ETSI GR ARF 012 V1.1.1 (2025-11)

GROUP REPORT

Augmented Reality Framework (ARF); Executive Summary of the Virtual World Standards Landscape Report and the Virtual World Standards Recommendations Report

Disclaimer

The present document has been produced and approved by the Augmented Reality Framework (ARF) ETSI Industry Specification Group (ISG) and represents the views of those members who participated in this ISG.
It does not necessarily represent the views of the entire ETSI membership.

Reference
DGR/ARF-0012

Keywords
augmented reality, metaverse

ETSI

650 Route des Lucioles
F-06921 Sophia Antipolis Cedex - FRANCE

Tel.: +33 4 92 94 42 00 Fax: +33 4 93 65 47 16

Siret N° 348 623 562 00017 - APE 7112B
Association à but non lucratif enregistrée à la
Sous-Préfecture de Grasse (06) N° w061004871

Contents

Intellectual Property Rights

Essential patents

IPRs essential or potentially essential to normative deliverables may have been declared to ETSI. The declarations pertaining to these essential IPRs, if any, are publicly available for **ETSI members and non-members**, and can be found in ETSI SR 000 314: *"Intellectual Property Rights (IPRs); Essential, or potentially Essential, IPRs notified to ETSI in respect of ETSI standards"*, which is available from the ETSI Secretariat. Latest updates are available on the ETSI IPR online database.

Pursuant to the ETSI Directives including the ETSI IPR Policy, no investigation regarding the essentiality of IPRs, including IPR searches, has been carried out by ETSI. No guarantee can be given as to the existence of other IPRs not referenced in ETSI SR 000 314 (or the updates on the ETSI Web server) which are, or may be, or may become, essential to the present document.

Trademarks

The present document may include trademarks and/or tradenames which are asserted and/or registered by their owners. ETSI claims no ownership of these except for any which are indicated as being the property of ETSI, and conveys no right to use or reproduce any trademark and/or tradename. Mention of those trademarks in the present document does not constitute an endorsement by ETSI of products, services or organizations associated with those trademarks.

DECT™, **PLUGTESTS™**, **UMTS™** and the ETSI logo are trademarks of ETSI registered for the benefit of its Members. **3GPP™**, **LTE™** and **5G™** logo are trademarks of ETSI registered for the benefit of its Members and of the 3GPP Organizational Partners. **oneM2M™** logo is a trademark of ETSI registered for the benefit of its Members and of the oneM2M Partners. **GSM®** and the GSM logo are trademarks registered and owned by the GSM Association.

BLUETOOTH® is a trademark registered and owned by Bluetooth SIG, Inc.

Foreword

This Group Report (GR) has been produced by ETSI Industry Specification Group (ISG) Augmented Reality Framework (ARF).

The present document provides an executive summary of the ETSI GR ARF 010 [i.8] Standards Landscape report and the ETSI DMI ARF 011 [i.9] Recommendations Report.

Modal verbs terminology

In the present document "**should**", "**should not**", "**may**", "**need not**", "**will**", "**will not**", "**can**" and "**cannot**" are to be interpreted as described in clause 3.2 of the ETSI Drafting Rules (Verbal forms for the expression of provisions).

"**must**" and "**must not**" are **NOT** allowed in ETSI deliverables except when used in direct citation.

Executive summary

The present document consolidates insights from two reports focusing on Virtual Worlds standardisation processes, standards and the role of standards for enhancing the European Virtual Worlds ecosystem. It provides an overview of the current standards landscape covering 912 standards and 354 technical reports across eight Virtual Worlds domains. The landscape report published by ETSI in 2025 [i.8] is the most extensive of its kind to date. While many standards exist, adoption among major industry players remains low, limiting interoperability. A fragmented and poorly coordinated standardisation system presents major challenges to improving future prospects for scalable Virtual Worlds ecosystems. Structural issues such as power imbalances, overlapping mandates, and regulatory uncertainty hinder progress. The study identified such barriers and, in its Recommendations Report [i.9], provided recommendations to improve coordination, inclusivity, sustainability, and trust. If and when followed, the data-driven recommendations provided to policymakers will foster stakeholder engagement, collaboration, and coordination of organizations and working groups. Together, these can support growth of a secure, inclusive, and innovation-friendly European Virtual Worlds economy.

Introduction

Virtual Worlds technologies are transforming how people work, interact, learn, and create within persistent, interactive 3D environments. These experiences, delivered through immersive interfaces, increasingly blur the boundaries between physical and digital realities. As the European Commission emphasized in its 2023 communication on Virtual Worlds [i.10], a thriving ecosystem will rely on the convergence of enabling technologies such as AI, 5G/6G, and IoT - supported by open standards. However, limited interoperability, inconsistent data exchange, and weak integration of existing protocols remain critical barriers to value creation and innovation. The research which the present document summarises was initiated to examine these concerns and to guide public and private stakeholders toward coordinated, standards-based solutions to addressing barriers.

1 Scope

The present document distils findings from two previously prepared ETSI Reports. They document the current state of Virtual Worlds standards and, based on standards and gaps, provide concrete recommendations. These reports are based on the systematic analysis of information in public documents, interviews with subject matter experts, standards, standardisation working group charters and documents, and reports of SDO activities about Virtual Worlds. The objectives of the research included identifying all standards and technical reports, in order to reduce duplication, conflicting initiatives, and to identify gaps in standards. Eight Virtual Worlds domains are defined and over 900 standards are examined for their technical coverage in the domains identified. Ongoing efforts, and coordination status were also assessed. Research also evaluated how structural and institutional limitations affect the development of standards and their adoption. Recommendations were framed around stakeholder groups including providers, policymakers, researchers, and end-users.

For policymakers seeking to expand the European standards-based Virtual Worlds ecosystem with support for innovation and through harmonized regulatory and technical approaches, the present document also summarises recommendations.

2 References

2.1 Normative references

Normative references are not applicable in the present document.

2.2 Informative references

References are either specific (identified by date of publication and/or edition number or version number) or non-specific. For specific references, only the cited version applies. For non-specific references, the latest version of the referenced document (including any amendments) applies.

NOTE: While any hyperlinks included in this clause were valid at the time of publication, ETSI cannot guarantee their long-term validity.

The following referenced documents may be useful in implementing an ETSI deliverable or add to the reader's understanding, but are not required for conformance to the present document.

[i.1] 3GPP TS 26.566: "Immersive Audio for Split Rendering Scenarios".

[i.2] 3GPP TR 26.866: "Immersive Audio for Split Rendering Scenarios; Performance characterization".

[i.3] AIMS - IP Media Experience (IPMX).

[i.4] CTA-2094: "HDR/XR metadata".

[i.5] CTA-2097: "XR experience comfort metrics".

[i.6] Eclipse Foundation: "Dataspace Protocol 2025-1", EDWG DSP, n.d.

[i.7] ETSI GS ARF 003: "Augmented Reality Framework (ARF); AR framework architecture".

[i.8] ETSI GR ARF 010 (V2.1.1): "Augmented Reality Framework (ARF); Virtual World Standards Landscape Report".

[i.9] ETSI DMI/ARF 0011 (V0.0.2) (2025-06): "Augmented Reality Framework (ARF); Virtual World Standards Recommendations Report Virtual World Standards Recommendations Report".

[i.10] COM(2023) 442/final: "Communication from the Commission to the European Parliament, the Council, the European economic and social committee and the committee of the regions - An EU initiative on Web 4.0 and virtual worlds: a head start in the next technological transition".

[i.11] IEC 62629 (all parts): "3D display devices".

[i.12] IEC PWI 110-39: "Contact-lens-based AR displays", in progress.

[i.13] IEC PWI 110-36: "Electronic displays: Durability test methods of eyewear display".

[i.14] IEC TR 63340-3:2025: "Electronic displays for special applications - Part 3: Gaming and e-sports".

[i.15] IEC TS 63528:2025: "Multimedia systems - Haptics - Haptics stimuli descriptors".

[i.16] IEC 63145 (series): "Eyewear display".

[i.17] IEC TR 63614-1: "Multimedia Systems and Equipment for Metaverse - Part 1: General".

[i.18] IEC TR 110-22: "Electronic Displays: Measurement Method of Volumetric Display".

[i.19] IEEE P2957™: "Standard for a Reference Architecture for Big Data Governance and Metadata Management".

[i.20] IEEE P7030™: "Recommended Practice for Ethical Assessment of Extended Reality (XR) Technologies".

[i.21] IEEE P7016™: "Standard for Ethically Aligned Design and Operation of Metaverse Systems".

[i.22] IEEE P2888.6™: "Standard for Holographic Visualization for Interfacing Cyber and Physical Worlds".

[i.23] IEEE 2048.x™ (all parts): "VR/AR Working Group (VRARWG)".

[i.24] IEEE P3079.2™: "Standard for Mixed Reality (MR) Framework for Motion Training".

[i.25] IEEE P3079.1™: "Motion to Photon (MTP) Latency in Virtual Environments".

[i.26] IEEE P3079.3.2™: "Standard for a Framework for Privacy Protection through Identifiability Management Arising from Avatar Interaction".

[i.27] IEEE P3079.3.1-2025™: "IEEE Approved Draft Standard for Service Application Programming Interfaces (APIs) for Digital Human Authoring and Visualization".

[i.28] IEEE P2874-2025™: "IEEE Approved Draft Standard for Spatial Web Protocol, Architecture and Governance".

[i.29] IEEE P3079.4™: "Standard for the Visual Quality Assessment of Auto-Stereoscopic Displays".

[i.30] IEEE P3322™: "Guide for Comfort Requirements for Extended Reality (XR) Devices".

[i.31] IETF RFC 9901: "Selective Disclosure for JSON Web Tokens".

[i.32] ISO 23353.3: "Blockchain and DLT - Auditing".

[i.33] ISO 23516.3: "Blockchain and DLT - Interoperability ".

[i.34] ISO 9241-313:2025: "Ergonomics of human-system interaction — Part 313: Optical measurement methods for reflective displays".

[i.35] ISO/TS 16551:2025: "Health informatics — Reference model for virtual reality (VR)-based clinical practice simulation".

[i.36] ISO/AWI TS 10303-1856: "Industrial automation systems and integration — Product data representation and exchange — Part 1856: Annotated 3d model equivalence triangulated shape module".

[i.37] ISO/AWI TS 10303-1857: "Industrial automation systems and integration — Product data representation and exchange — Part 1857: Annotated 3d model equivalence display attribute module".

[i.38] ISO/IEC PWI 24931-2: "Information Technology — Metaverse — Part 2: Framework and architecture".

[i.39] ISO/IEC PWI 24931-4: "Information Technology — Metaverse — Part 4: Reference model".

[i.40] ISO/IEC PWI 24931-5: "Information Technology — Metaverse — Part 5: Information model".

[i.41] ISO/IEC CD 20996.2: "Information technology — Cloud computing — Cloud service customer business continuity and resilience".

[i.42] ISO/IEC DIS 20151: "Information technology — Cloud computing and distributed platforms — Dataspace concepts and characteristics".

[i.43] ISO/IEC FDIS 23090-29: "Information technology — Coded representation of immersive media — Part 29: Video-based dynamic mesh coding (V-DMC)".

[i.44] ISO/IEC FDIS 23090-30: "Information technology — Coded representation of immersive media — Part 30: Low latency, low complexity light detection and ranging (LiDAR) coding".

[i.45] ISO/IEC 23090-32:2025: "Information technology — Coded representation of immersive media — Part 32: Carriage of haptics data".

[i.46] ISO/IEC 23093-3:2022: "Information technology — Internet of media things — Part 3: Media data formats and APIs".

[i.47] ISO/IEC 23093-1:2025: "Information technology — Internet of media things — Part 1: Architecture".

[i.48] ISO/IEC 23093-2:2022: "Information technology — Internet of media things — Part 2: Discovery and communication API".

[i.49] ISO/IEC DIS 24931-1: "Information Technology — Metaverse — Part 1: Concepts, definitions and terminology".

[i.50] ISO/IEC JTC 1: "WG 10 Internet of Things".

[i.51] ISO/IEC 22989:2022: "Information technology — Artificial intelligence — Artificial intelligence concepts and terminology".

[i.52] ISO/IEC 23894:2023: "Information technology — Artificial intelligence — Guidance on risk management".

[i.53] ISO/IEC 23090-1: "Coded Representation of Immersive Media — MPEG-I — Immersive Media".

[i.54] ISO/IEC 23090-27: "Coded Representation of Immersive Media — MPEG-I — Media, renderers, and game engines for render-based systems and applications".

[i.55] ISO/IEC 23090-28: "Coded Representation of Immersive Media — MPEG-I — Interchangeable scene-based media representations".

[i.56] ISO/IEC CD TR 23090-11: "Information technology — Coded representation of immersive media — Part 11: Network-based media processing implementation guidelines".

[i.57] ISO/IEC 23090-33:2025: "Information technology — Coded representation of immersive media — Part 33: Conformance and reference software for haptics coding".

[i.58] ISO/TR 9241-380:2022: "Ergonomics of human-system interaction — Part 380: Survey result of HMD (Head-Mounted Displays) characteristics related to human-system interaction".

[i.59] ISO 9241-391:2016: "Ergonomics of human-system interaction — Part 391: Requirements, analysis and compliance test methods for the reduction of photosensitive seizures".

[i.60] ISO/IEC DIS 27091: "Cybersecurity and Privacy — Artificial Intelligence — Privacy protection".

[i.61] ISO/IEC PRF 21134: "Information technology — Computer graphics, image processing and environmental data representation — Benchmarking of integrated indoor localization and tracking methods using dead reckoning".

[i.62] ISO/IEC CD 18038-2: "Computer graphics, image processing and environmental representation — Sensor representation in mixed and augmented reality — Part 2: Information modelling".

[i.63] ISO/IEC PWI 22626: "Motion capture".

[i.64] ISO/IEC DIS 23090-39: "Information technology — Coded representation of immersive media — Part 39: Avatar representation format".

[i.65] ISO/IEC 23090-23:2023: "Information technology — Coded representation of immersive media — Part 23: Conformance and reference software for MPEG immersive video".

[i.66] ISO/IEC PWI 23554: "Computer graphics, image processing and environmental data representation - Privacy Policy Requirements in Modelling and Simulation Environments".

[i.67] ISO/IEC DIS 20538: "Information technology — Computer Graphics, image processing and environmental data representation — Human information data model for VR-based smart cities".

[i.68] ISO/IEC 18026:2025: "Information technology — Spatial reference model (SRM)".

[i.69] ISO/IEC AWI 23595: "Computer graphics, image processing and environmental data representation - User Experience Design in AR/MR/VR".

[i.70] ISO/IEC PWI 23620-4: "Information technology - VR/AR/MR systems integration — Part 4: Virtual human model".

[i.71] ISO/IEC TR 16088:2025: "Information technology — Computer graphics, image processing and environmental representation — Constructs for visual positioning systems in mixed and augmented reality (MAR)".

[i.72] ISO/IEC PWI 26951: "Information technology — Computer graphics, image processing and environmental data representation — Visual protection in the metaverse".

[i.73] ISO/IEC 9234:2025: "Information technology — Information modelling for virtual, augmented and mixed reality based education and training systems".

[i.74] Recommendation ITU-T F.748.58: "Requirements and architectures of multimedia platform for digital human services using edge cloud".

[i.75] Recommendation ITU-T F.748.50: "Framework and requirements of digital human access interfaces".

[i.76] Recommendation ITU-T F.748.31: "Technical requirements and evaluation methods of 3D digital human system based on smart mobile devices".

[i.77] OGC: "3D Tiles v1.1".

[i.78] OGC: "OGC City Geography Markup Language (CityGML) Part 1: Conceptual Model Standard".

[i.79] OGC: "OGC GeoPose 1.0 Data Exchange Standard".

[i.80] OMG: "Data Product Ontology (DPROD)".

[i.81] OMG: "DDS Extensions for Time Sensitive Networking (DDS-TSN)".

[i.82] OMG: "Pedigree and Provenance Model and Notation (PPMN)".

[i.83] oneM2M TR-0069: "Bridging Metaverse and Physical World via oneM2M system".

[i.84] oneM2M: "Supporting Metaverse Services via Standardized oneM2M IoT Platform".

[i.85] OpenID®: "Digital Credentials Protocols (DCP) Working Group - Specifications".

[i.86] OpenID®: "EAP Working Group - Specifications".

[i.87] OpenID®: "Self-Issued OpenID Provider".

[i.88] SVTA: "Resolving User-Experience Issues for VR/XR Content by Customizing Congestion Control Logic to the VR/XR Service and to the Network".

[i.89] ToIP: "Authentic Chained Data Containers (ACDC)".

[i.90] ToIP: "Composable Event Streaming Representation (CESR)".

[i.91] Virtual Reality/Augmented Reality und immersive Technologien.

[i.92] W3C® - Draft Community Group Report 18 November 2025: "VCALM v0.9 - A Verifiable Credential API for Lifecycle Management".

[i.93] W3C® Recommendation 15 May 2025: "Verifiable Credentials Data Model v2.0".

[i.94] W3C® Candidate Recommendation Draft, 20 November 2025: "WebGPU".

[i.95] W3C®: "First Public Working Drafts: WebXR Depth Sensing, Hit Test, DOM Overlays Modules".

[i.96] Khronos® Group: "Kamaros Embedded Camera System API".

[i.97] ISO/IEC CD 11034: "Information technology — Cloud computing — Trustworthiness in cloud computing".

[i.98] ISO/IEC FDIS 23093-6: "Information technology — Internet of media things — Part 6: IoMT Media data formats and API for distributed AI processing".

[i.99] IEEE P7000™: "IEEE Standard Model Process for Addressing Ethical Concerns during System Design".

[i.100] ISO/IEC 23090-24: "Information technology — Coded representation of immersive media — Part 24: Conformance and reference software for scene description".

[i.101] ISO/IEC 16248: "Health informatics — Categorial structure for terminological systems of human anatomy".

[i.102] ISO/IEC PWI 24931-6: "Information Technology — Metaverse — Part 6: Metaverse governance".

3 Definition of terms, symbols and abbreviations

3.1 Terms

For the purposes of the present document, the following terms apply:

Artificial Intelligence (AI): technologies using computers and processors, including computer vision, machine learning, natural language recognition, data processing, and generative algorithms, that perform tasks to produce, refine and optimize elements of experiences in Virtual Worlds and, as a result, enrich and enhance the value to users

data management: processes, technologies, and policies for collecting, storing, processing, securing, and utilizing data within Virtual Worlds environments and experiences

NOTE: Effective data management underpins the functionality, scalability, and ethical operation of Virtual Worlds ecosystems.

human interface systems and devices: integrated systems of hardware and software components for acquisition of context and delivery of immersive experiences to users

NOTE: Together, components create systems and devices that, when used with design principles or guidelines, facilitate interaction with and immersion in virtual reality and augmented reality experiences.

immersive experiences: enabling technologies and actors involved in generating and packaging assets and behaviours for interactive, and digitally mediated activities or simulations within Virtual Worlds or mixed real-and-digital environments

NOTE: These experiences engage users through sensory inputs (e.g. visual, auditory, haptic) and dynamic interactions, offering opportunities for many use cases including economic activities, exploration, learning, entertainment, or collaboration in digitally constructed and mixed digital-physical world settings.

industry-driven standards development organization: independent entity formed and operating for the purpose of developing standards to meet requirements of its members and based on contributions from any member organization, including but not limited to private or publicly traded companies of any size, public agencies or institutes of higher learning, who pay membership dues, or are invited, and agree to organization's terms and conditions

infrastructure: foundational systems, technologies, and frameworks that enable the seamless operation, scalability of and interactivity within Virtual Worlds environments

NOTE: It encompasses the hardware, software, networking, and computational resources required to deliver immersive, real-time experiences, ensuring high performance, low latency, and accessibility across devices and platforms.

internationally mandated standards development organization: organization formed and operating for the purpose of developing standards to meet requirements of its members who are themselves the standardisation bodies of national member states, not based on payment of member dues

NOTE: Initiation of and contributions to activities are based on consensus of national bodies and their members, regardless of size. These organizations are recognized by national governments and their results can be the basis for national or muti-national legislation and regulations.

industry-driven standard: publication approved by membership of and released by an industry-driven standards development organization

National Standards Body (NSB): organization established and financed by a government for the purpose of developing, reviewing and publishing standards that are used in the government's jurisdiction

Open Standard: publicly available specifications and guidelines designed to ensure that different systems, software, and technologies can communicate and operate seamlessly together

NOTE 1: Open Standards may be royalty-free or have royalties associated with their use.

NOTE 2: Open Standards and Open Source technologies differ in their approaches but often converge on their goals.

reality capture: technologies for and processes of digitizing physical environments, objects, humans and their interactions for further use in immersive, interactive, and virtual representations or by agents

NOTE: It involves the use of technologies to collect spatial, visual, and sensory data, enabling the seamless integration of real-world elements into virtual and augmented reality experiences.

standard: document or other form of structured information containing a set of agreed-upon technical rules or specifications that, when approved and implemented independently by two or more entities, ensure that different technologies or products work together consistently and without transformation, such as for the exchange of data

standards working group: team of experts who collaborate to develop and document technical specifications or guidelines for a specific domain or topic

Technical Report (TR): document that explains the details, such as use cases, requirements, background, or reasoning behind a specific technical standard or group of standards

Virtual Economy: buying and selling, using systems of interconnected components that drive economic activities, transactions, and business models, of goods and services within virtual environments, including both digital and physical items within digital and mixed (digital-physical) environments

Virtual Society: communities of individuals and organizations who share common interests, operates under social norms, governance structures, and ethical frameworks and interact, collaborate, and engage in shared social activities within immersive environments or in the real world with assistance of immersive interfaces

Virtual Worlds: technologies, tools, processes and content that enrich and support computer-assisted experiences for users, blurring real and synthetic spaces and objects, enhancing and enriching in new and unpredictable ways the daily lives of citizens while they are socialising, working, learning, making transactions, playing and engaging in creative activities

NOTE 1: They encompass a wide range of digital experiences, from fully immersive Virtual Worlds to augmented reality overlays on the physical world.

NOTE 2: They can be used for a variety of purposes such as designing, making simulations, collaborating, learning, socialising, carrying out transactions or providing entertainment.

3.2 Symbols

Void.

3.3 Abbreviations

For the purposes of the present document, the following abbreviations apply:

2D	Two Dimensional
3GPP	3rd Generation Partnership Project
6G	Sixth Generation Cellular Network
ACDC	Authentic Chained Data Containers
AEC	Architecture, Engineering and Construction
AfA	Access for All
AI	Artificial Intelligence
AIMS	Alliance for IP Media Solutions
API	Application Programming Interface
AR	Augmented Reality
BIM	Building Information Modeling
BLE	Bluetooth® Low Energy
BuildingSMART	BuildingSMART International
CCPA	California Consumer Protection Act
CD	Committee Draft
CEI	Central European Initiative
CEN	European Committee for Standardisation (Comité Européen de Normalisation)
CESR	Composable Event Streaming Representation
CTA	Consumer Technology Association
DAO	Decentralized Autonomous Organization
DCP	Digital Credentials Protocol
DDS	Data Distribution Service
DID	Decentralized Identifier
DIF	Decentralized Identity Foundation
DIS	Draft International Standard
DLT	Distributed Ledger Technology
DOI	Digital Object Identifier
DOM	Document Object Model
DPROD	Decentralized Product Ontology (OMG)
DSP	Digital Signal Processor
EAP	Extension for Attribute Providers (OpenID)
EC	European Commission
EDWG	Eclipse Dataspace Working Group
EPRI	Electric Power Research Institute
ETSI	European Telecommunications Standards Institute
EU	European Union
EUDI	European Digital Identity

EUOS	European Standards Observatory
FAIR	Findability, Accessibility, Interoperability, and Reuse
FG-MV	Focus Group on Metaverse
GDPR	General Data Protection Regulation
glTF	graphic language Transmission Format
GNSS	Global Navigation Satellite System
GPU	Graphics Processing Unit
HDR	High Definition
HIF	Haptics Industry Forum
HIPAA	Health Insurance Portability and Accountability Act
HL7	Health Level Seven International
HLIG	High Level Internet Governance
HMD	Head-Mounted Display
ICAID	Industry Connections Activity Initiation Document
ICHOM	International Consortium for Health Outcomes Measurement
ICT	Information and Communication Technology
ID	Identifier
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IIoT	Industrial Internet of Things
IMRA	Industrial Metaverse Reference Architecture
IMVAAM	Industrial Metaverse Virtual Application Assessment Model
IMVCMM	Industrial Metaverse Virtual Capability Maturity Model
iOS	Apple Operating System for mobile devices
IoT	Internet of Things
IP	Intellectual Property
IPMX	Internet Protocol Media Experience
IPR	Intellectual Property Rights
IPT	Institute for Production Technology
ISAC	Integrated Sensing and Communication
ISAR	International Standards of Accounting and Reporting
ISO	International Organization for Standardisation
ISO/IEC JTC 1	Joint Technical Committee 1 of ISO und IEC
ITU	International Telecommunication Union
ITU-T	International Telecommunication Union - Telecommunication Standardization Sector
IVAS	Immersive Voice and Audio Services
JPEG	Joint Photographic Experts Group
JSON	Java Script Object Notation
JTC	Joint Technical Committee
JTC1	Joint Technical Committee 1
JWG	Joint Working Group
JWT	JSON Web Token
LiDAR	Light Detection and Ranging
Linux	Linux® Foundation

NOTE: Linux® is the registered trademark of Linus Torvalds in the U.S. and other countries.

MIIT	Ministry of Industry and Information Technology (China)
MML	Metaverse Markup Language
MoU	Memorandum of Understanding
MPEG	Motion Pictures Experts Group
MR	Mixed reality
MTP	Motion-to-Photon
NBMP	Network-Based Media Processing
NEM	New Digital Media Group (of NEM)
NFT	Non-Fungible Token
NPC	Non-Playable Characters
NQF	National Quality Forum
OGC	Open Geospatial Consortium
OMA3	Open Metaverse Alliance for Web3
OMG	Object Management Group
OMI	Open Metaverse Interoperability Group

oneM2M	oneM2M Partnership Project
Open3D	Open3D Foundation
OpenID	OpenID Foundation
OS	Operating System
OSCAR4US	Open Source Scalable and Continuous Augmented Reality Services for Urban Spaces
OWF	OpenWallet Foundation
P2E	Play-to-Earn
PII	Personally Identifiable Information
PPMN	Pedigree and Provenance Model and Notation
PRC	PEREY Research & Consulting
PWI	Proposed Work Item
QA	Quality Assurance
REST	Representational State Transfer
SAREF	Smart Applications REFerence
SC	SubCommittee
SDG	Sustainable Development Goals
SDK	Software Development Kit
SDO	Standards Development Organization
SIOP	Self-Issued OpenID Provider
SLAM	Simultaneous Localization and Mapping
SME	Small and Medium-sized Enterprises
SMPTE	Society of Motion Picture and Television Engineers
SOSA	Sensor, Observation, Sample, and Actuator ontology
SRA	Strategic Research Agenda
SVTA	Streaming Video Technology Alliance
TC	Technical Committee
TM Forum	TeleManagement Forum
ToIP	Trust over IP Foundation
TSN	Time Sensitive Networking
TSP	Trust Spanning Protocol
UI	User Interface
UI/UX	User Interface/User Interaction
UL	Underwriters Limited
UN	United Nations
UX	User Experience
VC	Verifiable Credentials
VC-API	Verifiable Credentials Application Programming Interface
VDC	Virtual Dimension Center
VFA	Volumetric Format Association
VPS	Visual Positioning System
VQEG	Video Quality Experts Group
VR	Virtual Reality
VRML	Virtual Reality Modeling Language
W3C	World Wide Web Consortium
WBAN	Wireless Body Area Network
WebXR	This is an abbreviation and the name of a standard
WG	Working Group
WG9	Working Group 9
WIP	Work in Progress
X3D	Extensible 3D Graphics
XR	Extended Reality
XR	Extended Reality

4 Context

4.1 Emerging Virtual Worlds

Virtual Worlds are rapidly evolving through the convergence of many enabling technologies, including but not limited to artificial intelligence, real-time graphics engines, high-speed communication networks, sensors, and immersive interface systems. These technologies are becoming progressively more powerful, portable, and economical to use, creating the infrastructure needed to support persistent, interactive, and shared digital environments.

The COVID-19 pandemic acted as a major catalyst for interest and investment in remote collaboration, digital interaction, and hybrid experiences. Industry leaders have further fuelled momentum by launching or announcing advanced XR devices and platforms, embedding immersive experiences deeper into the consumer and enterprise markets.

Although public and media attention has recently shifted toward generative AI, especially with the rise of tools like ChatGPT and diffusion-based image generators, key players across the tech industry continue to commit significant resources to developing virtual and augmented reality technologies. These investments suggest that Virtual Worlds remain a strategic priority, even as short-term hype cycles fluctuate.

As a result, the concept of Virtual Worlds is undergoing a quiet but steady transformation-from marketing-driven hype toward more technically-viable and economically justifiable Virtual Worlds use cases. These developments are laying the groundwork for the future standardisation, governance, and societal embedding of Virtual Worlds across sectors such as education, health, industry, and culture.

Figure 1 shows how the many diverse technologies upon which Virtual Worlds stakeholders are building interlock.

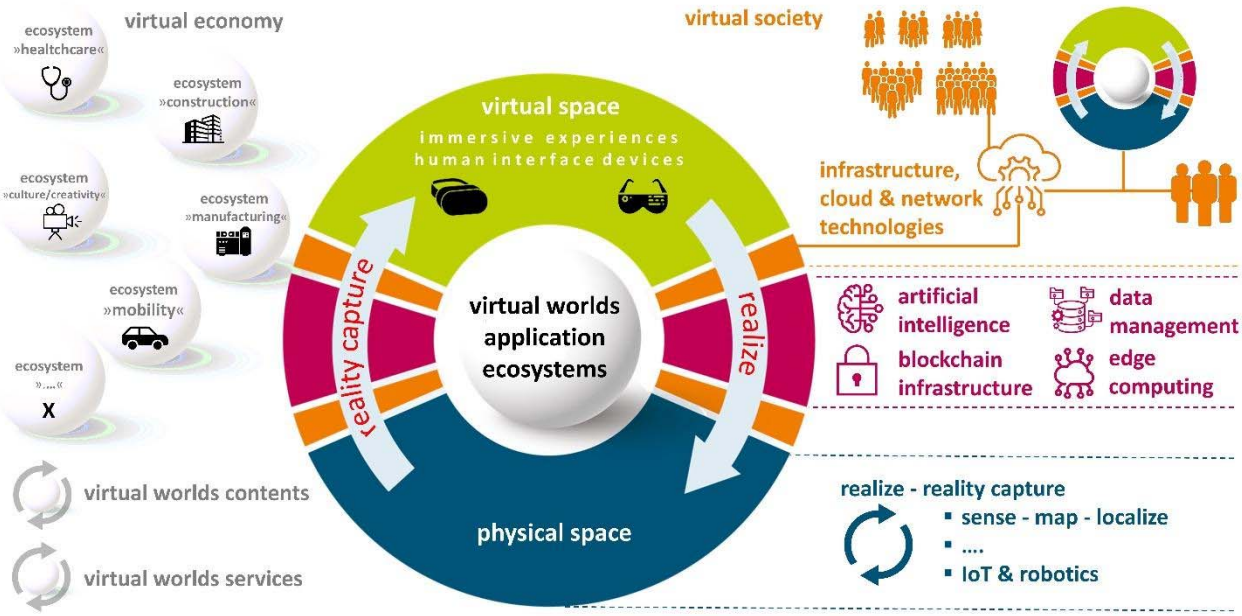


Figure 1: Enabling technologies contribute to development and delivery of Virtual Worlds experiences

The standardisation landscape in this area is dynamic and increasingly complex, with hundreds of working groups having emerged between 2000 and 2025. This growth reflects rising industrial, societal, and academic interest but also reveals the urgent need for systemic coordination. The present document provides evidence-based insights and recommendations to align fragmented standardisation initiatives and ensure coherent development paths across diverse domains such as infrastructure, data management, AI, immersive experiences, and virtual economies.

4.2 Objectives

While key elements for expansion of the European Virtual Worlds industry are in place, there remain many obstacles. Notable among the challenges are the lack of interoperability and technical approaches to ensure market openness, foster innovation, and protect consumers and businesses using Virtual Worlds. Reducing platform dominance and ecosystem fragmentation, supporting high-impact researchers and high quality content creators, and ensuring that rights are protected are key goals for Europe to gain and maintain a leading role in Virtual Worlds era.

The project that produced the two studies ([i.8], [i.9]) summarized in the present document support European goals for Virtual Worlds development by:

1) Assessing and documenting the relevance, current status and potential impact of Virtual Worlds standards and standardisation activities in eight domains through the most modern and comprehensive techniques available to date.

2) Identifying critical gaps in current standards and detecting structural or procedural weaknesses in the standardisation systems that hinder broad alignment, especially between industry-driven and internationally mandated SDOs, and delay or prevent adoption.

3) Delivering to stakeholders actionable recommendations for increasing coordination of standards and standardisation activities, stakeholder engagement, pre- and post-standardisation support, and to guide strategic investments.

Together, the above activities and their results contribute to a stronger, more agile European Virtual Worlds ecosystem built on open, consensus-based standards, user trust, and technological interoperability.

4.3 Usage

The present document is published by ETSI and directly supports the EU's agenda for global digital leadership, open standards, and technological sovereignty. The European Commission's strategic emphasis specifically fosters an open, interoperable, and human-centric Virtual Worlds ecosystem. Politically, it aligns with the Digital Decade Policy Programme 2030, the EU Strategy on Web 4.0 and Virtual Worlds, and the EU's Rolling Plan for ICT Standardisation.

It is designed for use by anyone or any institution that seeks to accelerate the convergence of spatial computing, immersive user interfaces, and digital ecosystems and to strengthen the foundations for the expansion of a strong European Virtual World ecosystem.

5 Methodology

5.1 Standards landscape development

The present document is based on use of a structured, multi-phase methodology to analyse the standardisation landscape for European Virtual Worlds. To permit the deeper study of documents and standardisation activities for different aspects of Virtual Worlds interoperability, the research team defined eight technological domains using EU reference materials and expert refinement.

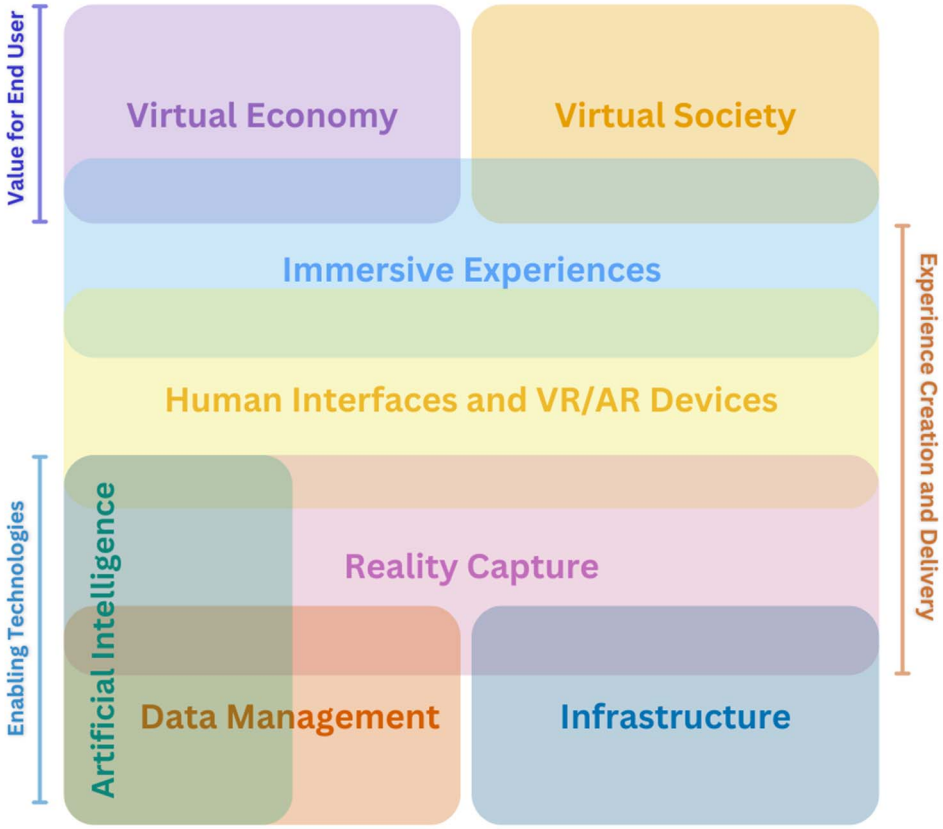


Figure 2: Eight Virtual Worlds domains form the framework for this standards landscape

The eight Virtual Worlds domains are arranged in the form of a technological hierarchy with infrastructure and data management forming the foundations in Figure 2, upon which the additional domains build. Each domain covers at least three components shown in Table 1. The full definitions of the domains and components, published in the ETSI Standards Landscape Report, were validated through examples and improved in an iterative manner until final.

Table 1: Eight Virtual Worlds domains and their components

Domain	Component #1	Component #2	Component #3	Component #4	Component #5
Infrastructure	Networks and Connectivity	Computational Resources	Content Delivery and Optimization		
Data Management	Data Protection	Data Collection and Processing	Data Compression, Resilience and Optimization	Data Integration and Interoperability	
Artificial Intelligence	Content Generation and Design	Environment and Experience Optimization	Interaction and Recognition	Real-time adaptation	Intelligent Virtual Entities
Reality Capture	Environmental Data Acquisition and Mapping	Human Capture, Recognition and Interaction	Digital Twins and Internet of Things Integration		
Human Interface Systems and Devices	Immersive Experience Form Factors	General Purpose Components	Selection, Control and Interaction Components	Feedback Mechanisms	Metrology for Systems and Displays
Immersive Experiences	Delivery, Recording and Communication	Realism and Immersion	Authoring and Design	Distributed Architectures	User Interaction Design and Usability
Virtual Society	Governance and Frameworks for Civil Society	Ethics and Accessibility	Open Social Structures and Interactions		
Virtual Economy	Identity and Representation of Entities	Verification of Authenticity, Ownership, Provenance and Traceability	Digital Goods and Services	Transactions and Business Models	Governance and Regulations

The dataset of open, consensus-based standards and technical reports analysed by the team in the research built upon and significantly expanded prior assets by the Virtual Dimension Center through targeted research of standards bodies' websites, landscapes, and other tools [i.91]. Figure 3 illustrates the research processes used in the project to ensure the dataset includes all relevant standards.

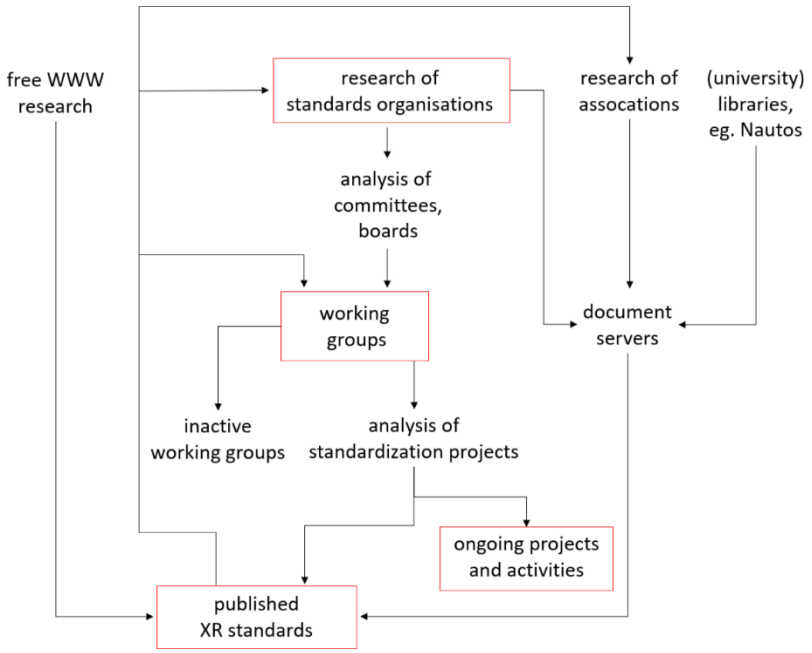


Figure 3: Methodology used in developing the project dataset used in the landscape and recommendation reports

Metadata, including document types, group affiliations, publication dates, and abstracts, were manually entered. English was used as the most common language, although some translated Mandarin and German documents were included.

Natural language processing was used to match standards and technical report segment summaries with virtual world domain and component definitions. Documents with high relevance were further reviewed by experts to compile ranked tables of standards and technical reports per domain. Using working group establishment dates and publication timelines, activity timelines informed discussion on the topic of relevance and how two types of standards organizations differ.

In presenting results, scatterplots and radar chart visualisations depict domain relevance and organizational activity. Interactive tools to position documents in a domain space based on weighted relevance scores are also published in the Standards Landscape Report addendum. To support deeper investigation by stakeholders, an archive (the addendum) published in parallel with the Standards Landscape report, provides data and tools for filtering.

The comprehensive approach taken by the research team ensures a transparent, replicable, and evidence-based foundation for identifying gaps and making recommendations.

5.2 Development of recommendations

To understand not only missing standards, but also tensions between existing specifications, in-progress efforts, and actual Virtual Worlds standardisation requirements, the research team combined several research methods. The approach emphasized that a gap is meaningful only when a clear demand exists without corresponding activity.

Data collection involved three streams. First, 71 publications, including standardisation roadmaps, provided contextual knowledge, especially on structural and contribution issues. In parallel, 19 qualitative interviews were conducted with European standards experts, vendors, consortia, and researchers. These followed a semi-structured guide covering technological requirements, barriers, success cases, gaps, and motivations. Finally, desk research mapped 388 standardisation activities from working groups and roadmaps; 188 were sufficiently well aligned with the eight previously-defined Virtual Worlds domains to be the basis for further analyses.

Data processing began with categorizing stakeholders and standardisation objectives. Literature review and expert validation helped form a coherent structure using large language models. This enabled systematic coding of statements to relevant stakeholder groups and objectives.

Content analysis matched standardisation activities to domains, based on document review and descriptions. Gap analysis was carried out by clustering gaps from interviews and publications using generative AI and iterative expert validation. Each gap was assigned to a domain, stakeholder group, and objective.

Due to limited interview data, gaps and opportunities in the domain of AI in Virtual Worlds posed a methodological challenge. To address this, six AI-specific academic publications were analysed.

Finally, results were visualized using Sankey diagrams to reveal domain relevance, gaps, and links to recommendations and stakeholder groups, supporting clarity and strategic insight.

6 Finding I: Current Virtual Worlds standardisation landscape

6.1 Standardisation objectives and stakeholders

Standardisation activities can accelerate the development of Virtual Worlds technologies and their adoption, emergence of new use cases and foster economic growth without compromising values embraced by European governments and people. For the purpose of identifying standardisation gaps and formulating recommendations for stakeholder groups, the present document aligns the gaps with specific goals. The present document used the five standardisation objectives as shown in Table 2.

Table 2: Five standardisation objectives

Objective	Description
Interoperability and compatibility	Standards ensure that Virtual Worlds products, systems, and services work together seamlessly and that they can be integrated with existing technologies while requiring minimal or no translation or additional interfaces.
Innovation and technology transfer	Standards provide a shared technical foundation and define an abstraction layer that fosters collaboration and helps to more efficiently transfer research into commercially-viable solutions.
Cost reduction and efficiency	Standardisation reduces variant diversity, streamlines production, and simplifies maintenance of Virtual Worlds technologies. It enables economies of scale by using standardized components.
Market access and trade facilitation	Harmonized Virtual Worlds standards reduce technical barriers to international trade and accelerate product approvals in foreign markets.
Quality assurance and product safety	Standards define minimum requirements for content, materials, testing methods, and safety features, which enhance Virtual Worlds service and product reliability and user trust.

The standardisation stakeholder groups in Table 3 are used for the purpose of identifying standardisation gaps and formulating recommendations in the remainder of the present document. The five stakeholder group definitions are summarized in Table 3.

Table 3: Five Virtual World standardisation stakeholder groups

Stakeholder Group	Description
Providers	All Virtual Worlds technology, component, product, content and service providers
Buyers	Corporate technology/IT groups, customers, users, any business that may use the Virtual Worlds technology to increase efficiency, add value to its products, data or services
Government	All national, regional, multinational and international public sector agencies, regulatory bodies, or other entities that develop and enforce policies for people and businesses
Researchers	Academics in universities, researchers in corporate centers, independent institutes and public/private research centers
Standardisation community	Those that operate and manage organizations for the purpose of developing and publishing standards

6.2 Standards and reports by Virtual Worlds domain

6.2.1 Key figures of the landscape

The researchers who prepared the present document compiled structured information about and closely studied the contents of 912 standards and 354 technical reports considered relevant for Virtual Worlds and published by Standards Development Organizations (SDOs). Technical reports complement the standards activities with research findings, recommendations and guidelines. Both standards and technical report datasets were analysed across multiple dimensions to understand their composition, historical trends, domain coverage and organizational contributors. In addition, over 50 Virtual Worlds standards landscapes were studied to ensure that the dataset is complete. Figure 4 shows how documents in the dataset were assigned to one of the eight Virtual Worlds domains (as defined in this clause below) with which it is most strongly aligned. Some standards are relevant for more than one domain, but the figure below is only taking the domain with which the standard is most highly correlated. There are over 200 standards that address multiple domains.

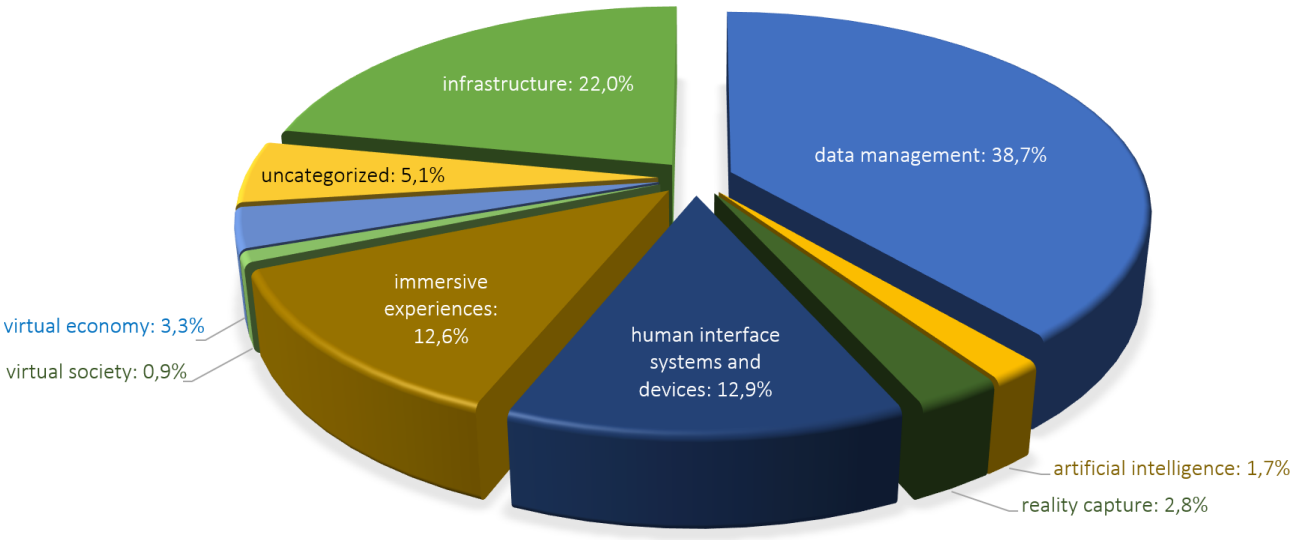


Figure 4: Standards published to date with their respective focus on eight Virtual Worlds domains [n=912]

6.2.2 Infrastructure

The infrastructure domain is divided into three components:

- Networks and Connectivity covers the communication systems that enable distributed and real-time Virtual Worlds interactions. This includes internet protocol development, World Wide Web architecture, high-throughput 5G and emerging 6G networks, latency optimization mechanisms, quantum networking, and network slicing techniques to allocate resources across user clusters or applications.
- Computational Resources refers to the processing systems that support rendering, simulation, and analytics within Virtual Worlds. This sub-domain includes cloud computing architectures, edge computing for localized real-time processing, quantum computing for advanced simulation workloads, and hybrid approaches that combine centralized and distributed models for performance and scalability.
- Content Delivery and Optimization focuses on the efficient transmission and adaptation of immersive content. It encompasses technologies such as real-time rendering and adaptive streaming, localization and relocalization (e.g. SLAM), and dynamic scene analysis for context-aware content delivery.

Table 4: Number of standards development organizations and standards published in Infrastructure domain

Infrastructure domain	
Standards Development Organisations	49
Standards published	335, including 111 standards from internationally-mandated SDOs

Standards working groups in 49 SDOs are engaged in infrastructure-related standardisation efforts, supporting protocol evolution, network architecture, and resource orchestration. See Table 4. The standards working groups actively working in this domain are listed in the relevant clause of the complete Standards Landscape Report [i.8]. Standards and influential technical reports cover areas such as network performance, computational offloading, streaming protocols, and distributed system design, and are foundational to enabling high-performance, interoperable virtual world experiences.

6.2.3 Data management

The Data Management domain was defined as encompassing four components:

- Data Protection covers the legal and ethical handling of user data in virtual environments. Topics include access control systems, biometric authentication, zero-knowledge privacy protocols, data provenance, ownership, security, and regulatory compliance (e.g. GDPR, CCPA, HIPAA). Ethical policies ensure fairness and transparency in data usage.
- Data Collection and Processing involves technologies that gather and manage data for real-time applications. This includes state synchronization to maintain consistent environments, distributed data processing (e.g. split rendering), motion tracking, scene analysis, and real-time integration of data from IoT devices.
- Data Compression, Resilience, and Optimization deals with techniques for handling large-scale 3D and volumetric data. It focuses on compression methods for models and media files, and on streaming optimization strategies to ensure efficient, high-quality delivery across devices.
- Data Integration and Interoperability enables seamless data exchange and system coherence across Virtual Worlds platforms. This includes semantic ontologies, metadata management systems, spatial databases, and mechanisms for maintaining temporal coherence and persistence of data and virtual entities.

Table 5: Number of standards development organizations and standards published in the Data Management domain

Data Management domain	
Standards Development Organisations	50
Standards published	435, including 161 standards from internationally-mandated SDOs

The data management domain is supported by standards working groups across 50 SDOs, addressing topics such as data privacy frameworks, real-time data flows, compression formats, and semantic interoperability. See Table 5. The standards working groups actively working in this domain are listed in the relevant clause of the complete Standards Landscape Report [i.8]. The most prominent standards are authored by the seven most active SDOs in this domain and address critical aspects of secure data handling, cross-platform data formats, and resilient system architectures. Leading technical reports provide additional guidance, use case insights, and implementation practices related to data governance, optimization, and compliance in immersive environments. These documents inform and complement the ongoing development of formal standards in the data management field.

6.2.4 Artificial Intelligence

The Artificial Intelligence domain in Virtual Worlds was defined as encompassing five components:

- AI-powered content generation and design includes technologies that automate the creation of digital assets. Topics are AI-driven asset generation, 3D model reconstruction from 2D inputs, neural radiance fields for scene synthesis, and automated environment generation-each reducing development effort while enhancing immersion.
- AI-powered interaction and recognition focuses on interpreting user behavior to improve interactivity. It includes machine learning for gesture and motion tracking, natural language processing for dialogue-capable avatars, and emotion recognition systems that respond to user expressions, voice, and posture.
- AI-powered intelligent virtual entities are systems that create autonomous agents. These include Non-Playable Characters (NPCs) and AI-powered agents capable of adapting to user actions and providing contextual support within XR environments.
- AI-assisted environment and experience optimization enhances the overall performance and realism of Virtual Worlds. It includes crowd simulation, predictive analytics for user behavior, spatial and semantic scene understanding, and procedural generation to dynamically optimize virtual settings.
- Real-time AI-assisted adaptation comprises technologies that continuously adjust virtual environments. Examples include dynamic scene rendering, adaptive rendering based on device performance and user focus, personalized experiences, and AI-driven physics simulations.

Table 6: Number of standards development organizations and standards published in Artificial Intelligence domain

Artificial intelligence domain	
Standards Development Organisations	7
Standards published	29, including 10 standards from internationally-mandated SDOs

Standards working groups in seven SDOs are active in this domain, addressing areas such as AI ethics, behavior recognition, machine learning models, and immersive content generation. See Table 6. The standards working groups actively working in this domain are listed in the relevant clause of the complete Standards Landscape Report [i.8]. The most relevant standards cover aspects such as AI safety, interoperability, behavioral modelling, and intelligent agent architecture in Virtual Worlds. Notable technical reports also support this domain by offering state-of-the-art insights, implementation frameworks, and emerging requirement analyses that guide pre-standardisation initiatives across AI applications in immersive environments.

6.2.5 Reality capture

The Reality Capture domain was defined as encompassing three components:

- Environmental Data Acquisition and Mapping includes technologies for capturing spatial, visual, and acoustic data about physical environments. Elements are reality capture pipelines, spatial mapping anchored in coordinate systems, photogrammetry across aerial, terrestrial, and close-range settings, camera systems (monocular, stereoscopic, plenoptic), volumetric capture for real-time 3D representations, and spatial audio using mono, stereo, or ambisonic formats.

- Human Capture, Recognition and Interaction focuses on systems that interpret human presence and behavior in real time. This includes emotional response mapping for avatar realism, body scanning via sensors, gesture and action capture for touchless interaction, facial recognition systems for authentication and expression detection, and modeling of user context based on spatiotemporal factors.

- Digital Twins and Internet of Things Integration integrates real-time data from connected devices to enhance immersion and environmental realism. It involves dynamic digital twins representing physical entities, and IoT systems supplying contextual sensor data-such as temperature or motion-for live responsiveness within virtual experiences.

Table 7: Number of standards development organizations and standards published in the Reality Capture domain

Reality capture domain	
Standards Development Organisations	15
Standards published	88, including 38 standards from internationally-mandated SDOs

Standards working groups in 15 SDOs are active in this domain, developing specifications for image acquisition, sensor calibration, capture device APIs, and volumetric media standards. See Table 7. The standards working groups actively working in this domain are listed in the relevant clause of the complete Standards Landscape Report [i.8]. The most significant standards in this domain originate from highly active SDOs, particularly in areas such as image compression (e.g. JPEG), video formats and volumetric content encoding (e.g. ISO/IEC JTC1 SC 29). Complementary technical reports support the evolution of this domain by addressing the performance, integration, and usability of reality capture technologies, with a focus on interoperability, scalability, and privacy-aware implementation strategies.

6.2.6 Human interface systems and devices

The Human Interface Systems and Devices domain was defined as encompassing six components:

- Immersive Experience Form Factors include the physical device configurations that enable users to engage with Virtual Worlds. These range from walk-in environments with multisensory feedback, projection systems and volumetric displays, handheld devices such as smartphones, head-worn devices like AR/VR headsets, and tethered systems that distribute processing between components. Field of view parameters are also essential for determining user immersion.

- General Purpose Components are foundational elements necessary for any immersive system to function. This includes sensors (e.g. LiDAR, cameras), Application Programming Interfaces (APIs), memory storage, optics and display technologies, data processing units such as GPUs, mechanical frames, and power supply solutions.

- Selection, Control, and Interaction Components enable intuitive interaction with virtual environments. This involves spatial computing, voice and speech input systems, keyboards (physical or virtual), 3D controllers, hand and gesture tracking, face and eye tracking, motion capture systems, and multimodal interaction combining various input types.

- Feedback Mechanisms enhance user awareness and realism by delivering output through various channels. These mechanisms include optical and auditory feedback, haptic and tactile systems that simulate physical sensations, cognitive load balancing for user comfort, spatial audio propagation for immersive soundscapes, and biometric feedback systems such as brain-computer interfaces.

- Metrology for Systems and Displays concerns the measurement and calibration of interface technologies. It ensures accurate rendering, perceptual realism, and user comfort through standardised validation procedures and system performance benchmarking.

Table 8: Number of standards development organizations and standards published in the Human Interface Systems and Devices domain

Human interface systems and devices domain	
Standards Development Organisations	31
Standards published	183, including 112 standards from internationally-mandated SDOs

Standards working groups in 31 SDOs are active in this domain, focusing on specifications for devices, user input technologies, sensor calibration, and interoperability of interface components. See Table 8. The standards working groups actively working in this domain are listed in the relevant clause of the complete Standards Landscape Report [i.8]. Standards in this domain address areas such as display ergonomics, haptic feedback protocols, sensor integration, and interaction control architectures. These are produced by the seven most productive SDOs contributing to this field. Important technical reports supplement formal standards by offering applied insights, research findings, and implementation frameworks related to usability, safety, and multimodal interface design in immersive systems.

6.2.7 Immersive experiences

The Immersive Experiences domain was defined as encompassing five components:

- Delivery, Recording, and Communication focuses on software frameworks and runtime engines that produce and transmit sensory-rich Virtual Worlds content in real time. Technologies include immersive applications, middleware for device-agnostic operation, avatar representation and personalization, social interaction platforms, experience recording and playback tools, and telepresence systems using video or 3D scans.

- Realism and Immersion comprises tools and engines that replicate real-world physics and perception. This includes scene description protocols, ambient intelligence for adaptive environments, stereoscopic rendering, depth perception techniques, physics and animation engines, procedural modeling, and advanced lighting and effects such as ray tracing and radiance fields.

- Authoring and Design deals with platforms and workflows for creating and compiling immersive content. It spans asset creation pipelines, authoring platforms using SDKs, APIs or no-code tools, spatial mapping and anchoring technologies, experience optimization, and collaborative prototyping environments that facilitate teamwork and iteration.

- Distributed Architectures support the scalable delivery of immersive content across multiple networked resources. This includes experience streaming protocols, hosted persistent environments, and synchronization mechanisms for maintaining consistency across users and devices in collaborative XR scenarios.

- User Interaction Design and Usability addresses interaction paradigms and user-centered design for immersive interfaces. Components include control elements for user customization, tracking tools for interaction refinement, spatial interface principles, user profile monitoring, and usability metrics covering safety, engagement, comfort, and satisfaction.

Table 9: Number of standards development organizations and standards published in the Immersive Experiences domain

Immersive experiences domain	
Standards Development Organisations	36
Standards published	268, including 165 standards from internationally-mandated SDOs

Standards working groups in 36 SDOs contribute to this domain, focusing on interoperability, avatar design, interaction protocols, rendering systems, and user experience metrics. See Table 9. The standards working groups actively working in this domain are listed in the relevant clause of the complete Standards Landscape Report [i.8]. Standards developed by the top seven SDOs provide technical foundations for real-time content delivery, environment rendering, and multisensory interaction design. Complementary technical reports address best practices, experimental findings, and emerging approaches in the design and implementation of immersive experiences. These documents support broader understanding and help bridge the gap between cutting-edge development and formal standardisation.

6.2.8 Virtual society

The Virtual Society domain was defined as encompassing three components:

- Governance and Frameworks for Civil Society focuses on replicating essential legal, ethical, and social frameworks from the physical world into virtual environments. Elements include digital citizenship (rights and responsibilities of users), personal identity management systems, privacy protection tools, mechanisms against discrimination, the right to be forgotten, and the principle of data sovereignty over personal and behavioural information in virtual spaces.

- Ethics and Accessibility addresses responsible behavior and inclusion. This sub-domain covers anti-harassment standards, age-appropriate guardrails, and accessibility measures designed to ensure equitable participation for users with diverse abilities and needs.

- Open Social Structures and Interactions concerns systems that enable healthy community dynamics and meaningful user engagement. These include community development tools, social graph visualizations, mechanisms for social presence, inclusive cultural representation, and platforms for shared experiences like virtual events and collaborative learning.

Table 10: Number of standards development organizations and standards published in the Virtual Society domain

Virtual society domain	
Standards Development Organisations	18
Standards published	59, including 24 standards from internationally-mandated SDOs

Standards working groups in 28 SDOs are engaged in shaping this domain. See Table 10. The standards working groups actively working in this domain are listed in the relevant clause of the complete Standards Landscape Report [i.8]. Their work spans the development of specifications for identity management, ethics, anti-discrimination policies, and inclusive community frameworks. The most significant standards have been developed by the seven most active SDOs and cover issues of identity verification, privacy, digital citizenship, and ethical governance in immersive environments. Accompanying technical reports explore best practices and emerging strategies for fostering safe, inclusive, and rights-based virtual societies. These documents help fill gaps in formal standards by providing actionable guidance for developers, regulators, and user communities.

6.2.9 Virtual economy

The Virtual Economy domain was defined as encompassing six components:

- Identity and Representation of Entities includes the technologies and frameworks for establishing verifiable digital identities in virtual environments. These systems cover digital identity attributes, account credentials, avatars, asset ownership (such as digital goods and NFTs), behavioral tracking within virtual economies, cross-platform identity management, and portable representations that maintain continuity across platforms.

- Verification of Authenticity, Ownership, Provenance, and Traceability focuses on mechanisms that confirm the integrity and origin of digital assets. This includes systems for digital rights and intellectual property management, Distributed Ledger Technologies (DLT), NFT protocols for secure and verifiable ownership, digital watermarks, and certificates attached to assets for validation and provenance tracking.

- Digital Goods and Services encompasses all tradeable or ownable digital assets in virtual environments. Topics include virtual goods (e.g. avatar items, tools, 3D objects), the gig economy for freelance digital work, digital real estate including overlays on physical property, and virtual/mixed events as monetized services like concerts or educational experiences.

- Transactions and Business Models involves the protocols and systems enabling economic exchange in immersive environments. This covers Play-to-Earn (P2E) mechanics, cross-platform value transfers, Decentralized Autonomous Organizations (DAOs), virtual marketplaces, in-world currencies, digital wallets, and smart contracts for automated transactions.

- Governance and Regulations addresses the legal, ethical, and administrative mechanisms regulating economic activity in virtual spaces. Topics include virtual justice systems, smart contract legal frameworks, cross-border jurisdiction, dispute resolution protocols, taxation models, and labor regulations for digital workspaces.

Table 11: Number of standards development organizations and standards published in the Virtual economy domain

Virtual Economy domain	
Standards Development Organisations	31
Standards published	84, including 32 standards from internationally-mandated SDOs

Standards working groups in 31 SDOs are engaged in the development of protocols and frameworks for the Virtual Economy. See Table 11. The standards working groups actively working in this domain are listed in the relevant clause of the complete Standards Landscape Report [i.8]. Their detailed structures, though extensive, underscore the high level of exploratory work currently under way. The most relevant standards originate from the seven most active SDOs and cover areas like asset tokenization, identity management, smart contract architecture, and interoperability of marketplaces and wallets. Prominent technical reports published by leading SDOs offer complementary insights into economic design, taxation frameworks, and transaction integrity for digital commerce in immersive ecosystems. These reports are instrumental in identifying pre-standardisation gaps and promoting aligned development across industry sectors.

6.2.10 Standards addressing multiple domains

Cross-domain standards refer to specifications that define architectures, conceptual models, protocols, interfaces, data formats, or other mechanisms intended to support interoperability across multiple Virtual Worlds domains-specifically, three or more of the eight domains defined.

The value of some cross-domain standards lies in their ability to enable a common language and interoperable processes between otherwise disparate systems and stakeholder communities. When experts from various domains collaborate, such standards allow different components and services to work together across use cases. For users, this results in reduced redundancy, clearer expectations, and a more cohesive experience.

Over 200 standards were identified as having a high alignment score (7 or above) in at least two of the Virtual Worlds domains, making them strongly cross-domain in nature. Due to the size and detail of this dataset, the full list is documented separately.

Developing effective cross-domain standards is a balancing act: they can accommodate the complex and varied requirements of multiple domains without sacrificing clarity or precision. When the contributing experts adequately represent the necessary areas of expertise, these standards can foster synergy, reduce duplication, and enhance system efficiency. Their adoption becomes more likely when they remain neutral in scope and flexible in implementation. Conversely, cross-domain standards may falter when contributor groups are incomplete, dependencies are not clearly addressed, or when the documents include prescriptive implementation details that constrain adaptation. Thus, well-composed cross-domain standards can serve as strategic enablers of sustainable and interoperable Virtual Worlds architectures.

6.2.11 Industry-specific standards

Each industry operates within a layered ecosystem of regulations and specialized standards that address distinct operational challenges. These standards are developed by both globally recognized SDOs and industry-specific alliances, often evolving to match emerging technological needs. As Virtual Worlds technologies gain traction, their successful integration into industrial ecosystems requires not only adoption by developers but also bi-directional interoperability with established industry standards. The clause of the Standards Landscape Report focusing on industry standards reverses the earlier focus: instead of showing how industry can benefit from Virtual Worlds standards, it recommends that Virtual Worlds developers identify popular, industry-specific standards which they may need to align with in order to penetrate targeted sectors. Three industries were selected to illustrate the recommendation.

Manufacturing Industry has long embraced digitalization through automation, robotics, and integration technologies under the umbrella of Industry 4.0. With the EU's vision for Industry 5.0 emphasizing sustainability, resilience, and human-centric systems, Virtual Worlds technologies present new opportunities. They can enhance design, simulation, planning, and training by embedding humans via avatars in digital environments. Digital Twins, Virtual Factories, and IIoT-based systems are increasingly reliant on standardised integration and cybersecurity frameworks. Standards from IEC, ISO, and various manufacturing consortia are central to this development, supporting transparent data flow and system-wide interoperability across the manufacturing ecosystem.

The Architecture, Engineering, and Construction (AEC) industries rely on robust standards to support digital transformation. Building Information Modelling (BIM) is a core framework that supports lifecycle management, design coordination, environmental assessment, and data interoperability. Standardisation spans international and industry-specific bodies such as CEN, ISO, ASTM, and the International Code Council. Topics include structural safety, sustainability, environmental compliance, and occupational protection. The rise of smart cities and digital urban infrastructure further integrates these standards into virtual planning and simulation environments, amplifying the relevance of BIM and related protocols for immersive, interoperable solutions.

Healthcare operates within a tightly regulated environment where standards ensure patient safety, data integrity, and interoperable care systems. Widely adopted frameworks developed by bodies such as HL7, ICHOM, and the National Quality Forum (NQF) support clinical data exchange, decision-making, outcome measurement, and regulatory compliance. Virtual Worlds technologies can contribute to training, telemedicine, simulation, and collaborative diagnostics-but only if they align with these well-established norms. The top 20 healthcare standards, while not exhaustively covered, emphasize the role of consensus-driven protocols in enabling safe integration of immersive technologies into sensitive health applications.

Industry-specific standards are foundational for unlocking the full potential of Virtual Worlds technologies in industrial applications. The examples of manufacturing, AEC, and healthcare illustrate the complexity and maturity of these environments. Developers of Virtual Worlds platforms could ensure alignment with these established norms to offer interoperable, compliant, and valuable solutions. Bi-directional standardisation-where Virtual Worlds systems both adopt and influence sectoral frameworks-is essential for deep integration. Ultimately, industry-specific cohesion will be a determining factor in the success of Virtual Worlds in real-world economic and operational contexts.

7 Finding II: Standardisation gaps, structural issues and strategic recommendations

7.1 Active standards bodies, working groups, and ongoing activities per Virtual Worlds domain

7.1.1 Key metrics in virtual worlds standardization efforts

Standardisation efforts among domains vary. Domains related to economic frameworks, interaction hardware, and immersive experience design are receiving the most coordinated attention, while critical technical and societal foundations-especially in AI and capture technologies-remain underrepresented.

Figure 5 visualizes the number of standards currently under development across eight Virtual Worlds domains (n=188). It reveals significant standardisation activity disparities. The highest concentration of new standards work seeks to address requirements for the Virtual Economy (33 standards), closely followed by Human Interface Systems and Devices (32), Data Management, and Immersive Experiences (each with 31). Infrastructure (20 standards) and Virtual Society (16) show moderate activity. Artificial Intelligence (12) and Reality Capture (13) have the lowest number of active standardisation efforts.

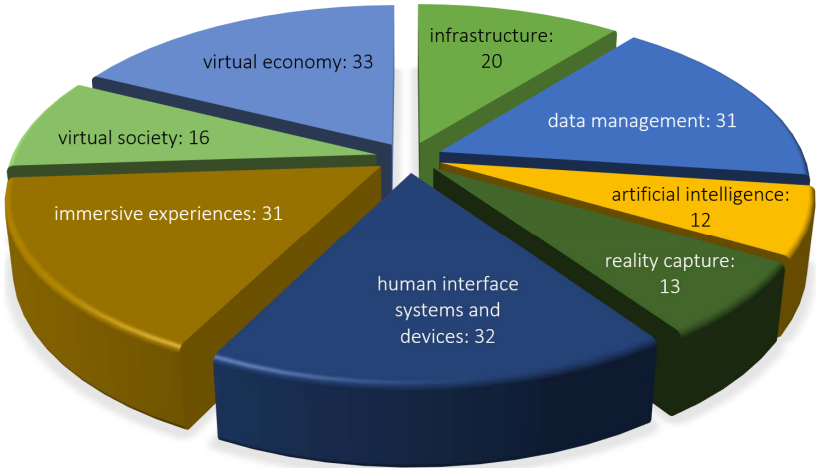


Figure 5: Virtual Worlds standards under development, per domain [n=188]

Figure 6 illustrates how 372 active working groups are distributed among eight Virtual Worlds domains. The largest concentration is in Data Management with 116 groups, followed by Infrastructure with 84 groups and Immersive Experiences with 45. Moderate activity is seen in Reality Capture (36), Virtual Society (31), and Human Interface Systems and Devices (29). Virtual Economy accounts for 24 groups, while Artificial Intelligence has the fewest with only 7. The distribution highlights a strong focus on data-centric and infrastructure standards, whereas AI-related standardisation is comparatively underrepresented.

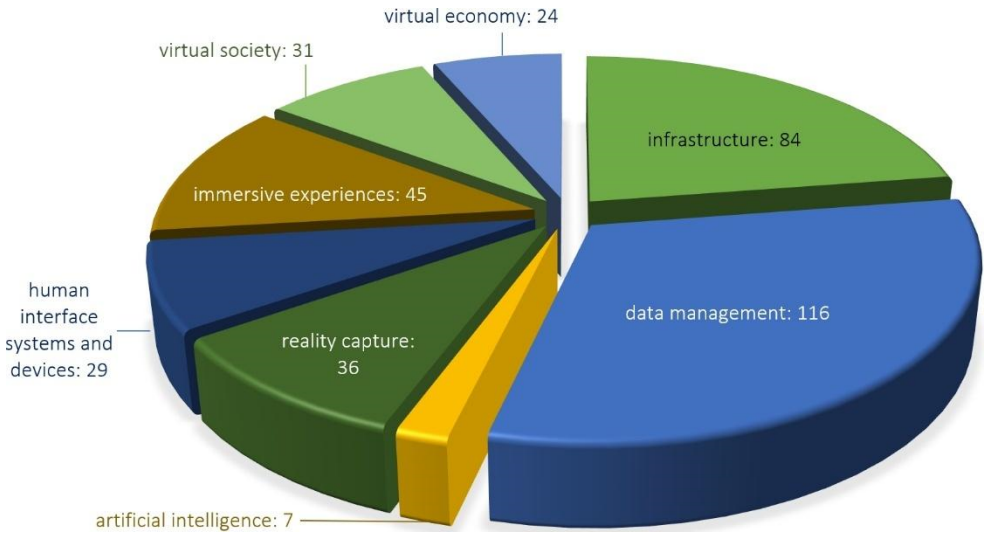


Figure 6: Virtual Worlds standards working groups, per domain [n=372]

7.1.2 Infrastructure

A diverse array of Standards Development Organizations (SDOs) are currently shaping the infrastructure domain for Virtual Worlds. The International Organization for Standardisation (ISO) and the International Electrotechnical Commission (IEC) are leading contributors through their joint technical committees. ISO/IEC JTC 1/SC 38 focuses on cloud computing and distributed platforms, while SC 24 and its working group WG 10 [i.50] are pioneering Virtual Worlds-specific frameworks (e.g. ISO/IEC 24931 series [i.38], [i.39], [i.40]). These efforts are complemented by initiatives from the Object Management Group (OMG), particularly around Data Distribution Service (DDS) protocols tailored for Time-Sensitive Networking (TSN) and monitoring. Additionally, AIMS (Alliance for IP Media Solutions) drives interoperability in media infrastructure through the IPMX [i.3] standard, targeting IP-based media transport. The European Commission plays a role via its EUDI Wallet Architecture, supporting secure and standardized digital identity management. Other active players include oneM2M, addressing IoT-to-metaverse integration; the OpenWallet Foundation (OWF), focusing on secure decentralized identity infrastructure; and the W3C, advancing WebGPU [i.94] for native-level GPU access on the web.

Several roadmaps are in active development or early drafting stages. The ISO/IEC 24931 series outlines a long-term modular standardisation trajectory, with Part 1 [i.49] (terminology), Part 2 [i.38] (architecture), and Part 4 [i.39] (reference model) building an integrated ecosystem model. These are in various stages of drafting (CD or PWI), reflecting a gradual but strategic roadmap toward Virtual Worlds-ready infrastructure. ISO/IEC CD 23090-11 [i.56] adds to this by providing network-based media processing guidelines, linking immersive media applications to cloud and edge processing.

OMG's DDS-TSN [i.81] initiative forms part of a roadmap toward deterministic, low-latency communication infrastructure for critical applications. Similarly, oneM2M TR-0069 [i.83] by oneM2M envisions a roadmap for hybrid physical-virtual integration, addressing latency, data security, and interoperability. China's MIIT is following a national strategic roadmap, formalizing Virtual Worlds computing platform standards under government supervision. These parallel roadmaps often aim to converge on interoperability, latency reduction, data sovereignty, and resilience, but coordination across SDOs remains limited, and mutual dependencies are not always transparent.

Infrastructure-related standardisation is notably dynamic. ISO/IEC JTC 1/SC 38 is expanding standards on cloud business continuity (ISO/IEC CD 20996.2 [i.41]), vital for Virtual Worlds platform reliability. ISO/IEC 23093-1 [i.47] and ISO/IEC 23093-2 [i.48] detail the Internet of Media Things architecture and APIs, facilitating media device interoperability in IoT ecosystems. NBMP (Network-Based Media Processing) activities are maturing, supporting in-network computation and rendering, critical for performance-sensitive VR/AR applications. OMG is iterating on specifications for status monitoring and time-sensitive extensions for DDS middleware. Their work supports granular visibility into system performance and deterministic network behavior. Meanwhile, W3C's WebGPU [i.94] standard-now in candidate recommendation phase-enables web applications to leverage modern GPU capabilities for real-time rendering and computation. Emerging actors such as the OpenWallet Foundation are operationalizing digital identity infrastructure (e.g. Askar, Solid Data Wallet), while MIIT's working group in China is drafting technical requirements for Virtual Worlds computing platforms, likely influencing regional and sectoral compliance models.

Standardisation in the Virtual Worlds domain "Infrastructure" in a nutshell:

- Leading SDOs: ISO/IEC (JTC1 SC 24, SC 29, SC 38), OMG, W3C, AIMS, oneM2M, OWF, MIIT.
- Roadmaps: ISO/IEC 24931 [i.38], [i.39] [i.40], [i.49], OMG DDS-TSN, EC EUDI Wallet, oneM2M TR-0069 [i.83], MIIT's strategic roadmap.
- Current projects: NBMP, Cloud continuity, Internet of Media Things, WebGPU, decentralized identity systems, monitoring frameworks.

7.1.3 Data Management

The data management domain of Virtual Worlds is shaped by a wide ecosystem of standardisation bodies and working groups. The ISO/IEC JTC 1 subcommittees SC 24 (graphics, data modeling) and SC 38 (cloud computing) are central players, developing standards such as ISO/IEC DIS 20151 [i.42] (dataspace concepts), ISO/IEC PWI 24931-5 [i.40] (metaverse information models), and ISO/IEC 23093-3 [i.46] (media data APIs). Meanwhile, the IEEE contributes through multiple initiatives, including IEEE P2874 [i.28] (Spatial Web Protocol) and IEEE P2957 [i.19] (Big Data Governance). The World Wide Web Consortium (W3C) provides a critical backbone for identity and credential management with its Verifiable Credentials (VC) suite, complemented by the Decentralized Identity Foundation (DIF) and the OpenID Foundation, which focus on selective disclosure and digital credentialing protocols. Similarly, the Trust over IP (ToIP) Foundation develops decentralized identity tools like CESR [i.90] and ACDC [i.89] for verifiable data lineage. Other groups include the Eclipse Dataspace Working Group (EDWG), creating interoperable data exchange protocols (DSP) [i.6], and the Object Management Group (OMG) with its Pedigree and Provenance Model (PPMN) [i.82]. Specialized bodies such as the OpenWallet Foundation and companies, such as Msquared, contribute implementations like the Learner Credential Wallet and Metaverse Markup Language (MML), pushing forward modular, open-source solutions.

Current roadmaps emphasize secure, interoperable, and privacy-preserving data ecosystems. ISO/IEC DIS 20151 [i.42] outlines a foundational vision for dataspace infrastructures-covering interoperability, governance, and scalability-serving as a future reference for cross-domain data sharing. Parallel developments in ISO/IEC PWI 24931-5 [i.40] aim to build a consistent data model for Virtual Worlds, a cornerstone for platform interoperability and structured data exchange. IEEE's P2957 [i.19] introduces a machine-readable big data architecture roadmap focused on metadata registries, persistent identifiers, and data type conversion, supporting FAIR principles across diverse environments. Additionally, W3C's VC-API, DIF's JSON Schema for Verifiable Credentials, and the OpenID Digital Credentials Protocol (DCP) [i.85] articulate a path toward trust-based identity ecosystems built on user control and selective data sharing. These roadmaps tend to converge on a few strategic principles: decentralized trust, semantic interoperability, standard data schemas, and composable identity/data credentials. However, their governance remains highly fragmented across foundations, SDOs, and open-source consortia.

Several initiatives are active and progressing. The Dataspace Protocol (DSP) [i.6] by EDWG operationalizes data federation frameworks, enabling organizations to negotiate access and enforce usage policies. ISO's EXPRESS-Q and Annotated EXPRESS work enhance schema expressiveness for product and structured data. At the same time, standards like ISO/IEC 11034 [i.97] address cloud trustworthiness, while ISO/IEC DIS 23090-39 [i.64] develops avatar data exchange formats-a unique intersection of personal data and immersive representation. The IETF is advancing SD-JWT (Selective Disclosure JWT) [i.31], allowing granular claim release while safeguarding privacy-critical for identity and compliance in immersive platforms. Simultaneously, CESR [i.90] and ACDC [i.89] from the Trust over IP Foundation support cryptographically secure, event-driven data streams and provenance chains. These mechanisms enable tamper-evident data lineage and trustworthy real-time data flows. W3C's VC-API and the Learner Credential Wallet push forward lifelong learning credentialing and decentralized portfolio management. On the immersive media side, IEEE's 2048.3 and 2048.10 [i.23] once proposed standards for immersive video/audio formats, although their current momentum appears stalled.

Standardisation in the Virtual Worlds domain "Data Management" in a nutshell:

- Active bodies: ISO/IEC (JTC1 SC 24, SC 38), IEEE (2048 [i.23], P2874 [i.28], P2957 [i.19]), W3C, DIF, Trust over IP, OpenID, OMG, EDWG.
- Roadmaps: Emphasize dataspace architectures, privacy-preserving identity, big data governance, and immersive content exchange.
- Activities: Focus on interoperable data exchange, verifiable credentials, data provenance, and cloud trust frameworks.

7.1.4 Artificial Intelligence

Several standards development organizations are actively addressing AI within Virtual Worlds. The ISO/IEC JTC 1/SC 24 and SC 29 are central actors, particularly through working groups like WG 7 (image processing and computer vision) and JWG 12 (XR-based information systems). ISO/IEC 23093-6 [i.98] and ISO/IEC DIS 24931-1 [i.49] lay groundwork for data semantics and terminology alignment [i.49]. IEEE plays a pivotal role with its IEEE P7000 [i.99] (AI ethics), especially IEEE P7016 [i.21] (Ethically Aligned Metaverse Systems) and IEEE P7030 [i.20] (Ethical Assessment of XR). Additionally, IEEE P3079.3.1 [i.27] focuses on APIs for digital human authoring, a critical interface layer for AI avatars and agents. The ITU-T engages through standards such as Recommendation ITU-T F.748.58 [i.74] and Recommendation ITU-T F.748.50 [i.75] (F.DHAI), defining frameworks for cloud-edge multimedia platforms and digital human access interfaces, respectively. These support real-time, AI-powered avatar services. Other actors include the Trust over IP Foundation (AI Management Task Force), Linux Foundation (Decentralized Trust WG), and Open3D Foundation, which focuses on simulation, physics, and AI integration in game engines. The Consumer Technology Association (CTA) and NEM's New Digital Media Group also contribute cross-sector coordination.

Roadmapping efforts underline the need for interoperable, transparent, and ethical AI deployment in immersive contexts. The ITU FG-MV roadmap frames AI as a foundational enabler for personalization, real-time decision-making, and autonomous interaction. It calls for standards in algorithmic transparency, AI-assisted rendering, and ethical agent design. IEEE's Industrial Metaverse report emphasizes AI's role in digital twin systems, advocating for interoperability standards for predictive analytics, simulated intelligence, and edge-AI deployment. The roadmap also highlights risk assessment, traceability, and bias mitigation. The ISO/IEC JTC 1 AI roadmap refers to pre-existing standards such as ISO/IEC 22989 [i.51] and ISO/IEC 23894 [i.52], recommending their adaptation to Virtual Worlds contexts. These standards address trustworthy AI, including safety, explainability, and algorithmic fairness. Finally, the Khronos Group's glTF roadmap anticipates AI-enabled 3D asset generation. However, the lack of formal linkage to AI model interchange formats like ONNX suggests a coordination gap that could limit standard interoperability across AI pipelines.

AI-related standardisation is rapidly expanding across multiple layers. ISO/IEC's 23093-6 [i.98] supports distributed AI processing in media-rich IoT environments. ISO/IEC 27091.3 [i.60] is under development for AI privacy protection, providing guidance across the AI lifecycle. ISO/IEC PWI 23620-4 [i.70] defines virtual human models in XR learning contexts, enhancing realism and didactic value. IEEE P3079.3.1 [i.27] targets cross-platform APIs for digital humans, while IEEE P7016 [i.21] and IEEE P7030 [i.20] guide ethical design and assessment of AI-powered XR systems. These initiatives promote accountability in AI decision-making, particularly in emotionally responsive or behavior-adaptive virtual agents. The ITU's work on Recommendation ITU-T F.748.58 [i.74] and Recommendation ITU-T F.748.50 [i.75] (F.DHAI) supports cloud-edge orchestration for immersive AI avatars. These standards focus on low-latency, high-interactivity services that are critical for scalable virtual humans. China's MIIT is contributing national standards for AI-driven avatar and digital human generation platforms, although many documents remain unpublished. Their focus is on industry coordination and domestic platform consistency. Despite this activity, there remain critical interoperability gaps, ethical blind spots, and regulatory fragmentation. Most implementations are proprietary, limiting open innovation. Coordination between SDOs, industry, and regulators is still underdeveloped.

Standardisation in the Virtual Worlds domain "Artificial Intelligence" in a nutshell:

- Active Bodies: ISO/IEC (JTC1 SC 24, SC 29), IEEE (P7000 [i.99], P3079 [i.25] & [i.24]), ITU-T, Trust over IP, Linux Foundation, Open3D, CTA, NEM.
- Roadmaps: Emphasize AI ethics, digital twins, adaptive services, and transparency; key documents from ITU FG-MV, IEEE, ISO/IEC, and Khronos.
- Key Activities: Digital human APIs, AI-enhanced XR ethics, cloud-edge orchestration for avatars, privacy-preserving AI, semantic scene interpretation, and distributed AI media processing.

7.1.5 Reality Capture

Several international standardisation bodies are actively contributing to the development of the reality capture domain in Virtual Worlds. ISO/IEC JTC1/SC24 plays a central role through standards like ISO/IEC 18026 [i.68] (Spatial Reference Model), ISO/IEC TR 16088 [i.71] (Visual Positioning Systems), and ISO/IEC PWI 22626 [i.63] (Motion Capture). These efforts define the foundational models and data structures required for aligning virtual content with real-world spatial contexts. IEEE's 2048 working group contributes two standards: IEEE 2048.7 [i.23], which specifies the mapping of virtual objects in real-world coordinates, and IEEE 2048.8 [i.23], which focuses on interaction protocols between virtual and physical environments. Although IEEE 2048.8 [i.23] has shown little progress recently, its original scope reflects ongoing relevance. The Open Geospatial Consortium (OGC) is another major player, particularly through GeoPose [i.79] and CityGML [i.78] standards, which are essential for geospatial anchoring and digital twin interoperability. ETSI is indirectly involved via its ARF (Augmented Reality Framework) [i.7], and oneM2M advances its MetaIoT [i.84] initiative, which connects IoT infrastructure with Virtual Worlds environments. Additional contributions come from IEC TC 100/TA 18, which develops guidance for remote assist systems, and from specialized efforts such as the Volumetric Format Association and BuildingSMART International, focusing on 3D capture and BIM integration.

Multiple organizations have outlined roadmaps that address technical trajectories for reality capture. OGC's roadmap emphasizes semantically enriched geospatial models and robust interoperability between 3D spatial datasets and immersive systems. This includes ongoing evolution of standards such as CityGML 3.0 [i.78] and 3D Tiles [i.77]. IEEE's Industrial Metaverse report envisions advanced sensor fusion and spatial computing frameworks, supporting applications like real-time digital twins and AR-enhanced industrial maintenance. ISO/IEC continues to expand its MPEG-I and MPEG-V standards to accommodate dynamic mesh compression and LiDAR point cloud encoding (e.g. ISO/IEC FDIS 23090-29 [i.43] and ISO/IEC FDIS 23090-30 [i.44]), with the aim of supporting real-time immersive rendering. ITU-T's FG-MV roadmap highlights the convergence between reality capture, AI-based perception, and location-aware networking infrastructure. Across these roadmaps, common priorities emerge: low-latency data streams, accurate spatial localization, cross-platform compatibility, and open APIs for seamless integration. However, implementation lags remain due to fragmented industry alignment and the absence of universal middleware to translate between competing standards.

A broad range of current standardisation efforts are underway in the reality capture domain. ISO/IEC TR 16088 [i.71] is nearing finalization and defines architectural components for visual positioning systems, including data fusion from image databases, GNSS, inertial sensors, and mapping frameworks. ISO/IEC FDIS 23090-30 [i.44] introduces a codec for LiDAR compression optimized for real-time use, while ISO/IEC FDIS 23090-29 [i.43] defines tools for dynamic mesh compression using video-based methods. These standards support immersive applications such as AR-assisted navigation and volumetric communication. ISO/IEC PRF 21134 [i.61] is developing benchmarks for integrated indoor localization using dead reckoning, establishing reproducible evaluation protocols. ISO/IEC CD 18038-2 [i.62] formalizes information models for integrating sensor data into virtual environments. ISO/IEC DIS 20538 [i.67] defines a data model for representing human-related sensor data in smart city simulations. Additional work includes the proposed ISO/IEC PWI 22626 [i.63] standard for capturing and exchanging motion data from human actors. Meanwhile, oneM2M's MetaIoT [i.84] project creates semantic models and APIs for embedding IoT sensors and physical devices into Virtual Worlds frameworks, extending to smart cities, industrial AR, and digital twins. These activities collectively advance the precision, realism, and interoperability of spatial data in virtual environments, though adoption by commercial platforms remains limited.

Standardisation in the Virtual Worlds domain "Reality Capture" in a nutshell:

- Leading bodies: include ISO/IEC (JTC1 SC24), IEEE (2048 series [i.23]), OGC (GeoPose, CityGML), ETSI (ARF), and oneM2M (MetaIoT).
- Roadmaps: focus on spatial data fusion, low-latency capture pipelines, dynamic mesh/LiDAR compression, and semantic geospatial modeling.
- Ongoing activities: span visual positioning, sensor and motion data models, benchmarking of localization methods, and integration of real-world sensor data into immersive digital contexts.

7.1.6 Human Interface Systems and Devices

Human interface systems are addressed by a wide spectrum of standardisation organizations. Khronos Group's Kamaros working group is developing an embedded camera API that is agnostic to device type, therefore, including but not limited to human interface systems [i.96]. The IEEE plays a dominant role with multiple active projects, particularly within its 3079 series, which addresses latency, motion training, and immersive visual quality. For example, IEEE P3079.1 [i.25] focuses on reducing Motion-to-Photon (MTP) latency, a critical determinant of user comfort in VR. IEEE P3079.2 [i.24] and its sub-series (3079.2.1 [i.25]) define frameworks for motion training systems, standardizing interfaces and sensor synchronization in mixed reality environments. Complementing these efforts, IEEE P2888.6 [i.22] develops holographic visualization standards for bridging the cyber-physical divide. The Haptics Industry Forum (HIF) is spearheading the standardisation of haptic primitives through a Universal Haptics API, aiming to foster cross-platform tactile feedback design. The IEC, particularly through its Technical Committee 110, contributes substantially via standards such as IEC 63145 (focused on VR eyewear) [i.16], IEC 63528 (haptic descriptors) [i.15], and IEC 62629 [i.11] (3D and volumetric displays). ISO engages through its 9241 series on human-system ergonomics, with ISO/TR 9241-380 [i.58] addressing biomedical risks in head-mounted display use and ISO 9241-391 [i.59] focusing on mitigation of photosensitive seizures. Across these bodies, the emphasis lies in harmonizing ergonomic, optical, and interaction-specific dimensions of human-device interfaces in XR environments.

Standardisation roadmaps in the human interface domain focus on performance, interoperability, and health safety in immersive experiences. IEEE's trajectory centers on immersive interaction reliability, seeking to reduce latency, standardize gesture-based input, and ensure seamless haptic feedback. Its IEEE P3322 [i.30] guideline outlines XR device comfort requirements, encompassing physical ergonomics, optical properties, and interface responsiveness. IEC's roadmap is oriented toward measuring and certifying immersive hardware quality, with particular focus on optical performance, display durability (IEC 63145-30) [i.16], and sensor integration (IEC 63145-40 [i.16]). Notably, IEC PWI 110-39 [i.12] explores specifications for contact-lens-based AR displays, signaling a shift toward ultra-miniaturized interface systems. ISO prioritizes human safety and usability in immersive systems, with ISO 9241-313 [i.34] offering standards for reflective display measurement and ISO/IEC 23090-32 [i.45] defining haptic data transport formats for media synchronization. These roadmaps align toward a common vision: multisensory, ergonomic, and interoperable XR interfaces that are safe and accessible across platforms and user demographics.

Active projects in this domain span haptics, optics, motion sensing, and system latency optimization. The Haptics Industry Forum is finalizing the specification of cross-device haptic primitives, enabling consistent tactile experiences. ISO/IEC 23090-33 [i.57] and ISO/IEC 23090-32 [i.45] support this by standardizing the encoding and transport of haptic signals. IEEE is advancing motion training standards through IEEE P3079.2 and IEEE P3079.2.1 [i.24], which define application interfaces, sensor alignment methods, and user interaction design for MR-based training environments. IEEE P3079.4 [i.29] addresses visual quality of autostereoscopic displays, introducing machine-learning methods for objective assessment. In parallel, IEC is formalizing several technical standards on VR/AR display optics, including IEC 63145-201-10 [i.16] (lens measurement), and IEC 63145-50 [i.16] (user interaction methods). The organization is also developing standards for contact lens displays (IEC PWI 110-39 [i.12]), volumetric imaging (IEC TR 110-22 [i.18]), and display durability (IEC 110-36 [i.13]). ISO continues to refine standards that mitigate risks associated with HMD usage, while IEEE 3322 focuses on generalized comfort requirements for XR wearables. Although the ecosystem is active and technically rich, a lack of convergence across display and haptic subsystems, combined with ongoing proprietary implementations, still inhibits widespread interoperability and mass deployment.

Standardisation in the Virtual Worlds domain "Human Interface Systems and Devices" in a nutshell:

- Leading SDOs: include IEEE (3079 [i.25] & [i.24], 2888.6 [i.22], 3322 [i.30]), IEC (TC 110, TA 18), ISO (9241 series), and Haptics Industry Forum (Universal Haptics API).
- Roadmaps: prioritize ergonomics, latency reduction, haptic and visual quality, miniaturized AR optics, and safe interaction protocols.
- Ongoing activities: span motion training standards, autostereoscopic and contact lens display evaluation, haptic transport protocols, and comfort benchmarks for immersive wearables.

7.1.7 Immersive Experiences

The immersive experiences domain is supported by a dense network of standardisation bodies, most prominently ISO/IEC JTC 1/SC 29 and SC 24, Khronos Group, IEEE, 3GPP, IEC, W3C, and CTA. ISO/IEC SC 29 leads through its MPEG-I 23090 series, covering architectural frameworks, immersive audio/video coding, dynamic mesh compression, scene representation, and haptic data transport. SC 24 complements this with UX-focused developments, including ISO/IEC AWI 23595 [i.69] (UX design for XR) and ISO/IEC 9234 [i.73] (VR/AR/MR learning systems modeling). IEEE's 2048 series expands into immersive media taxonomy, quality metrics, user interface standardisation, and content rating systems. The 3GPP defines technical and performance specifications for immersive audio under split rendering scenarios (e.g. 3GPP TR 26.866 [i.2] and 3GPP TS 26.566 [i.1]), supporting mobile-to-headset workflows. IEC TC 100 and TC 110 are active in specifying display performance (IEC TR 63340-3 [i.14]), multimedia metaverse architectures (IEC TR 63614-1 [i.17]), and haptic integration (ISO/IEC 23090-32 [i.45]). The W3C's WebXR group has established foundational APIs and modules for browser-based immersive experiences, including hit testing [i.95], depth sensing, DOM overlays, and AR extensions. The Consumer Technology Association contributes with metadata (CTA-2094 [i.4] for HDR/XR) and experience comfort metrics (CTA-2097 [i.5]). While activity levels vary, several bodies are coordinating efforts toward standardized, interoperable, and perceptually rich XR content delivery.

The roadmaps across organizations reveal a shared orientation toward modular, scalable, and perceptually optimized XR environments. ISO/IEC's MPEG roadmap anticipates the evolution of immersive media from fixed content to adaptive, render-based, and sensor-informed applications. This includes architectural convergence for audio, video, scene graphs, haptics, and user interfaces. IEEE 2048.x [i.23] envisions taxonomic coherence and metric alignment across immersive media types. 3GPP's roadmap for immersive audio in constrained devices supports mobile-rendering pipelines, aiming to extend spatial audio quality to AR glasses and lightweight devices. IEC TC 100 is establishing foundational architectural reference models (IEC TR 63614-1 [i.17]) for multimedia systems in Virtual Worlds contexts. W3C's modular WebXR roadmap enables browser-based access to depth data, AR interfaces, and DOM elements, reflecting a progressive migration of immersive UX to the web. The SVTA [i.88] (Streaming Video Technology Alliance) contributes with strategies to optimize network-level behavior for XR streaming and congestion control. While most roadmaps share the goal of improving realism, usability, and efficiency, the regulatory and implementation pacing differs considerably between industrial, academic, and consumer-facing bodies.

Numerous immersive experience standards are currently under development or in finalization. ISO/IEC 23090-32 [i.45] and ISO/IEC FDIS 23090-29 [i.43] focus on haptics transport and dynamic mesh coding, respectively, while ISO/IEC 23090-27 [i.54] and ISO/IEC 23090-28 [i.55] specify render-based scene and media representation frameworks. ISO/IEC 23090-1 [i.53] serves as the architectural backbone for immersive media systems. Complementing this are reference software and conformance standards like ISO/IEC 23090-24 [i.100] and its amendment on haptics, avatars, and lighting. IEEE P2048.9 [i.23] (audio metrics), P2048.2 [i.23] (video quality), and P2048.6 [i.23] (immersive UI design) aim to align subjective and objective quality metrics across media types. 3GPP's ISAR codec is operationalized through 3GPP TS 26.566 [i.1] and 3GPP TR 26.866 [i.2], optimizing immersive audio in distributed rendering setups. CTA-2094 [i.4] is widely adopted in HDR10+ content pipelines, while CTA-2097 [i.5] attempts to formalize comfort thresholds in XR, though its status remains unclear. IEC TR 63340-3 [i.14] addresses gaming/e-sports display metrics, and IEC TR 63614-1 [i.17] develops a base framework for Virtual Worlds media systems. W3C's WebXR modules-Hit Test [i.95], Depth Sensing, AR Module Level 1, and DOM Overlays-enable web-native immersive experiences with increasing complexity. Additional work from the ITU (P.IXC) addresses XR quality assessment methodologies, while the VR/AR Association and SVTA [i.88] contribute practice-oriented guidelines on 3D modeling and content delivery optimization. Despite occasional stagnation in individual IEEE 2048 [i.23] sub-projects, the overall pace of specification development remains high and cross-sectorally integrated.

Standardisation in the Virtual Worlds domain "Immersive Experiences" in a nutshell:

- Leading bodies: include ISO/IEC (JTC1 SC29, SC24), IEEE (2048 series [i.23]), W3C (WebXR), 3GPP (IVAS), ITU-T (P.IXC), SVTA, and IEC (TC 100, 110).
- Roadmaps: prioritize immersive media architecture, UI/UX standardization, multi-sensory integration, and web-based interoperability.
- Ongoing activities: include MPEG standards for audio/video/haptics, WebXR module expansion, split rendering audio specs, and immersive UX design frameworks.

7.1.8 Virtual Society

The Virtual Society domain is increasingly shaped by standardisation efforts focusing on ethics, governance, accessibility, and digital identity. The IEEE leads several initiatives in this area. IEEE P3079.3.2 [i.26] defines a framework for privacy protection in avatar-based interaction by managing Personally Identifiable Information (PII) within Virtual Worlds environments. It specifies principles and mechanisms for the collection, storage, sharing, and deletion of identity-related data. IEEE P7030 [i.20] complements this with a broader ethical assessment framework for XR technologies, covering social impacts, technical risks, and value-sensitive design, guided by the IEEE Ethically Aligned Design principles. ISO and IEC are jointly developing standards with a focus on inclusivity and governance. ISO/IEC 16248 [i.101] addresses cognitive accessibility for users with learning disabilities in digital learning environments, providing guidelines for user interface design and interaction logic. ISO/IEC JTC1/SC24/WG10 is responsible for ISO/IEC PWI 24931-6 [i.102] (unpublished yet) on metaverse governance, aiming to define frameworks for interoperability, ethics, and regulatory compliance. Additionally, ISO/IEC PWI 26951 [i.72] focuses on visual security in Virtual Worlds, developing protocols to protect avatars and digital representations against manipulation or identity spoofing. ISO/IEC PWI 23554 [i.66] explores privacy policy requirements in modeling and simulation environments, particularly in AR/VR contexts. The ITU contributes with its recommendation F.DH-PE [i.76], which sets evaluation methods and system requirements for digital human platforms. Meanwhile, China's MIIT works on a classification system for virtual digital humans to support regulatory frameworks and technology coordination. The Open Metaverse Interoperability (OMI) Group expands glTF extensions for avatars and physics-based simulations, while the OpenWallet Foundation leads several identity-related initiatives. These include the Bifold wallet, Credo credentialing framework, Multipaz identity credential system, and a unified VC-API for verifiable credentials. W3C's Verifiable Credentials [i.92] Data Model 2.0 [i.93] ensures cryptographically secure, privacy-preserving credential exchange across domains.

Strategic standardisation roadmaps in this domain converge on ethics, privacy, accessibility, and trust infrastructure. IEEE's roadmap emphasizes identifiability management and ethical XR system evaluation, proposing tools for risk analysis, fairness, and user-centered design. ISO/IEC's AfA and metaverse initiatives prioritize inclusive digital environments, targeting cognitive, sensory, and interaction accessibility, as well as governance mechanisms to structure policy development, stakeholder roles, and data regulation. W3C's trajectory in digital identity and credentials underscores selective disclosure, zero-knowledge proofs, and cryptographic trust layers that decouple identity from central authorities. The ITU and China's MIIT align toward interoperability and classification systems for digital humans, advocating shared taxonomies and quality assurance frameworks. The OpenWallet Foundation's multi-pronged roadmap promotes reusable, privacy-conscious components for decentralized identity infrastructure, emphasizing compliance and ecosystem interoperability. Overall, these roadmaps point toward ethical, interoperable, and user-sovereign systems, although global synchronization remains a challenge, particularly across jurisdictions with differing regulatory philosophies.

Several active standardisation projects are defining the foundations of a secure and inclusive Virtual Society. IEEE P3079.3.2 [i.26] formalizes data governance mechanisms for avatar-based PII. IEEE P7030 [i.20] develops a comprehensive ethical assessment toolkit for XR technologies, covering classification schemes, methodological principles, and alignment with human values. ISO/IEC 16248 [i.101] defines cognitive accessibility layers for learning environments, while ISO/IEC PWI 23554 [i.66] provides privacy policy structures for immersive simulations. ISO/IEC PWI 24931-6 (unpublished yet) works toward governance frameworks to ensure legal compliance, data protection, and stakeholder accountability in the Virtual Worlds. ISO/IEC PWI 26951 [i.72] introduces technical protocols for visual integrity and avatar authentication to combat manipulation and identity forgery. The ITU's F.DH-PE [i.76] sets criteria for evaluating digital human platforms across performance and interaction dimensions. W3C's Verifiable Credentials [i.92] Data Model 2.0 [i.93] advances credential portability and cryptographic assurance. The OpenWallet Foundation contributes core infrastructure components such as VC-API for verifiable credential exchange, the Multipaz identity model, and application frameworks for secure identity wallets across platforms. MIIT's digital human classification initiative further anchors these developments within a national regulatory strategy. Collectively, these activities aim to embed ethics, identity trust, and social inclusion into the technical substrates of Virtual Worlds.

Standardisation in the Virtual Worlds domain "Virtual Society" in a nutshell:

- Leading bodies: include IEEE (P3079.3.2 [i.26], P7030 [i.20]), ISO/IEC (JTC1/SC24, WG10), W3C (VC 2.0), ITU (F.DH-PE), MIIT (PRC), and the OpenWallet Foundation.
- Roadmaps: emphasize cognitive accessibility, privacy protection, ethical assessment, governance frameworks, and decentralized identity infrastructure.
- Ongoing activities: span identifiability management, visual security, digital credential APIs, avatar classification, and inclusive user interface standards.

7.1.9 Virtual Economy

The Virtual Economy domain is highly dynamic, with a wide array of standards development organizations (SDOs) contributing from fields such as blockchain, identity, digital assets, and Virtual Worlds commerce. The ISO/TC 307 plays a foundational role by developing standards like ISO 23353.3 [i.32] on blockchain auditing and ISO 23516.3 [i.33] for interoperability across distributed ledger systems. These form the backbone of verifiable, interoperable economic transactions. The OpenWallet Foundation (OWF) is a prominent actor in decentralized identity and wallet infrastructure. Their projects include the OWF EUDI Wallet Kit for mobile ID wallets, the Tuvali offline credential exchange (BLE-based), and the Farmworker Wallet OS, which targets financial inclusion for underserved communities. Their Trust Spanning Protocol (TSP) and Multiformat-VC packages advance interoperable digital credentialing. The Decentralized Identity Foundation (DIF) develops low-level specifications for secure, user-centric identity systems. Notable projects include the BBS Signature Scheme + Blind Signatures extension and Sidetree REST API for managing DIDs across various ledgers. The OpenID Foundation contributes enterprise-ready authentication protocols (e.g. EAP [i.86]), while the Object Management Group (OMG) is responsible for the DPROD [i.80] ontology for decentralized data product marketplaces. Additionally, TeleManagement Forum (TM Forum) offers a monetization framework (v2.0) for Virtual Worlds business models, addressing pricing, value chains, and regulatory safeguards. On the national level, the Chinese Ministry of Industry and Information Technology (MIIT) leads with sector-specific standards, including the Industrial Metaverse Reference Architecture and capability maturity models for industrial digitalization.

Roadmaps for virtual economic standardisation reflect a strategic pivot toward verifiability, interoperability, and decentralization. The ISO/TC 307 roadmap emphasizes trust-building through auditability, consistent credentialing, and blockchain system interoperability. OpenWallet Foundation's roadmap supports modular, cross-platform infrastructure for identity wallets and digital asset exchange, with an emphasis on privacy, accessibility, and real-world utility. National efforts-particularly those from MIIT in China-illustrate a state-driven approach to virtual economic infrastructure. These include comprehensive frameworks for industrial Virtual Worlds integration, such as factory simulation standards, virtual exhibition guidelines, and sectoral capability maturity models. These plans emphasize synchronized digital transformation in industry, guided by structured planning and evaluation metrics. The OMG's work on decentralized Data Product ontologies (DPROD) [i.80] and the DIF's standards for decentralized identity form the semantic and infrastructure layer of future economic ecosystems. Combined with TM Forum's monetization frameworks, the direction is toward sustainable, accountable, and user-empowering economies in Virtual Worlds. However, a lack of alignment between jurisdictional policies and technical standards remains a critical roadblock.

Numerous projects are in advanced stages across all technical and regulatory layers of the Virtual Economy. ISO/IEC is actively developing standards for product data representation (e.g. ISO/AWI TS 10303-185 [i.36] and ISO/AWI TS 10303-1857 [i.37]), blockchain auditing (ISO 23353.3 [i.32]), and immersive health simulations (ISO/TS 16551 [i.35]). ISO/IEC 23090-23 [i.65] defines conformance testing for immersive video systems-critical for trust in virtual goods and experiences. The OpenWallet Foundation is running multiple open-source projects: the OWF EUDI Wallet Kit, Tuvali for offline credential exchange, Multiformat VC for iOS, and the Trust Spanning Protocol for secure cross-domain communication. DIF's Sidetree REST API and Blind Signatures extend the privacy and usability of DID systems. OpenID's EAP [i.86] and SIOP-based [i.87] authentication protocols add enterprise-grade security and scalability to decentralized systems. China's MIIT has introduced an entire suite of national standards addressing industrial Virtual Worlds maturity (IMVCMM), application evaluation (IMVAAM), reference architecture (IMRA), and design of virtual factories and exhibition halls. These efforts aim at operationalizing the Virtual Economy within strategic industrial sectors. TeleManagement Forum's Monetization v2.0 standard is already in use to structure value chains in Virtual Worlds commerce. OMG's DPROD [i.80] profile enables decentralized, ontology-driven data marketplaces, expanding economic models based on verifiable and federated data services.

Standardisation in the Virtual Worlds domain "Virtual Economy" in a nutshell:

- Leading bodies: include ISO (TC 307, TC 184), OpenWallet Foundation, Decentralized Identity Foundation, OpenID Foundation, OMG, TM Forum, and China's MIIT.
- Roadmaps: focus on decentralized identity, interoperable blockchain frameworks, industrial metaverse integration, and monetization mechanisms.
- Ongoing activities: range from wallet and credential APIs, industrial simulation standards, auditing protocols, to ontology-based data marketplaces and BLE-based identity exchange.

7.2 Virtual World standardisation gaps

The research identified and classified standards gaps in eight Virtual Worlds domains. The highest number of gaps were found in the domain of immersive experiences (20 %), followed closely by data management (19 %). These high percentages correlate with the broad scope and age of these domains. In contrast, artificial intelligence, reality capture, and Virtual Economy were underrepresented-likely due to a lack of focused expertise and fewer previous studies in these areas, rather than a real absence of gaps.

Artificial Intelligence remains critically underrepresented in current Virtual Worlds standardisation efforts, despite its central role in future immersive systems. Gaps also remain in content moderation and ethical frameworks, which are essential for ensuring user safety and accountability in immersive environments.

Adoption of existing standards across the Virtual Worlds landscape remains uneven and generally limited. While certain technical areas-such as device hardware or network protocols-benefit from established and widely implemented standards, adoption in more dynamic or integrative domains like AI, immersive experiences, or governance frameworks is still rare. This disparity is largely driven by fragmentation, overlapping or competing standards, low discoverability, and the lack of validation mechanisms such as testbeds or conformance benchmarks. As a result, developers and platform providers often rely on proprietary or siloed solutions, further slowing convergence and interoperability.

The analysis further defined nine standards gaps clusters. See Table 12. These clusters provide a thematic lens to assess deficiencies across Virtual Worlds.

Table 12: Clusters of standardisation gaps identified

Cluster	Main Gaps / Issues
Infrastructure, integration, and interoperability	Fragmentation across networks, platforms, and data systems. No interoperable frameworks for identity, assets, and immersive environments. Limits scalability, seamless integration, and collaboration.
XR display hardware & device interoperability and integration	Missing specifications for displays, sensors, and haptics. Incompatible interfaces and calibration standards reduce modularity and cross-platform use.
Data privacy & security	No consistent standards for personal and biometric data protection. Weak identity management, consent mechanisms, and ethical data handling.
User experience & accessibility	Lack of ergonomic design standards. Poor support for diverse users. Need for inclusive UI design, consistent interactions, and assistive technology integration.
Ethics, regulatory frameworks & governance	No harmonized legal frameworks or ethical guidelines. Uncertainty in moderation, user protection, and digital identity. Lacking transparent and participatory processes.
Content media formats & protocols	Fragmented standards for video, 3D, and spatial data. Limits content exchange and consistent rendering across platforms.
Health & safety	Gaps in addressing physical and psychological risks. Missing standards for safe device use, moderation, age restrictions, and vulnerable group protection.
Terminology & definitions	Inconsistent terminology and overlapping taxonomies. Creates confusion in policy, interoperability, and tool development.
Digital economy & asset management	No standards for virtual goods, NFTs, or transactions. Problems with interoperability, IP protection, and fair valuation mechanisms.

When reviewing standards gaps by cluster, infrastructure emerged as the largest category-unsurprising given the foundational role connectivity plays in Virtual Worlds. In second place were gaps in the areas of ethics and governance, which corresponds to EU regulatory requirements. Content media gaps came third, reflecting rapid technical evolution and inconsistent interoperability standards.

Looking at standards gaps by stakeholder group, Virtual Worlds providers were associated with the highest number (37 %) of gaps, especially in technical and content-related clusters. Buyers, researchers, and standardisation bodies also play roles, though responsibilities often overlap. Heatmaps and Sankey diagrams further illustrate that providers are expected to lead on infrastructure, content protocols, and integration standards.

Finally, standards gaps by standardisation goals reveal that addressing interoperability and compatibility remains the central aim. Gaps linked to innovation support, efficiency, market access, and product safety also persist but to varying degrees. Mapping gaps across objectives helps prioritise efforts and align strategies with tangible ecosystem benefits.

In Figure 7 a Sankey diagram visualizes how four stakeholder groups are linked to different thematic gaps in Virtual Worlds standardisation (group five - the SDOs - were taken out as they are obviously always linked to standardisation gaps). On the right hand side, Figure 6 illustrates the number of mentioned gaps assigned to the identified nine gap clusters. Each flow represents perceived relevance or concern expressed by stakeholders regarding a specific topic. This figure reveals that stakeholder priorities are unevenly distributed. While ethical governance and infrastructure are seen as critical by nearly all groups, areas like digital economy, standard vocabulary, and safety protocols receive comparatively less engagement-highlighting blind spots that may require policy and coordination efforts.

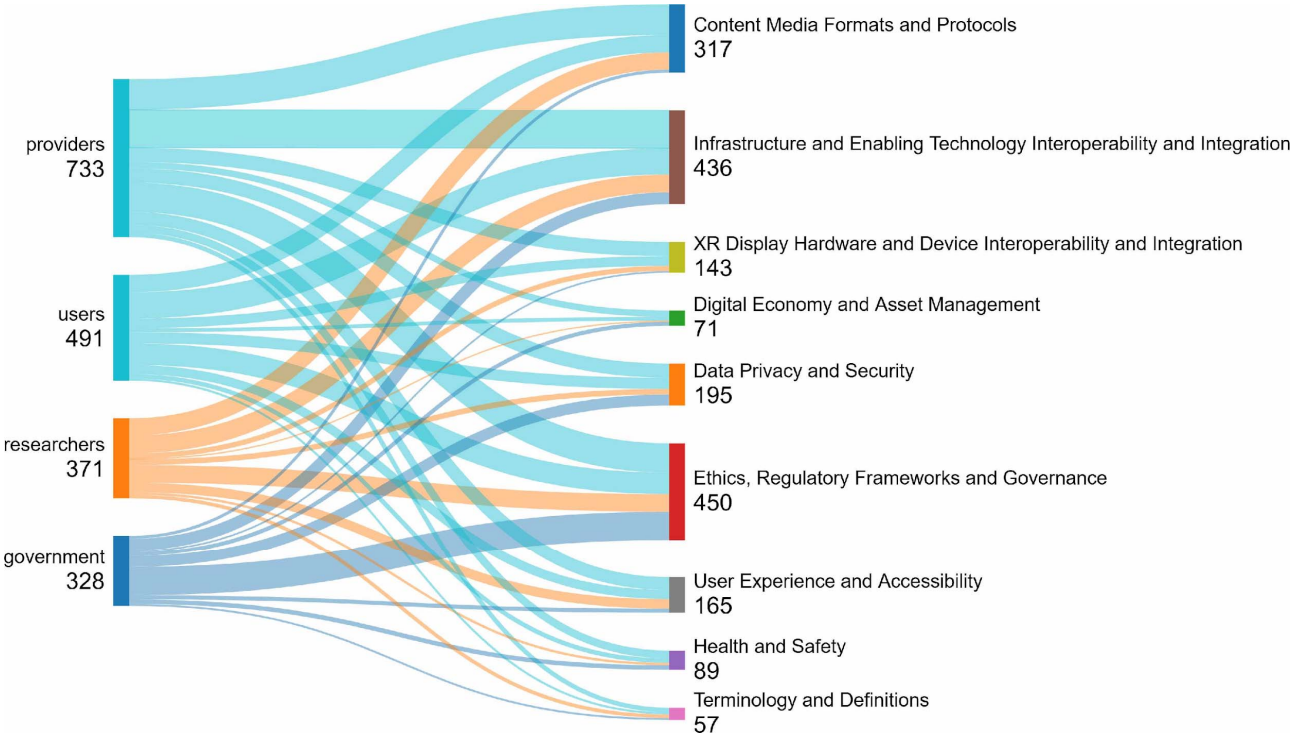


Figure 7: Virtual Worlds standardisation stakeholder groups related to standardisation gaps

Virtual Worlds standardisation gaps in a nutshell:

- Standards gaps by gap clusters: infrastructure and enabling technology as the largest category, followed by ethics and governance gaps.
- Standards gaps by stakeholder group: virtual world providers were associated with the highest number of gaps, followed by buyers, researchers, and standardisation bodies.
- Standards gaps by standardisation goals: interoperability and compatibility remain the central aims.

7.3 Structural and contribution issues of the Virtual Worlds standardisation system

Structural and contribution issues in eight Virtual Worlds domains were assessed across a wide range of standardisation activities. These were grouped into clusters. See Table 13. Most issues were concentrated in the infrastructure domain (30 %), where overlapping working groups, opaque procedures, and high participation costs create barriers. Surprisingly, a high share of issues (22 %) was also found in the Virtual Society domain, where progress relies more on political will and public leadership than on formal standardisation bodies. Other domains like immersive experiences also face fragmentation, but lesser-known standardisation efforts hinder cross-sector visibility and collaboration.

The present document identified ten thematic structural and contribution issues clusters defined, each illustrating systemic weaknesses in the standardisation ecosystem.

Table 13: Clusters of structural and contribution issues identified

Cluster	Main Issues
Process & pace challenges	Misalignment between fast tech development and slow, rigid standardisation. Inefficient consensus, outdated governance, and mismatched timelines delay innovation and adoption.
Fragmentation & lack of coordination	Disconnected bodies, overlapping mandates, and siloed projects cause duplication, conflicting specs, and poor interoperability.
Transparency, accessibility & inclusion barriers	Dominance of large regional players. Exclusion of SMEs, civil society, and non-English speakers. High costs, complex language, and opaque processes limit inclusiveness.
Resource & funding constraints	High participation fees, limited public investment, and reliance on short-term funding weaken sustained collaboration, especially for open initiatives and national committees.
Incentives & motivation challenges	Lack of recognition, financial support, and tangible outcomes. Conflicting goals and misaligned requirements discourage engagement and create impractical standards.
Dominance & proprietary control	Large corporations push vendor lock-in, closed platforms, and selective engagement. They shape standards in their favor and resist interoperability.
Geopolitical factors & politicisation	National agendas and major power influence create competing frameworks. Political interests overshadow technical merit and fragment the global landscape.
Standardisation infrastructure & tooling deficiencies	Outdated digital platforms, missing collaboration tools, and weak version control reduce efficiency and consensus building.
Regulatory & legal complexities	Jurisdictional differences, unclear guidance for emerging tech, and opaque IPR policies raise legal uncertainty and hinder adoption.
Awareness, communication & education issues	Low visibility of standards, weak educational support, and poor communication strategies. Fragmented messaging, ambiguous terminology, and limited training reduce trust and understanding.

The present document proceeds to evaluate structural and contribution issues by cluster, with fragmentation and coordination issues taking the lead, followed by pace and process challenges, and dominance of large market players. Surprisingly, tooling infrastructure issues were ranked lower, suggesting that existing tools may be underutilised rather than lacking entirely.

Analysis of structural and contribution issues by stakeholder group assigns 42 % of the issues to Virtual Worlds providers, particularly concerning coordination and dominance. Researchers also face challenges, often due to theoretical work that overlooks real-world applicability. However, issues often span multiple stakeholder groups, and interpretations could consider the diversity within each.

Finally, the present document maps structural and contribution issues by standardisation objectives. Unsurprisingly, the most urgent objective remains achieving interoperability and compatibility. Fragmented coordination continues to block progress toward this goal. The data suggest that without systemic improvements in how standardisation efforts are managed, Virtual Worlds interoperability and alignment with broader ICT ecosystems will remain out of reach.

Figure 8 illustrates how different stakeholder groups are linked to structural challenges in Virtual Worlds standardisation. On the right hand side, the figure illustrates the number of mentioned structural and contribution issues assigned to the identified issues clusters. The most cited issue is the fragmentation and lack of coordination across standard-setting efforts, followed by slow and inefficient processes. Concerns about dominance by proprietary actors and barriers to transparency and inclusion also feature prominently. While some challenges-like legal complexities or tooling gaps-are more specific to certain groups, the overall picture reveals a need for more collaboration, openness, and strategic alignment in the standardisation ecosystem.

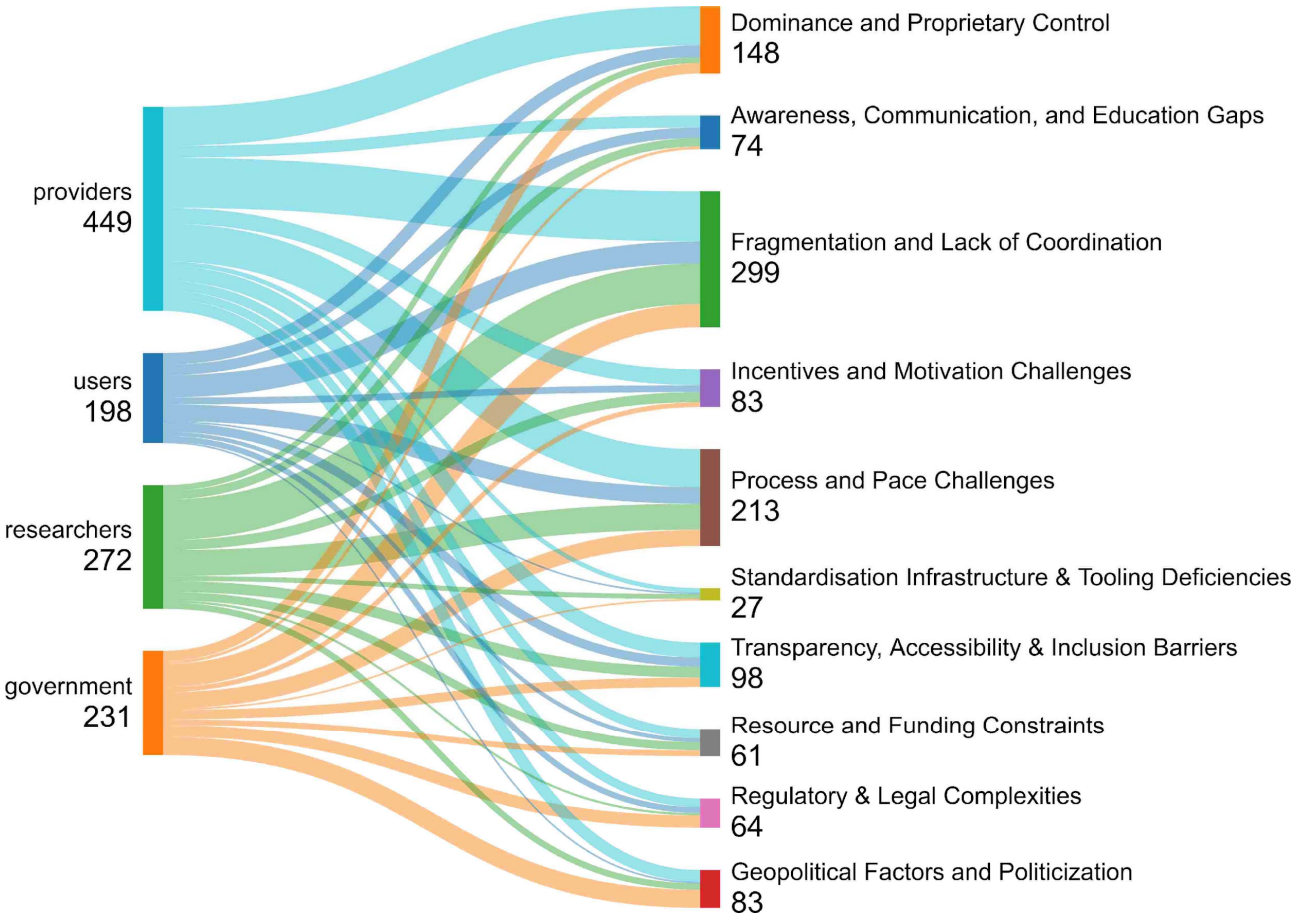


Figure 8: Virtual Worlds standardisation stakeholder groups related to structural standardisation challenges

Structural and contribution issues of the Virtual Worlds standardisation system in a nutshell:

- Structural and contribution issues by issues clusters: fragmentation and coordination issues take the lead, followed by pace and process challenges.
- Structural and contribution issues by stakeholder group: providers come first, particularly concerning coordination and dominance, followed by researchers due to too theoretical work.
- Structural and contribution issues by standardisation objectives: the most urgent objectives remain interoperability and compatibility due to fragmented coordination.

7.4 Recommendations

7.4.1 Standardisation objectives

One of the most urgent needs to be addressed is the lack of interoperability and compatibility, which continues to limit the scalability and openness of Virtual Worlds. Despite the existence of earlier standards such as VRML or X3D, adoption remains limited, and many platforms still operate in closed silos. To address this, the present document recommends building coordinated frameworks across SDOs, reusing existing interoperable standards where possible, and retiring obsolete ones. Recent initiatives like OSCAR4US and OMA3's InterWorld Portaling System show that cross-platform identity, asset portability, and positioning systems are achievable, but they require stronger alignment and broader adoption.

Supporting innovation and technology transfer is equally critical. Standards play an essential role in bridging research and deployment by providing common technical abstractions and reducing integration burdens. However, many innovators-especially in fast-evolving domains like AI or immersive human interfaces-remain unaware of how standardisation can support their work. The present document encourages the use of open-source toolkits, such as StereoKit, and greater involvement in early-stage research projects like OpenVerse and XR4Human. At the same time, standardisation groups will need to proceed cautiously in areas like brain-computer interfaces, where the underlying technologies are still immature.

The objective of cost reduction and efficiency gains is another major driver. By enabling modular system design, component reusability, and common protocols, standards can lower both development and operational costs. While today's Virtual Worlds platforms are still emerging, the long-term promise of reduced energy use, easier maintenance, and fewer integration failures is evident. The present document also points to indirect cost benefits, such as those gained from immersive telepresence, which can reduce the need for physical travel. However, these efficiencies remain difficult to quantify in early-stage markets, and further research is encouraged.

Facilitating market access and trade through harmonised standards is essential to ensuring that European Virtual Worlds technologies can scale globally. Differences in jurisdiction, regulation, and data protection rules currently create uncertainty for developers and users. The present document recommends aligning Virtual Worlds standards with evolving EU regulations such as the AI Act and GDPR, while also piloting regulatory sandboxes and new legal constructs like a 28th regime for digital environments. Additionally, inclusive design standards and certification schemes anchored in EU values could help identify trustworthy solutions and support small and medium-sized enterprises in reaching international markets.

Finally, quality assurance and product safety are central to building user trust in immersive technologies. While some areas-like hardware safety for VR headsets-are already covered by existing technical norms (e.g. UL 8400), major gaps persist in areas such as content moderation, accessibility, and inclusive user experience design. Ethical frameworks from organizations like IEEE and ITU provide useful starting points, but their implementation remains limited. The present document urges the development of benchmarkable, testable standards that protect vulnerable users, support human-centric interaction, and ensure that emerging virtual environments are not only functional but also safe, inclusive, and socially responsible.

Recommendations related to standardisation objectives in a nutshell:

- Interoperability and Compatibility: Fragmentation hampers scalability; coordinated cross-SDO frameworks and reuse of interoperable standards (e.g. X3D, OSCAR4US) are needed for identity, asset, and spatial portability.
- Innovation and Technology Transfer: Standards can support deployment by offering technical abstractions; open-source tools and early research (e.g. XR4Human) should be leveraged, especially in fast-evolving areas like AI.
- Efficiency and Market Access: Modular design and shared protocols can reduce costs; aligning standards with EU laws (e.g. GDPR, AI Act) and using regulatory sandboxes can ease market entry and support SMEs.
- Trust and Safety: Gaps in content moderation, accessibility, and ethics should be addressed through testable, inclusive standards that ensure safe and responsible virtual experiences.

7.4.2 Standardisation stakeholders

For providers, the central recommendation is to move beyond proprietary ecosystems and contribute actively to the development and adoption of open, interoperable standards. Providers-from global tech companies to agile startups-can begin to embed privacy-by-design, ethical frameworks, and sustainability into the core of their technologies. They are also urged to engage with both formal and informal SDOs, invest in cross-platform compatibility, and prepare for future developments like post-quantum security. Through strategic standardisation, providers can foster market openness while still protecting innovation-driven business models.

The role of buyers, including enterprise users, public agencies, and civic institutions, is to exert influence through demand. Buyers are encouraged to include standardisation criteria in procurement processes, thereby creating incentives for open, secure, and accessible Virtual Worlds technologies. Governments in particular can shape the market through tendering rules and funding instruments. By insisting on interoperability, transparency, and ethical compliance, buyers can accelerate the adoption of trustworthy standards and prevent technological lock-in.

When it comes to government, the present document highlights its multifaceted responsibility as regulator, funder, and system architect. Public authorities could align legislation and policy with strategic standardisation goals, fostering environments that support innovation without compromising public interest. Governments are urged to adopt forward-looking regulatory models such as sandboxes, integrate standards into public investment programs, and enforce inclusive and sustainable technology development. They could also support open access to test environments and tools that enable SMEs and civil society to participate meaningfully.

The contribution of researchers is critical to bridging knowledge gaps, translating innovation into technical standards, and identifying long-term risks and opportunities. Research institutions, including universities and industrial labs, are encouraged to support pre-standardisation work such as terminology, taxonomies, and use case analysis. Researchers could also engage with ongoing standardisation processes to test, validate, and refine specifications-particularly in domains like AI, immersive interaction, and ethics. Their independent perspective helps ensure that standards remain grounded, credible, and future-oriented.

Finally, the standardisation community itself could modernise to keep pace with the complexity and speed of Virtual Worlds development. SDOs and consortia are urged to update their technical infrastructure, embrace digital-first collaboration tools, and make contribution pathways more transparent and inclusive. This includes better onboarding, multilingual documentation, and more dynamic lifecycle management. By reducing entry barriers and fostering open, modular development, standardisation bodies can build trust and widen participation across sectors, geographies, and organisation types.

Recommendations related to standardisation stakeholders in a nutshell:

- Providers should move beyond proprietary systems, embed ethics, privacy, and sustainability by design, support cross-platform standards, and engage in both formal and informal SDOs to drive open innovation.
- Buyers (enterprises, governments, institutions) are encouraged to include standardisation criteria in procurement to drive demand for secure, ethical, and interoperable technologies and prevent vendor lock-in.
- Governments should act as regulators, funders, and system architects by aligning laws with standardisation goals, enabling regulatory sandboxes, supporting public testbeds, and enforcing inclusive development.
- Researchers are vital for translating innovation into standards, identifying long-term risks, and contributing to terminology, validation, and testing, particularly in AI, ethics, and immersive systems.
- SDOs and Consortia should modernize tools and processes - offering transparent, inclusive participation, multilingual documentation, and digital-first collaboration - to attract broader and more diverse contributors.

7.4.3 Clusters of recommendations

Recommendations for standardising Virtual Worlds are grouped, including recommendations across eight domains. The highest density of recommendations appears in data management and immersive experiences, while domains such as reality capture and artificial intelligence show fewer recommendations due to their emerging status and more limited expert engagement.

The recommendations fall into fifteen cross-cutting clusters, reflecting the complex, interdisciplinary nature of Virtual Worlds.

Table 14: Clusters of recommendations

Cluster	Main Recommendations
Concepts, terminology & taxonomy	Standardise terms, reference models, and language for semantic and technical interoperability. Support consistency and collaboration across domains.
Governance, legal & economic frameworks	Harmonise digital rights, liability, economic models, and regulations at European and international levels.
Ethics & responsible innovation	Embed human-centric design, prevent misuse, and guide responsible AI and immersive technology deployment.
Digital literacy, education & awareness	Develop curricula, certifications, and public initiatives to raise literacy and enable inclusive participation.
Technical infrastructure interoperability	Harmonise interfaces, APIs, and data protocols for cross-platform interaction, IoT integration, and real-time services.
XR hardware & devices	Define ergonomic, safety, and power standards to ensure cross-vendor compatibility and user health.
Digital content interoperability	Establish shared formats for 3D assets, avatars, and immersive media to enable fluid workflows and mobility.
Quality, performance & metrics	Create benchmarks for latency, comfort, and system integrity using transparent, certified testing protocols.
User identity, safety, security & privacy	Implement robust, verifiable identity systems, ethical safety protocols, and privacy-preserving data flows.
Accessibility & user experience	Ensure universal usability, inclusive design, and localised content to reduce participation barriers.
Industry-specific applications	Adapt core standards to health, education, culture, manufacturing, and align with sectoral regulation.
Sustainability & environmental impact	Promote energy-efficient architectures, recyclability, and circular economy principles for resilience.
Geospatial data & digital twins	Standardise real-time mapping, spatial anchoring, and open coordinate systems to connect physical and virtual worlds.
Quantum technologies & cryptography	Adopt post-quantum cryptography and secure communication standards to future-proof security.
Standardisation organisations & processes	Evolve governance with faster cycles, broader participation, transparency, and test-driven development.

Quantitatively, most recommendations examined in the assessment concern the technical infrastructure for Virtual Worlds, followed by clusters on identity and safety, content interoperability, and standardisation process reform. These priority areas reflect both high technical urgency and critical policy relevance.

Across stakeholder groups, Virtual Worlds providers are the ecosystem segment to which are most recommendations are addressed, followed by standardisation bodies. While providers and standards bodies could improve their support for interoperability standards adoption, in order to succeed, many recommendations will benefit from coordinated contributions from researchers, buyers, and government stakeholders.

Mapped against strategic objectives, the recommendations overwhelmingly focus on interoperability, confirming that while many standards already exist, their adoption remains too low to realise their full potential. Broader uptake, alignment, and trust frameworks are needed to reduce fragmentation and avoid reliance on proprietary ecosystems.

Figure 9 visualizes the distribution of stakeholder engagement with recommended standardisation themes for Virtual Worlds. It illustrates the number of mentioned recommendations assigned to the identified recommendations clusters. The strongest alignment is seen around governance and institutional processes, with all groups-especially SDOs, providers, and governments-highlighting the urgent need for clearer structures, regulatory alignment, and coordination between standardisation actors. This reflects ongoing fragmentation and a shared desire for coherent frameworks that enable trust, accountability, and scalability across platforms and jurisdictions.

Terminology and taxonomy is also a high-priority area, particularly for users, researchers, and SDOs, underscoring the lack of consistent language and conceptual models across domains. Without shared definitions, efforts to harmonize standards, ensure interoperability, or engage new stakeholders are severely hindered. This is closely tied to education and awareness, another domain receiving significant attention, suggesting that better onboarding, documentation, and public-facing explanations are seen as essential for adoption and inclusion.

Ethics and accessibility, and privacy, identity, and security rank prominently, with input from users, governments, and researchers reflecting strong concern for human-centric design, social inclusion, and protection from harm in immersive systems. These areas indicate growing awareness of virtual environments' societal impacts and the need for normative safeguards.

More technical themes-such as data and geospatial systems, technical infrastructure and devices, and sector-specific standards-are primarily championed by providers and researchers, indicating their focus on performance, integration, and context-aware applications. These foundational technologies are critical for ensuring that Virtual Worlds are not only functional but also scalable and adaptable to various domains like healthcare, mobility, or education.

In contrast, immersive experience design and innovation enablement receive the least attention, suggesting that creative, design-led, and experimental aspects of Virtual Worlds development are not yet fully integrated into the standardisation discourse. This is a notable gap, as these dimensions are important to user satisfaction, market growth, and future adaptability.

Overall, the diagram reveals a clear prioritisation of governance, infrastructure, and foundational definitions, but also a relative neglect of experiential and future-facing dimensions. Balancing structural reforms with innovation-oriented standards will be crucial to ensuring that Virtual Worlds are not only reliable and interoperable, but also engaging, inclusive, and forward-looking.

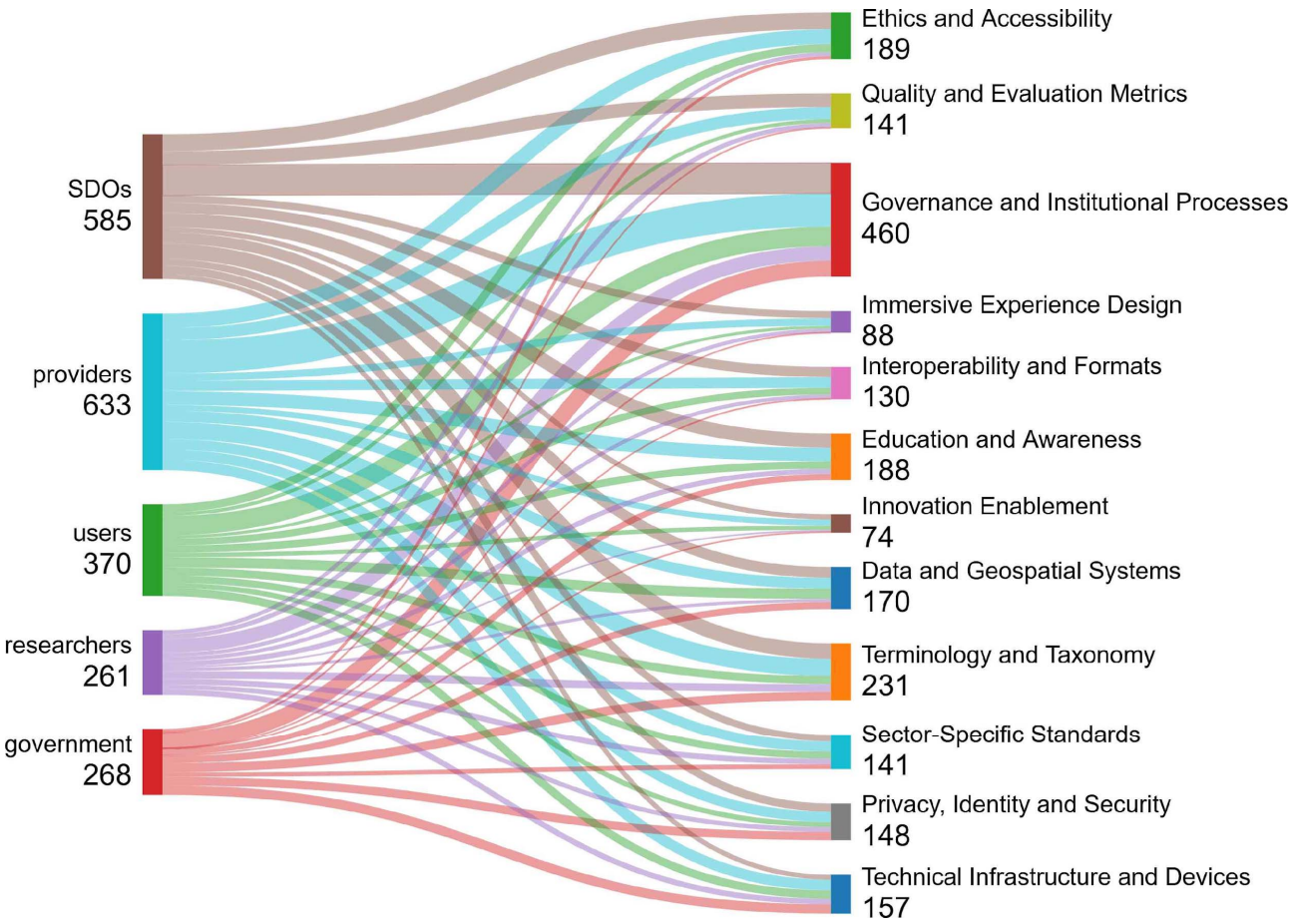


Figure 9: Virtual Worlds standardisation stakeholder groups related to standardisation recommendations

Recommendations on standardisation over all eight Virtual Worlds domains in a nutshell:

- Most recommendations provided fall under technical infrastructure, followed by clusters on identity and safety, content interoperability, and standardisation process reforms.
- Most frequently addressed: Virtual Worlds providers.
- Most actions require coordinated contributions from researchers, buyers, and governments.
- Most important strategic objectives: interoperability, broader uptake, alignment, and trust frameworks.

7.4.4 Further recommendations

Fragmentation of standards and lack of coordination continue to pose serious obstacles to efficient and inclusive standardisation. Standards fragmentation and coordination could be addressed through stronger alignment among formal Standards Development Organizations (SDOs), industrial consortia, and domain-specific initiatives. The present document advocates for joint roadmaps, shared planning frameworks, and cross-domain working groups to prevent duplication and encourage strategic convergence. Increased transparency-via open repositories and collaborative platforms-will enable stakeholders to identify overlapping efforts early and contribute more effectively.

To overcome persistent barriers within the standardisation ecosystem, a suite of actions is proposed under structural and contribution issues recommendations. These include modernising governance processes, simplifying contribution pathways, and ensuring more equitable access. Special emphasis is placed on supporting small and medium-sized enterprises (SMEs), civil society, and less-represented geographies. The recommendations call for multilingual resources, accessible tooling, and improved onboarding practices. By lowering these thresholds, the standardisation process can become more inclusive, agile, and responsive to diverse societal needs.

Before any formal standard is created, pre-standardisation activities play a critical role in shaping its foundation. These early-phase efforts involve interdisciplinary research, real-world prototyping, and the development of shared vocabularies and conceptual models. Such groundwork ensures that emerging standards are rooted in concrete user needs, technology trends, and ethical considerations. Pre-standardisation also helps align stakeholders on common goals, paving the way for smoother development of specifications.

After a standard is published, post-standardisation activities become essential to ensure its adoption and effectiveness. This includes the development of testbeds, conformance benchmarks, and reference implementations. These practices help validate standards in operational settings and identify technical or usability gaps. Certification frameworks and continuous feedback mechanisms further support uptake, enabling standards to evolve as technologies and societal expectations change.

Further recommendations in a nutshell:

- Tackle Fragmentation and Coordination Gaps: Stronger alignment between SDOs, industry consortia, and domain initiatives is needed through joint roadmaps, cross-domain working groups, and open collaboration platforms.
- Lower Structural Barriers to Participation: Governance processes should be modernized with simplified, equitable contribution pathways - especially for SMEs, civil society, and underrepresented regions - via multilingual resources and accessible tools.
- Strengthen Pre-standardisation Efforts: Early interdisciplinary research, prototyping, and vocabulary building are essential to ensure standards address real-world needs and ethical considerations from the outset.
- Support Post-standardisation Adoption: Implementation should be guided by testbeds, certification schemes, and feedback loops to validate standards and enable continuous improvement in line with technological evolution.

7.4.5 New research and standardisation activities

The future development of Virtual Worlds will rely not only on the adaptation of existing standards but also on initiating new, targeted research and standardisation activities. These are divided into technical and societal themes, each addressing pressing gaps and opportunities.

Artificial Intelligence remains largely unaligned with Virtual Worlds developments. Despite the abundance of AI-related standards, few address its use in immersive environments. Coordination initiatives like the Metaverse Standards Forum's AI x Metaverse working group are emerging to align efforts and reduce redundancy. Research could focus on AI for procedural content generation, personalization, and intelligent agent behavior. Collaboration between AI and Virtual Worlds stakeholders, including EU projects and commercial actors, is vital.

In Reality Capture and Description, the lack of integration between geospatial and 3D graphics communities hinders augmented reality systems. Standards for VPS (Visual Positioning Services) and semantic frameworks describing the physical world could be developed in tandem with industry and academic input. Coordination between semantic initiatives (e.g. SOSA, SAREF) is needed to prevent fragmentation.

Cross-Reality Transition technologies remain experimental. Research is required into display materials and identity persistence across modalities. Seamless user experiences in hybrid environments depend on continuity in interface and cognitive flow.

Industry-Specific Use Cases and Requirements have yet to be fully explored. While many sectors-manufacturing, mobility, healthcare, education-stand to benefit, their needs differ significantly. Sectoral research is needed to tailor Virtual Worlds technologies and accelerate adoption.

Robust User Studies and benchmarking frameworks are essential. Existing studies are limited in scope and comparability. Research projects could develop repeatable, cross-cultural methodologies and datasets to evaluate interaction, cognition, and usability across platforms.

The concept of Time and Temporality in Virtual Worlds, including synchronization, persistence, and history, remains underdeveloped. Basic and applied research is needed to address time representation and coordination across systems.

Integrated Sensing and Communication (ISAC), especially in 6G networks, offers promise for detecting and interacting with passive physical elements. Its integration into immersive environments requires new standards and testing.

Unified Security Frameworks for Virtual Worlds are lacking. Current efforts are dispersed and not tailored to unique challenges like avatar identity, virtual asset protection, or immersive safety. Coordination among SDOs (e.g. W3C, ISO/IEC) and additional research are required to bridge gaps.

Emerging Display Technologies are a bottleneck for widespread AR adoption. High-resolution, low-power, adaptive optics are needed, along with cost-efficient, lightweight designs and standardised calibration systems. Lightfield and novel lens technologies are areas of active exploration.

User Inputs could evolve beyond current devices. Research into secure, multimodal input-including biometric and gesture-based systems-is necessary to ensure privacy, reliability, and universal accessibility in virtual environments.

Several Other Technical Topics merit attention. These include Wireless Body Area Networks for sensor integration, QA standards tailored to virtual applications, standards for real-time collaboration, embodiment protocols, and multisensory feedback systems. Each could play a defining role in how Virtual Worlds develop.

In parallel to the technical fields, Economic and Societal Topics also require deeper exploration.

Cryptocurrencies and their use in Virtual Worlds pose regulatory, ethical, and operational challenges. The lack of oversight and transparency demands research into secure, interoperable standards, financial crime prevention, and sustainable digital economies.

Evolving Virtual Worlds business models disrupt traditional supply and value chains. Issues such as price elasticity, gratification dynamics, and secondary markets remain poorly understood. New methodologies could assess how these models interact with both virtual and real-world economies.

Energy usage in and by Virtual Worlds is increasing but poorly quantified. Life cycle assessments and Net-Zero goals for hardware could guide development. Research and standards promoting energy-efficient design are essential.

Protection versus Innovation remains a critical balancing act. Intellectual property frameworks could be refined to ensure creativity and openness are preserved while rights are respected. Future standards could support this balance.

The Promotion of Positive Societal Impacts is necessary for public trust and ecosystem maturity. This includes research on accessibility, inclusion, mental health, and ethical engagement, as well as expanding projects like XR4Human that develop participatory governance models.

Finally, Content Moderation for Immersive Experiences is underdeveloped. There is a need for standards addressing user conduct, trust frameworks, and moderation protocols specific to Virtual Worlds interaction, ensuring user safety and accountability.

Virtual Worlds span an extraordinary range of challenges and opportunities. Addressing these through research-driven standardisation will be crucial to ensuring their interoperability, inclusivity, and sustainability. The study provides a roadmap for future research priorities that can bridge critical gaps and ensure that Virtual Worlds technologies evolve in a coherent and responsible manner.

Potential new research and standardisation activities in a nutshell:

- Align AI and Virtual Worlds: bridge gaps between AI standards and immersive applications (e.g. agents, personalization) through coordinated initiatives like AI x Metaverse.
- Advance core technical areas: develop integrated standards for geospatial-3D data (VPS), cross-reality continuity, immersive security, and next-gen input/display technologies (e.g. lightfield, 6G ISAC, WBANs).
- Support sector-specific needs: tailor standards for industries like healthcare, mobility, and education, while improving user studies and benchmarking across cultures and platforms.
- Address socioeconomic dimensions: regulate crypto and digital assets, promote energy-efficient design, balance IP protection with openness, and encourage research on inclusion, mental health, and governance.
- Strengthen trust and safety: create immersive-specific content moderation standards and trust frameworks to ensure accountability and user protection in virtual environments.

8 Conclusions

8.1 Standardisation landscape

The high number and diversity of standards for use in Virtual Worlds reveals both its richness and its complexity. The analyses performed for the present document identifies a wide array of standardisation documents ranging from broad conceptual frameworks to narrow technical specifications. Some standards apply across multiple domains, while others are tightly focused. This diversity itself is not problematic; it reflects the maturity and adaptability of the field. However, for potential adopters, this multitude can be disorienting. The presence of overlapping standards that address similar requirements in subtly different ways-often without any practical testing or comparative validation-undermines clarity and confidence. This form of fragmentation is rooted in systemic characteristics of the standardisation landscape and is not likely to resolve in the short term. That said, consolidation, comparative studies, and application-driven selection could significantly enhance the usability and coherence of this standards ecosystem.

Improved collaboration among standardisation bodies is widely recognised as essential to addressing this fragmentation. While evidence of cross-SDO cooperation remains limited and often informal, several initiatives signal a cultural shift. Chief among them is the Metaverse Standards Forum launched by the Khronos Group in 2022, which quickly attracted over 2,600 member organisations. However, many SDOs remain constrained by governance rules that prevent participation in other membership-based alliances. Liaison mechanisms offer a partial solution, allowing exchange without formal membership. More promising still is the prospect of contributor-level mapping, which could trace who is contributing to which standards, under which affiliations. This approach could reveal overlaps, build trust, and support convergence across efforts currently siloed by institutional boundaries.

A critical structural barrier emerged in the discovery that there is a lack of standards for standardisation information itself. In the process of assembling this study's dataset, the team encountered wide inconsistencies in how standards are described, classified, and structured. Basic metadata such as versioning, development stage, or responsible working group is often missing, incomplete, or inconsistently labeled. Even the terminology used within and between SDOs varies significantly. Terms such as "Virtual Worlds" or "metaverse" lack shared definitions, and even seemingly well-understood words like "standard" or "recommendation" are interpreted differently. Without a harmonised way of describing standards and their interrelationships, efforts like standards mapping are hindered. More importantly, this confusion makes it harder for newcomers and developers to understand the relevance and applicability of existing standards-delaying or deterring adoption.

Finally, the ultimate goal of standardisation-standards adoption-depends on visibility, clarity, and practical value. A standard achieves impact only when it is implemented and used. The fragmentation, lack of discoverability, and inconsistent structuring described above pose real risks to adoption. Without tools to monitor uptake or assess relevance in context, it remains difficult for developers, organisations, or regulators to confidently rely on existing standards. The future of Virtual Worlds standardisation hinges not only on developing new standards, but on making the existing body of work navigable, interoperable, and useful. Achieving this requires a coordinated effort to standardise the standards system itself.

Conclusions on mapping the standardization landscape of virtual worlds in a nutshell:

- Rich but Fragmented Landscape: The standardization ecosystem is diverse and technically mature, yet fragmented, with overlapping or inconsistent standards that confuse potential adopters.
- Need for Institutional Collaboration: Cross-SDO cooperation is limited; initiatives like the Metaverse Standards Forum are promising, but structural and governance barriers persist.
- Lack of Metadata Standards: There is no standardized way to describe or classify standards themselves - leading to inconsistencies in terminology, structure, and traceability.
- Adoption Barriers: Without clear structure, discoverability, or tools to assess applicability, existing standards remain underused - highlighting the need to "standardize the standards system".

8.2 Recommendations for the standardisation of Virtual Worlds

8.2.1 Conclusions per Virtual Worlds domains

Table 15 summarises the conclusions and recommendations for Virtual Worlds standardisation, structured by domain, highlighting priority actions, systemic needs, and future directions.

Table 15: Conclusions and recommendations for standardisation by Virtual World domain

Domain	Conclusions and Recommendations
Infrastructure	Prioritise interoperability via shared reference architectures and modular design principles. Align cloud, edge, and networking capabilities with immersive applications. Harmonise high-throughput connectivity and resource orchestration for resilient infrastructure.
Data Management	Establish common schemas, metadata structures, and secure exchange protocols. Strengthen governance of identity, spatial, and behavioural data with lifecycle management and access control. Bridge digital twins and Virtual Worlds through interoperable formats.
Artificial Intelligence	Standardise transparency, safety, and fairness in immersive AI. Develop explainable AI protocols, agent interoperability, and model portability. Support real-time AI responses for adaptive, natural interactions.
Reality Capture	Create accurate, interoperable standards for spatial digitisation. Align 3D scanning, photogrammetry, and sensor fusion. Ensure unified coordinate systems and compatible formats for reliable integration.
Human Interface Systems & Devices	Promote device abstraction and inclusive design. Enable integration via unified APIs. Apply ergonomic, safety, and accessibility benchmarks to ensure consistent user experiences.
Immersive Experiences	Standardise content rendering, avatar behaviour, and runtime interoperability. Develop reference models for experience design, authoring, and usability assessment. Embed inclusive and ethical design principles.
Virtual Society	Build frameworks for identity, rights, and participation. Standardise privacy, user safety, and inclusive social structures. Adopt governance models and anti-discrimination safeguards.
Virtual Economy	Develop interoperable protocols for asset ownership, smart contracts, and value exchange. Ensure authentication, provenance, and consumer protection across platforms.

8.2.2 Top ten recommendations

Government stakeholders play a pivotal role in shaping the development and adoption of Virtual Worlds technologies. Their responsibilities extend far beyond technical oversight: they encompass regulatory frameworks, policy design, public procurement, funding of research and innovation, and-crucially-the safeguarding of societal values such as privacy, safety, and inclusion. Against this backdrop, the research conducted for the present project highlights one challenge above all others: the lack of technical interoperability. Fragmented standards, overlapping initiatives, and uneven adoption currently represent the most significant barriers to the broader uptake of Virtual Worlds technologies across Europe.

The European Commission's strategy for Virtual Worlds distinguishes itself by prioritising citizen rights, ethical considerations, and the creation of an open and inclusive digital environment. This approach is particularly ambitious given Europe's diverse multinational, economic, and linguistic landscape. Achieving such a vision requires well-coordinated action at technical, administrative, and financial levels, as well as stronger bridges between European initiatives and international standardisation efforts. Without these measures, Europe risks falling behind in shaping the rules, technologies, and values of the immersive environments that are rapidly emerging worldwide.

The ten recommendations presented here directly respond to these challenges. They are grounded in evidence from over 900 standards and 350 technical reports, combined with expert interviews, stakeholder consultations, and mapping of nearly 400 working group activities. They target both technological and societal dimensions, ranging from highly technical interoperability issues to the broader policy and governance frameworks that define how Virtual Worlds evolve.

Some recommendations focus on reducing fragmentation in the standards landscape by supporting the continuous development and adoption of European and international technical standards. These cover critical topics such as content and data interoperability, spatio-temporal computing, industry-specific extensions, and privacy-by-design principles. Others address structural barriers by calling for greater engagement of European buyers and providers-including SMEs and research organisations-in the standardisation process, ensuring that the resulting frameworks genuinely meet stakeholder needs.

Equally important are measures that emphasise communication, awareness, and education. Campaigns to promote standards as industry best practices can accelerate adoption and professional development, while dedicated training programmes for executives and technical experts-such as a proposed European Virtual Worlds Standards Leadership Program-would strengthen Europe's capacity to implement and benefit from standards. In parallel, better access to information is required: improved registers and more transparent documentation of standards would make it easier for developers, companies, and governments to find, understand, and apply relevant frameworks.

The recommendations also stress the importance of practical validation. Standards could not remain abstract technical documents but could be tested and proven through independent implementations before approval. Supporting infrastructures, such as European implementation support centres and a central clearing house for compliance services, are needed to reduce the risks and costs of adoption while providing certification mechanisms that ensure trust and accountability.

Finally, public procurement emerges as a powerful strategic tool. By embedding requirements for standards compliance in EU tenders and funding programmes, the European Commission can create strong market incentives for providers to align with interoperable, secure, and sovereign solutions. In this way, the EU not only strengthens its internal digital ecosystem but also positions itself as a global leader in shaping open, ethical, and future-oriented Virtual Worlds.

Taken together, these ten recommendations provide a comprehensive roadmap. They address interoperability, transparency, education, validation, and governance-while remaining firmly anchored in European values. Their implementation would help transform Virtual Worlds from fragmented, proprietary ecosystems into open and trustworthy environments that serve citizens, industries, and societies across Europe.

Top ten recommendations:

1) Promote and enforce European and international technical standards for interoperability, privacy, and industry-specific applications in virtual worlds.

2) Remove barriers so that more European buyer and provider stakeholders can participate in standardization processes.

3) Build awareness campaigns to highlight the benefits of standards and strengthen their adoption in industry.

4) Require that standards be approved only after several independent implementations have proven their practicality.

5) Improve coordination of policy and standards across EU member states, projects, and international bodies.

6) Integrate standards compliance into EU procurement and funding programs to drive demand for interoperable solutions.

7) Enhance the accessibility and transparency of existing standards and projects through improved registries.

8) Establish Europe-wide education programs on standards to train professionals and executives with hands-on practice.

9) Provide incentives and support centers for developers to facilitate easier implementation of standards.

10) Create a European clearinghouse for standards compliance offering testing and certification services.

Annex A:
Fact sheet

Study timeline: November 2024 - November 2025

Data analysed:

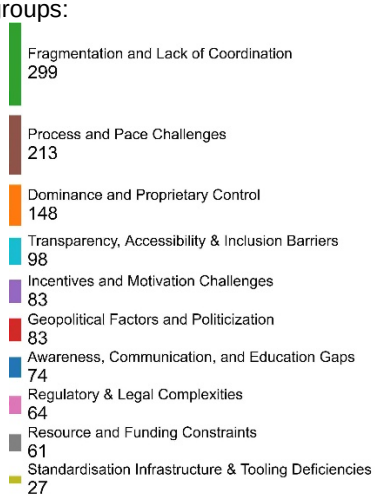
- 179 standards developing organisations, 388 standards working groups, 912 standards, 354 technical reports, 71 third-party Virtual Worlds standards landscapes, including recommendations and standardisation roadmaps, and 6 scientific publications in the combined field of standardisation for Virtual Worlds and artificial intelligence.
- 19 qualitative interviews were conducted with Virtual Worlds standardisation experts, among them 6 Virtual Worlds vendors, 5 Virtual Worlds associations, 2 academic researchers, 3 corporate researchers, and 3 general standards experts.
- 814 standards gaps, 549 structural and contribution issues, and 919 recommendations were extracted and processed.

Methodology: iterative data research, qualitative interviews, linguistic dataset analysis supported by large language models, statistical dataset analysis

Findings:

The Virtual Worlds standards gaps were clustered into nine groups and those groups sorted according to the frequency of occurrence:

The structural and contribution issues of the Virtual Worlds standardisation system were clustered into ten groups:



The recommendations for Virtual Worlds standardisation were clustered into twelve groups:

Qualitative outcomes: The standardization ecosystem is diverse and mature yet fragmented, with overlapping or inconsistent standards that confuse adopters. Cross-SDO cooperation is limited; initiatives like the Metaverse Standards Forum are promising but face structural and governance barriers. No common method exists to classify or describe standards, creating inconsistencies in terminology, structure, and traceability. Lacking structure, discoverability, and applicability tools, many standards remain underused-underscoring the need to "standardize the standards system." Infrastructure requires interoperable architectures; Data Management needs common schemas and lifecycle controls; AI requires transparency and agent interoperability; Reality Capture should align spatial digitization technologies; Human Interfaces should standardize APIs, ergonomics, and inclusivity; Immersive Experiences need ethical design and runtime interoperability; Virtual Society needs frameworks for rights, privacy, and governance; and the Virtual Economy depends on secure, interoperable ownership and transaction protocols. Shared reference models, harmonized terminology, and stronger SDO collaboration are critical to reduce fragmentation, improve discoverability, and support integration across domains. New activities should address emotion-aware systems, volumetric media, and ethical governance through interdisciplinary, research-driven approaches anticipating future demands.

Potential new research and standardisation activities: Align AI and Virtual Worlds by bridging gaps between AI standards and immersive applications (e.g. agents, personalization) through initiatives like AI x Metaverse. Develop integrated standards for geospatial-3D data (VPS), cross-reality continuity, immersive security, and next-gen input/display technologies (lightfield, 6G ISAC, WBANs). Tailor standards for sectors such as healthcare, mobility, and education, while improving user studies and benchmarking across cultures and platforms. Address socioeconomic issues by regulating crypto and digital assets, promoting energy-efficient design, balancing IP protection with openness, and advancing research on inclusion, mental health, and governance. Strengthen trust and safety with immersive-specific content moderation standards and trust frameworks to ensure accountability and user protection.

Annex B: Bibliography

- Abdelkafi, Nizar; Bolla, Raffaele; Rodriguez-Ascaso, Alejandro; Wetterwald, Michelle; Bekkers, Rudi: Understanding ICT Standardisation. Principles and Practice. ETSI: Sophia Antipolis, 2021.
- ATU Blog post May 21 2025: "ATU and the Metaverse Institute Sign Landmark MoU on African Metaverse Governance".
- Bøgh, Signe Annette (editor): "A World Built on Standards - A Textbook for Higher Education". Danish Standards Foundation: Copenhagen, 2015.
- Boyce, Jill & Dore, Renaud & Dziembowski, Adrian & Fleureau, Julien & Jung, Joel & Kroon, Bart & Salahieh, Basel & Malamal Vadakital, Vinod & Yu, Lu. (2021): "MPEG Immersive Video Coding Standard". Proceedings of the IEEE. PP. 1-16. 10.1109/JPROC.2021.3062590.
- Boyce, Jill: MPEG-I Future Directions, SMPTE 2018, 2018, pp. 1-12, DOI: 10.5594/M001830. Retrieved May 25th 2021.
- Boyd-Noronha, April; et. al: "Immersive Technology Standards for accessibility, inclusion, ethics, and safety". Special Edition Cyber XR-2020-1.0: Cyber-XR Coalition: 2020.
- Brennesholtz, Matthew. (2018). 3-1: "Invited Paper: VR Standards and Guidelines. SID Symposium Digest of Technical Papers". 49. 1-4. 10.1002/sdtp.12476.
- Bundesnetzagentur, Standardisation Activities in Quantum Technologies: Status and Perspectives, Bundesnetzagentur, Bonn, Germany, Mar. 2023.
- Chi, Cheng, Daozhuang Lin, Ramesh Ramadoss, Yu Yuan, Zihang Yin, Can Luo, Wenqu Chen, Bin Yang, Ling Wei, and Ralf Ma: "The Industrial Virtual Worlds Report". The Industrial Virtual Worlds Report, November 2023, 1-20.
- Coors, Volker: OGC Interoperable Geodaten für Simulation und Gaming; Geo & Games @ Game Days 2021, Hochschule für Technik, Stuttgart, Germany: May 27th 2021.
- Council of Europe: "The metaverse and its impact on human rights, the rule of law and democracy". Strasbourg, France, 2024.
- Council of the European Union: Metaverse - Virtual Worlds, Real Challenges; Council of the European Union; Brussels, Belgium: March 2022.
- Cox, Shereen; Svarverud, Ellen; Adams, Jonathan, et al.: XR4Human: "D2.1: Mapping of the ethical Issues in XR-overview of Ethical Frameworks: A Scoping Review", XR4Human Consortium Feb 25 2023.
- Cozzi, Patrick; Lille, Sean: 3DTiles NEXT. November 2024: Dec 6, 2021.
- Deakin, Ian; Figueredo, Ken: "In Anticipation of Metaverse Standardisation", ATIS: March 7th, 2023.
- Dosch, Christoph; Oliphant, Andrew; Neudel, Ralf: Annex to NEM SRA v7: Relevant Standardisation bodies for NEM research topic - Strategic Research Agenda "Networked and Electronic Media" European Technology Platform.; NEM Networked & Electronic Media Initiative: Brussels, November 2009.
- Dropmann, Ulrich: NOKIA Building the Metaverse. Standards and Policies. HLIG: Open Forum on Governance of Virtual Worlds, April 23rd, 2024.
- ETSI GR ARF 001 (V1.1.1): "Augmented Reality Framework (ARF); AR standards landscape".
- ETSI GR ARF 002 (V1.1.1): "Augmented Reality Framework (ARF); Industrial use cases for AR applications and services".
- ETSI GR ARF 007 (V1.1.1): "Augmented Reality Framework (ARF); Standards landscape for ETSI AR Functional Reference Model".

- European Commission: "An EU initiative on Web 4.0 and Virtual Worlds: a head start in the next technological transition".
- European Commission: European Citizens' Panel on Virtual Worlds. Final Report. April 2023.
- European Commission: "Next Generation Virtual Worlds: Societal, Technological, Economic and Policy Challenges for the EU", Brussels, Belgium: 2023.
- European Commission: Rolling Plan for ICT Standardisation: "Web 4.0 and Virtual Worlds".
- European Parliament: Metaverse Opportunities, risks and policy implications. European Parliament, Strasbourg: June 2022.
- European Parliament: Virtual Worlds Opportunities, risks and policy implications; European Parliament, Strasbourg: June 2022.
- Fraunhofer IPT: Standards für Augmented-Reality-Anwendungen in der Produktion. In: Virtual Reality Magazin; retrieved May 25th 2021; Vaterstetten, Germany: August 4th 2020.
- Görlich, Daniel; Akincir, Tayfun; Meixner, Gerrit (2022): An Overview of User Interface and Interaction Design Patterns for VR, AR, and MR Applications. Mensch und Computer 2022 - Workshopband. DOI: 10.18420/muc2022-mci-ws06-419. Bonn, Germany: Gesellschaft für Informatik e.V.. MCI-WS06: Augmenting Usability Evaluation. Darmstadt, Germany: September 4th -7th 2022.
- Green, Lloyd / IEEE Standards Association: Standardisation Needs and Efforts in Virtual Reality/Augmented Reality; presentation at Augmented World Expo USA 2017, Santa Clara, California May 31- June 2, 2017.
- Gutiérrez, Jesús; Pérez, Pablo: VQEG. An Overview on Standardisation for Social XR. Spring School Social XR, Politécnica de Madrid; Madrid, Spain: April 4th 2023.
- Hong, Jungha; Sang, Ziqin; Kipssaita, Stella; Anthopoulos, Leonidas: "ITU Focus Group on metaverse (FG-MV)". FGMV-52 Metaverse standardisation landscape for gap analyses. International Telecommunications Union (ITU): Geneva, Switzerland, June 2024.
- IEC TR 63308:2021: "Virtual reality equipment and systems - Market, technology and Standards requirements", Nr. 63308; Oct. 2024; IEC: London, UK: July 9th 2021.
- Institute of Electrical and Electronics Engineers (IEEE™), The IEEE™ Global Initiative on Ethics of Extended Reality (XR) Report-Business, Finance, and Economics, Ethics-Economics. IEEE™, Piscataway, New Jersey, USA: 30th March 2022.
- Institute of Electrical and Electronics Engineers (IEEE™): Augmented Reality Directions and Standards. Industry Connections Activity Initiation Document (ICAID). IEEE™, Piscataway, USA: March 2014.
- Int.net Interoperability Network for the Energy Transition: Evolution of Interoperability Standards. Int.net Consortium 2023 https://intnet.eu/.
- Int.net Interoperability Network for the Energy Transition: Information Models Coordination and Governance: Standardisation Recommendations.
- Int:net and AIOTI, Information Models Coordination and Governance: Standardisation Recommendations, Draft Report, November 2024.
- Jung, T et al., February 2024: "Metaverse for service industries: Future applications, opportunities, challenges and research directions".
- Kadlubsky, Alina; Kumar, Sathiya; Salazar, Mikel: XR4HUMAN. D4.1: D4.1: "Map existing and emerging requirements for interoperability in XR and Spatial Computing". Project XR4Human (grant Agreement no.: 101070155), Brussels: 31.10.2023.
- Krause, Susanne (Fraunhofer IPT): Standards für Augmented-Reality-Anwendungen in der Produktion. In: Virtual Reality Magazin, 4 Aug 2020.

- Kung, Antonio: CEI Tech backbone Toolkit for Open Edge Ecosystem by Holistic Assurance Framework. CEI-Sphere Internal Presentation, January 3, 2025.
- Ladikas, Miltos; Madeira, Octavia; Hahn, Julia; et al.: XR4HUMAN. D3.1: State-of-art in XR policy debates. Project XR4Human (grant Agreement no.: 101070155), Brussels: April 30 2023.
- Lang, Michael; Schneider, Jörg; Hemberger, Klaus: Metaverse. Status, Perspektiven für die Standardisierung und Regulierung, Internal Report 2023.
- ISO/IEC JTC 1: "JTC 1 Standards and Standardisation for the Metaverse", Lee, M. W. et al., Aug. 21, 2023.
- Lee, M. W. et al., White Paper: Guidelines for Developing VR and AR Based Education and Training Systems. ISO/IEC JTC 1, VR AR for Education Ad Hoc Group, Aug. 12, 2019.
- Lee, M. W. JTC 1/SC 24 Standards and Projects for the Metaverse, presented at ISO/IEC Workshop: Standards for the Metaverse, ISO/IEC, Geneva, Switzerland, Jun. 26, 2023.
- Lee, Sungyoung. Khan, Wajahat Ali; Hussain, Jamil; Ali, Bilal; Satti, Fahad Ahmed: "Standards for usability/UX evaluation process of VR/MAR contents," presented at the ISO/IEC JTC 1/SC24 WG9 & Web3D Meetings, Seoul, Korea, January 24, 2019.
- McGarr, Tim / British Standards Institution; Boreham, Michael / Futuresource Consulting Ltd: The Requirement for Standards in the VR and AR Sectors. British Standards Institution (BSI), London, UK: March 2018.
- McWilliams, G.; et. al.: "Shaping the Metaverse: policy engagement with immersive technologies in the UK, Queen's University Belfast, Belfast, UK: December 3rd 2024.
- Metaverse Standards Forum 2024 annual report.
- Metaverse Standards Forum: Metaverse Autonomous Agent (agentic AI) Support Use Case and Interop Requirements January 8 2025.
- Mirt, Jernej: "Standardisation Could Be A Major Problem For Virtual Reality"; Medium: April 18th 2016.
- Open Geospatial Consortium: OGC Standards Roadmap.
- OpenVerse Consortium: An Augmented Summary of the First Workshop of the Series: "Foresighting the Technologies and Co-Factors that May Shape the Future of Virtual Worlds and the Web 4.0" April 2025.
- Penczek, John: Medical Extended Reality Summit. Overview of Visual Performance Standards for Virtual and Augmented Reality. 2024 Medical Extended Reality Summit; College Park Marriott Hotel & Conference Center, Hyattsville, Maryland, USA: April 16th-17th, 2024.
- Perey, Christine: Enterprise AR Interoperability and Standards Webinar. Augmented Reality Enterprise Alliance AREA: Oct. 9th 2019, retrieved May 25th 2021.
- Perey, Christine: Enterprise Augmented Reality Vision, Interoperability Requirements, and Standards Landscape, EPRI Electric Power Research Institute: Program on Technology Innovation; EPRI, Palo Alto, USA: May 2017.
- Price, Antoinette: The role of international standards in virtual education and training systems. In: e-tech News & views from the IEC. International Electrotechnical Commission, Geneva, Switzerland: June 1st 2020.
- RH Nuttall blog post March 2025: "The Five Largest Manufacturing Sectors in the EU: Growth Trends & Challenges".
- Runde, C.: Global Monitor for XR and Virtual Worlds standards, specifications, guidelines and recommendations; XR EXPO, Stuttgart, April 4th 2024; Virtual Dimension Center (VDC): Fellbach, Germany: 2024.
- Runde, C.: Normung und Regulierung für eXtended Reality und das Virtual Worlds. In: 16. Security Forum der TH Brandenburg: "Virtual Worlds und Security"; Brandenburg, 18.1.2024; Technische Hochschule Brandenburg: 2024; DOI: 10.6084/m9.figshare.25027862.

- Runde, C.: XR Standardisation - The status quo and path ahead of us, in Proceeding of the 2023 IEEE International Conference on Metrology for eXtended Reality, Artificial Intelligence and Neural Engineering, Milan, Italy; IEEE™, October 2023.
- Runde, C.: XR-Standardisierungslotse: Die Zukunft gestalten. V/AR-Standards mitbestimmen und mitentwickeln durch Mitwirkung in aktiven Arbeitsgruppen. Virtual Dimension Center: Fellbach, Germany: April 11th 2023.
- Runde, C.: XR-Standardisierungslotse: Strukturiert und standardisiert V/AR-Lösungen einsetzen und entwickeln - Best Practices nutzen: XR-Management-Standards. Virtual Dimension Center: Fellbach, Germany: April 11th 2023.
- Runde, Christoph: Applikationszentrum V/AR. Bericht #24. Anwender-Hersteller-Dialog: Positionspapier V/AR-Standardisierung: Status Quo und Bedarfe; Virtual Dimension Center (VDC): Fellbach, Germany: May 31st 2021, DOI: 10.6084/m9.figshare.14909928.
- Runde, Christoph: The eXtended Reality & Metaverse Standards Register and Regulation Issues; In: oneM2M Partnership Project: oneM2M Technical Plenary 63; Bundesnetzagentur: Mainz, Germany: February 28th 2024.
- Runde, Christoph: XR & Virtual Worlds Standardisation. A Global Overview. In: EU VR/AR Industrial Coalition: Online workshop of the VR/AR Industrial Coalition; Brussels, Belgium: September 27th 2024.
- Schreer, Oliver; et al.: "XR4All Revised Landscape Report 2020". XR4All Consortium; Brussels, Belgium: 2020.
- Shim, Kyu-Won: Medical 3D Printing Scanning and Standards Requirements. In: ISO/IEC JTC 1/SC24 WG9 & Web3D Meetings, Seoul, Korea: 24th January 2019.
- Standards Australia: "The Metaverse and Standards", November 2022.
- StandICT. EUOS EU Observatory for ICT Standardisation; retrieved Feb 2025; StandICT.eu 2026 project; Brussel, Belgium: 2024.
- Stockhammer, Thomas: MPEG Immersive Media. MP20 Standardisation Roadmap. In: International Telecommunication Union, ITU-T Study Group 16 Meeting, Geneva, 16-27 January 2017. Geneva: January 19th 2017.
- Timmerer, Christian: Immersive Media Delivery: Overview of Ongoing Standardisation Activities. IEEE Communications Standards Magazine, New York, USA: December 2017.
- Timmerer, Christian: MPEG Standardisation Roadmap, ISO/IEC JTC1 SC29/WG11 MPEG, 122nd meeting, San Diego, CA, USA, Doc. N17506, April, 2018.
- Vogel, Uwe: Eyewear Display Standardisation; Fraunhofer Institute for Organic Electronics, Electron Beam and Plasma Technology FEP, 01109 Dresden, Germany: February 8th 2019.
- Wajahat, Ali Kahn; Lee, Sung Ryong; Kim, Gerard: Standards for usability/UX evaluation process of VR/MAR contents. In: ISO/IEC JTC 1/SC24 WG9 & Web3D Meetings; retrieved May 25th 2021, Seoul, Korea: January 24th 2019.
- Wien, Mathias; Boyce, Jill M.; Stockhammer, Thomas; Peng, Wen-Hsiao: Standardisation Status of Immersive Video Coding. In: IEEETM Journal on Emerging and Selected Topics in Circuits and Systems, volume: 9, Issue: 1, pp. 5 - 17: March 2019.
- Won Lee , Myeong: JTC 1/SC 24 Standards and Projects for the Virtual Worlds. ISO/IEC Workshop: Standards for the Virtual Worlds; ISO-IEC, Geneva, Switzerland: June 26th 2023.
- Won Lee , Myeong; et. al.: Virtual Worlds. JTC1 Technology Trend Report. International Organization for Standardisation (ISO); Geneva, Switzerland: 2024.
- Won Lee, Myeong; et al.: JTC 1 Standards and Standardisation for the Virtual Worlds; retrieved Nov. 2024; Geneva, Switzerland: August 21st, 2023.

- Won Lee, Myeong; et al.: White Paper. Guidelines for Developing VR and AR Based Education and Training Systems. ISO/IEC JTC 1/VR AR for Education Ad Hoc Group; ISO/IEC: August 12th 2019.
- World Economic Forum: Interoperability in the Virtual Worlds. Briefing Paper January 2023; Davos, Switzerland: 2023.
- Yan, Yu and Korbert, Charlotte. Shaping the technology roadmap of Virtual Reality (VR) and augmented reality (AR). Challenges and standardisation needs. IEEE Digital Senses, May 26th 2017.

History

Version	Date	Status
V1.1.1	November 2025	Publication