms and devices.

- **Infrastructure, Governance & Ecosystem Layer**
  The top layer includes standards and practices for identity, security, privacy, data Covers standards for real-time data interaction, including Digital Twin protocols and interoperability frameworks such as ISO 23247.

The Taxonomy in the Metaverse provides a critical structure to align technology components with real-world applications. By organizing the ecosystem into distinct but connected layers—and linking each to appropriate international standards—developers, regulators, and organizations can collaborate effectively. This structured approach is key to building a scalable, interoperable, and ethically governed Metaverse that integrates Digital Twins, VR, AR, and MR in meaningful ways.

A unified understanding of terminology, definitions, and taxonomy is vital for building an open, inclusive, and interoperable Metaverse. As immersive technologies and Digital Twins become central to digital transformation strategies, the role of standardisation becomes more critical. Collaboration between industry and standardisation bodies will ensure that the Metaverse evolves as a secure, ethical, and scalable ecosystem—serving both human and machine interactions in the physical and virtual worlds alike.

2.2 Data Frameworks and Interoperability requirements

The Metaverse is a complex and dynamic digital ecosystem where people, machines, virtual environments, and data interact in real time. For this system to function seamlessly, it relies on robust data frameworks and interoperability standards that ensure different systems, platforms, and devices can communicate, understand, and use data consistently. The foundational elements for the Metaverse avoid that the metaverse would be fragmented, siloed, and unscalable.

Interoperability forms the backbone of successful digital ecosystems. SENSE identifies essential data frameworks enabling the seamless exchange and synchronization of contextual information across heterogeneous platforms. Emphasis is placed on standards such as NGSI-LD, which supports linked data principles, and JSON-LD serialization for flexible, semantically enriched data representation. The framework also accounts for geospatial data, temporal aspects, and dynamic context updates critical for real-time applications.

2.2.1 Data Frameworks

A data framework in the Metaverse refers to the structure and rules that govern how data is collected, modeled, shared, and maintained. These frameworks define:

- Data Models: How virtual and physical elements are digitally represented (e.g., people, places, products).
- Metadata Schemas: Contextual information that gives meaning to data (e.g., time, location, ownership).
- Data Flow Protocols: How data moves between systems (e.g., sensors to digital twins, avatars to environments).
- Access & Governance Rules: Who can access data, under what conditions, and how it's protected.

In a digital twin of a building, sensors might continuously stream data about temperature, energy use, and occupancy. As an example a robust data framework ensures this information is semantically consistent and ready for use in VR visualizations or automated controls.

2.2.2 Interoperability in the Metaverse

Interoperability is the ability of different systems and devices to exchange and use information without loss of meaning or function. In the Metaverse, this includes the compatibility of:

- **Avatars** and user identities across platforms.
- **Digital assets**, such as 3D models, animations, and environments.
- **Device interfaces**, from AR glasses to VR headsets.
- **Data sources**, including IoT devices, simulation engines, and databases.

Achieving interoperability is essential to creating a seamless user experience and avoiding data duplication, technical incompatibilities, or closed ecosystems. Key Existing Standards Enabling Data and Interoperability Several recognized standards and frameworks support data and interoperability within XR and Metaverse ecosystems:

- **ISO 23247 (Digital Twin Framework for Manufacturing)**: While focused on industrial use, this standard outlines how digital twins interact with physical assets via consistent data exchange and semantic models. It provides a base structure for integrating real-world data into virtual environments.
- **ISO/IEC 21838 (Top-Level Ontologies)**: This series supports semantic interoperability by aligning different domain-specific data models. It's especially useful in multi-disciplinary digital twin implementations within smart cities or healthcare applications in the Metaverse.
- **Khronos glTF (GL Transmission Format)**: A key format for transmitting and rendering 3D content efficiently. It supports textures, animations, and geometry, and ensures visual assets are interoperable across engines and platforms.
- **OpenXR (Khronos Group)**: This API standard enables cross-platform XR development. It abstracts hardware differences and allows apps to run consistently across multiple devices, ensuring a common data flow and user input structure.
- **W3C WebXR Device API**: This web standard enables XR experiences through browsers and defines how spatial data is handled in a web environment, allowing easy integration with real-time data sources and services.
- **MPEG-V (ISO/IEC 23005)**: This standard provides a framework for connecting virtual environments with real-world devices, facilitating sensory interoperability (e.g., touch feedback or environmental control) and contextual data exchange.
- **IEEE P2874 (in development)**: A draft standard under IEEE for digital asset metadata and interoperability in the Metaverse, addressing ownership, portability, and provenance of virtual goods and identities.

2.3 Identity Frameworks and Security requirements

In the Metaverse—a continuously expanding, interconnected digital environment—identity and security are foundational elements. They ensure users, systems, and assets can interact safely and meaningfully across platforms and realities. As immersive technologies like VR (Virtual Reality)**,** AR (Augmented Reality)**,** MR (Mixed Reality), and Digital Twins converge, identity frameworks and security protocols are crucial to maintaining trust, integrity, and interoperability.

Robust identity management and security protocols are foundational to trustworthiness in metaverse and digital twin environments. SENSE delineates identity frameworks that ensure authentication, authorization, and accountability, balancing user privacy with system integrity. These frameworks integrate with broader cybersecurity standards, ensuring resilience against emerging threats while enabling fine-grained access control.

2.3.1 Identity Frameworks in the Metaverse

An identity framework governs how entities—humans, machines, virtual agents, or digital assets—are identified, verified, and represented across interconnected digital spaces. In the Metaverse, identity must be persistent, interoperable, and privacy-aware.

Key components of identity frameworks include:

- **Digital Identity**: A unique, verifiable digital representation of a user or asset, often including credentials, avatars, behavioural traits, and metadata.
- **Authentication & Authorization**: Mechanisms to verify identity (e.g., biometrics, cryptographic keys) and control access to spaces, content, or services.
- **Decentralized Identity (DID)**: A model where users control their own identity data, often built using blockchain-based verifiable credentials (W3C DID standard).
- **Interoperability**: Support for identity portability across platforms (e.g., same user profile in multiple virtual worlds).

These identity components are essential in Digital Twin environments as well—for example, ensuring that only authorized systems or users can interact with the virtual model of a city's infrastructure or a connected vehicle.

2.3.2 Security in the Metaverse

Security in the Metaverse must account for the complexity of interactions between physical and virtual systems. Security measures must protect user data, system integrity, digital assets, and communications across various devices and networks.

Key security concerns and solutions include:

- **Data Confidentiality & Encryption**: Ensuring data (e.g., biometric inputs, behavioural logs) is transmitted and stored securely.
- **Access Control**: Defining who can interact with or manipulate specific elements in virtual environments, especially relevant for critical Digital Twin systems.
- **Device Security**: Safeguarding headsets, sensors, and AR devices from physical and software-based threats.
- **Content Authenticity**: Preventing falsification or manipulation of virtual objects or experiences.

2.3.3 Existing Standards and Initiatives

Several international standards and initiatives provide the foundation for identity and security in immersive environments:

- **W3C DID & Verifiable Credentials**: These specifications define decentralized identifiers and cryptographically verifiable credentials that support user-controlled identity across different platforms.

- **ISO/IEC 24760 (Identity Management Framework)**: Offers a structured approach for managing identities, covering identity proofing, credential issuance, and identity federation—vital for cross-platform interaction.

- **ISO/IEC 29115 (Entity Authentication Assurance Framework)**: Defines levels of assurance for digital identity verification, helping determine how strong an authentication process must be depending on the risk.

- **IEEE 2410 (Biometric Open Protocol Standard – BOPS)**: Provides methods for securely managing and transmitting biometric identity data—especially relevant in immersive systems using eye tracking or gesture recognition.

- **ISO/IEC 27001 (Information Security Management)**: A general but highly relevant framework that sets best practices for data security and system protection, widely applicable to Metaverse infrastructure.

- **OASIS OpenID Connect & OAuth 2.0**: Widely adopted protocols for web-based identity and access management, which are being extended into XR environments and integrated into identity layers of Metaverse platforms.

Identity and security frameworks are not optional in the Metaverse—they are the invisible scaffolding that allows for trusted, safe, and user-centric interaction. By adopting and aligning with existing international standards, Metaverse platforms, XR applications, and Digital Twin systems can ensure secure, privacy-preserving identity management and cross-platform interoperability. As this ecosystem evolves, harmonizing identity governance with robust cybersecurity will be essential for user protection, ecosystem integrity, and long-term scalability.

2.4 Ethical Aspects, Design and Operation Requirements

The Metaverse continues to evolve into a complex, interactive, and immersive digital ecosystem, the importance of embedding ethical principles, sound design guidelines, and robust operational frameworks becomes critical. The convergence of Virtual Reality (VR)**,** Augmented Reality (AR)**,** Mixed Reality (MR)**,** and Digital Twins creates new opportunities but also brings unique social, psychological, and technical challenges that must be managed through structured governance and international standards. Ethical considerations, including data privacy, user consent, inclusivity, and fairness, are integral to SENSE's design and operational guidelines. The deliverable emphasizes the necessity of embedding ethical principles in both system architecture and governance models, ensuring that immersive technologies enhance societal benefits without compromising individual rights or amplifying biases.

2.4.1 Ethical Aspects in the Metaverse

Ethics in the Metaverse encompasses a wide range of responsibilities towards users, communities, and societies. The immersive and persistent nature of these environments introduces new dimensions of risk:

- **Privacy and Data Sovereignty**: Continuous user tracking (e.g., eye movements, gestures, biometric feedback) demands strict safeguards around consent, data ownership, and usage transparency.
- **Digital Well-being**: Extended use of immersive technologies can impact cognitive health, mental well-being, and physical safety. Ethical frameworks advocate for user-centered design to prevent overexposure or dependency.
- **Bias and Inclusion**: Avatars, AI, and virtual agents must be designed to avoid reinforcing stereotypes or exclusion. Ensuring representational fairness and cultural sensitivity is a core ethical mandate.
- **Freedom, Safety, and Harassment Prevention**: Users must be protected from manipulation, misinformation, and virtual abuse. Ethical design ensures safety controls, consent-based interactions, and respectful engagement.

These issues are being addressed at various levels, including industry consortia and research ethics boards. While formal ethical standards specific to the Metaverse are still in development, foundational principles are often drawn from broader digital ethics frameworks.

2.4.2 Design Requirements for Immersive Systems

Designing for the Metaverse requires more than graphical fidelity—it must incorporate human factors, accessibility, and multi-platform adaptability:

- **Human-Centered Design (HCD)**: Standards such as **ISO 9241-210** emphasize usability, accessibility, and user satisfaction. HCD ensures that immersive experiences are intuitive and inclusive.

- **Safety by Design**: Especially for physical interactions in VR/MR, design must minimize risks of physical collisions, motion sickness, and disorientation.

- **Interoperability by Design**: Open and standardized formats such as **glTF** (for 3D assets) and **OpenXR** (for XR interfaces) must be prioritized to avoid vendor lock-in and fragmentation.

- **Scalability**: Designs should account for diverse network conditions, device capabilities, and regional infrastructures to ensure equal access.

Good design in the Metaverse is ethical design—it protects the user, promotes inclusivity, and ensures experiences are enriching, not exploitative.

2.4.3 Operational Requirements and Standards

Operational requirements involve managing and maintaining the systems that power immersive experiences and digital twins. These include performance, governance, data management, and reliability. Key standards and frameworks include:

- **ISO/IEC 27001**: For information security management, applicable to Metaverse data services and digital twin infrastructures.

- **ISO 37106 / ISO 37101**: These smart city standards guide operational and governance frameworks, useful in digital twin environments simulating urban systems.

- **IEEE P7000 Series**: Although not all finalized, this series addresses ethical system design, including algorithmic bias (P7003), data privacy (P7002), and human well-being (P7010).

- **ISO/IEC 25010**: This standard for system and software quality provides guidance on reliability, maintainability, and usability—core to immersive applications.

Operational excellence in the Metaverse also depends on continuous monitoring, failover strategies, user support, and ethical AI integration.

The ethical, design, and operational dimensions of the Metaverse are deeply intertwined. Creating immersive environments that are safe, inclusive, and reliable requires not just technical expertise, but a principled approach grounded in established standards. As the Metaverse matures, adherence to these frameworks will be essential in building trust, ensuring accessibility, and supporting sustainable digital societies.

2.5 Virtual Reality (VR) State of Play

SENSE surveys the state of the art in immersive reality standards, documenting ongoing initiatives and identifying gaps. Virtual Reality standards focus on immersive rendering, user interaction, and device interoperability. Augmented Reality efforts emphasize spatial mapping, contextual augmentation, and real-world alignment. Mixed Reality standards integrate elements of both VR and AR, supporting seamless transitions between physical and virtual realms. This multi-faceted overview guides strategic alignment and collaborative development within the metaverse ecosystem.

Virtual Reality (VR) plays a central role in enabling immersive experiences within the Metaverse. It offers fully computer-generated, interactive 3D environments where users are visually, aurally, and physically engaged through headsets, controllers, and sensor-based systems. In the context of the Metaverse, VR is not only a gateway to presence-driven experiences but also a foundational layer for simulating digital twins, virtual economies, and shared virtual spaces.

2.5.1 Technological Landscape and Use Cases

The current VR ecosystem within the Metaverse encompasses a wide range of applications:

- **Social VR and Virtual Worlds**: Multi-user VR platforms support real-time interaction, education, entertainment, and remote collaboration (e.g., virtual offices, concerts, simulations).
- **Training and Simulation**: Used extensively in sectors like manufacturing, healthcare, and defence to replicate complex environments and scenarios.
- **Digital Twin Visualization**: VR serves as the immersive interface for navigating and interacting with real-time data models of physical assets, such as smart buildings, factories, or infrastructure.

The convergence with haptics, spatial audio, and biometric tracking enhances realism and contributes to a more embodied presence in digital environments.

2.5.2 Integration and Interoperability Challenges

Despite advancements, the VR ecosystem still faces challenges in the Metaverse:

- **Hardware fragmentation** creates barriers to consistent user experience.
- **Data silos** between VR platforms hinder seamless identity, asset, and environment transfer.
- **Latency and scalability** issues, especially in networked VR environments, require ongoing refinement of transmission standards and edge computing integration.

Virtual Reality remains one of the most mature and impactful technologies shaping the Metaverse. Its capabilities in immersive engagement, simulation, and interaction make it indispensable for applications across industries. Continued alignment with open, internationally recognized standards is essential to ensure VR's long-term role in an inclusive, and interoperable Metaverse ecosystem.

2.6 Augmented Reality (AR) State of Play

Augmented Reality (AR) is a key enabler of the Metaverse, bridging the digital and physical worlds by overlaying interactive virtual elements onto real-world environments. Unlike Virtual Reality (VR), which immerses the user in a fully synthetic space, AR enhances real-world perception, making it particularly valuable for location-based services, industrial operations, education, and user-guided interaction with physical objects and spaces.

In the Metaverse context, AR serves as a practical interface for real-time interaction with digital content mapped to physical surroundings—essential for applications such as smart cities, digital twins, and immersive collaboration.

2.6.1 Technological Landscape and Applications

AR in the Metaverse is evolving rapidly, with applications expanding across:

- **Smart Infrastructure and Digital Twins**: AR visualizes real-time data from physical assets (e.g., energy grids, vehicles, equipment) through spatially aware interfaces.
- **Retail and Navigation**: Consumers engage with products, instructions, or locations through AR overlays—offering a digitally enriched user journey.
- **Industrial and Medical Training**: AR supports procedural guidance, remote assistance, and task-based interaction in complex environments.
- **Public Services and Urban Experience**: In smart cities, AR enables interactive wayfinding, real-time public data, and user feedback systems.

AR acts as a gateway to the spatial internet—enabling context-aware, persistent, and meaningful interactions that align digital content with the user's physical environment.

2.6.2 Key Integration Challenges

Despite the rapid advancement of AR in Metaverse applications, several challenges persist:

- **Spatial Anchoring and Persistence**: Maintaining accurate alignment between digital content and real-world coordinates over time remains technically complex.
- **Privacy and Ethics**: As AR relies heavily on real-world data (e.g., cameras, location), robust frameworks for data protection and user consent are critical.
- **Device Compatibility**: Variability in AR hardware capabilities (e.g., phones vs. headsets) can affect experience quality and requires adaptable design strategies.
- **Bandwidth and Processing Constraints**: Real-time AR content rendering requires efficient data transmission and edge processing, especially for mobile and wearable use cases.

AR is a cornerstone technology for a spatially integrated Metaverse, where digital content complements and enhances the physical world. By leveraging open standards such as OpenXR, glTF. AR can achieve the interoperability, security, and scalability necessary for broad adoption. As use cases expand across industries and urban environments, the role of AR in the Metaverse will become increasingly essential.

2.7 Mixed Reality (MR) State of Play

Mixed Reality (MR) represents the convergence of the physical and digital realms, enabling users to interact with and manipulate both real-world and virtual elements in real time. In the context of the Metaverse, MR stands out as a dynamic interface where digital content is not only overlaid onto the physical world (as in Augmented Reality, AR) but is contextually aware and responsive to the environment and user actions—unifying features from both AR and Virtual Reality (VR).

MR extends the immersive experience by anchoring holograms, 3D content, or simulations to the physical world, allowing a continuous spectrum of interaction that is both spatial and semantic. This capability is essential in complex, real-time environments such as industrial operations, digital twin navigation, and collaborative virtual spaces.

2.7.1 Application Domains and Integration

In the Metaverse, MR is particularly useful where precision, interactivity, and environmental awareness are critical. Key applications include:

- **Digital Twins Visualization and Control**: MR enables intuitive interfaces for operating and monitoring digital representations of physical systems (e.g., manufacturing lines, smart buildings).
- **Collaborative Design and Engineering**: Professionals can co-create, manipulate, and inspect shared 3D content embedded within their physical environment.
- **Field Operations and Maintenance**: MR supports hands-free instructions, remote expert guidance, and interactive diagnostics directly linked to physical machinery.
- **Healthcare and Education**: MR environments facilitate interactive learning, surgical planning, and patient education using real-time, context-aware overlays.

Unlike AR or VR alone, MR fosters a more seamless and bidirectional interaction between real and virtual inputs.

2.7.2 Technical Challenges and Considerations

Despite its potential, MR integration into the Metaverse faces ongoing challenges:

- **Environmental Mapping and Anchoring**: Reliable spatial understanding and persistent object tracking are required to ensure virtual elements remain stable and contextually relevant.
- **Hardware Variability**: MR experiences depend on a range of devices—from mobile phones to head-mounted displays—with diverse capabilities and sensor arrays.
- **Latency and Responsiveness**: To maintain immersion and prevent disorientation, MR systems must minimize latency in content rendering and user interaction.
- **Data Synchronization**: Accurate, bi-directional data flow between the real world and virtual systems (such as digital twins) is necessary for real-time decision-making.

Mixed Reality is emerging as one of the most powerful interaction paradigms in the Metaverse, offering the ability to merge and manipulate physical and virtual content seamlessly. As industrial, educational, and public sector use cases grow, MR will become a key interface layer for interacting with digital twins, collaborative virtual environments, and spatial services.

2.8 SENSE Standardization Landscape

This section contextualizes SENSE within the broader standardization ecosystem, mapping its interfaces and complementarities with entities such as ISO, IEEE, ETSI, and the Metaverse Standards Forum. By positioning itself strategically, SENSE facilitates coordinated standard development, accelerating innovation and adoption.

Establishing shared definitions and interoperable systems requires strong coordination among standardisation bodies and industry consortia. Several organisations are actively shaping the standards that underpin XR technologies and the Metaverse.

2.8.1 ISO/IEC 19775:2022 – X3D Architecture and Components

ISO/IEC JTC 1/SC 24 develops international standards in computer graphics, image processing, and environmental data representation. Notable specifications include **ISO/IEC 19775** (X3D), which provides a standard for real-time 3D content, and **ISO/IEC 23005** (MPEG-V), which addresses interactions between virtual and physical worlds.

X3D (Extensible 3D) is a standardized architecture for representing and communicating 3D scenes. It enables the creation of interactive 3D content that can be used across different platforms and systems. For the Metaverse and XR applications, X3D provides a consistent framework to build complex, interoperable 3D environments that can be rendered in browsers, AR devices, or VR headsets. Its XML-based structure allows integration with other data formats, making it suitable for real-time simulations, education, healthcare, and smart city visualizations.

2.8.2 ISO/IEC 23005 – MPEG-V: Media Context and Control

MPEG-V is a standard designed to connect digital content (like video or audio) with real-world objects and sensors. It enables devices in a virtual environment to interact with the physical world and vice versa. In VR/AR/MR contexts, MPEG-V is crucial for enabling haptic feedback, environmental responses (e.g., adjusting room lighting based on a virtual scene), and sensory interaction. In the Metaverse, it helps create immersive and adaptive experiences by linking media content with context-aware physical systems.

2.8.3 OpenXR (Khronos Group, 2024)

The Khronos Group maintains **OpenXR**, a royalty-free standard that enables consistent access to XR platforms and devices, and **glTF**, a compact format for efficient transmission of 3D assets. These are foundational for cross-platform VR/AR content.

OpenXR is an open, royalty-free API standard that allows developers to build XR applications once and deploy them across a wide range of hardware platforms—VR headsets, AR glasses, and MR devices. It simplifies development by providing a unified interface for device input, rendering, and tracking. For the Metaverse, OpenXR is essential to ensuring device-agnostic access to immersive environments, encouraging interoperability and reducing fragmentation across the XR ecosystem.

2.8.4 glTF (Khronos Group)

glTF (GL Transmission Format) is a lightweight 3D file format designed for efficient transmission and loading of 3D models. It's often described as the "JPEG of 3D" due to its compact size and fast rendering. In XR and Metaverse applications, glTF ensures seamless exchange of 3D assets across platforms, enabling high-quality graphics in games, digital twins, virtual storefronts, and interactive environments without compromising performance.

2.8.5 IEEE P2048 Metaverse Standards (IEEE SA, 2024)

The IEEE Standards Association is leading several initiatives under the IEEE P2048 Metaverse Standardization Series, which addresses interoperability, architecture, and terminology for the Metaverse and Digital Twins. The IEEE P2048 series is a set of working standards aimed at defining the fundamental architecture, interfaces, and terminology for the Metaverse. These standards tackle key areas such as interoperability, identity, ethics, and security. For developers and regulators, IEEE's work is vital in creating a trusted, standardized foundation upon which future Metaverse infrastructures can be safely and fairly built, enabling cohesive interaction between virtual environments and real-world systems.

2.8.6 Metaverse Standards Forum (2023)

The Metaverse Standards Forum (MSF), founded in 2022, is a cross-industry group focusing on practical implementation of standards to promote interoperability. The forum includes companies like Meta, Microsoft, NVIDIA, and supports alignment with other bodies like ISO, W3C, and Khronos.

The Metaverse Standards Forum is a collaboration among industry leaders and standards organizations to coordinate and accelerate the development of open Metaverse standards. Rather than creating new standards from scratch, it supports the alignment and integration of existing ones like OpenXR, glTF, and ISO frameworks. The Forum helps ensure that technologies used in different XR and digital twin applications can work together, paving the way for an inclusive and interoperable Metaverse.

2.8.7 W3C WebXR Device API (2023)

W3C (World Wide Web Consortium) has published the **WebXR Device API**, enabling immersive experiences directly through web browsers without needing platform-specific software.

The WebXR API allows developers to create XR experiences directly within web browsers without requiring dedicated apps or platforms. It supports both VR and AR devices, enabling web-based immersive content. For the Metaverse, WebXR democratizes access, allowing users to engage with 3D environments and XR content via standard web technologies. It also supports easier integration with online services, making it ideal for education, e-commerce, and virtual collaboration.

2.8.8 ISO 23247 – Digital Twin Framework for Manufacturing

ISO 23247 offers a reference architecture for Digital Twins in manufacturing, laying groundwork for broader applications in smart cities, healthcare, and infrastructure.

This standard provides a reference model for creating digital twins in manufacturing environments. It defines how physical systems (like machines or products) are mirrored digitally, including data capture, modeling, and real-time synchronization. ISO 23247 serves as a foundational building block for Digital Twins in broader Metaverse contexts, such as smart cities, logistics, or infrastructure, allowing virtual replicas to inform, simulate, and optimize real-world systems.

The figure 1 represent the SENSE landscape addressing the different areas of Standards identified as relevant and beyond the SENSE's timeline deployment of standards plan.

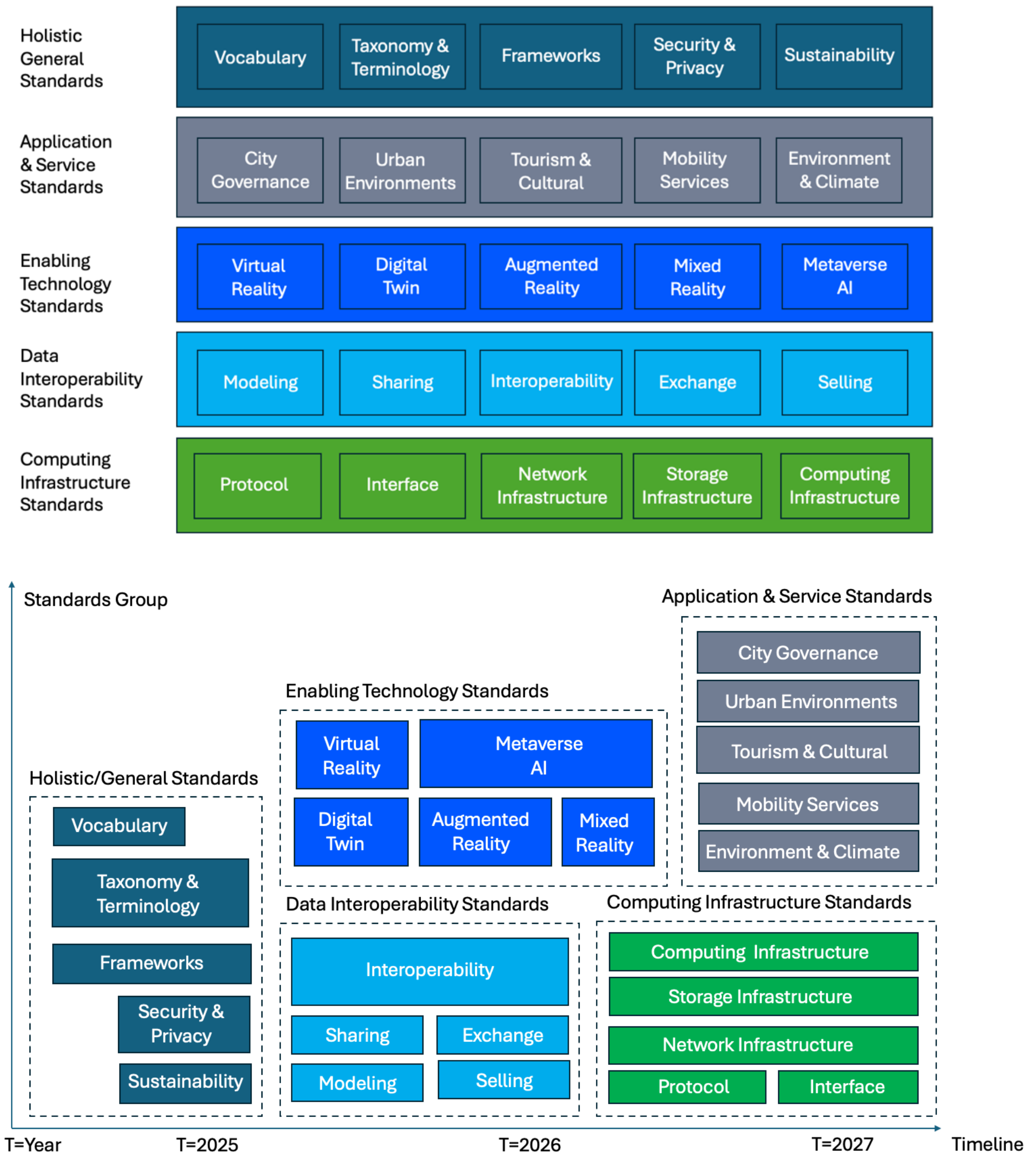

Figure 1 – SENSE Standardisation Landscape

3 Metaverse Specifications

3.1 Digital Twin Standards

Digital Twin (DT) technology has emerged as a cornerstone of Industry 4.0 and Smart Cities development, transforming the way physical assets, processes, and systems are designed, monitored, and optimized. At its core, a digital twin is a dynamic virtual representation of a real-world entity, continuously updated with real-time data and capable of simulating behaviour under varying conditions. This paradigm fosters a data-driven approach to decision-making and predictive maintenance, facilitating enhanced performance, sustainability, and resilience across sectors.

Standardization plays a pivotal role in ensuring the interoperability, reliability, and scalability of digital twin implementations. With the increasing adoption of DTs across diverse domains, consistent standards are essential for aligning terminology, data exchange protocols, modeling approaches, and lifecycle integration.

This section provides an in-depth examination of digital twin standards, categorized into component, product/asset, process, system, and urban digital twin specifications. It also explores ISO/IEC 30173:2023, the principal international standard governing digital twins.

3.1.1 Component Digital Twin Specification

Component digital twins represent the most granular level in the digital twin hierarchy. They model individual parts or sub-assemblies, capturing detailed characteristics such as geometry, material properties, and performance data.

3.1.1.1 Key Aspects:

- **Granularity**: Focuses on the smallest physical units in a product or system.
- **Fidelity**: High-resolution modeling and simulation capabilities.
- **Lifecycle Integration**: Covers design, manufacturing, maintenance, and end-of-life phases.
- **Data Interfaces**: Requires standardized APIs for data input/output, enabling integration with larger assemblies.

3.1.1.2 Use Cases:

- Predictive maintenance of jet engine turbine blades.
- Material fatigue analysis in structural components.
- Additive manufacturing quality control.

3.1.1.3 Challenges:

- Harmonizing multi-physics simulation tools.
- Capturing real-time performance data at micro-scale resolution.

3.1.2 Product or Asset Digital Twin Specification

At this level, the digital twin represents a full product or asset, composed of multiple components. These twins are used to monitor and manage performance, reliability, and lifecycle costs.

3.1.2.1 Key Aspects:

- **System Integration**: Aggregates multiple component twins.
- **Behavior Modeling**: Incorporates functional logic, control systems, and performance metrics.
- **Lifecycle Traceability**: Tracks asset usage history, maintenance logs, and upgrades.

3.1.2.2 Use Cases:

- Fleet management of vehicles.
- Wind turbine performance optimization.
- Medical device usage analytics.

3.1.2.3 Standards Involved:

- ISO 10303 (STEP) for product data representation.
- ISO 14224 for asset reliability and maintenance data.

3.1.3 Process Digital Twin Specification

Process digital twins simulate sequences of operations or workflows, capturing the dynamics and interdependencies of tasks. These are especially crucial in manufacturing, logistics, and healthcare.

3.1.3.1 Key Aspects:

- **Temporal Modeling**: Focuses on time-dependent behaviours.
- **Resource Allocation**: Models human, material, and machine interactions.
- **KPI Monitoring**: Tracks throughput, efficiency, and bottlenecks.

3.1.3.2 Use Cases:

- Production line optimization.
- Patient flow in hospital settings.
- Supply chain resilience testing.

3.1.3.3 Standards Involved:

- BPMN for business process modeling.
- ISA-95 for enterprise-control system integration.

3.1.4 System Digital Twin Specification

A system digital twin encapsulates the interrelationships among multiple assets and processes within a cohesive operational framework. These twins are common in industrial facilities, data centers, and infrastructure networks.

3.1.4.1 Key Aspects:

- **Hierarchical Modeling**: Supports multi-layered views from component to enterprise level.
- **Behavioural Emulation**: Includes control logic, sensor feedback, and system dynamics.
- **Interoperability**: Requires harmonization of heterogeneous data sources.

3.1.4.2 Use Cases:

- Power grid stability analysis.
- Airport operational planning.
- Smart factory orchestration.

3.1.4.3 Standards Involved:

- OPC UA for machine-to-machine communication.
- ISO/IEC 30182 for smart city concept models.

3.1.5 System Urban Digital Twin Specification

Urban digital twins extend the digital twin concept to city-scale systems, integrating infrastructure, mobility, energy, and citizen engagement components.

3.1.5.1 Key Aspects:

- **Geospatial Integration**: Utilizes GIS data and 3D city models.
- **Multi-Stakeholder Governance**: Involves public, private, and civil society actors.
- **Real-Time Analytics**: Processes streaming data from urban IoT devices.

3.1.5.2 Use Cases:

- Urban traffic simulation.
- Disaster response planning.
- Environmental monitoring and emissions tracking.

3.1.5.3 Standards Involved:

- CityGML for 3D city modeling.
- ISO 37120 for city indicators.

3.1.6 ISO/IEC 30173:2023 Digital Twin Standards

ISO/IEC 30173:2023 serves as the foundational international standard for digital twins. It provides a common vocabulary, reference architecture, and a set of principles guiding the development and operation of digital twins.

3.1.6.1 Key Provisions:

- **Terminology**: Standardizes key definitions across disciplines.
- **Reference Architecture**: Proposes a multi-layered framework including data, model, and control layers.
- **Interoperability Guidelines**: Emphasizes open interfaces and semantic consistency.
- **Lifecycle Management**: Addresses creation, evolution, and decommissioning of digital twins.

3.1.6.2 Strategic Impact:

- Facilitates cross-sectoral adoption.
- Enhances global compatibility of DT implementations.
- Supports regulatory compliance and certification schemes.

Table 1 - Key Standards Supporting Digital Twins and the Metaverse

Standard	Relevance to SENSE
ISO/IEC 30173:2023	Defines the core concepts and reference architecture for digital twins in information technology, providing a universal framework to build interoperable digital twin systems.
ISO 10303-1:2020 (STEP)	A standard for product data exchange in industrial automation. Supports interoperability in digital twin systems by enabling consistent representation of complex 3D and product data.
ISO 14224:2016	Specifies how to collect and exchange maintenance and reliability data in industrial sectors. Important for keeping digital twins up to date and relevant over time.
ISA-95 (2020)	A standard for integrating business systems and industrial control systems. Enables hierarchical interoperability in digital twin environments used in AR/VR dashboards.
OMG BPMN 2.0 (2014)	Business process modeling notation standard used to represent workflows and operations. Facilitates human and AI interaction within the Metaverse through digital twin automation.
OPC UA (2022)	A machine-to-machine communication standard that enables secure, real-time data exchange across industrial devices—forming the backbone of operational digital twins.
ISO/IEC 30182:2017	Provides a data interoperability model for smart cities. Serves as a reference for aligning digital twin components in city-scale Metaverse environments.

ISO 37120:2018	Offers city performance indicators, aiding the integration of measurable urban metrics into digital twin-based smart city simulations and planning tools.

Table 2 - Key related to standards works Supporting Digital Twins and the Metaverse

Related Work	**Relevance to SENSE**
Standard / Reference	**Explanation / Relevance**
Kolbe (2009)	Describes a model for representing 3D urban environments. Essential for building spatially accurate, semantically rich digital twins in city-scale Metaverse projects.
Glaessgen & Stargel (2012)	Early articulation of the digital twin concept by NASA, proposing its use for predictive maintenance and simulation in aerospace—now applied across sectors.
Lee, Bagheri & Kao (2015)	Proposes a cyber-physical system architecture that connects sensors, machines, and digital platforms—a precursor to scalable and interactive digital twin ecosystems.
Boschert & Rosen (2016)	Explores the simulation components of digital twins, focusing on how real-time feedback and models drive accurate digital representations—critical for high-fidelity MR/VR integrations.
Grieves & Vickers (2017)	Introduced the foundational concept of the Digital Twin, emphasizing its role in mitigating complex and unpredictable behaviours in large systems—core to enabling reliable virtual representations in the Metaverse.
Kritzinger et al. (2018)	Conducts a systematic review of digital twin applications in manufacturing, providing classifications and use cases that support VR/MR implementations.
Tao et al. (2018)	Analyzes the relationship between digital twins and cyber-physical systems, clarifying their integration in smart manufacturing—essential knowledge for immersive industrial Metaverse applications.
Qi & Tao (2018)	Examines the convergence of digital twins and big data, explaining their synergistic value for real-time analytics in immersive industrial environments.
Batty (2018)	Reflects on the emergence of digital twins in urban analytics. Highlights their transformative role in data-driven smart city planning within the Metaverse.
Madni, Madni & Lucero (2019)	Discusses how digital twins enhance model-based systems engineering. Supports the creation of interoperable digital platforms across physical-virtual systems.
Fuller et al. (2020)	Reviews enabling technologies and challenges for digital twins, helping identify gaps and future directions in XR integration and system design.
Jones et al. (2020)	Offers a structured literature review on digital twins, defining their characteristics and clarifying terminology essential for standardization and interoperability in Metaverse applications.

3.2 Virtual Reality (VR) Standards

Virtual Reality (VR) is a cornerstone of Digital Twin technology, offering immersive interfaces and real-time interaction with digital replicas of physical systems. VR standards ensure interoperability, usability, and integration of VR environments within Digital Twin ecosystems. This section explores the standards landscape surrounding VR in the context of the Metaverse and Digital Twin applications.

3.2.1 Metaverse Standards Forum

The Metaverse Standards Forum (MSF) is a consortium formed to foster interoperability standards for an open and inclusive metaverse. Launched in 2022, the forum includes a range of stakeholders from major tech firms (e.g., Meta, Microsoft, NVIDIA) to standards development organizations (SDOs) like the Khronos Group, W3C, and Open Geospatial Consortium.

One of the Forum's major contributions lies in identifying gaps in interoperability standards and coordinating activities among existing SDOs. Rather than creating new standards, the MSF catalyzes collaboration and harmonization across existing efforts. For Digital Twin systems that rely on immersive interfaces, the MSF's push towards standardized scene graphs, avatars, and real-time spatial data exchange is pivotal.

Key projects of the MSF relevant to Digital Twins include:

- Interoperable 3D asset pipelines
- Digital identity and presence
- Spatial computing protocols
- Real-time simulation integration

The MSF's open nature allows a wide range of industries to contribute, thus enhancing cross-domain applicability. For instance, the Forum's working groups are delving into use cases in manufacturing, healthcare, and smart cities—domains where Digital Twins are heavily employed.

3.2.2 Metaverse JTC 1 Standards

The Joint Technical Committee 1 (JTC 1) of ISO/IEC, focused on information technology, has initiated a subcommittee (SC 42) and various working groups aimed at standardizing AI, big data, and now, the Metaverse. These efforts are crucial in underpinning the data-centric architecture of Digital Twins.

ISO/IEC JTC 1's engagement with the Metaverse integrates foundational standards from:

- ISO/IEC 23005: MPEG-V (media context and control)
- ISO/IEC 30173: Digital avatars
- ISO/IEC DIS 23094: Neural network compression and representation.

Their relevance to Digital Twin frameworks lies in standardizing how sensory and environmental data is interpreted, how avatars and agents behave within simulated environments, and how large-scale data flows are structured.

A notable initiative under JTC 1 is the development of a Metaverse Reference Architecture, which incorporates Digital Twin interfaces as a core module. It aims to align efforts from digital identity, interaction models, and extended reality (XR) ecosystems.

In contrast to purely commercial forums, JTC 1 provides a formal, consensus-driven path to international standardization, ensuring that Digital Twin applications achieve global interoperability and compliance.

3.2.3 IEEE Metaverse Standards

The Institute of Electrical and Electronics Engineers (IEEE) has approached Metaverse and VR standards with an emphasis on ethical AI, human-centric design, and system interoperability. The IEEE P2048 series, titled "Standard for a Framework and Definitions for the Metaverse," is an umbrella initiative breaking down the components of the Metaverse, including spatial computing, avatar behaviour, and digital object modeling.

Among the most pertinent IEEE standards for Digital Twins are:

- IEEE P2048.1: Overview and general principles
- IEEE P2048.2: Metaverse terminology and definitions
- IEEE P2048.5: Avatar representation and modeling
- IEEE P7010: Wellbeing Metrics for Ethical AI and XR systems

The IEEE approach emphasizes inclusive, safe, and privacy-aware VR environments. For Digital Twins deployed in critical sectors—like aerospace or healthcare—these aspects are not optional but fundamental. The IEEE's focus on ethical design aligns well with broader digital responsibility trends in smart technologies.

IEEE also collaborates with industry on simulation standards such as IEEE 1516 (High-Level Architecture for Modeling and Simulation), which serves as a foundational layer for VR-enabled Digital Twin platforms.

Furthermore, IEEE engages in workshops and open-source collaborations to advance common data models, interoperability protocols, and open APIs. This support ecosystem accelerates the deployment of standards-compliant Digital Twin solutions across VR interfaces.

Table 3 - Key Standards Supporting Virtual Reality and the Metaverse

Standard / Initiative	**Explanation / Relevance**
Metaverse Standards Forum (2023)	A collaborative industry initiative to harmonize and accelerate the adoption of open standards across the Metaverse ecosystem, ensuring interoperability and cross-platform compatibility.
Khronos glTF (2023)	A compact, efficient 3D asset format essential for transmitting high-fidelity models in real-time Metaverse and XR environments.
W3C WebXR Device API (2024)	A web standard that enables immersive AR/VR experiences directly in browsers, supporting device-agnostic access to Metaverse environments.
ISO/IEC JTC 1 (2023)	A key ISO/IEC committee coordinating Metaverse and Digital Twin standardization in IT, including data frameworks and interoperability models.
ISO/IEC 30173:2023 – Digital Avatars	Defines structure and semantics for digital avatars in the Metaverse, including identity attributes, behaviour, and appearance.
ISO/IEC DIS 23094 (2024)	Standard for AI-driven video compression, enabling efficient real-time streaming of rich immersive media in XR and Metaverse contexts.
IEEE P2048 Series (2024)	A suite of in-development standards addressing technical architecture, ethics, and interoperability for the Metaverse.
IEEE 1516-2010 – HLA	A framework for distributed simulation, enabling scalable, synchronized environments relevant for collaborative XR and digital twin applications.
OGC Metaverse Standards (2023)	Open Geospatial Consortium standards for spatial data interoperability, supporting geolocation and 3D mapping in city-scale digital twins.
Meta Presence Platform (2023)	Tools and SDKs for building spatially aware, interaction-rich AR/VR experiences on Meta devices, integrating with the broader Metaverse.
NVIDIA Omniverse (2024)	A collaborative 3D design platform enabling real-time digital twin development and simulation, promoting standard-based interoperability (USD, MDL).
Microsoft Mesh & Digital Twins (2023)	Combines mixed reality collaboration (Mesh) with Azure Digital Twins to bridge physical environments and the Metaverse.
Unity Digital Twin Solutions (2023)	Real-time 3D tools and pipelines to create interactive digital twins for urban, industrial, and simulation environments.

Autodesk Forge (2024)	A cloud-based platform offering APIs and services for creating, viewing, and managing digital twins, commonly used in architecture and manufacturing.
ISO/IEC 23005:2022 – MPEG-V	Defines media context and control interfaces, allowing synchronization between virtual experiences and real-world inputs or devices.
Digital Twin Consortium (2023)	Publishes frameworks and glossaries for digital twin development and governance, focusing on interoperability and lifecycle integration.
ETSI Human Factors for XR (2023)	Addresses accessibility, usability, and human impact in XR system design—key for inclusive and ethical Metaverse experiences.
ITU-T FG-MV (2023)	ITU's focus group on Metaverse studies international requirements, standards gaps, and infrastructure considerations.
WEF Metaverse Governance Toolkit (2024)	Provides policy and governance guidance for responsible development and use of Metaverse technologies across sectors.
W3C Immersive Web Working Group (2024)	Develops APIs and specifications to enable XR content on the web, driving openness and standards-based innovation.
ISO/IEC SC 42 – AI & Big Data (2023)	Establishes AI governance, trust, and interoperability frameworks that overlap with XR systems and intelligent digital twins.
OpenXR (2023)	A cross-platform API standard for accessing VR/AR/MR hardware, ensuring broad compatibility across devices and XR runtimes.
AI4EU – Ethical AI and XR (2024)	Promotes ethical AI integration into XR systems, focusing on human-centered, transparent, and responsible technology use.
IEEE P7010-2022	Provides guidelines for assessing how autonomous systems impact human well-being—relevant for ethical Metaverse design.
ISO/TC 184/SC 4 – Industrial Data (2024)	Develops standards for product lifecycle and industrial data exchange, supporting real-time synchronization in digital twin systems.
World Avatar Project (2023)	Uses semantic web and linked data for dynamic, intelligent digital twins—foundational for scalable, adaptive Metaverse systems.
Open Digital Twin Framework (2024)	Offers interoperability guidelines and reference models for digital twin architecture across domains.
Bosch VR-enabled Digital Twins (2024)	Industrial applications of VR-based twins for manufacturing insights, human-in-the-loop simulations, and remote diagnostics.
Siemens Industrial Metaverse (2023)	Siemens' strategy and platform integration of digital twins, simulation, and automation for large-scale industrial Metaverse solutions.

3.3 Augmented Reality (AR) Standards

Augmented Reality (AR) is rapidly becoming a cornerstone in the ongoing transformation of urban environments into smart cities. By superimposing digital information on the physical world, AR enables intuitive, immersive experiences that can enhance the way people interact with city infrastructure, services, and information [1]. Applications range from real-time navigation and public transportation overlays to heritage tourism, emergency response, urban planning, and citizen engagement. As the use of AR accelerates, the demand for standardized frameworks to ensure interoperability, accessibility, safety, and ethical compliance becomes increasingly urgent [2].

Standardization is critical for ensuring that AR technologies work seamlessly across devices, platforms, and networks. Without coherent standards, the AR ecosystem risks becoming fragmented, limiting innovation and public trust [3]. As a response, international standardization bodies and industry consortia have begun to formalize technical, ethical, and procedural guidelines for AR implementation. This section discusses three major initiatives contributing to this effort: the Metaverse Standards Forum, the ISO/IEC JTC 1 committee, and the IEEE Standards Association.

3.3.1 Metaverse Standards Forum

The Metaverse Standards Forum (MSF) emerged as a collaborative effort to align various stakeholders on the interoperability standards needed to support an open and inclusive metaverse [4]. While the concept of the metaverse encompasses a broader range of technologies, AR is one of its most tangible and immediate components. The MSF includes participants from industry, academia, standards development organizations (SDOs), and government agencies, aiming to consolidate technical requirements, identify gaps in current standards, and foster pre-standardization activities [5].

Within the AR context, the MSF supports the development of common protocols for spatial mapping, digital object rendering, identity management, and persistent content anchoring [6]. For example, in urban navigation systems, AR elements like directional arrows and contextual labels need to be consistently positioned in the user's physical space, regardless of the hardware used [7]. This consistency is only achievable through standardized geospatial reference systems and content alignment protocols [8].

The MSF also promotes open collaboration with existing standards organizations such as the Open Geospatial Consortium (OGC), Khronos Group, and the World Wide Web Consortium (W3C) [9]. These collaborations help harmonize overlapping efforts in 3D content formats, web-based AR frameworks, and device interoperability. For smart cities, this ensures that AR services such as wayfinding, real-time pollution overlays, or maintenance instructions for urban infrastructure can be uniformly accessed by citizens and city workers [10].

Importantly, the Forum prioritizes inclusive design, addressing accessibility and localization to support diverse user needs. This is particularly relevant for municipalities aiming to deploy AR services equitably across various demographic groups, including elderly populations and individuals with disabilities [11].

3.3.2 JTC 1 Augmented Reality Standards

The Joint Technical Committee 1 (JTC 1) of ISO/IEC has played a leading role in the standardization of information technologies, including AR. Under Subcommittee 24 (SC 24), which deals with computer graphics, image processing, and environmental data representation, JTC 1 has developed several key standards relevant to AR applications [12].

JTC 1 standards focus on both the technical architecture and data representation models that underpin AR systems. One major contribution is the framework for AR reference models, which defines how data flows between sensors, processing units, and user interfaces [13]. This includes specifications for scene graph management, object tracking, gesture recognition, and multimodal interactions, all of which are essential for delivering coherent AR experiences [14].

In smart city contexts, JTC 1 standards support applications such as AR-assisted public services. For instance, maintenance crews using AR glasses can access real-time information about underground utility networks or power grids without referring to paper-based maps [15]. The standards ensure that such data is displayed accurately, based on consistent 3D spatial models and reliable sensor integration [16].

Moreover, JTC 1 has developed standards for multimedia content representation and streaming, enabling AR systems to render and synchronize complex media in real-time [17]. This is crucial in use cases such as AR-based tourism guides or event broadcasting, where video, audio, and interactive elements must be harmonized.

JTC 1 also addresses the integration of AR with other emerging technologies such as artificial intelligence, big data, and the Internet of Things (IoT). For example, combining AI-driven facial recognition with AR could allow personalized overlays in public spaces, provided that such integrations comply with privacy and ethical standards [18].

3.3.3 AT IEEE Augmented Reality Standards

The IEEE Standards Association (IEEE SA) has initiated several projects that address the ethical, technical, and societal implications of AR. While IEEE's focus is broader than AR alone, many of its initiatives have direct relevance to AR applications, particularly in urban and civic environments [19].

Among the most prominent efforts is the IEEE P2048 series, which explores ethical considerations for extended reality (XR), including AR. These standards define principles for transparency, data governance, user consent, and digital inclusion. For example, in a smart city deployment where AR is used for law enforcement or surveillance, IEEE P2048 provides guidance to prevent misuse of personal data and ensure that systems remain accountable [20].

From a technical standpoint, IEEE is also developing standards that cover aspects such as latency management, edge computing integration, and wearable device interoperability. These are essential for AR systems operating in real-time, high-density environments like transportation hubs or emergency response zones. IEEE's work on low-latency network protocols and time synchronization helps ensure that AR content is delivered without delays or inconsistencies, which is critical for both user experience and safety.

In addition, the IEEE collaborates with other organizations to develop interoperable metadata models and data schemas that support AR content portability. This ensures that digital overlays created for one platform or device can be reused across others, fostering a more sustainable and adaptable AR ecosystem.

IEEE also plays a key role in capacity building and policy advocacy, offering training materials and guidelines to municipal stakeholders. These resources help cities evaluate and adopt AR technologies responsibly, balancing innovation with ethical risk management.

AR continues to evolve, its integration into the fabric of smart cities will depend on well-coordinated standardization efforts. The combined contributions of the Metaverse Standards Forum, ISO/IEC JTC 1, and IEEE SA represent a foundational step toward building robust, interoperable, and citizen-centric AR systems. These efforts not only ensure technical compatibility but also address the ethical, accessibility, and governance challenges that come with deploying AR at urban scale.

Through continued collaboration and cross-domain standardization, AR can move from isolated applications to a fully integrated component of digital urban infrastructure. By doing so, cities will be better equipped to provide inclusive, responsive, and intelligent services that meet the needs of an increasingly connected population.

Table 4 - Key Standards Supporting Augmented Reality and the Metaverse

Standard / Source	**Explanation / Relevance**
Metaverse Standards Forum (2023)	Cross-industry group promoting interoperability for AR/VR systems; facilitates integration across platforms and devices within the Metaverse.
Khronos Group – glTF and AR Standards (2023)	glTF provides a standardized 3D asset format for lightweight, platform-neutral AR content exchange and rendering.
OGC – Open Geospatial Standards (2023)	Develops AR geospatial standards that support accurate positioning and anchoring of digital objects in physical space, vital for location-based AR.
W3C – WebXR Device API (2022)	Enables web-based AR/VR applications to run directly in browsers, improving accessibility and standardization for AR content delivery.
ISO/IEC JTC 1 (2023)	Technical committee working on global AR and Metaverse standards, covering system architecture, security, and interoperability.
ITU – AR Use in Smart Cities (2021)	Explores AR applications in urban environments (e.g., navigation, maintenance), promoting interoperability and data security in public infrastructure.
UN ESCAP – Digital Inclusion (2022)	Recommends inclusive AR design for smart cities, ensuring equitable access to spatial computing technologies.

ISO/IEC 18038 (2020)	Provides a reference model for AR systems, defining core components, interactions, and system behaviour for consistent development.
ISO/IEC 23000-13 (2021)	Standard for describing media context and spatial scenes, supporting dynamic AR interactions and content adaptation.
ISO/IEC JTC 1 SC 24 (2022)	Specializes in computer graphics and AR integration, enabling standardized visual representation and rendering across platforms.
European Commission – Horizon AR Projects (2021)	Supports AR R&D for industrial applications like maintenance and training, often aligned with emerging standards and data formats.
IEEE AR Interoperability WG (2023)	Focuses on creating AR interface and data exchange standards to ensure seamless operation across devices and software environments.
IEEE P2048 – XR Ethics Guidelines (2023)	Provides ethical principles and technical recommendations for privacy, identity, and safety in XR systems including AR.
IEEE SA XR Policy Initiative (2022)	Drives policy and regulatory considerations for XR technology deployment, including AR, emphasizing user rights and responsible data use.
NIST AR Guidelines (2022)	Provides best practices for implementing AR in public spaces, addressing usability, safety, and accessibility concerns.
WEF – XR Responsible Innovation (2023)	Advocates for inclusive, safe, and ethical AR deployment as part of broader Metaverse governance and innovation efforts.

Table 5 - Key related to standards works Supporting Augmented Reality and the Metaverse

Standard / Source	Explanation / Relevance
Azuma (1997)	Foundational academic survey defining AR's core components: real-time interaction, 3D registration, and the overlay of virtual content on physical environments.
Billinghurst & Kato (2002)	Introduced collaborative AR systems, where multiple users interact in real time with shared digital objects—central to social AR in the Metaverse.
Schmalstieg & Hollerer (2016)	Comprehensive textbook detailing AR architecture, tracking, rendering, and hardware, forming the theoretical base for AR standards.
Mystakidis (2022)	Highlights the role of immersive AR in future education, advocating for inclusive design and ethical frameworks in digital learning spaces.

3.4 Mixed Reality (MR) Standards

Mixed Reality (MR), as an extension of Augmented and Virtual Reality, blends real and virtual environments to create interactive, immersive experiences that respond to the user's physical context. In smart cities and digitally augmented environments, MR holds the potential to revolutionize how people interact with public infrastructure, services, and digital content. Its applications span urban mobility, collaborative design, public safety, tourism, healthcare, and beyond. However, as MR technologies grow in sophistication and adoption, a cohesive framework of standards becomes critical to support their interoperability, security, accessibility, and ethical use.

In this section, we examine three leading efforts contributing to the standardization of MR: the Metaverse Standards Forum, ISO/IEC JTC 1, and the IEEE Standards Association. These initiatives address a wide range of challenges, from technical system integration to ethical principles and user experience design. Each plays a key role in ensuring MR systems can be deployed at scale while maintaining compatibility across platforms, devices, and application domains.

3.4.1 Metaverse Standards Forum

The Metaverse Standards Forum (MSF) provides an open, collaborative platform for organizations working to develop interoperability standards across the metaverse landscape, including Mixed Reality. As MR combines physical and digital elements in a persistent, interactive continuum, the need for coherent spatial and data frameworks is especially critical [21]. MSF prioritizes the harmonization of protocols for rendering, scene understanding, user interaction, spatial anchoring, and real-time collaboration.

For MR to function reliably in smart city contexts—for instance, enabling city planners to visualize infrastructure upgrades through holographic overlays—standardized reference frames, mesh representations, and user experience models are essential [22]. MSF members include technology developers, government bodies, and academic institutions who are shaping the foundation for interoperable MR environments [23].

One of the major areas of collaboration involves the integration of MR with geospatial data layers, which is vital for use cases such as digital twin simulations or spatial analytics for city resilience planning [24]. These applications depend on shared coordinate systems, metadata schemas, and rendering protocols to ensure accuracy and usability.

The MSF also interfaces with content and asset management systems to address challenges in asset portability. For example, MR architectural models developed in one design platform should be compatible with civic visualization tools used by urban planning departments [25]. To achieve this, the MSF supports open standards for 3D content interchange (e.g., glTF, USD) and real-time rendering APIs [26].

As MR moves toward more socially integrated and persistent experiences, the Forum emphasizes user identity, privacy, and safety protocols. These considerations are especially important for MR systems operating in public environments or involving personal data [27].

3.4.2 JTC 1 Mixed Reality Standards

ISO/IEC Joint Technical Committee 1 (JTC 1) plays a pivotal role in the international standardization of MR technologies. Its subcommittees, particularly SC 24 (computer graphics) and SC 29 (multimedia coding), have initiated the development of several foundational standards for MR [28].

JTC 1 defines MR in terms of its fusion of digital and physical interaction layers, with standards encompassing display technologies, interaction modalities, spatial mapping, and multimodal feedback [29]. For MR applications in smart cities, these standards support the consistent implementation of visualization tools, such as those used for infrastructure inspection, emergency planning, or construction monitoring [30].

A significant contribution from JTC 1 is the standardization of immersive content representation through the MPEG-I (Immersive Media) framework. This supports MR by enabling synchronized rendering of volumetric video, spatial audio, and environmental context data [31]. JTC 1's metadata and sensor interface standards ensure that MR devices can interface with city data systems, facilitating applications like smart parking visualization or interactive cultural heritage guides [32].

Another key area is the integration of MR with other emerging technologies. For example, standards for MR-IoT convergence support real-time visualization of sensor networks or maintenance operations on digital twins of city infrastructure [33]. These integrations enable predictive analytics and situational awareness through intuitive visual interfaces.

JTC 1 is also addressing the accessibility of MR technologies by promoting inclusive design practices. Standards for adaptive user interfaces, multimodal input (voice, gesture, eye tracking), and localization contribute to MR systems that are accessible across different user groups [34].

Security and trust are also central to JTC 1's MR work. Data encryption, digital identity validation, and secure communication channels are essential for MR applications in healthcare, public safety, or citizen engagement [35].

3.4.3 IEEE Mixed Reality Standards

The IEEE Standards Association is advancing the field of MR through both technical and ethical frameworks. One of its hallmark initiatives is the IEEE P2048 series, which addresses extended reality (XR), including MR, from a systems engineering and ethics perspective [36].

These standards provide guidelines for developers and policymakers on responsible MR development. Key topics include algorithmic transparency, user consent, inclusivity, and psychological safety [37]. In urban environments, where MR applications may be embedded in public transportation hubs or educational settings, these guidelines help build trust and ensure responsible deployment.

IEEE is also involved in the development of low-latency communication standards critical for MR systems. These include edge computing architectures and synchronization protocols that enable seamless interaction between virtual elements and the physical environment [38]. For example, IEEE standards for time-sensitive networking (TSN) support stable, real-time updates essential for applications like MR-guided surgeries or firefighting [39].

Device interoperability is another focal point. IEEE is working on standards that ensure MR headsets, haptic devices, and environmental sensors can function together within an integrated ecosystem. This is especially relevant for collaborative MR applications in education or industrial training [40].

IEEE's contribution to smart cities also includes standardization of digital twin platforms, where MR is used as a visualization and interaction layer. These standards support citywide simulations, energy efficiency planning, and citizen engagement tools through immersive, data-driven interfaces [41].

Ethical data governance is reinforced by IEEE's standards on data minimization, anonymization, and rights-based design. These considerations ensure MR platforms comply with international data protection regulations and foster long-term societal trust [42].

3.4.4 Concluding Remarks

As Mixed Reality becomes an integral part of the digital urban experience, standardization emerges as a critical enabler for responsible, interoperable, and scalable deployment. Through the combined efforts of the Metaverse Standards Forum, ISO/IEC JTC 1, and IEEE SA, a robust framework is being constructed to support MR across technical, ethical, and experiential dimensions.

These standards ensure that MR solutions are not only functionally effective but also secure, inclusive, and aligned with societal values. They provide the infrastructure for cities to integrate MR into public services, transportation systems, education platforms, and civic engagement initiatives. With these foundations, MR can serve as a transformative tool in building smarter, more connected, and more human-centric urban environments.

Table 6 - Key Standards Supporting Mixed Reality and the Metaverse

Standard / Source	Explanation / Relevance
Metaverse Standards Forum (2023)	Promotes **interoperability frameworks** for MR and XR technologies, fostering collaboration between industries and platforms.
Open Geospatial Consortium (2022)	Defines **geospatial data standards** that allow MR content to be precisely anchored in real-world locations, essential for location-aware MR applications.
Khronos Group – USD & glTF (2023)	**glTF** and **Universal Scene Description (USD)** are standards for 3D asset exchange and rendering, supporting realistic object integration in MR environments.
W3C – Immersive Web WG (2022)	Develops APIs like **WebXR** to enable MR and XR experiences directly in web browsers, standardizing cross-platform access.
World Economic Forum (2022)	Offers governance principles and guidelines for **privacy, security, and safety** in MR and spatial computing experiences.
ISO/IEC JTC 1 SC 24 (2021)	Leads global efforts in **standardizing MR system components**, interfaces, and architecture for consistent deployment.

ISO/IEC 23090-5 (2020)	Part of MPEG-I, focuses on **immersive media standards**, including volumetric video and spatial audio essential to MR environments.
ITU-T (2022)	Provides use case and **interoperability frameworks** for MR in **public safety**, including disaster response and field visualization tools.
ISO/IEC JTC 1 (2023)	Coordinates **immersive content and system** standards across MR, AR, and VR domains to ensure global coherence.
EU Smart Cities Marketplace (2022)	Explores MR in **urban service delivery**, such as infrastructure visualization, smart mobility, and public engagement.
IEEE Smart Cities TC (2022)	Focuses on **MR and IoT integration** for dynamic city services, enabling data overlays and situational awareness.
ISO/IEC Guide 71 (2014)	Ensures **accessibility in ICT systems**, including MR, promoting inclusive design for diverse user needs.
NIST Security Framework (2022)	Provides **security frameworks and best practices** for immersive systems, addressing data integrity and user safety in MR platforms.
IEEE P2048 (2023)	Draft standard on **ethics in XR**, including MR—addresses bias, identity, and consent in immersive environments.
IEEE SA – XR Trustworthiness (2021)	Develops criteria for **trustworthy XR systems**, focusing on transparency, explainability, and reliability in MR.
IEEE 802.1 TSN (2022)	**Time-Sensitive Networking (TSN)** ensures low-latency, synchronized communication—critical for real-time MR responsiveness.
IEEE SA Edge Computing WG (2023)	Supports **distributed processing for MR**, reducing latency and improving system scalability through edge integration.
IEEE P3333.1.3 (2022)	Standardizes **3D imaging and display systems** for MR, including stereoscopic rendering and depth sensing techniques.
ISO/IEC Digital Twin Reference Architecture(2023)	Aligns **digital twin frameworks** with MR, enabling synchronized virtual-physical simulations in manufacturing, health, and urban design.
IEEE Ethically Aligned Design (2019)	Provides overarching **ethical guidelines** for immersive and intelligent systems, applicable to MR in areas like surveillance, education, and enterprise.

Table 7 - Key related to standards works Supporting Mixed Reality and the Metaverse

Standard / Source	Explanation / Relevance
Milgram & Kishino (1994)	Introduced the foundational **MR continuum**, framing MR as the space between real and virtual environments—a conceptual basis for all MR system design.
Billinghurst et al. (2015)	Comprehensive **survey of AR**, which heavily overlaps with MR; outlines technical challenges and user interface considerations critical to MR development.

4 Metaverse City Components Specifications

4.1 Metaverse City Infrastructure

The emergence of the metaverse as a viable construct for urban innovation represents a radical transformation of how city infrastructure is designed, operated, and experienced. Unlike traditional urban systems, which rely solely on physical infrastructure and centralized control, metaverse-enabled cities utilize immersive technologies, decentralized platforms, and intelligent automation to create responsive, participatory, and inclusive urban environments. In a metaverse city, real-time digital layers augment physical structures, allowing for seamless interaction between people, places, and services in hybrid virtual-physical spaces.

4.1.1 Description

This new paradigm encompasses a variety of technologies including digital twins, artificial intelligence (AI), extended reality (XR), edge computing, and blockchain. These technologies converge within a spatial computing framework that facilitates synchronous, immersive experiences for users in real-world contexts. The result is a digitally augmented urban space that supports everything from personalized mobility guidance and AR-assisted emergency response to virtual zoning consultations and metaeconomies built on NFTs and virtual land markets.

At its core, a metaverse city infrastructure is not defined solely by hardware or data pipelines, but by an integrated ecosystem of standards-based systems that ensure semantic interoperability, security, and ethical governance. City infrastructure becomes programmable, interoperable, and updatable, much like software platforms, allowing municipalities to quickly adapt to shifting citizen needs, environmental changes, and technological advancements.

4.1.2 Technology-Related Standards

A truly functional metaverse city infrastructure depends on an expansive set of interconnected technology standards. These standards span digital representation, immersive content delivery, real-time communications, data governance, cybersecurity, identity management, and accessibility. The challenge lies not only in selecting appropriate standards but also in aligning them across jurisdictions, devices, vendors, and public-private partnerships.

Key standardization bodies include the International Organization for Standardization (ISO), International Electrotechnical Commission (IEC), Institute of Electrical and Electronics Engineers (IEEE), World Wide Web Consortium (W3C), International Telecommunication Union (ITU), and the Open Geospatial Consortium (OGC). Each provides specialized contributions to the metaverse landscape.

In particular, the ISO/IEC JTC 1/SC 41 subcommittee addresses standards for IoT and digital twins, critical to the dynamic representation of physical infrastructure. The ISO 19100 series and OGC CityGML focus on geospatial encoding, essential for spatially accurate rendering in mixed-reality environments. IEEE P2048 addresses ethical and functional considerations for extended reality systems.

Blockchain and decentralized systems are governed by ISO/TC 307, which defines frameworks for distributed ledgers, consensus protocols, and smart contracts. These underpin secure transactions and identity validation in virtual economies. Meanwhile, standards like ISO/IEC 27001 and ISO/IEC 27701 offer guidance for cybersecurity and data privacy.

As metaverse cities rely on immersive and inclusive user interfaces, accessibility and universal design are addressed by ISO/IEC Guide 71 and W3C's Web Content Accessibility Guidelines (WCAG). Standards in this category ensure that digital services are usable by all populations, regardless of disability or digital literacy.

4.1.3 Technology Standards Description/Specification

This section outlines the most relevant categories of standards in greater technical detail, emphasizing their role in establishing a functional and scalable metaverse city infrastructure.

4.1.3.1 Spatial and Geospatial Standards

- **ISO 19107** (Spatial Schema): Defines spatial characteristics of features, enabling accurate modeling of urban geometries.
- **OGC CityGML 3.0**: Provides a framework for semantic 3D city models, essential for managing urban digital twins.
- **ISO 19115**: Supports metadata for geographic data, allowing interoperability among municipal data platforms.

4.1.3.2 Immersive Media and Rendering Standards

- **ISO/IEC 23090-5 (MPEG-I Scene Description)**: Facilitates synchronized rendering of 3D scenes, animations, and volumetric assets.
- **Khronos Group glTF**: A file format for efficient transmission and loading of 3D scenes and models, optimized for XR platforms.
- **Universal Scene Description (USD)**: Used for large-scale AR/VR content interchange and spatial coordination.

4.1.3.3 Communication and Real-Time Data Exchange

- **WebRTC and WebSocket**: Protocols enabling low-latency peer-to-peer communication.
- **MQTT (OASIS)**: A lightweight messaging protocol for constrained devices and intermittent networks.

- **IEEE 802.1 Time-Sensitive Networking (TSN)**: Ensures deterministic real-time communications for critical urban systems.

4.1.3.4 Digital Twin and IoT Frameworks

- **IEEE P2413**: Establishes an architectural framework for the IoT, extensible to digital twins.
- **ISO/IEC 30173 (AWI)**: A forthcoming standard on digital twin reference architecture for smart cities.
- **ISO/IEC 20922 (MQTT)**: Governs messaging between twin layers and edge-cloud infrastructures.

4.1.3.5 Ethics, Governance, and Cybersecurity

- **IEEE P7000 Series**: A set of ethical guidelines for system design, addressing bias, consent, and human rights.
- **ISO/IEC 27001**: Offers a framework for establishing an information security management system (ISMS).
- **ISO/IEC 27701**: Enhances ISO/IEC 27001 by adding data privacy capabilities.

4.1.3.6 Blockchain and Identity Management

- **ISO/TC 307**: Defines security, privacy, governance, and interoperability standards for blockchain.
- **Decentralized Identifiers (DIDs)**: A W3C standard allowing for verifiable, self-sovereign identity.
- **Verifiable Credentials (VCs)**: Supports credential exchange in virtual services.

4.1.3.7 Accessibility and Inclusiveness

- **ISO/IEC Guide 71**: Ensures design considerations for older persons and persons with disabilities.
- **WCAG 2.1**: Provides guidelines for accessible digital content across devices and platforms.

4.2 Metaverse City Frameworks

A metaverse city framework provides the architectural blueprint and governance model necessary to integrate virtual, augmented, and physical environments into a unified urban system. Unlike traditional urban planning, which focuses primarily on physical infrastructure, metaverse city frameworks bridge the digital and real worlds by incorporating spatial computing, immersive platforms, decentralized data ecosystems, and AI-driven services. These frameworks outline how virtual public services, citizen avatars, digital twins, urban simulations, and economic layers such as tokenized transactions and virtual land management can be systematically coordinated and governed.

4.2.1 Description

Metaverse city frameworks are not just technological constructs but sociotechnical systems that align digital capabilities with civic goals. They define roles for stakeholders, principles for ethical governance, technical specifications for interoperability, and metrics for sustainability, inclusion, and resilience. A well-structured metaverse city framework ensures that digital transformation enhances—not replaces—physical urban life, and that all citizens can participate in and benefit from these innovations.

Frameworks are especially valuable in ensuring cross-domain integration. For instance, they enable synchronization between transportation simulations in digital twins, emergency response protocols in AR interfaces, and real-time energy management systems. By embedding standards into urban policy and design processes, these frameworks create a foundation for agile governance, participatory planning, and trust-centered digital public services.

4.2.2 Framework-Related Standards

The realization of metaverse city frameworks depends on a suite of interrelated standards that guide the design, operation, and governance of virtual-physical ecosystems. These standards define interfaces, protocols, ontologies, and governance principles, and are developed by international bodies such as ISO, IEC, IEEE, ITU-T, OGC, and W3C.

Key areas addressed by framework-related standards include:

- **Urban Digital Twin Governance**: ISO/IEC AWI 30173 and IEEE P2413 provide foundational models for managing synchronized digital and physical city components.
- **Immersive User Interfaces**: ISO/IEC 23090 and Khronos Group standards support visual continuity, content alignment, and real-time performance.
- **Data Ethics and Digital Rights**: IEEE P7000 series and ISO/IEC 27560 define guidelines for ethical system design, algorithm transparency, and user consent.
- **Identity and Trust Management**: Standards from W3C (DID and VC) and ISO/IEC 24760 series address identity federation, authentication, and trust verification.
- **Interoperability and Semantic Integration**: RDF, OWL, and SHACL from W3C enable shared meaning across heterogeneous data streams.
- **Public Participation Platforms**: Standards such as ISO 37106 (Sustainable Cities) and ISO 37122 (Smart Cities Indicators) ensure inclusiveness and transparency in civic digital platforms.

Together, these standards provide a cohesive framework for coordinating complex city functions in a digital-first environment while ensuring that ethical, legal, and technical safeguards are in place.

4.2.3 Frameworks Standards Description/Specification

To support comprehensive metaverse city planning, each standards category brings its own contribution:

4.2.3.1 Governance and Architecture

- **IEEE P2413**: Establishes a reference architecture for IoT applicable to urban digital ecosystems.
- **ISO/IEC AWI 30173**: Proposes a reference framework for digital twins in cities, including lifecycle management and feedback loops.
- **ISO/IEC 38505-1**: Provides principles for governing data as an asset.

4.2.3.2 Immersive Interfaces and User Experience

- **ISO/IEC 23090-3**: Supports immersive content delivery, critical for MR-based urban dashboards.
- **Khronos glTF & USD**: Enable efficient interchange of 3D content and assets across multiple platforms.

4.2.3.3 Ethics and Privacy

- **IEEE P7006**: Establishes a standard for personal data privacy for algorithmic systems.
- **ISO/IEC 27560:2022**: Specifies privacy requirements for city data ecosystems.
- **IEEE P7001**: Addresses transparency in autonomous systems for public trust.

4.2.3.4 Identity and Trust Systems

- **W3C DID**: Facilitates decentralized, user-controlled identity in public services.
- **ISO/IEC 24760-1**: Defines a framework for identity management.
- **W3C Verifiable Credentials**: Allows verifiable identity claims in both physical and virtual public spaces.

4.2.3.5 Interoperability and Data Modeling

- **W3C RDF and OWL**: Support machine-readable semantic data exchange.
- **W3C SHACL**: Validates conformance of data graphs to defined ontologies.

4.2.3.6 Public Engagement and Smart City Indicators

- **ISO 37106:2018**: Guides city administrations in digitally-enabled service delivery.
- **ISO 37122:2019**: Defines indicators for smart city progress, usable in metaverse dashboards.

4.3 Metaverse City Data

Metaverse city data constitutes the digital core of urban environments augmented through immersive, intelligent, and interactive technologies. It encompasses the continuous flow of information generated by IoT sensors, urban systems, citizen interactions, virtual assets, and digital twin models. In a metaverse-enabled city, data is not only passively collected but actively interpreted, shared, and utilized in real time to support decision-making, user experiences, governance, and predictive simulations.

4.3.1 Description

Unlike traditional urban data systems that operate in silos, metaverse city data is inherently interoperable, decentralized, and semantically enriched. It supports both operational tasks—such as traffic management and energy distribution—and experiential services, including augmented navigation, virtual citizen engagement, and metaeconomic transactions. The complexity of these data interactions requires standardization in how data is collected, modeled, transmitted, secured, and governed.

As cities evolve into spatially-aware, mixed-reality environments, data must flow seamlessly across devices, applications, institutions, and citizens. This necessitates the adoption of a coherent data framework aligned with international standards to ensure interoperability, scalability, ethical compliance, and data sovereignty. The strategic value of city data becomes amplified in the metaverse, where digital representations of urban systems become platforms for innovation, service delivery, and participatory governance.

4.3.2 Data-Related Standards

The foundation of metaverse city data management lies in robust data-related standards that enable structured collection, secure exchange, and intelligent use of data across spatial and temporal dimensions. International standards organizations such as ISO, IEC, IEEE, OGC, and W3C have developed a wide array of specifications that directly support metaverse city data ecosystems.

Key areas addressed by these standards include:

- **Data Collection and Encoding**: Standards for sensor data formats and time-series structures (e.g., ISO/IEC 30141, IEEE 1451).
- **Geospatial and Semantic Annotation**: OGC SensorThings API, ISO 19156 (Observations and Measurements), and W3C RDF/OWL.
- **Data Quality and Provenance**: ISO/IEC 25012 (Data Quality Model) and W3C PROV.
- **Real-Time Data Streams**: WebSocket, MQTT, and W3C SPARQL Update.
- **Data Privacy and Governance**: ISO/IEC 27701, ISO/IEC 29100, IEEE P7002 (Data Privacy Process).

- **Data Sharing and Open Access**: DCAT (Data Catalog Vocabulary), ISO 19115, and INSPIRE Directive principles.

These standards ensure that city data can be exchanged across platforms and stakeholders without losing meaning, integrity, or privacy. They are crucial for aligning city data strategies with smart governance, urban resilience, and citizen-centric service delivery.

4.3.3 Data Standards Description/Specification

4.3.3.1 Sensor and Stream Data Standards

- **IEEE 1451**: Defines smart transducer interface standards, enabling plug-and-play sensor integration.
- **ISO/IEC 30141**: Reference architecture for IoT, guiding end-to-end data acquisition and context modeling.
- **OGC SensorThings API**: Provides RESTful interfaces for managing time-series observations and metadata.

4.3.3.2 Semantic Web and Geospatial Standards

- **W3C RDF/OWL**: Enables semantic data representation and interoperability.
- **ISO 19156**: Defines a standard model for environmental and observational data.
- **GeoSPARQL**: Supports querying of spatial data using semantic technologies.

4.3.3.3 Data Quality, Provenance, and Interoperability

- **ISO/IEC 25012**: Offers a taxonomy and metrics for evaluating data quality attributes.
- **W3C PROV**: Provides a model for expressing provenance information.
- **ISO 19115**: Specifies metadata for geospatial datasets to support discovery and reuse.

4.3.3.4 Real-Time and Event-Driven Communication

- **MQTT and WebSocket**: Lightweight protocols used for real-time, low-latency data transfer.
- **W3C SPARQL 1.1 Update**: Supports dynamic updates to RDF datasets.
- **Apache Kafka** (de facto standard): Facilitates scalable data pipelines and event streaming.

4.3.3.5 Privacy, Ethics, and Data Governance

- **ISO/IEC 27701**: Extends ISO/IEC 27001 to include personal data processing.
- **ISO/IEC 29100**: Establishes a privacy framework applicable to city data systems.
- **IEEE P7002**: Guides privacy and security in automated and data-driven systems.

4.3.3.6 Data Sharing, Licensing, and Access

- **W3C DCAT**: A vocabulary for publishing data catalogs on the web.
- **INSPIRE Directive**: EU framework ensuring harmonized spatial data sharing.
- **Creative Commons Licenses**: Common legal tools for open data distribution.

5 Data-Related & Adoption of Standards

This section explores the requirements and best practices for data sharing and exchange in Digital Twin ecosystems, with a specific focus on the SENSE-NGSI framework.

5.1 Data Sharing & Exchange

The emergence of Digital Twins and the metaverse has catalysed a paradigmatic shift in how data is generated, shared, and exchanged across domains. As these technologies become more integral to sectors ranging from manufacturing to urban planning, the ability to seamlessly share and exchange data among stakeholders has become a prerequisite for interoperability, efficiency, and innovation.

5.1.1 Prerequisites and Requirements

Establishing effective data sharing and exchange mechanisms for Digital Twins and metaverse environments requires a foundational set of prerequisites and requirements. These can be categorised into technical, semantic, legal, and organisational domains.

Technical Requirements

Technical interoperability is central to data exchange. This necessitates adherence to open standards and protocols that support heterogeneous system integration. Commonly used standards include ISO 10303 (STEP), ISO 15926, and OPC UA. These enable the representation and exchange of product and process data across various lifecycle stages.

Moreover, data must be discoverable, accessible, and reusable—key principles embedded in the FAIR data guidelines. APIs, microservices, and edge computing infrastructure are pivotal for enabling real-time and scalable data exchange in Digital Twin applications.

Semantic Requirements

Semantic interoperability ensures that data retains its meaning when transferred between systems. Ontologies and data models play a vital role in achieving this. Initiatives like the Industry Ontologies Foundry (IOF) and the W3C Web of Things (WoT) provide a common vocabulary for describing entities and relationships.

Furthermore, metadata frameworks and context information models—such as those defined in NGSI-LD—enable dynamic and meaningful interaction between distributed digital entities. These ensure consistent interpretation and integration of data from diverse sources.

Legal and Ethical Requirements

Data sharing in the context of Digital Twins and the metaverse must comply with data protection regulations such as the GDPR in the EU or CCPA in California. Consent management, data anonymisation, and purpose limitation are critical considerations.

Ethical data governance frameworks are also essential. These involve establishing accountability mechanisms, auditing capabilities, and transparency policies to ensure that data sharing does not infringe on users' rights or introduce systemic biases.

Organisational Requirements

Organisational alignment is required to overcome silos and encourage cross-functional collaboration. This includes governance structures for data stewardship, role-based access control, and cross-organisational service level agreements (SLAs).

Digital readiness, including the availability of skilled personnel and organisational culture supportive of data-driven decision-making, is equally important.

5.1.2 Adoption & Best Practices

Best practices for the adoption of data sharing and exchange mechanisms in Digital Twins and metaverse implementations hinge on strategic planning, standardisation, and iterative deployment.

Incremental Adoption Strategy

Adopting data sharing capabilities should follow an incremental strategy that begins with internal system integration and scales up to inter-organisational collaboration. Pilot projects and proof-of-concept studies are effective in demonstrating feasibility and value.

Standardisation and Interoperability

Harmonisation with existing standards is crucial. The adoption of open standards such as NGSI-LD, ISO 23247, and IEEE 2413 reduces vendor lock-in and fosters an ecosystem of compatible solutions.

The use of digital thread principles, wherein a continuous data flow links various stages of an asset's lifecycle, ensures traceability and contextual awareness across domains.

Data Governance and Policy Alignment

Establishing clear data governance frameworks is a cornerstone of successful adoption. These frameworks should define data ownership, sharing agreements, data quality metrics, and compliance protocols. Leveraging policy-driven access control models ensures security and trustworthiness in multi-tenant environments.

Technology Stack and Infrastructure

Cloud-native architectures and edge computing solutions enhance scalability and performance. Containerised microservices, orchestration tools (e.g., Kubernetes), and event-driven architectures enable flexible and resilient data exchange mechanisms.

5.1.3 SENSE-NGSI Adoption-Adaptation User Guide

The Next Generation Service Interface (NGSI) modeling framework has emerged as a critical enabler for semantic interoperability in smart environments, IoT platforms, and digital twin applications. This section explores the principles of NGSI framework from a perspective of the modeling, its architectural constructs, and its strategic importance for the development of dynamic, interconnected digital ecosystems including the metaverse. It examines how NGSI facilitates data harmonization, real-time context management, and model-driven integration within heterogeneous digital infrastructures. The discussion integrates standards perspectives and illustrates the role of NGSI in advancing digital twin fidelity and metaverse immersion.

The SENSE-NGSI framework represents a significant advancement in enabling interoperable and adaptive data sharing for Digital Twins. SENSE (Smart Entity Normalisation for Semantic Exchange) builds on the NGSI-LD standard to provide a structured approach for entity normalisation and contextual interaction.

Framework Overview

SENSE-NGSI extends the capabilities of NGSI-LD by introducing a layered architecture:

- **Data Acquisition Layer**: Interfaces with IoT devices and legacy systems to gather real-time data.
- **Semantic Normalisation Layer**: Utilises ontologies to harmonise incoming data.
- **Context Broker Layer**: Mediates data requests and responses using NGSI-LD protocols.
- **Adaptation Interface Layer**: Provides connectors to external platforms and digital twin instances.

Adoption Methodology

1. **Assessment**: Evaluate the current infrastructure, identify integration points, and map existing data models to NGSI-LD entities.
2. **Configuration**: Deploy the FIWARE-based context broker, integrate ontologies, and implement data adapters.
3. **Pilot Testing**: Conduct scenario-based testing to validate interoperability, latency, and semantic consistency.
4. **Deployment**: Roll out the solution incrementally, ensuring proper monitoring and feedback loops.
5. **Optimisation**: Continuously refine data mappings, governance policies, and integration strategies based on operational insights.

Adaptation Guidelines

Adaptation involves tailoring the SENSE-NGSI components to specific domain requirements.

This includes:

- Extending ontologies to cover domain-specific concepts.
- Integrating with external APIs (e.g., BIM platforms, simulation engines).
- Enabling federated identity and access management for secure data sharing.

The flexibility of the SENSE-NGSI framework allows organisations to evolve from isolated digital models to integrated, cross-domain Digital Twin ecosystems, thereby realising the full potential of the metaverse.

Despite its advantages, NGSI modeling faces challenges related to scalability, semantic complexity, and evolving domain-specific requirements. Managing massive volumes of heterogeneous data and ensuring consistency in semantic definitions across diverse stakeholders remain ongoing issues.

5.1.3.1 SENSE NGSI Vocabulary and Terminology

Understanding the vocabulary and terminology underpinning NGSI (Next Generation Service Interfaces) is critical for ensuring semantic interoperability across Digital Twins and the metaverse. NGSI, developed under the FIWARE framework, defines a context information management model based on entities, attributes, metadata, and subscriptions. As Digital Twin ecosystems become more complex, establishing a harmonised vocabulary across platforms and domains is essential.

Entities, Attributes, and Metadata
At the heart of NGSI are entities, which represent real or virtual objects (e.g., a temperature sensor or a virtual avatar). Each entity includes:

- **Attributes**: Define the properties of an entity (e.g., "temperature" or "location").
- **Metadata**: Supplementary data that qualify the attribute (e.g., timestamp or accuracy).

This tripartite model enables systems to exchange and reason over rich contextual data, supporting real-time and historical insights.

Context Models and Ontologies
Semantic clarity is achieved through standardised context models. NGSI supports:

- **JSON-LD for Linked Data**: Integrates NGSI with semantic web technologies.
- **Context Registries**: Allow dynamic discovery and federation of context sources.
- **Common Data Models**: Such as those in Smart Data Models initiative, enhancing domain-wide consistency.

Ontologies further enrich NGSI by embedding relationships, hierarchies, and formal semantics. Use of OWL or RDF allows machines to infer new knowledge, critical in autonomous Digital Twin applications.

NGSI-LD: Linked Data Evolution

NGSI-LD extends NGSIv2 by introducing:

- **Linked Data Support**: Entities are linked via relationships, enabling graph traversal.
- **Temporal Features**: Supports versioning, time-series queries, and historical analytics.
- **GeoJSON**: For expressing geospatial context.

NGSI-LD aligns with ETSI standards, making it suitable for large-scale federated systems where provenance and interoperability are essential.

Digital Twin Taxonomies in NGSI

NGSI enables Digital Twins by defining entities such as:

- **Digital Asset**: Represents a virtual replica of a physical entity.
- **SensorTwin**: Encapsulates real-time sensor data.
- **SimulationModel**: Represents algorithms or physics-based models.

These taxonomies align with ISO 23247 for Digital Twin Frameworks, and are enriched through metadata (e.g., fidelity, update rate).

Cross-Domain Vocabulary Harmonisation

The metaverse integrates diverse domains: urban, health, industrial, and social. NGSI facilitates harmonisation through:

- **Modular Vocabularies**: Extensible data models for sector-specific adaptations.
- **Interlingual Mapping**: Aligns with vocabularies like schema.org, SOSA/SSN, and OPC UA.
- **Governance Models**: Managed vocabularies to reduce semantic drift.

Use Case Example: Smart City Interoperability
In a smart city metaverse:

- Traffic sensors use NGSI entities to share congestion levels.
- Digital Twins of roads receive updates and simulate alternative flows.
- Citizens interact with a visualised 3D city twin using consistent terms across applications.

Challenges and Recommendations
- **Semantic Conflicts**: Standardising units, definitions, and contexts is crucial.
- **Version Control**: Maintaining consistency across evolving vocabularies.

- **Governance Bodies**: Suggested formation of neutral groups to steward domain vocabularies.

A shared NGSI vocabulary fosters scalable, federated Digital Twin systems and underpins a cohesive metaverse. Its strength lies in semantic precision, extensibility, and support for linked data principles.

5.1.3.2 SENSE NGSI Modeling

The proliferation of digital ecosystems encompassing Internet of Things (IoT), smart cities, Industry 4.0, and emerging metaverse environments necessitates robust frameworks for managing context-aware information. NGSI modeling stands as a pivotal technology standard that structures how contextual data is represented, exchanged, and interpreted across distributed systems. Originating from ETSI's efforts and evolving through initiatives like FIWARE, NGSI provides a language for semantic descriptions of entities and their relationships, ensuring interoperability and real-time responsiveness.

5.1.3.3 Conceptual Foundations of NGSI Modeling

At its core, NGSI modeling is based on a meta-model that structures contextual information into entities, attributes, and metadata. Entities represent real-world or digital objects (e.g., a sensor, vehicle, or virtual avatar), attributes define properties of entities (e.g., temperature, location), and metadata qualifies these attributes (e.g., accuracy, timestamp). This layered approach enables flexible and extensible models that can be adapted for various domains.

A key principle is the clear differentiation between static and dynamic information, facilitating efficient context updates without re-transmitting invariant data. NGSI also promotes the use of standardized vocabularies and ontologies, enhancing semantic alignment across disparate systems.

5.1.3.4 NGSI Information Model and API

The NGSI information model prescribes how data is structured and interconnected, while the NGSI API standardizes the mechanisms for data querying, updating, and subscription management. The information model uses JSON-LD format, allowing integration with linked data principles and semantic web technologies. This integration enables NGSI to act as a bridge between IoT data streams and higher-level knowledge graphs.

The NGSI API supports operations such as entity registration, attribute updates, and subscription-based event notifications, critical for real-time applications. This design aligns with RESTful principles, ensuring ease of adoption and integration into cloud-native and edge computing environments.

5.1.3.5 Standards and Interoperability

NGSI modeling is strongly aligned with international standards, notably those from ETSI (European Telecommunications Standards Institute), OMA (Open Mobile Alliance), and ISO/IEC. ETSI's NGSI-LD standard, the latest evolution, incorporates linked data and semantic web technologies to enhance interoperability and context expressiveness.

The standardization efforts emphasize vendor-neutrality and scalability, enabling NGSI to serve as a foundational layer for smart infrastructure ecosystems. This includes harmonizing with protocols such as MQTT and OPC-UA to bridge data transport and semantic layers.

5.1.3.6 NGSI Modeling in Digital Twins

Digital twins represent virtual counterparts of physical entities, designed for monitoring, simulation, and predictive analytics. NGSI modeling contributes fundamentally to digital twin architectures by providing a structured schema for representing both the static attributes and the dynamic context of physical assets.

By encapsulating real-time sensor data, operational states, and environmental context within NGSI entities, digital twins become not only accurate replicas but also responsive digital agents capable of driving autonomous decision-making. The semantic richness enabled by NGSI fosters multi-domain integration and cross-system interoperability, essential for complex digital twin scenarios in manufacturing, urban planning, and health systems.

5.1.3.7 NGSI and the Metaverse

The metaverse, envisioned as a persistent, interconnected 3D virtual universe, demands extensive context modeling and seamless integration of physical and digital experiences. NGSI's semantic framework supports the creation of interoperable virtual entities and their contextual relationships, facilitating the dynamic synthesis of metaverse environments.

NGSI's support for real-time updates, subscription models, and linked data semantics enables user avatars, objects, and environments in the metaverse to be context-aware and responsive. This enhances immersion by allowing continuous synchronization between physical sensor networks and virtual worlds, bridging IoT infrastructure with metaverse platforms.

5.1.3.8 Technical aspects of NGSI Data Modeling

NGSI models employ JSON-LD serialization to represent entities, attributes, and relationships. JSON-LD integrates linked data principles by embedding context URIs, enabling semantic interoperability. Data types are extensible, accommodating simple literals, complex objects, and geo-coordinates.

NGSI specifications define operations for creating, updating, querying, and subscribing to context data. This lifecycle management ensures timely and relevant data propagation, critical in real-time applications such as digital twins and metaverse environments.

NGSI supports complex queries filtering entities based on attribute values, types, and geospatial constraints. Subscription mechanisms notify applications about changes in context data, enabling reactive systems and event-driven architectures.

5.2 SENSE Data Privacy

Data privacy in the context of Digital Twins and the metaverse is a multifaceted challenge that necessitates comprehensive frameworks to ensure the confidentiality, integrity, and availability of sensitive information. As Digital Twin ecosystems increasingly rely on real-time data acquisition and analysis, the preservation of privacy becomes critical—not only for regulatory compliance but also for maintaining stakeholder trust and enabling sustainable digital innovation. This section outlines the core prerequisites, best practices, and a user guide for implementing robust security mechanisms in SENSE-enabled environments.

5.2.1 Prerequisites and Requirements

Ensuring data privacy within Digital Twin and metaverse ecosystems demands the implementation of foundational principles encompassing technical, legal, procedural, and ethical dimensions.

Technical Requirements

Key technical requirements include data encryption at rest and in transit, secure data storage, and anonymisation techniques. Homomorphic encryption and differential privacy mechanisms are increasingly employed to protect sensitive data during computation. In addition, Secure Multi-Party Computation (SMPC) and Trusted Execution Environments (TEEs) are being used to maintain data privacy during processing across distributed nodes.

Privacy by design and by default must be embedded within the system architecture, ensuring that user data is protected from the outset. Decentralised identity models and privacy-enhancing technologies (PETs) support self-sovereign identity and minimal data exposure.

Legal and Regulatory Requirements

Compliance with data protection laws such as GDPR, HIPAA, and the CCPA is non-negotiable. These frameworks mandate clear rules for data minimisation, purpose limitation, and user consent. Organisations must implement Data Protection Impact Assessments (DPIAs), appoint Data Protection Officers (DPOs), and ensure breach notification protocols are in place.

Cross-border data flow regulations also necessitate data localisation strategies or adoption of standard contractual clauses (SCCs) for international data exchange.

Procedural and Ethical Requirements

Ethical guidelines must be incorporated to ensure that privacy considerations go beyond compliance. This includes transparency in data usage, inclusive design to avoid bias, and periodic audits for accountability. Clear data classification and handling policies need to be defined and enforced.

Role-based access control, multi-factor authentication, and continuous monitoring systems are required to ensure that only authorised personnel can access sensitive data.

5.2.2 Adoption & Best Practices

Adopting robust data privacy measures in Digital Twin environments entails the integration of policy, technology, and organisational change. Below are best practices identified across successful implementations.

Risk-Based Frameworks

A privacy risk assessment must precede system design, guiding the deployment of appropriate security controls based on data sensitivity and threat models. Frameworks such as NIST Privacy Framework and ISO/IEC 27701 can be employed to guide this process.

Privacy Engineering Principles

Designing systems with privacy in mind includes the implementation of pseudonymisation, data minimisation, and consent management platforms. These technical mechanisms should be complemented by strong user interface design that enhances transparency and control.

Federated Learning and Edge Privacy

Emerging best practices include federated learning, which enables machine learning across decentralised data without centralising sensitive information. Coupled with edge computing, this allows processing to occur close to the source, reducing data exposure.

Governance and Policy Integration

Effective privacy governance requires alignment between IT, legal, and business units. Privacy policies should be integrated into corporate governance frameworks, with designated roles and responsibilities for enforcement.

5.2.3 Security Authentication-Authorization User Guide

Authentication and authorisation are fundamental components of privacy-preserving Digital Twin systems. This guide offers a roadmap for implementing secure identity and access management (IAM) within the SENSE framework.

Framework Components

1. **Identity Management**: Implement decentralised identity (DID) systems compatible with W3C standards. These allow entities to own and control their digital identities without relying on central authorities.
2. **Authentication Mechanisms**: Deploy multi-factor authentication (MFA), including biometric and token-based systems. OAuth 2.0 and OpenID Connect protocols ensure secure and standardised authentication.
3. **Authorisation Protocols**: Implement role-based and attribute-based access control (RBAC/ABAC) to enforce granular permissions. XACML and UMA (User-Managed Access) frameworks support policy-driven access.
4. **Audit and Logging**: Maintain immutable logs of access attempts, authentication events, and data transactions. This supports non-repudiation, forensic analysis, and compliance verification.

Deployment Phases

- **Assessment**: Map out identity domains, assess data sensitivity, and identify access control requirements.
- **Integration**: Deploy IAM systems integrated with context brokers and external systems.
- **Testing**: Conduct penetration tests, security audits, and simulate threat scenarios.
- **Operation**: Continuously monitor access logs, update policies, and audit compliance.
- **Review**: Periodically reassess risk models and authentication policies in response to evolving threats.

Advanced Techniques [102]

- **Zero Trust Architecture**: Adopt a zero-trust model where no user or device is inherently trusted. Continuous validation and micro-segmentation are key principles.
- **Blockchain-Based Access Control**: Explore the use of blockchain for decentralised identity verification and policy enforcement.

Data privacy is a cornerstone of trust and functionality in Digital Twin and metaverse applications. By adhering to comprehensive technical, legal, and ethical requirements, adopting proven best practices, and deploying secure authentication and authorisation mechanisms, organisations can ensure resilient and privacy-respecting digital ecosystems.

5.3 Data Protection

In the increasingly interconnected environments of Digital Twins and the metaverse, data protection is both a foundational requirement and a continuously evolving challenge. Beyond ensuring privacy, data protection includes safeguarding data from corruption, unauthorised access, and loss, while maintaining its availability and integrity. As immersive, real-time systems become pervasive, the role of comprehensive data protection grows indispensable to trust, compliance, and performance.

5.3.1 Prerequisites and Requirements

Technical Requirements
Effective data protection starts with a solid technical foundation. This includes:

- **Data Integrity Controls**: Hashing algorithms (e.g., SHA-3) and digital signatures ensure data integrity during storage and transmission.
- **Encryption**: Advanced encryption standards (AES-256) must be applied at rest and in transit.
- **Redundancy and Backups**: Use of distributed storage systems and frequent backups to avoid data loss.
- **Access Controls**: Implementation of fine-grained access controls to restrict unauthorised use.
- **Real-time Monitoring**: Integration of Intrusion Detection Systems (IDS) and Security Information and Event Management (SIEM) platforms to monitor threats.

Regulatory and Legal Requirements
International standards and regulations frame data protection policies. These include:

- ISO/IEC 27001 and ISO/IEC 27002 for information security.
- GDPR and CCPA for ensuring lawful and fair data processing.
- Sector-specific standards such as IEC 62443 (industrial automation).

Organisations must also prepare for audit readiness and incident response aligned with regulatory expectations.

Organisational and Ethical Considerations
Institutions must foster a data-centric culture through:

- **Governance Frameworks**: Establishing data ownership, stewardship, and accountability structures.
- **Training**: Ongoing workforce training on handling sensitive data.
- **Ethical Oversight**: Inclusion of ethics boards or review committees to assess data collection and usage practices.

5.3.2 Best Practices

Data Lifecycle Management

From creation to deletion, data should be governed by clear policies:

- **Data Classification**: Tagging data by sensitivity to guide protection levels.
- **Retention Policies**: Ensuring data is not kept longer than necessary.
- **Secure Disposal**: Methods such as cryptographic erasure or physical destruction.

Zero Trust Model Implementation

Trust no device or user by default. Adopt principles of:

- **Continuous Verification**: Validate identity and context dynamically.
- **Microsegmentation**: Isolate workloads to reduce lateral movement.
- **Least Privilege**: Provide minimal necessary access.

Threat Intelligence and Response

Deploy proactive measures:

- **Vulnerability Scanning**: Regular automated testing for software flaws.
- **Threat Intelligence Feeds**: Integration with real-time threat data.
- **Incident Response Plans**: Preparedness for breach scenarios with defined roles and communication protocols.

Cloud and Edge Considerations

Given the decentralised nature of Digital Twins:

- **Secure Cloud Interfaces**: Encrypted APIs and identity federation across clouds.
- **Edge Device Protection**: Use of hardware security modules (HSMs) and firmware integrity checks.

5.3.3 SENSE Adoption-Adaptation

SENSE (Secure and ENcrypted Smart Environments) provides a modular framework to support data protection tailored to smart, cyber-physical ecosystems.

SENSE Architectural Overview

SENSE uses a layered architecture:

- **Perception Layer**: Protects sensor integrity using anomaly detection.
- **Network Layer**: Implements blockchain-based data transfer for tamper-evident records.
- **Service Layer**: Applies access control lists and data validation services.
- **Application Layer**: Enforces user-level protections through secure app containers.

Adaptation Strategies

Organisations can tailor SENSE to their environments through:

- **Policy Mapping**: Aligning SENSE modules with internal data policies and external regulations.
- **Modular Deployment**: Phased implementation starting from high-risk components.
- **Feedback Loops**: Integrating logs and analytics for dynamic policy refinement.

Integration with Digital Twin Platforms

SENSE can be integrated with Digital Twin orchestration engines and middleware via:

- **APIs and SDKs**: Enabling programmable control over data streams.
- **Data Provenance Tools**: Establishing traceability from source to consumption.
- **Smart Contracts**: Automating policy enforcement in blockchain-based systems.

Scalability and Interoperability

SENSE supports:

- **Interoperability**: With standards like NGSI-LD, OPC UA, and MQTT.
- **Scalability**: Through distributed node architecture and lightweight agents.

Evaluation and Auditing

Success metrics include:

- **Compliance Scorecards**: Aligned with ISO/IEC 27001.
- **Resilience Testing**: Simulated stress and fault injections.
- **Audit Trails**: Immutable and exportable logs for review.

6 Conclusions

SENSE's holistic standardization approach addresses the multifaceted challenges of building interoperable, secure, and ethical digital ecosystems that span digital twins and metaverse domains. By harmonizing terminology, aligning technical frameworks, and embedding ethical governance, based on standards and best practices SENSE will pave the way for scalable, user-centric, and trustworthy immersive environments. The convergence of these standards will accelerate innovation, enhance cross-domain collaboration, and unlock the full potential of digital transformations in urban, industrial, and social contexts. SENSE's developments focus on enhancing data integration, automated ontology alignment, and hybrid edge-cloud deployments to improve performance and reduce latency. Additionally, the convergence of NGSI with blockchain and decentralized identity frameworks holds promise for trust and security in digital twin and metaverse applications.

The development and governance of the Metaverse and related XR technologies depend heavily on international standardization. Various organizations (as described below) are playing crucial roles in defining standards and guidelines that ensure open, interoperable, and scalable digital ecosystems.

1. **ISO/IEC JTC 1/SC 24** – This subcommittee of ISO/IEC focuses on computer graphics, image processing, and environmental data representation. It is responsible for foundational standards like ISO/IEC 19775 (X3D) and ISO/IEC 23005 (MPEG-V), which address representation and interaction in virtual environments.
2. **Khronos Group** – An industry consortium that develops open standards such as **glTF** (GL Transmission Format) for 3D models and **OpenXR**, a royalty-free standard for accessing XR platforms and devices [Khronos, 2024].
3. **Metaverse Standards Forum (MSF)** – Launched in 2022, the MSF brings together organizations to promote interoperability through pragmatic, action-based projects. It includes key players like Meta, Microsoft, NVIDIA, and standards bodies such as IEEE and W3C [Metaverse Standards Forum, 2023].
4. **W3C (World Wide Web Consortium)** – The W3C plays an essential role in web-based standards for immersive environments, including WebXR Device API, which allows web applications to interact with XR devices [W3C, 2023].
5. **IEEE P2048 Series** – A set of ongoing IEEE standards projects focused on the Metaverse. These include definitions, frameworks for interoperability, and methodologies for evaluating Metaverse environments [IEEE Standards Association, 2024].
6. **BuildingSMART and ISO 23247** – In the field of Digital Twins, standards like ISO 23247 provide a reference architecture for digital representation of physical industrial systems, while BuildingSMART promotes open BIM (Building Information Modeling) standards for the construction and facility management sectors.

Despite significant progress, achieving a fully interoperable and ethical Metaverse poses complex challenges. Data privacy, digital identity management, accessibility, and content moderation are among the pressing concerns. Furthermore, aligning commercial interests with open standards remains a delicate balance. However, collaboration across public and private sectors, along with user-centric design and regulatory oversight, can foster inclusive and sustainable growth of these digital ecosystems. Digital and virtual technologies are no longer fringe innovations; they are central to the evolving human experience. The integration of XR, Digital Twins, and the Metaverse into everyday life marks a transformative shift that demands coherent technical standards and ethical frameworks.

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