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GROUP REPORT

Augmented Reality Framework (ARF); Virtual World Standards Landscape Report

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Foreword

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

The present document provides a deep analysis of standards and standardization activities conducted in various Standards Development Organizations (SDOs) and other fora, as available at the time of publishing. The analysis is performed on all public information about standardization activities that impact development of virtual world technologies and the creation of value using these technologies, including enabling technologies, components, services and human interface systems and devices. It also examines standards that address challenges common across all types of virtual worlds including transactions, governance, cybersecurity and privacy.

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).

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Executive summary

The present document aims at providing a landscape of standardization activities in the field of Virtual Worlds. Providing the current status of virtual world standardization activities in a public resource such as the present document and its supporting materials can increase general understanding of virtual world technologies in the context of the general technology lifecycle where innovation often proceeds in tandem with standardization and through collaborations between diverse stakeholders of an ecosystem, as defined in [i.9] and [i.10]. It also serves as input to the EC's 2026 Rolling Plan for ICT standardisation [i.11].

After introducing the scope of virtual worlds and purpose of the research, the present document describes the current trends underpinning the emergence of virtual worlds. The following clauses present details about interoperability standards, working groups and standards development organizations focusing on technology in eight domains, based on analyses performed on the largest data set about virtual world standards and standardization activities compiled to date.

This standards landscape and the analyses conducted in its preparation demonstrate that many stakeholders have recognized the need to define interfaces and protocols for virtual worlds interoperability. Hundreds of standards designed to overcome virtual world interoperability obstacles have been published. However, independent research based on the data set associated with the present document and this landscape [i.12] also reveals that companies most heavily invested in the potential rewards from the success of virtual worlds have rarely implemented interoperability standards in their products, tools or services.

Introduction

For the purpose of strong alignment with European Commission (EC) policies and communications, the terms "virtual worlds," as defined in clause 3.1, or "virtual world technologies" to include all enabling technologies, are used throughout the present document except in the following cases:

- the legal or official title of an entity includes "metaverse";
- the authors of a published document or paper use "metaverse" in the title or text of their work;
- the title or summary of a working group or activity uses "metaverse."

Virtual world technologies provide access to and interactive experiences for users within persistent, 3D environments. Delivered using augmented, virtual or mixed reality human interfaces, virtual world experiences blur real and synthetic spaces and objects enhancing and enriching in new and unpredictable ways the daily lives of people while they are socialising, working, learning, making transactions, playing and engaging in creative activities. As described in the EC's Communication COM(2023) 442 "An EU initiative on virtual words" [i.13], an economically productive ecosystem of innovative European stakeholders will build upon the convergence of advanced technologies (e.g. AI, 5G/6G, IoT, etc.) to deliver persistent 3D real-time immersive environments.

An interconnected virtual world ecosystem may offer many economic and societal benefits [i.14]. However, there are also many challenges to overcome before the promise of virtual worlds can be delivered at scale [i.15]. Recognizing that, to flourish, the virtual world ecosystem will need support from the public sector to balance their investments with reasonable levels of risk, the European Commission has embarked on numerous actions focusing on virtual worlds. For high innovation and return on investment, there also needs to be integration with existing technology and opportunities for collaboration across the ecosystem. Further, when virtual world technology providers agree on protocols interfaces or policies where data (including metadata) will be protected and under user control, virtual worlds will be fit for people [i.16]. Interoperability standards will also permit data interchanges between virtual worlds without loss or compromise of information or value [i.17], [i.18].

Low interoperability between virtual world components, tools, services and content is recognized as a major obstacle to integration and the creation of new value through collaboration between virtual world stakeholders [i.12]. In addition to interoperability, for businesses and people to engage in virtual world economies, the technologies that they adopt will also need to ensure security for protection of privacy and other fundamental rights. Prior to raising its investments in actions to increase interoperability, security and privacy for virtual world users, the EC seeks a comprehensive, objective assessment of available standards. Standards and standardization activities for the development of a healthy virtual world ecosystem are the focus of the research conducted for the present document. The results are provided in the present document.

1 Scope

The present document provides a comprehensive assessment and analysis of 912 standards and 354 technical reports about virtual worlds domains compiled as of February 14, 2025. The documents pertain to one or more of eight virtual worlds subject matter areas ("domains"), as these are defined in the present document.

In addition to analysing the documents, the project also studied the most relevant working groups and the standards development organizations in which members of these working groups conduct their activities. The present document includes summaries of working group activities and, based on publicly available attributes, compares the different virtual world standardization activities to date.

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] ISO/IEC 12113:2022: "Information technology — Runtime 3D asset delivery format — Khronos glTF™ 2.0".

[i.2] ISO/IEC 27001: "Information security, cybersecurity and privacy protection — Information security management systems — Requirements".

[i.3] ISO/IEC 60601: "Medical electrical equipment".

[i.4] ANSI/CAN/UL 8400: "Virtual Reality, Augmented Reality and Mixed Reality Technology Equipment".

[i.5] ISO/IEC Guide 2:2004: "Standardization and related activities - General vocabulary".

[i.6] ISO/IEC Directives, Part 1 (clause 2): "Procedures for the technical work — Consolidated ISO Supplement — Procedures specific to ISO".

[i.7] ISO 26324: "Information and documentation — Digital object identifier system".

[i.8] ISO 10303: "Industrial automation systems and integration — Product data representation and exchange".

[i.9] ISO R&I Papers: "Standards and innovation - What does the research say?", January 2022.

[i.10] Technological Forecasting and Social Change, Volume 153, Markard, J.: "The life cycle of technological innovation systems", April 2020.

[i.11] European Commission 2026: "Rolling Plan for ICT standardisation 2026".

[i.12] PEREY Research & Consulting: "Analysis of Commercial Implementations of Metaverse Standards", June 2025.

[i.13] European Commission's Communication COM(2023) 442: "An EU initiative on Web 4.0 and virtual worlds: a head start in the next technological transition".

[i.14] Council of the European Union, General Secretariat of the Council: "Metaverse - Virtual world, real challenges", Publications Office of the European Union, 2023.

[i.15] Hupont Torres, I., Charisi, V., De Prato, G., Pogorzelska, K., Schade, S. et al.: "Next generation virtual worlds - Societal, technological, economic and policy challenges for the EU", Publications Office of the European Union, 2023.

[i.16] European Commission: "Virtual Worlds fit for people", 2023.

[i.17] N. Abdelkaf, R. Bekkers, R. Bolla, A. Rodriguez-Ascaso, M. Wetterwald: "Understanding ICT Standardization: Principles and Practice", ETSI, 2021.

[i.18] European Commission: "Embracing open standards for open data: The ecosystem of interoperability across Europe", June 2024.

[i.19] European Commission: "Fact Pages - Virtual Worlds", 2024.

[i.20] European Commission: "Common European Data Spaces", July 2025.

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 world environments and experiences

NOTE: Effective data management underpins the functionality, scalability, and ethical operation of virtual world 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 standard: publication approved by membership of and released by an industry-driven standards development organization

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

NOTE: Members of industry-driven standards development organizations include but are 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.

industry-specific standards: standards that are developed to meet the specific requirements of an industry such as healthcare, automotive, manufacturing or military simulation

infrastructure: foundational systems, technologies, and frameworks that enable the seamless operation, scalability of and interactivity within virtual world 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 standardization 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.

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

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, operate 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: persistent, immersive environments based on 3D and Extended Reality (XR) technologies

NOTE 1: The definition is based on that which is provided by the European Commission [i.19].

NOTE 2: They encompass a wide range of digital experiences, from fully immersive virtual worlds to augmented reality overlays on the physical world.

NOTE 3: 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
5G	Fifth Generation communication technology
5G-MAG	5G Media Action Group
6G	Sixth Generation communication technology
ADA	App Defense Alliance
AI	Artificial Intelligence
AIMS	Alliance for IP Media Solutions
ANAB	ANSI National Accreditation Board
ANEC	European Association for the Coordination of Consumer Representation in Standardisation
ANSI	American National Standards Institute
AOUSD	Alliance for Open USD
API	Application Programming Interface
AR	Augmented Reality
ASAM	Association for Standardization of Automation and Measuring systems
ASF	Apache Software Foundation
ASTM	Advancing Standards Transforming Markets
ASWF	Academy Software Foundation
ATIS	Alliance for Telecommunications Industry Solutions
BDSV	Big Data Service Virtualization
BF	Broadband Forum
BIM	Building Information Modelling
BSI	British Standards Institution
C2PA	Coalition for Content Provenance and Authenticity
CCPA	California Consumer Privacy Protection Act
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
CES	Consumer Electronics Show
CESI	Chinese Electronics Standardization Institute
COM	Communication by the European Commission
COPPA	Children Online Privacy Protection Act
CORBA	Common Object Request Broker Architecture
CSA	Cloud Security Alliance
CSS	Cascading Style Sheets
CTA	Consumer Technology Association
DAO	Decentralized Autonomous Organizations
DASH	Dynamic Adaptive Streaming over HTTP
DCC	Digital Credentials Consortium
DeFi	Decentralized Finance
DICOM	Digital Imaging and Communications in Medicine
DID	Decentralized Identifier
DIF	Decentralized Identity Foundation
DIN	Deutsches Institut für Normung
DKE	Deutsche Kommission Elektrotechnik Elektronik Informationstechnik im DIN und VDE
DOA	Digital Object Architecture
DOI	Digital Object Identifier
DOIF	Digital Object Identifier Foundation
DONA	Digital Object Number Authority
DRM	Digital Rights Management
DTC	Digital Twin Consortium
DVB	Digital Video Broadcasting
ECMA	European Computer Manufacturers Association
EIDR	Entertainment Identifier Registry association
ELF	Express Language Foundation
EMVA	European Machine Vision Association
EPC	Energy Performance Certificate
EPRI	Electric Power Research Institute

ETSI	European Telecommunication Standards Institute
EU	European Union
EUOS	European Observatory for ICT Standardisation
FGMV	Focus Group on Metaverse
FIWARE	FIWARE Foundation
GDPR	General Data Protection Regulation
GHBMC	Global Human Body Models Consortium
glTF	graphics Library Transmission Format
GML	Geographic Markup Language
GPS	Global Positioning System
GPU	Graphics Processing Unity
GS1	Global Standards 1
GSM	Global System for Mobile Communications
GTAMG	Global Tech Advocates Metaverse Group
HEVC	High Efficiency Video Coding
HFES	Human Factors and Ergonomics Society
HIF	Haptics Industry Forum
HIPAA	Health Insurance Portability and Accountability Act
HL7	Health Level Seven International
HSI	Healthcare Standards Institute
HTML	Hypertext Markup Language
IAB	International Advertising Bureau
ICAID	Industry Connections Activity Initiation Document
ICHOM	International Consortium for Health Outcomes Measurement
ICT	Information and Communication Technology
IDEA	Immersive Digital Experiences Alliance
IDS	International Data Space
IDSA	International Data Spaces Association
IDTA	Industrial Digital Twin Association
IEA	International Ergonomics & human factors Association
IEC	International Electrotechnical Commission
IEEE™	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IFC	Industry Foundation Classes
IIoT	Industrial Internet of Things
IOF	Industrial Ontology Foundation
IoT	Internet of Things
IP	Internet Protocol
ISA	International Society of Automation
ISO	International Standards Organization
ITU-T	International Telecommunications Union
JPEG	Joint Photographic Experts Group
JTC	Joint Technical Committee
JTC1	Joint Technical Committee 1
LF	The Linux® Foundation

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

M2M	Machine-to-Machine
MIIT	Chinese Ministry of Industry and Information Technology
MIPI	Mobile Industry Processor Interface Alliance
MIT	Massachusetts Institute of Technology
MML	Metaverse Markup Language
MPAI	Motion Picture, Audio, Data Coding by Artificial Intelligence
MPEG	Motion Picture Experts Group
MPEG-I	Motion Picture Experts Group - Interactive
MR	Mixed Reality
NATO	North American Treaty Organization
NEM	New European Media initiative
NEMA	National Electrical Manufacturers Association
NFT	Non-Fungible Tokens
NGSI	Next Generation Service Interfaces

NIST	National Institute of Standards and Technology
NLP	Natural Language Processing
NPC	Non-Playable Characters
NQF	National Quality Forum
NSO	NATO Standardization Office
O3DF	Open 3D Foundation
OARC	Open AR Cloud Association
OASIS	Organization for the Advancement of Structured Information Standards
OGC	Open Geospatial Consortium
OIDF	OpenId Foundation
OMA	Open Mobile Alliance
OMA3	Open Metaverse Alliance for Web3
OMF	Open Metaverse Foundation
OMG	Object Management Group
OMI	Open Metaverse Interoperability Group
OSVR	Open Source Virtual Reality
OWASP	Open Worldwide Application Security Project
P2E	Play-to-Earn
QoE	Quality of Experience
RAN	Radio Access Network
RFID	Radio Frequency Identification
RMA	Responsible Metaverse Alliance
SAC	Standardization Administration of China
SAE	Society of Automotive Engineers
SAML	Security Assertion Markup Language
SDO	Standards Development Organization
SID	Society for Information Display
SISO	Simulation Interoperability Standards Organization
SMPTE	Society of Motion Picture and Television Engineers
STEP	Standard for Exchange of Product Model data
SVTA	Streaming Video Technology Alliance
SWF	Spatial Web Foundation
TIA	Telecommunications Industry Association
TIFCA	The International Future Computing Association
TMF	TeleManagement Forum
ToIP	Trust over IP Foundation
TOSCA	Topology and Orchestration Specification for Cloud Applications
TTA	Telecommunications Technology Association
UBL	Universal Business Language
UDP	User Datagram Protocol
UHD	Ultra High Definition
UL	Underwriters Laboratory
UML	Unified Modelling Language
UN	United Nations
VDA	Verband Der Automobilindustrie
VDC	Virtual Dimension Center
VDE	Verband der Elektrotechnikm Electronik and Informationstechnik
VDI	Verein Deutscher Ingenieure
VESA	Video Electronics Standards Association
VFA	Volumetric Format Association
VQEG	Video Quality Experts Group
VR	Virtual Reality
VRM	VRoid Model
VSF	Video Services Forum
VWS	Virtual World Society
W3C®	World Wide Web Consortium
WBA	World Broadband Association
WCAG	Web Content Accessibility Guidelines
WFS	Web Feature Service
WIPO	World Intellectual Property Organization
WMS	Web Map Service
XML	eXtensible Markup Language

XR	eXtended Reality
XRA	eXtended Reality Association
XRSI	eXtended Reality Safety Intelligence

4 Emerging Virtual Worlds

4.1 Enabling technologies are maturing

Virtual worlds have been developing in the public imagination for decades. From science fiction books and motion pictures to platforms and mobile applications, the vision of alternate realities for exploration, business, leisure and education has fuelled investment in many generations of technology innovation. These innovations have delivered a suite of enabling technologies:

- Powerful programmable processors.
- Ubiquitous connected spaces and devices.
- Microscopic, low power sensors.
- High-speed networks.
- Artificial Intelligence.
- Optical components, controller devices and tracking for immersive human interface systems.
- Secure, scalable systems for transactions.
- Distributed information technology architectures to deliver content to users in real time and many more.

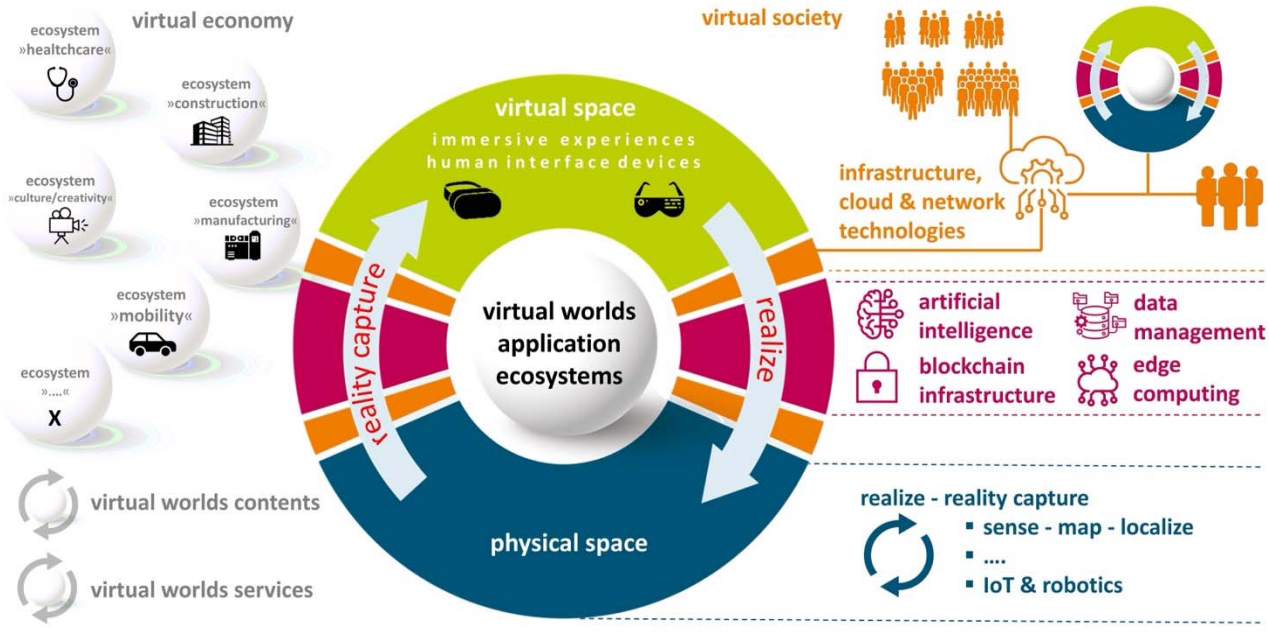

Figure 1: Enabling technologies contribute to development and delivery of virtual world experiences

Figure 1 shows how the many diverse technologies upon which virtual world stakeholders are building interlock. To deliver new experiences and create value in virtual society and virtual economies, there is a continuously spinning cycle of innovation and commercialization. As the building blocks for the virtual world industry, the enabling technologies on the right side of the figure are evolving at different rates; all are receiving investment to drive innovation and reduce their costs. Many research and development projects are actively developing new hardware and software with which to integrate these technologies and open new frontiers for their utilization at the centre of the figure.

Each generation of virtual world technology improves upon its predecessors.

EXAMPLE: Microsoft® introduced HoloLens® for enterprise augmented reality in 2015, shortly after the acquisition of OculusVR by Facebook®, and, based on newer and more mature enabling components, it released HoloLens2 four years later. Facebook (now Meta®) has regularly released advances in its Quest® display, making them more powerful, lighter and more affordable with each generation.

The Covid-19 pandemic, during which people and employees were isolated from one another, brought a surge of new investments and the pace of technological innovation focusing specifically on reaping the benefits of virtual world technologies accelerated significantly. In the past five years, companies in many sectors have accelerated experimentation with and deployment of virtual world-enabling technologies and using virtual worlds. The large technology provider companies have continued to invest in improvement of enabling technologies, leading to benefits such as reduced power consumption and size, higher mobility and increased performance.

When, in late 2021, Facebook® renamed itself to Meta Platforms and revealed its plans to focus more of its research and development efforts on metaverse capabilities, many other large technology companies paid attention. Some followed the trend. There was an explosion of activity focusing on virtual worlds and metaverse technologies. In mid-2023, as AI began to receive greater attention from executives and strategists, investments in virtual world slowed, however, it continues. After much anticipation, in 2024, Apple® introduced their Apple VisionPro® extended reality display and tools for developing experiences for its users. During the industry correction and shift in emphasis to AI, many virtual world industry provider segment stakeholders decided to change their investment strategies and reduce their activities in virtual worlds technology (e.g. Microsoft announced it would no longer be providing HoloLens, Magic Leap® changed its business model to technology licensing, numerous small companies developing virtual world software filed for bankruptcy or pivoted to AI topics). While the leading technology companies no longer focus as much on virtual world products and services as before, in 2025 they continue to invest heavily in enabling technologies and tools to accelerate the development of virtual worlds.

4.2 Virtual world standardization efforts follow

4.2.1 Introduction

In parallel with the maturation of enabling technologies and introduction of new virtual world and immersive displays between 2015 and 2025 other trends are apparent. One of the trends is the development of consensus-based standards. Before examining trends, the present document explains how standardization and standards are defined for the project. The project adopts the ISO/IEC Guide 2:2004 [i.5], definition of standardization as the "establishment, in order to address actual or potential problems, of provisions for common and repeated use, aimed at the achievement of the optimum degree of order in a context". Consensus, while not directly addressed in the definition of standardization, is one of the critical principles for a group to be considered a standards development organization in the research conducted for this project. Consensus in a standards development body requires the resolution of substantial objections, is an essential procedural principle and a necessary condition.

For standardization activities to reach their objectives, the ISO/IEC Directives Part 1 [i.6], states that the members of a group have demonstrated competence and expertise in the domain of the standard, and that to be considered successful in their aim, the results will be widely recognized and generally applied. To be applied or "adopted" using the language of standardization communities, standards need to fulfil a need, be impartial, clear, accurate and unambiguous. If very few companies, or only a fraction of the target community for a standard adopts a standard, then the objective of the working group (and the value of a standard to increase interoperability) is not met.

The goal to develop virtual world interoperability standards is not a new one. Driven largely by research and academic laboratories in the beginning, it can be traced back to the 1980s.

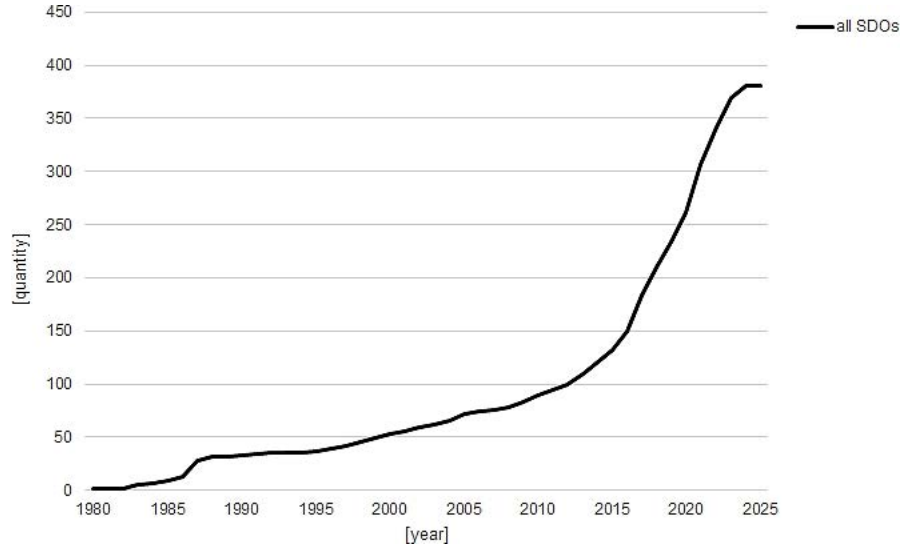

Figure 2: Number of Virtual World Standards Working Groups initiated (accumulated from 1980-2025)

Figure 2 shows that as early as 1983 (at least 30 years prior to introduction of commercial immersive technology displays suitable outside of a laboratory) some SDOs were establishing virtual world standards working groups. These activities were driven by corporate and academic research groups until, in 2000, there began to be increased interest from industry. This activity, as measured by the number of new standards working groups created for the purpose of developing virtual world standards, increased significantly around 2015. In the period between 2020 and 2024 there has been a rapid proliferation of new working groups created on virtual world standards. In 2015, there were approximately 100 standards working groups focusing on virtual world interoperability. By 2020, there were 200 and, in 2024, there were nearly 380 that had been initiated. Not all remained active over the 40-year period. Many of the standards development projects started by research groups in the early phase of this trend were closed or merged so it is incorrect to suggest (and the data set does not reflect) that there are 380 active standards working groups today.

While it is not possible to fully analyse the reasons for standards development groups stopping their activities, several factors have contributed in the past and continue to be issues preventing the fulfilment of the goals of virtual world standardization activities in many working groups.

4.2.2 Low collaboration

One factor that consistently reduces the impact of standards for virtual worlds is low coordination and collaboration between standards development organizations actively pursuing the same objectives. While examples of working groups doing their due diligence and identifying virtual world standards in advance of developing their new standards exist, and collaboration can be done through liaisons and other tools, the pattern observed in this research project is of competition more than collaboration between working groups and standards development organizations.

One reason for this tendency is simply due to lack of awareness. New standardization activities initiated within some SDOs are not promoted outside the SDO by its standards working group or technical committee. Even when announcements are made to members, the policies of some internationally mandated SDOs only permit member states vote to approve or decline the creation of new work items. Finally, if and when standards development groups begin their work, there is little to no visibility regarding who is contributing so those outside the group itself do not know anything regarding the process. These factors discourage collaboration and increase the likelihood of two or more groups working on the same or similar requirements.

One reason for some lack of transparency in some standardization activities is the business model of the SDO. If an SDO's business model is to generate operating revenues from the sale of its standards, it cannot also release the working group's assets. Another reason that some groups keep tight control over their work has to do with the risk of a member intentionally or unintentionally introducing intellectual property that encumbers the final standard. To reduce the risk of inadvertently including IP in a standard and resulting in unanticipated liabilities, SDOs can, and generally speaking do, impose strict policies on what and how contributions are made to a document.

These are factors that are more noticeable in the large internationally mandated SDOs than in industry-driven SDOs.

4.2.3 Low industry participation

Many standards working groups in the data set for this project began forming before the virtual world technologies had stabilized (had not reached technology readiness levels above 5 or 6). Some can argue that they have not stabilized to date and will not be mature (and ready for useful standardization activities to be adopted) for decades. The data set does not provide this type of forward-looking information.

New standards working groups focusing on virtual worlds began to be established with these requirements on their formation documents as early as the 1980s. Then new projects conducted by leading technology companies with large customers in various industry and the lessons acquired from the re-introduction of VR into homes and facilities between 2011-2015, identified many new interoperability requirements. By 2015 and in the decade since, these (and pre-existing) standardization groups had driven the establishment of dozens of new standardization projects each year to address the perceived future virtual world interoperability requirements.

Unfortunately, demand from customers for the early generation virtual world products is low. The slower-than-anticipated pace of virtual world technology adoption reduced the financial incentives for companies to invest in innovations to drive virtual world projects. As a result of competing business priorities, numerous virtual world standards have been published without the engagement of two critical stakeholder groups of the virtual world ecosystem: the end customers and those who build and sell virtual world products and services to the end customers. These virtual world stakeholders have been reluctant to date to disclose or document their true and full requirements or activities (conducted in isolation). For the end customers of virtual worlds, their attention is focused on trying to make everything work. When asked which standards a company supports, one end customer decision maker replied with another question: which is more important: technologies that work to increase value, improve the company's bottom line and reduce risks or technologies that interoperate? Both goals will need to be achieved if virtual worlds are to be successful.

Without the active involvement of all segments of the virtual world ecosystem, requirements are unclear and validation of new interoperability standards, such as their adoption by companies or agencies adopting virtual worlds, has not been possible. While people have tried using virtual worlds in their homes and enterprise customers have begun numerous pilot projects and demonstrated hundreds of proof-of-concept projects, the vendors building and selling virtual world products and services continue to focus on securing and holding the largest market share. The most common approach for gaining and retaining their market share is to keep the customer using a closed technology silo. The end customers' frustrations with immature technological solutions and the vendors' reliance on closed, proprietary technologies have contributed to many standardization activities lacking real world implementations and validation. This issue is not resolved for many standardization activities, but there have been some successes.

4.2.4 Notable exceptions

A few notable exceptions to this rule need to be highlighted. First, in the domain of infrastructure technologies, standardization activities in SDOs recognized by governments (the internationally mandated SDOs) and the adoption of standards for communications networks is higher than in any other virtual world domain. This trend is a direct reflection that, for communications to be productive outside of one network, networks connect data and people with one another. This basic principle has been proven early in the telephony era and repeatedly demonstrated with the internet and Web eras. This exception is also relatively well established in data management domain due to the need for data interchanges in industrial use cases (not involving people, but supporting their participation if and when immersive technologies are integrated).

Second, there are circumstances in which an industry-driven standards group has followed guidelines of an internationally recognized SDO and is qualified to submit its standards for review and potential approval by an internationally recognized SDO. In these cases, the adoption and impact of the industry-led SDOs is highest. This is not a question of double counting (i.e. the same industry-driven SDO standard and a standard published by an internationally recognized SDO have different identifiers).

EXAMPLE: Khronos® Group glTF 2.0 runtime 3D asset delivery standard which is ratified by ISO/IEC JTC1 and published as ISO/IEC 12113:2022 [i.1], and several Open Geospatial Consortium® standards which have been developed, often in collaboration with experts in other organizations, to deliver fundamental geospatial information standards that are subsequently ratified by ISO Technical Committee 211.

4.3 Contrasting standardization approaches

4.3.1 Introduction

In the project data set and for purposes of the present document, the distinction is made between industry-driven organizations, national standards bodies and internationally mandated (and recognized) standards bodies. Table 1 provides examples of industry-driven standardization groups that have virtual world standards working groups, national standards groups with virtual world standardization activities and those organizations that are internationally mandated and that also publish standards relevant for virtual worlds ecosystem stakeholders.

Table 1: Examples (not exhaustive list) of three types of organizations developing virtual world standards

Industry-driven SDOs	National SDOs	Internationally mandated SDOs
Open Geospatial Consortium (OGC)	DIN (Germany)	International Standards Organization (ISO)
World Wide Web Consortium (W3C®)	ANSI (United States)	International Engineering Commission (IEC)
Khronos Group	British Standards Institute (United Kingdom)	International Telecommunications Union (ITU)
IEEE™ Standards Association	Standards Australia (Australia)	CEN/CENELEC
ETSI	Chinese Electronics Standardization Institute (China)	ETSI

While all industry-driven standardization groups encourage international contributor participation, for purposes of the present document the former is called "industry-driven SDOs." These groups are primarily (but not exclusively) headquartered in the United States and are usually incorporated with a tax-exempt status. Their membership is open. They are composed of private and public companies, government agencies, universities and non-profit organizations. Membership is granted based on annual dues.

For virtual world standardization, the primary alternative to industry-driven standards development organizations are the "internationally mandated" SDOs, or "recognized SDOs" for simplicity, in which nation-states (i.e. the national standards bodies) are the primary means of participation. Contributions to these standards working groups are made through registration with a national standards committee (middle column of Table 1) and subsequent participation, largely through meetings.

In Figure 3, the standards working groups in the data set that are in operation at the time of this research are associated with one of the two SDO types then filtered by the country in which the SDO they are operating under is legally headquartered.

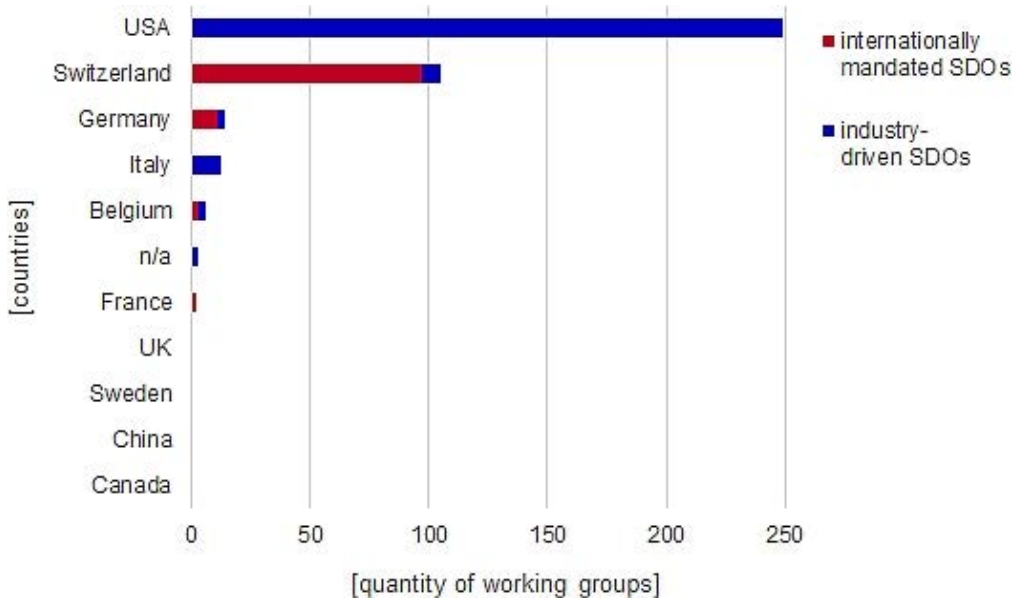

Figure 3: Legal headquarter distribution (country) of two types of SDOs within which working groups are developing virtual world standards

It is evident from Figure 3 that most standards working groups currently working on virtual world standardization activities are affiliated with industry-driven SDOs which are legally incorporated in the United States, while most internationally mandated SDOs are incorporated in Switzerland and Germany.

4.3.2 Timing is important

These distinctions between two types of standardization bodies highlight several important trends that are evident in the data sets for this project as well as in industry adoption. The first noticeable trend, illustrated in Figure 4, is that initiation of new standards working groups by industry-driven standardization development organizations has risen significantly since approximately 2018.

In 2024, there were approximately twice as many standards working groups formed in industry-driven SDOs than were formed and operating within the internationally mandated standards development bodies.

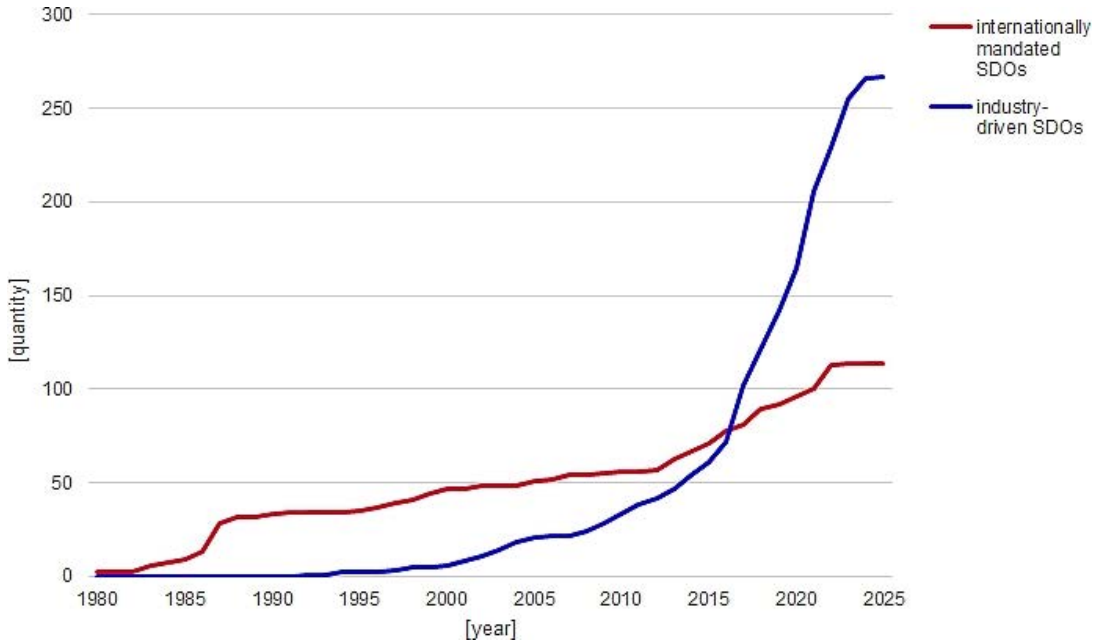

Figure 4: Growth of Standards Working Groups in Industry-Driven SDOs and Internationally mandated SDOs (1980-2024)

One factor that is at the root of this difference is the membership composition. The industry-driven SDOs are, as their name indicates, composed of technology industry stakeholders. Typically, the stakeholders in such organizations do not approve the initiation of projects before the members of a working group identify a clear interoperability requirement for which they seek resolution through standards. While the interval between initiation of industry-driven standardization activities and publication can be lengthy (e.g. years), the procedures for standards development in industry-driven SDOs frequently encourage a high degree of collaboration between members and there is often a shared sense of urgency among the working group members of industry-driven SDOs.

Many comparisons between the two types of standards development organizations were made for this research.

EXAMPLE: Out of 912 standards in the data set, 525 were published by internationally mandated SDOs and 387 were published by industry-driven SDOs. From the set of 912 standards, approximately 400 were chosen on the basis of their being the 50 standards whose description best fit definitions of virtual world domains. Figure 5 compares the relative publication rates of top 50 standards by domain from the two types of SDOs.

In the infrastructure and data management domains there were almost the same number of top standards published by the internationally mandated SDOs and industry-driven SDOs. For human interface systems and devices, there were more standards published by internationally mandated SDOs. The trend is reversed for the standards classified as the top standards for virtual economy. Further analysis can be performed on the basis of more criteria to understand these differences and their likely impacts on virtual world technology development and interoperability.

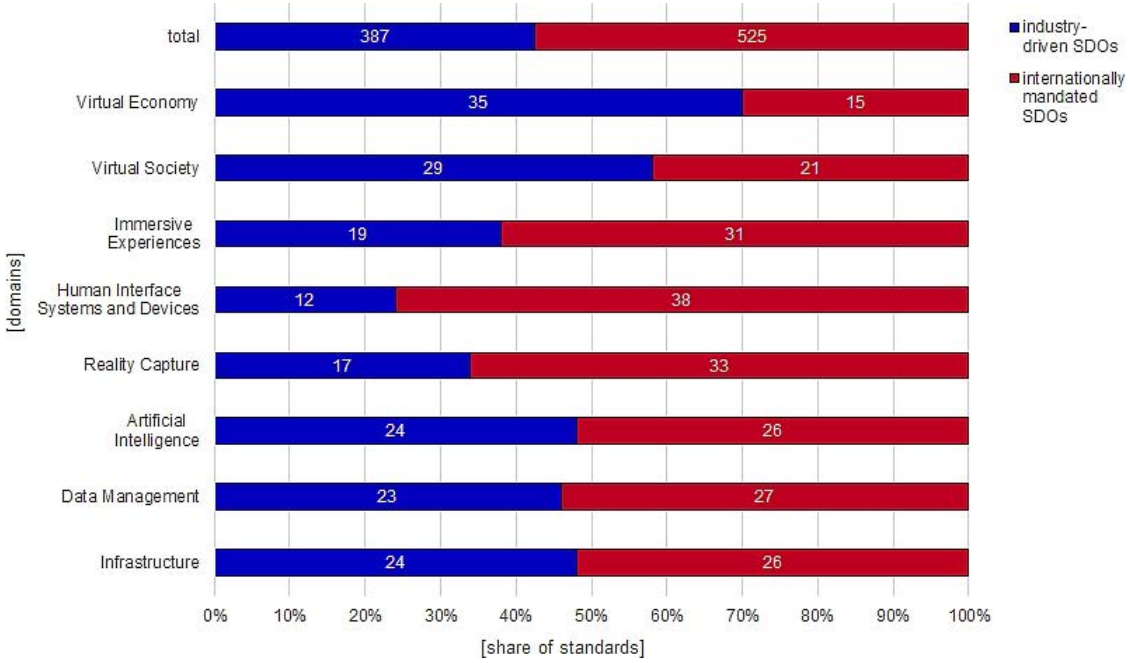

Figure 5: Comparison of SDO type publications based on top 50 standards published in each virtual world domain and the total number of standards in the data set

4.3.3 Supporting documentation

Another difference between the two types of standardization groups is how their membership supports the standards on which their members contribute and publish. While more standards relevant to virtual world technologies have been published by internationally mandated SDOs than industry-driven SDOs (525 vs. 387), the publication of a standard is insufficient for it to be adopted at scale. Without the support of outside groups that have a stake in the adoption of a standard, the standards published by internationally mandated SDOs are left with low documentation to support developers in understanding why a standard is important, how to determine if an implementation is compliant or to create extensions or profiles that may apply to their use cases.

In addition to standards, industry-driven standardization groups publish many technical reports, white papers, guidelines and other documents to aid their members (and other members of the virtual world ecosystem) to understand the purpose of the standard and apply its solutions to address interoperability requirements.

In Figure 6, the number of documents published by type (technical reports and standards) by the two categories of SDOs are compared. The data set contains more technical reports about standardization and interoperability of virtual world technologies published by industry-driven SDOs (289) than documents of the same category published by the internationally mandated SDOs (65). It is not possible to assess the quality or the focus of all the technical reports at a granular level, however, in an attachment provided as a supplement for the present document, metadata about and titles of the top technical reports are presented by the domain in which the publications are relevant.

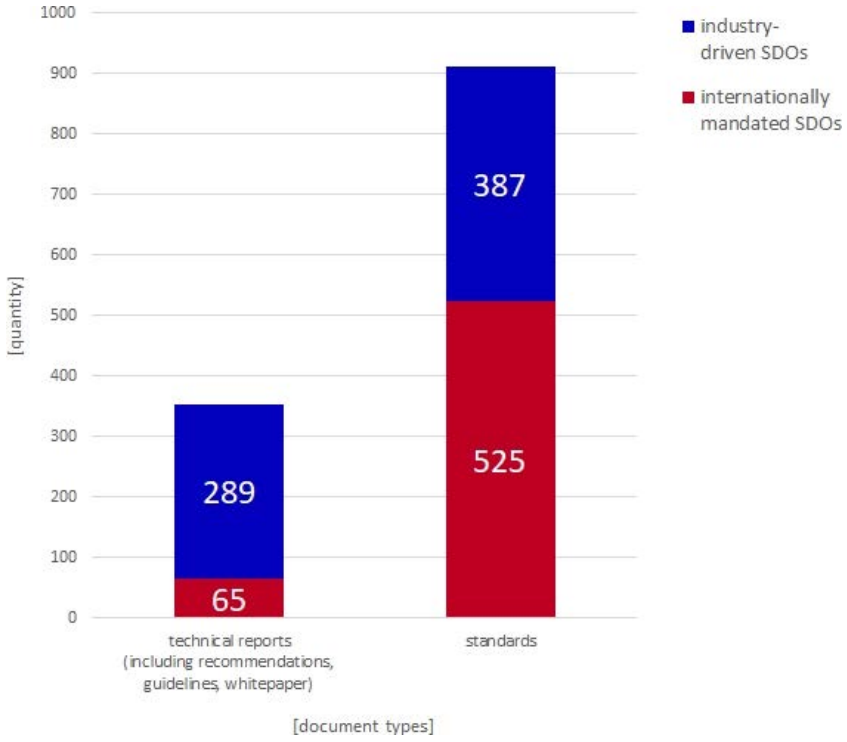

Figure 6: Comparison of document type (Technical reports vs standards) published by industry-driven SDOs and internationally mandated SDOs

Finally, the data set studied for this project and shown in Figure 7 reflects that the internationally mandated SDOs published virtual world relevant standards earlier than the industry-driven SDOs. These standards may have emerged early in the technology lifecycle from research and government-funded projects. In some cases, the internationally-mandated standards do not match a pressing interoperability requirement about which industry stakeholders agree. The publication dates of standards do not necessarily reflect or permit any conclusions about the adoption level of the published standards. However, a recently published independent research report using the data set associated with the present document clearly documents that standards developed by industry-driven SDOs have been more frequently implemented by virtual world industry stakeholders [i.12]. In other words, the industry-driven SDO activities (as measured by publication topics, number of publications and date) are published when stakeholders perceive a need and are delayed several years in comparison with the internationally mandated SDO virtual world standards.

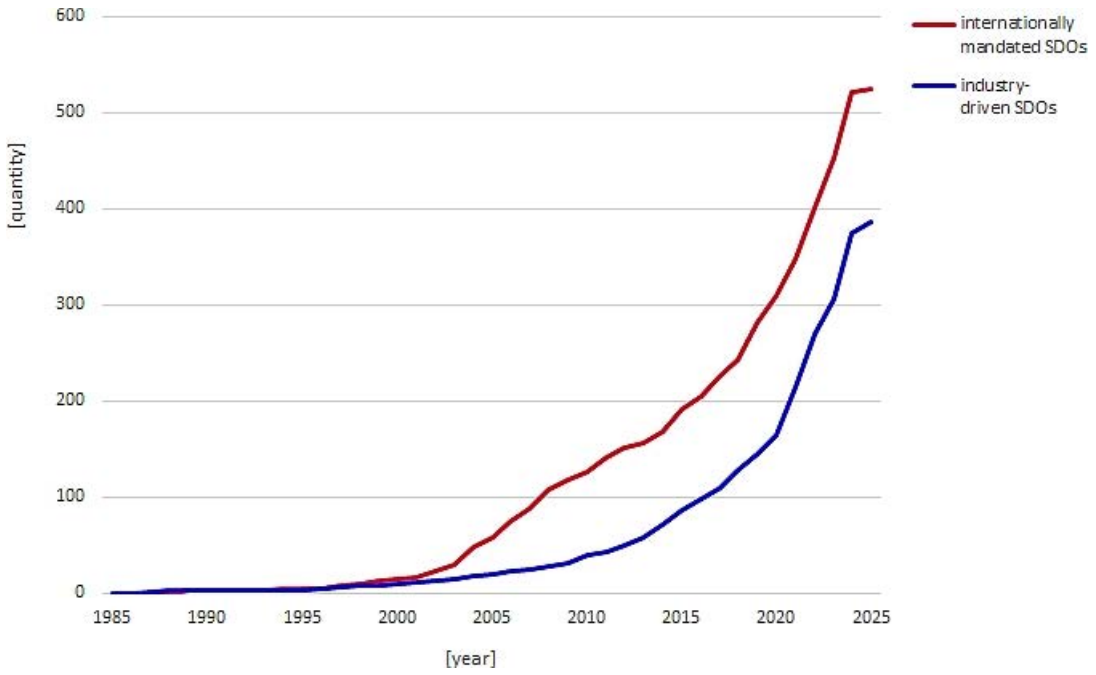

Figure 7: Comparison of publication dates of virtual world standards by industry-driven SDOs and internationally mandated SDOs (912 standards)

4.4 Trends in standards and technical reports

4.4.1 Introduction

The researchers on this project 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. 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 world standards landscapes were studied to ensure that the data sets were complete.

4.4.2 Domain focus

Standards of relevance in at least one virtual world domain began to be published as early as 1987. Figure 8 illustrates the number of relevant standards in the data set published over a 20-year period (2005-2024).

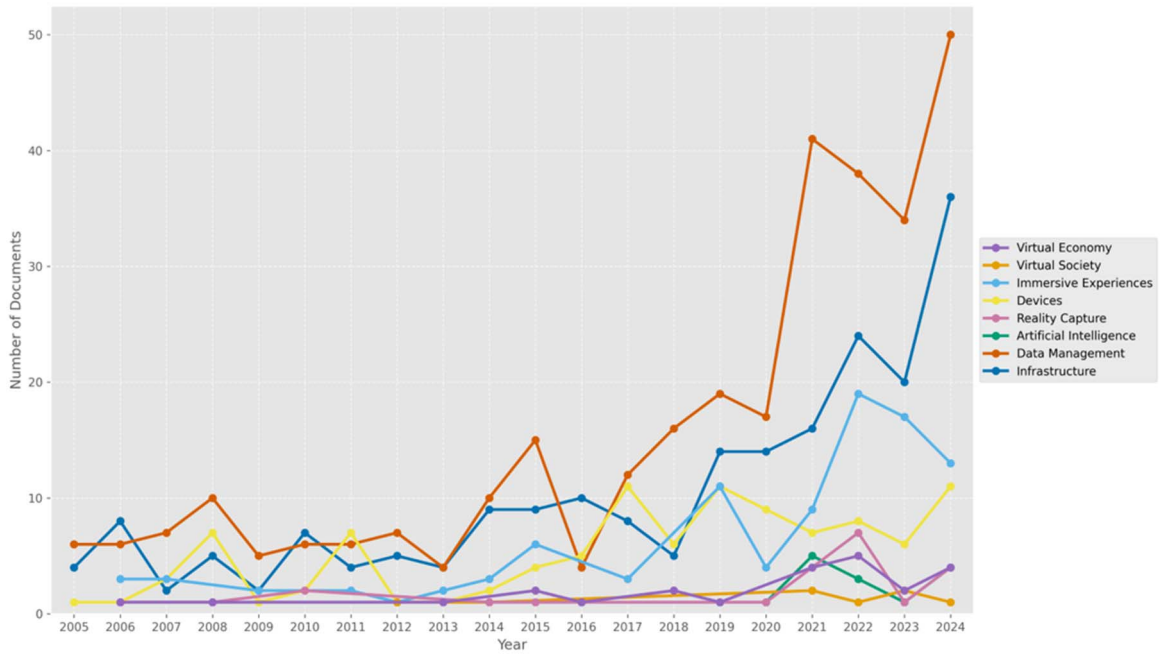

Figure 8: Number of standards published by domain (2005-2024)

In dedicated clauses below, the definitions of domains and a deeper examination of standards in each will be provided. Trends in standardization activity by domain are shown in Figure 8. It illustrates that in the first 10 years of the period, development has been strongest in the data management and infrastructure domains. There were relatively few standards published about virtual society, virtual economy and immersive experiences before 2015. Since approximately 2017, standardization activities about Immersive Experiences began to increase. In contrast, standards for human interface systems and devices have been steady but not numerous. This reflects the relatively immature nature of the technologies in this domain. It is also noteworthy that there are relatively few standards being published about four of the eight virtual world domains studied in the present document: the use of artificial intelligence in virtual worlds, reality capture, virtual society and virtual economy.

In Figure 9, the standards in the data set for this study are assigned to one of the eight virtual world domains (as defined for the present landscape in clause 5) with which it is most strongly aligned. Some standards are relevant for more than one domain, but Figure 9 is only taking the "primary" domain (the one that is most highly correlated). There are hundreds of standards that address multiple domains. An analysis of the top 219 cross-domain standards is introduced in clause 14 and a table containing those standards is in the attachment.

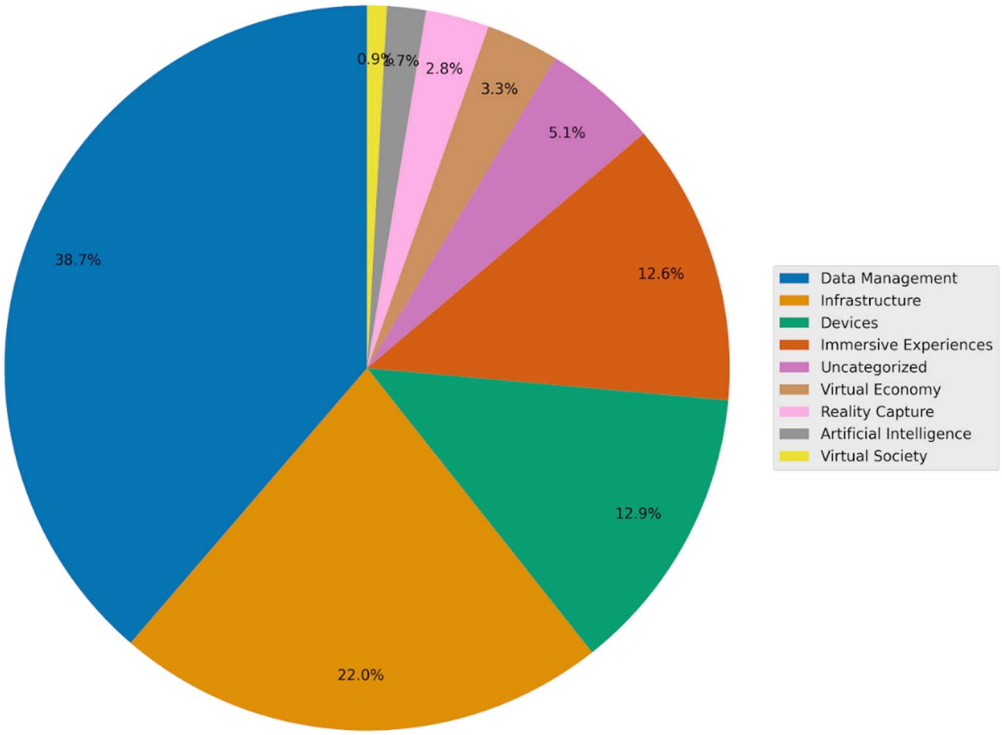

Figure 9: Standards published to date with primary focus on eight virtual world domains

The top ten standards development organizations (in terms of the number of specifications published) studied in this project are interested in two or more virtual world domains as defined in this project. This is a reflection of a relatively low degree of specialization, at least at the SDO level. Deeper analyses detect that, in most of the SDOs, the subcommittees and working groups take a narrower focus. For deeper exploration of the domains on which different SDOs are concentrating their efforts, the supplementary materials accompanying the present document include an interactive representation of number of documents published in each domain by the top 20 SDOs in terms of document number. Annex B of the present document also provides spider figures and more detailed information about the SDOs in the dataset.

4.4.3 Specialization

By analysing the proximity of the standards in the data set to the topics defined as the eight virtual world domains, another pattern can be observed: few standards published to date focus exclusively on one domain. Many standards and standardization activities seek to address technology components across two or more domains in the virtual world ecosystem.

Figure 10: Data management standards distribution across eight virtual world domains

As shown in Figure 10 for standards that are predominantly addressing the data management standards (the largest group of relevant standards in the data set), few of the standards in the data set have, to date, focused solely on a narrow requirement or objective within the data management domain. The methodology used to create and to read the scatterplots used in the present document based on the data set and how to interpret them is provided in clause A.6.

For deeper exploration of trends with respect to domain focus, between different SDOs, the supplementary materials accompanying the present document include an interactive representation of number of standards published in each domain area by the SDOs with the highest number of documents in the data set. The file in the archive gr_arf010v020101p0.zip has the title "Interactive_standards_SDO_radar_chart.html". Using the interactive representation, it is possible to click on any point to see the name of the standard and the SDO responsible for its publication.

This lack of focus or specialization has important implications, especially for two groups of stakeholders: standards contributors and standards adopters. If an expert in a specific domain wishes to contribute to a standard, their unique value may not be incorporated into the final standard if the standard covers many topics and requirements. Furthermore, collaboration often results in a compromise, usually defining the lowest common denominator to which all the participants agree. The contributors in the standards working group may not reach consensus and choose to omit potentially important solutions to an interoperability obstacle.

It is important to note that as a general rule, all implementation details are avoided in standards in order for vendors who adopt a particular standard have the opportunity to innovate and add unique value while also meeting their minimum interoperability and standards compliance objectives. When a standard is not tightly focused on a requirement, there may be sections of the standard that address architecture or other aspects with which a vendor is not comfortable. In these cases, the adoption of the standard by some stakeholders may not be possible or not bring sufficient value to justify its implementation.

For standards adopters the dilemma presents other problems that are, in some cases, acute. If the solution for an interoperability obstacle is included in one standard, but the standard's scope includes topics that the adopter of the standard wishes to address in a proprietary manner, then the solution developed does not comply fully with the standard. When those who are likely to adopt a standard are closely advising the work, or directly involved in standards development, such issues are far less frequently encountered.

Not all the 920 standards in the data set studied in this project are considered sufficiently well matched with the virtual world domain definitions to be considered important in one or more domains of interest. This could be a consequence of the standard identified not directly targeting virtual world requirements but contributes, instead, to the advancement of enabling technologies. There are also standards that focus on the specific requirements of an industry and the use of virtual world is included as one way to meet industry requirements. The project has identified but not studied at a deep level, standards that are relevant for virtual world developers that seeks adoption of their solution in a vertical industry. A dedicated clause highlighting how industry-specific standards play an important role in the virtual world ecosystem is included in the present document.

While many standards identified are not specific in their approach to virtual world interoperability, there are also those at the other end of the spectrum that contribute in a significant manner to most virtual world domains. This trend to cover many domains in one standard is prominent in the data set. A dedicated clause about cross-domain standards accompanies a table of 219 cross-domain standards in the attachment.

4.4.4 Technical Reports support standardization activities

Publication of technical reports are an important means for standards experts and working groups to provide support to the virtual world ecosystem. One way that technical reports can support successful standardization activities is by defining precise requirements for interoperability. This has been a strong pattern in the infrastructure and data management domains. Frequently, when published by industry-driven SDOs, technical reports also provide guidance for those considering implementation or adoption of a specific standard.

As previously noted, the data set used for this project contains information about 354 technical reports.

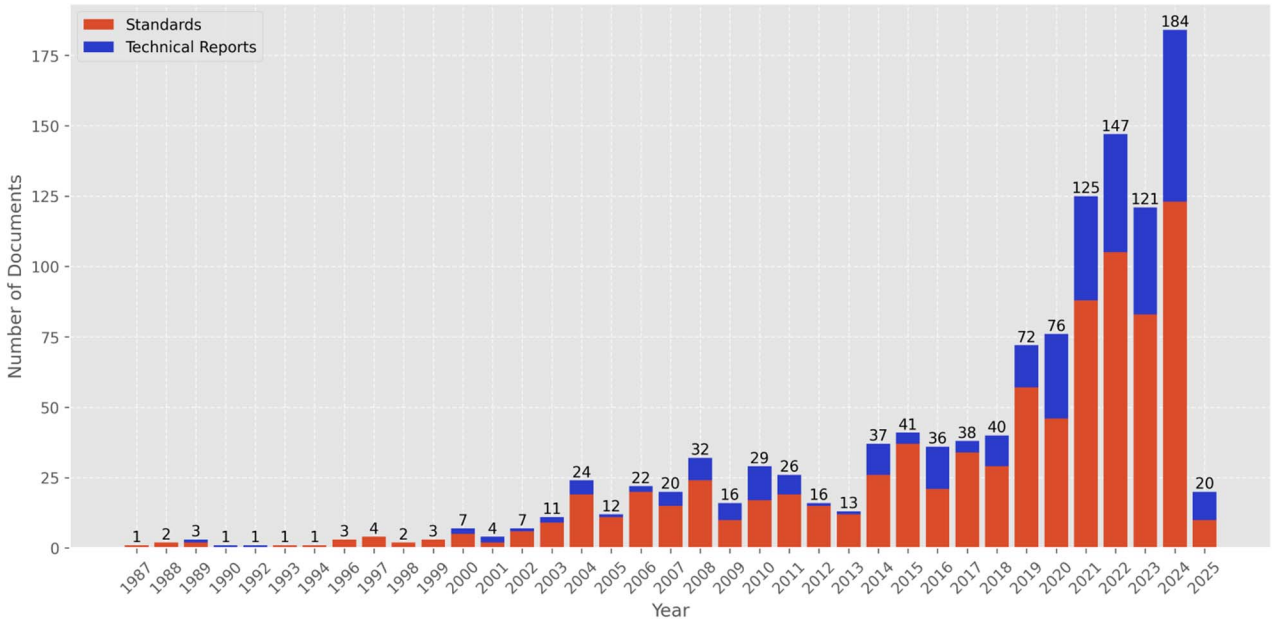

Figure 11: Technical report and standard publication rate (1987-2025)

Figure 11 shows that the number of technical reports about virtual world standardization is increasing with respect to the number of standards published per year.

The data set also permits analyses of technical reports publication dates by domain, as shown in Figure 12.

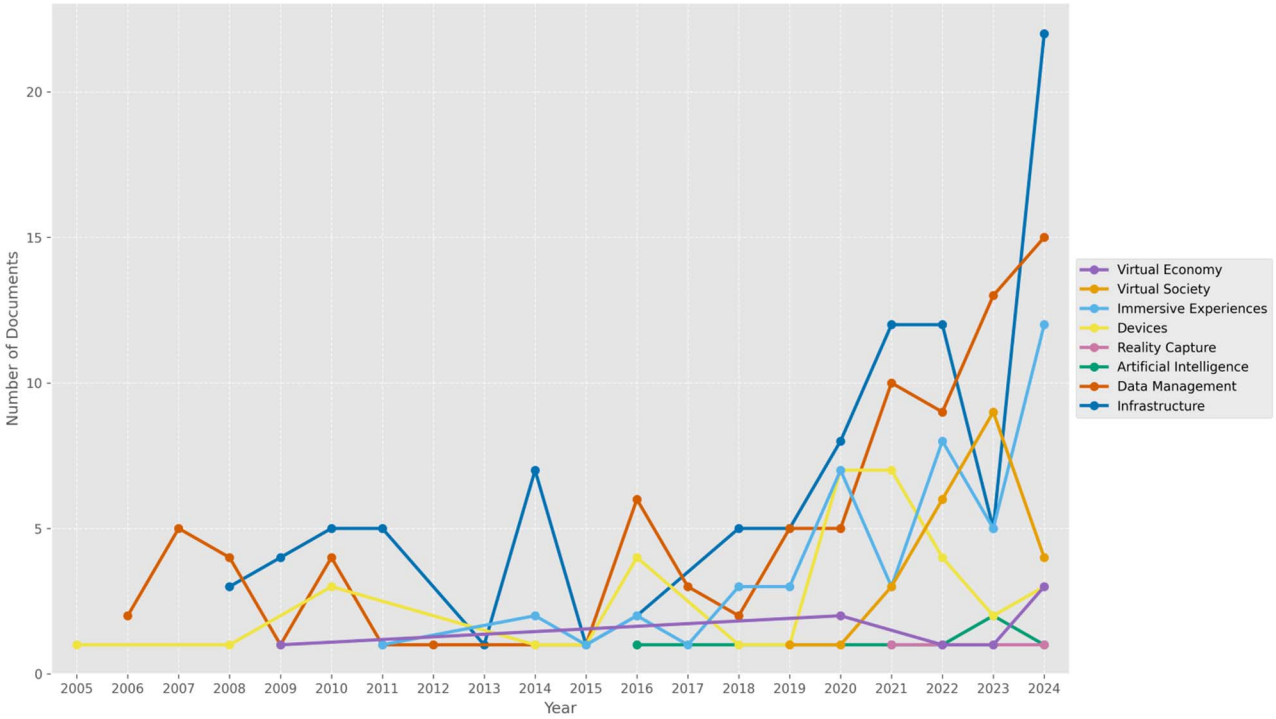

Figure 12: Technical reports published by domain (2005-2024)

In Figure 12 it is possible to detect trends in technical report publication over a 20-year time frame. Technical reports with greatest emphasis to date have been published about the Infrastructure and Data Management domains. In recent years, more standards have sought to address Immersive Experiences and, in 2023, there was a surge in technical reports about Virtual Society requirements. In the Virtual Society and Reality Capture domains, increased development can be detected in both the standards and technical report datasets in the past five years but these remain very low by comparison with the future requirements. Technical reports about human interface systems and devices and artificial intelligence in virtual worlds domains are also few. It is not possible to conclude from the data the reasons for these topics having not received greater attention. It may lead to the conclusion that standardization efforts in these domains will increase in the coming years.

In Figure 13, the technical reports in the data set for this study are assigned one of the eight virtual world domains (as defined for the present landscape in clause 5) with which the present document is most strongly aligned.

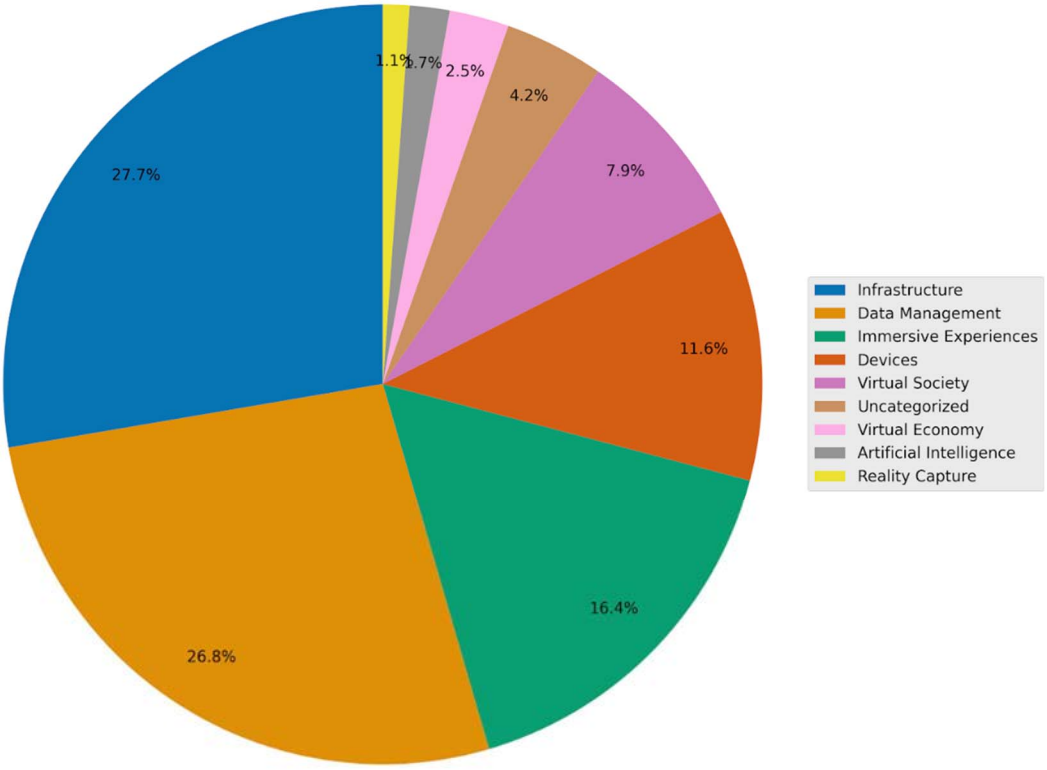

Figure 13: Technical reports published to date with primary focus on eight virtual world domains

4.5 Standards adoption

One of our goals, as part of its assessment of the importance of specific virtual world standards or groups of standards, is to study industry adoption of interoperability standards. The objective assessment of adoption of individual standards at a detailed level is not possible, however, with the data set and using a bespoke deep research agent to search for information published on the Web, an independent research report provides data about 29 leading virtual world companies and their adoption [i.12].

Having searched for evidence of standards implementations by technology providers, three points have been observed:

- Virtual world customers (those buying or using virtual world technologies) are not requesting or requiring interoperability of their virtual world technology suppliers.
- When considering virtual world interoperability broadly (e.g. at a societal level), there has yet to be one or more strong requirements for standards adoption, hence, adoption is low and information about adoption rates is scarce.
- The internationally recognized standards development organizations frequently do not invest in development of supporting materials for those implementing a standard, testing and certification platforms nor have they recommended the ongoing collaboration of standards-adopting entities. In contrast, some industry-driven SDOs (e.g. W3C®, OGC, Khronos® Group) have associated with certification bodies, or created their own certification services for the study of compliance with one or more standards. These standards compliance certification services can generate revenues in the place of licensing or selling access to the organization's standards. They are also useful for measuring the adoption of one or more standards published by the SDO.

Despite the obstacles faced when seeking to compile detailed information about adoption, some information has been acquired through the research conducted for the present document. Across 25 leading virtual world technology companies analysed, certain standards and organizations emerge as recurring themes, indicating an emerging industry recognition of the benefits of interoperability standards. The most frequently mentioned standards and the companies that have publicly announced their support appear in the list below:

- OpenXR (Khronos® Group) is by far the most frequently mentioned virtual world technical standard across the board, particularly for hardware compatibility and software interoperability. Companies like: Amazon®, Google®, HTC, Microsoft®, Magic Leap, Qualcomm®, Samsung®, Sony®, Unity and others explicitly state that they support or adopt OpenXR. This suggests a strong industry push towards open and cross-platform immersive experiences.

- glTF 2.0 (Khronos® Group) is another prominent virtual world standard. Khronos glTF is recognized for its efficiency in 3D asset transmission and interoperability. Companies like: Amazon, Google, Epic Games, Microsoft, and Nvidia mention or utilize glTF, indicating its importance for 3D content in virtual worlds.

- Web Content Accessibility Guidelines (W3C®) is another recurring theme, especially in Immersive Experience standards. Companies like: Amazon, Apple, Google, HTC (via XRA guidelines), Magic Leap, Roblox, Sony, and Siemens reference or align with WCAG principles, highlighting a growing awareness of inclusive design in digital experiences.

- 5G/6G standards (3GPP®) are particularly relevant for companies in the infrastructure domain of virtual worlds. Companies like: Ericsson, Huawei, Nokia, and Qualcomm contribute to and adopt 3GPP standards, especially for 5G and beyond. The services specified in 3GPP standards are seen as crucial for enabling high-bandwidth, low-latency virtual world experiences.

- ISO/IEC 27001 [i.2] (ISO/IEC) is a widely adopted security standard. ISO/IEC 27001 [i.2] certification is frequently mentioned by companies like Dassault Systèmes, Ericsson®, HTC, Huawei®, Meta®, Microsoft®, Sony®, and Tencent ®. This indicates a baseline commitment to information security management, although its specific application to virtual world solutions is rarely mentioned.

- WebXR (W3C®) support is mentioned by some companies including Amazon®, Google®, and Niantic that are striving to deliver browser-based virtual world experiences, but its adoption is less pronounced than that of Khronos® OpenXR, possibly due to the current device-centric nature of virtual world experiences.

- ISO/IEC 60601 [i.3] and ANSI/CAN/UL 8400 [i.4] are standards that were developed with a high level of contributions from Meta®, Apple®, Google®, Microsoft®, Sony® and others, however publicly available information on the adoption of these standards for user safety is limited to usage in medical and enterprise applications.

While not standards or contributing to interoperability of virtual world technologies, adoption of data protection regulations such as GDPR, COPPA, CCPA are widely referenced by leading virtual world companies, including Amazon®, Apple®, Epic Games ®, Meta®, Microsoft®, Niantic, and Roblox™. This reflects a broad awareness and compliance effort related to user data to avoid the risk of encountering roadblocks in countries where implementation of these regulations is required.

4.6 Conclusions

This clause of the present document has described the data set compiled for the present document. It has explored several trends in the data about standards publications and technical reports, standards development working groups, and compared the publications released by two types of standards development organizations.

The analyses performed were useful for understanding the time scales over which virtual world standardization activities have taken place and the recent acceleration in activity. They also revealed a distinct concentration of industry-driven SDOs in the United States.

While not the focus of the present document, the size and richness of the project data set will permit the identification and detailed study of interoperability gaps which may be the focus of future research and standardization support programs.

5 Eight virtual world domains

To permit the deeper study of documents and standardization activities for different aspects of virtual world interoperability, the project has defined eight technological domains. Figure 14 illustrates how the eight domains are interlocking. It uses a "technology stack" view of the domains with the communication infrastructure domain at the bottom, forming the base of the ecosystem, and the user and value creation domains (i.e. virtual society and virtual economy) at the top.

The artificial intelligence domain is portrayed in a vertical orientation in the landscape map to communicate that the technologies it contains overlap with other enabling technologies, probably with all the domains. For simplicity and illustrative purposes, Figure 14 only shows the artificial intelligence domain overlapping with the lower three domains: infrastructure, data management and reality capture.

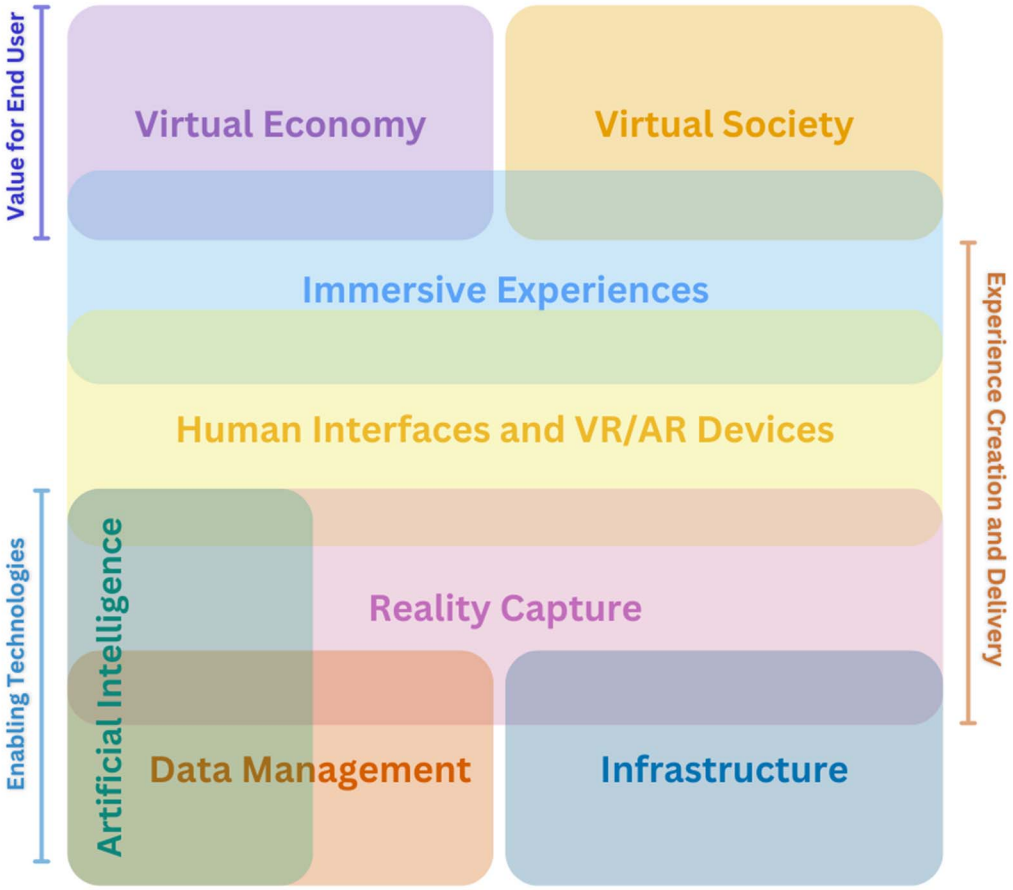

Figure 14: Eight virtual world domains form the framework for this standards landscape

Table 2: Eight virtual world 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

This is the organizational framework that will be followed for the next eight clauses of the present document. Each clause begins with definitions of the virtual world domain and its components.

6 Infrastructure

6.1 Domain Scope

6.1.1 Introduction

Infrastructure for virtual worlds refers to the foundational systems, technologies, and frameworks that enable the seamless operation, scalability of and interactivity within virtual world environments. 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.

There are three components of the infrastructure domain considered in this landscape.

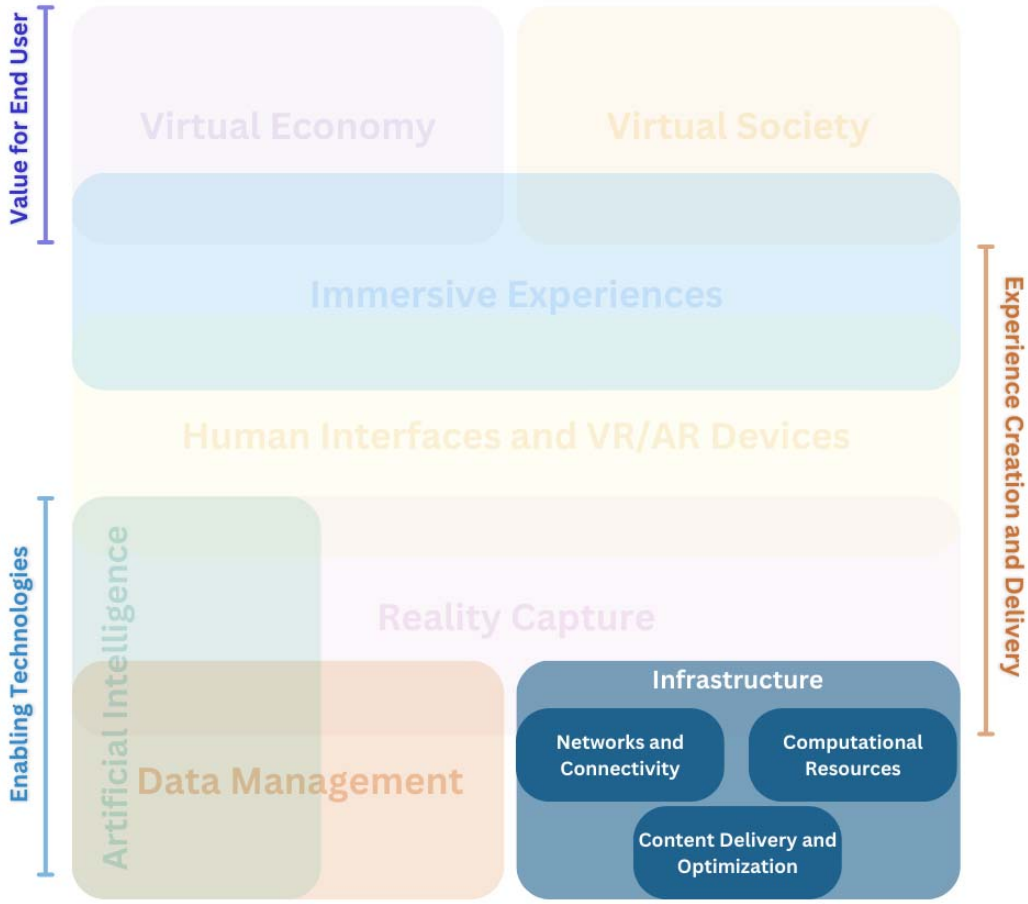

Figure 15: Components of the infrastructure domain

These components are described in clauses 6.1.2, 6.1.3 and 6.1.4.

6.1.2 Networks and Connectivity

Networks provide the essential communication systems for access to and data transmission of data for distributed, efficient low-latency interactions. This component includes these topics:

- Network Connection and Internet Protocols: Protocols responsible for establishment of connections and transmitting packetized data between hosts across network boundaries.
- World Wide Web: Protocols and Application Programming Interfaces for resolution of queries in a virtual world, establishment and verification of connections between a browser and server (hosting data) or peers, and subsequently assembling of information (text, images, video or audio) presented in 2 or 3 dimensions in a W3C®-compliant browser.
- High-Speed Networks (5G, 6G): Provide the bandwidth and low latency necessary for streaming XR content and supporting real-time interactions.
- Quantum Networking: Advanced networking technologies utilizing quantum principles for secure and high-speed virtual world communications.
- Latency Optimization: Techniques for minimizing delays in data transmission to maintain real-time responses and seamless interactivity.
- Network Slicing: Technology that creates multiple virtual networks to optimize performance for different virtual world applications.

6.1.3 Computational resources

Computational resources component of infrastructure includes all platforms, servers and systems that process data for use in immersive environments and experiences. This component includes these topics:

- Quantum Computing: Emerging technologies offering computational power for solving complex rendering and simulation challenges.
- Cloud Computing: Centralized platforms for handling computationally intensive tasks such as rendering, localization, storage, and AI processing, enabling device-agnostic accessibility.
- Edge Computing: Distributed computational nodes located near users to reduce latency and enhance performance in real-time applications.
- Hybrid Models: Combining cloud and edge computing to balance scalability and responsiveness.

6.1.4 Content delivery and optimization

The content delivery and optimization component encompasses systems for efficiently localizing users and delivering high-quality virtual world experiences from servers to user devices. This component includes these topics:

- Localization and relocalization: Technologies and systems enabling devices and users to obtain their position and orientation relative to the other objects in real-world or virtual spaces in six degrees of freedom, including but not limited to use of visual positioning through images, GPS, tags or other means, frequently providing Simultaneous Localization and Mapping.
- Scene Analysis and Experience Streaming: Technologies that process and deliver virtual environments in real time, dynamically adapting to user interactions and device capabilities.
- Real-Time Rendering and Optimization: Advanced algorithms and hardware that enable the generation of immersive visuals instantaneously, such as foveated rendering and adaptive scaling.
- Streaming Protocols: Specialized network protocols for real-time transmission of high-volume digital content using network infrastructure and network-based resources and for delivery of full experiences to human interaction systems and devices.

6.2 Standards Development Organizations

There are 49 different standardization development organizations with working groups contributing to virtual world infrastructure standards in the data set. The internationally mandated SDOs have published 111 (approximately one third) out of the 335 standards identified as being relevant for this domain as defined above.

6.3 Standards Working Groups

Standards working groups are the units of a standards development organization that permit stakeholders and experts to contribute to standardization activities. Due to the large number of standards working groups and the detailed information about their year of formation and scope, it is necessary to provide these in a separate file for further study. The metadata about and descriptions of standards working groups in this domain are compiled in a spreadsheet with the title "Top_standards_working_groups_in_infrastructure_domain.xlsx" contained in archive gr_arf010v020101p0.zip.

6.4 Standards

Figure 16 shows the number of standards with the highest ranking in infrastructure domain topics, published by the seven most prolific standards development organizations. This includes standards in the data set for the infrastructure domain topics that are relevant to some stakeholders, however, do not rise to the highest ranking needed to be included in the table of top standards.

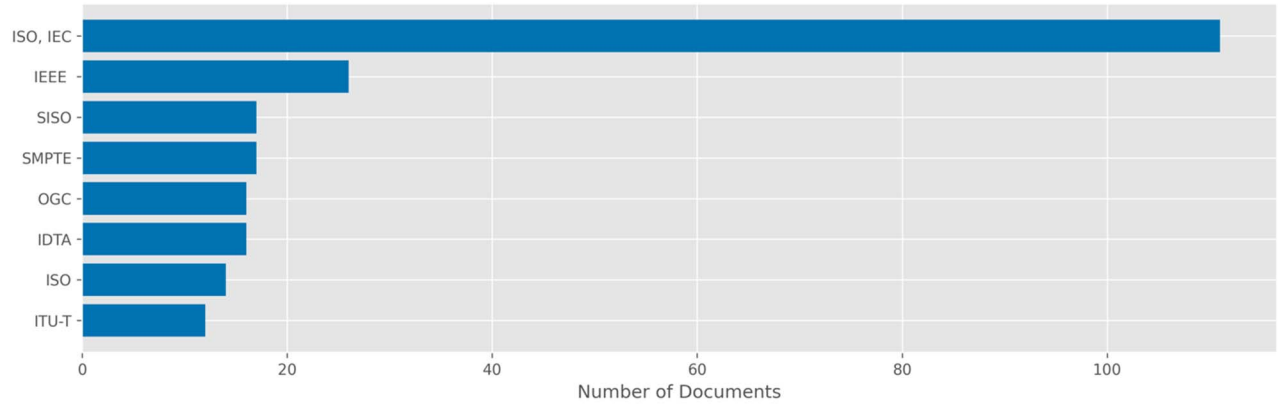

Figure 16: Number of standards published in Infrastructure domain by top seven SDOs

Due to the very large size of the data set and the details available for further study, the table containing information about the top standards in the infrastructure domain is provided as a spreadsheet with the title "Top_standards_in_the_infrastructure_domain.xlsx" contained in archive gr_arf010v020101p0.zip.

6.5 Technical Reports

Figure 17 shows the number of technical reports with the highest ranking in infrastructure domain topics, published by the seven most prolific standards development organizations.

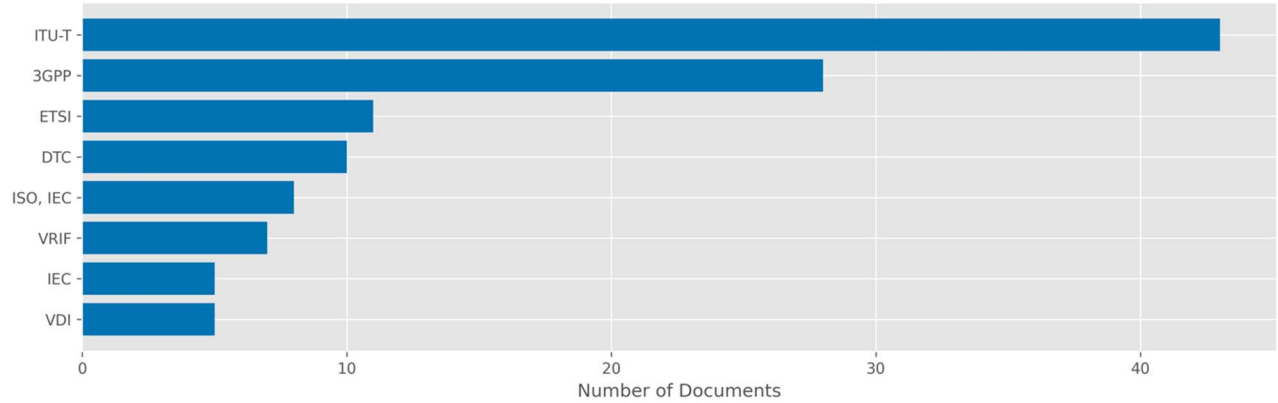

Figure 17: Number of technical reports published in infrastructure domain by top seven SDOs

Due to the very large size of the data set and the details available for further study, the table containing information about the top technical reports in the infrastructure domain is provided as a spreadsheet in file "Top_technical_reports_in_the_infrastructure_domain.xlsx" contained in archive gr_arf010v020101p0.zip.

6.6 Conclusions

Beginning with their development for telephony services in the early 20th century, standards for infrastructure interoperability have been important for nearly a century. Communications are amplified and more often reach their objectives in the modern world when networks are connected. For virtual worlds, the value of connectedness is magnified when the user's display or interface device seeks to distribute the contents (memory usage) or the computational tasks (e.g. rendering) to the network's servers on the edge or elsewhere.

There continues to be development of new standards in the internationally recognized SDOs to meet emerging virtual world interoperability and other requirements, particularly for low latency and access to high processing capabilities accessible to devices at the edge. In general, as a result of a long heritage of interoperability requirements, adoption of standards in the infrastructure domain is frequently less contentious among those developing and selling technologies for communications than for those companies developing virtual world end user products or services.

7 Data Management

7.1 Scope

7.1.1 Introduction

Data management in this context refers to the processes, technologies, and policies for collecting, storing, processing, securing, and utilizing data within virtual world environments and experiences. Effective data management underpins the functionality, scalability, and ethical operation of virtual world ecosystems.

There are four components in this domain.

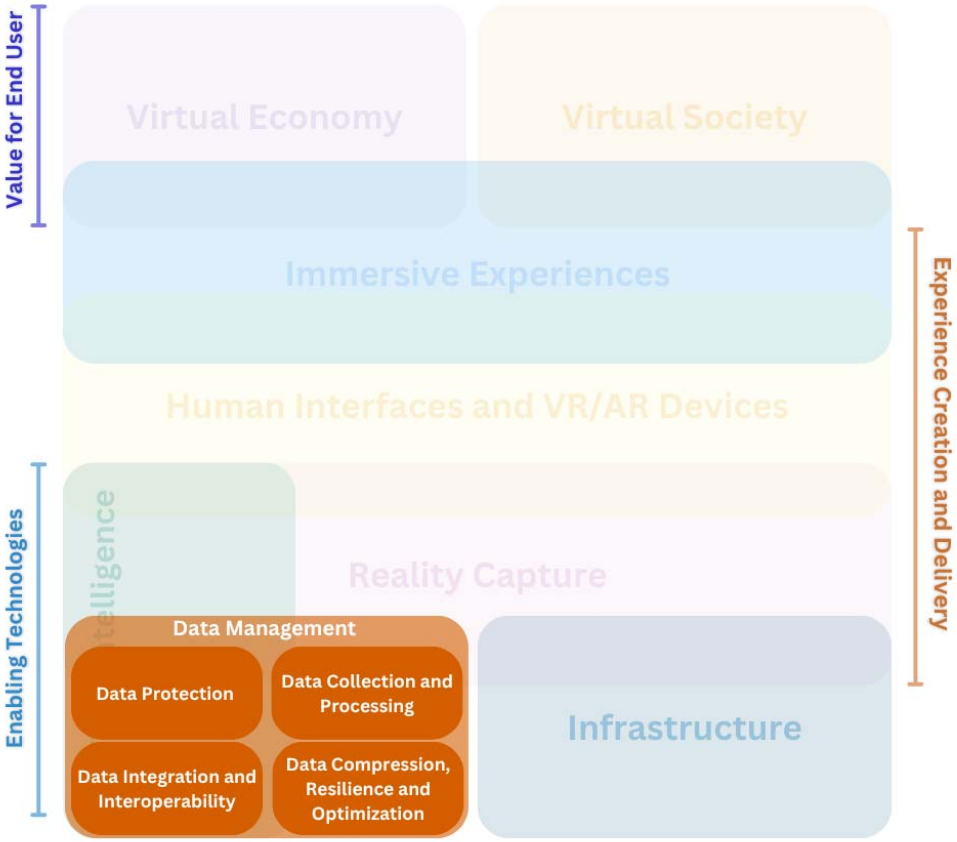

Figure 18: Components of the data management domain

These components are described in clauses 7.1.2, 7.1.3, 7.1.4 and 7.1.5.

7.1.2 Data protection

The data protection component covers the definition and enforcement of legal and ethical standards for handling data in or about virtual worlds, handling and protection of user data. This component includes these topics:

- Access Control Framework: Systems governing user permissions and resource access in virtual environments.
- Biometric Authentication: Use of biological characteristics for secure access to virtual environments.
- Zero-Knowledge Privacy: Cryptographic methods allowing verification without revealing private information in virtual worlds.

- Data Provenance: Tracing and conserving metadata about the origins of any data entering or being consumed within virtual worlds.
- Data Privacy: Safeguarding Personally Identifiable Information (PII) and ensuring users control how their data is collected, stored, and shared.
- Data Security: Implementing encryption, authentication, and access control to protect sensitive data from breaches.
- Data Ownership: Establishing clear frameworks for users to own and manage their generated data, such as behavioural analytics or avatar data.
- Regulatory Compliance: Ensuring data handling aligns with laws like GDPR, CCPA, and HIPAA, particularly for sensitive data such as biometrics and spatial mappings.
- Ethical Data Use Policies: Guidelines for transparent data practices, avoiding bias, and ensuring fairness when using data in virtual world processes.

7.1.3 Data collection and processing

Data collection and processing component covers all technologies for efficiently gathering and processing data for real-time virtual world applications. This component includes these topics:

- State Synchronization: Technologies ensuring consistent environmental states across multiple users and platforms.
- Distributed Data Processing: Systems that, by virtue of being deployed across multiple, interconnected computational nodes, increase system redundancy to increase efficiency and ensure resilience and reliability. Split rendering is an example of distributed data processing.
- Scene Analysis and Motion Tracking: Collecting spatial and movement data to enable realistic interactions, object placement, and adaptive environments.
- IoT Data Integration: Incorporating real-time data streams from connected devices (e.g. sensors, cameras) into virtual environments.

7.1.4 Data compression, resilience and optimization

Data compression, resilience and optimization component includes all techniques for managing large-scale 3D and volumetric data to ensure performance and scalability. This component includes these topics:

- Compression of 3D and Volumetric Data: Reducing the size of 3D models, textures, and volumetric media files for efficient storage and transmission without sacrificing quality.
- Streaming Optimization: Technologies and techniques ensuring seamless delivery of high-resolution content to user devices through adaptive streaming techniques.

7.1.5 Data integration and interoperability

Data integration and interoperability components facilitates the seamless data sharing, analysis, integration and utilization across virtual world platforms and ecosystems. This component includes these topics:

- Ontologies and Semantic Alignments: Databases, metadata and software that reconcile differences in terminologies used by different systems and that relationships between components of one or more virtual world systems are interchangeable.
- Metadata Management: Systems for tagging and organizing data for efficient retrieval, contextual relevance, and enhanced functionality across platforms.
- Spatial Database: Specialized databases designed to store and query 3D spatial data for virtual environments.

- Temporal Persistence and Coherence Systems: Technologies and systems ensuring consistent behaviour, including user modifications and continuity of virtual world elements over time.

At the European level, data management standards are also reflected in European Dataspaces projects that aim to make more data available for access and reuse in different sectors [i.20]. In the context of data spaces, virtual worlds can be considered both as a standalone domain and as an interdisciplinary area that can intersect with the currently identified fields.

7.2 Standards Development Organizations

There are 50 different standardization development organizations with working groups contributing to virtual world data management standards in the data set. The internationally mandated SDOs have published 161 (approximately one third) out of the 435 standards identified as being relevant for this domain as defined above.

7.3 Standards Working Groups

Standards working groups are the units of a standards development organization that permit stakeholders and experts to contribute to standardization activities. Due to the large number of standards working groups and the detailed information about their year of formation and scope, it is necessary to provide these in a separate file for further study. The metadata about and descriptions of standards working groups in this domain are compiled in a spreadsheet with the title "Top_standards_working_groups_in_data_management_domain.xlsx" contained in archive gr_arf010v020101p0.zip.

7.4 Standards

Figure 19 shows the number of standards with the highest rankings in the data management domain topics, that are published by the seven most prolific standards development organizations. This includes standards in the data set for data management domain topics that are relevant to some stakeholders, however, do not rise to the highest ranking needed to be included in the table of top standards.

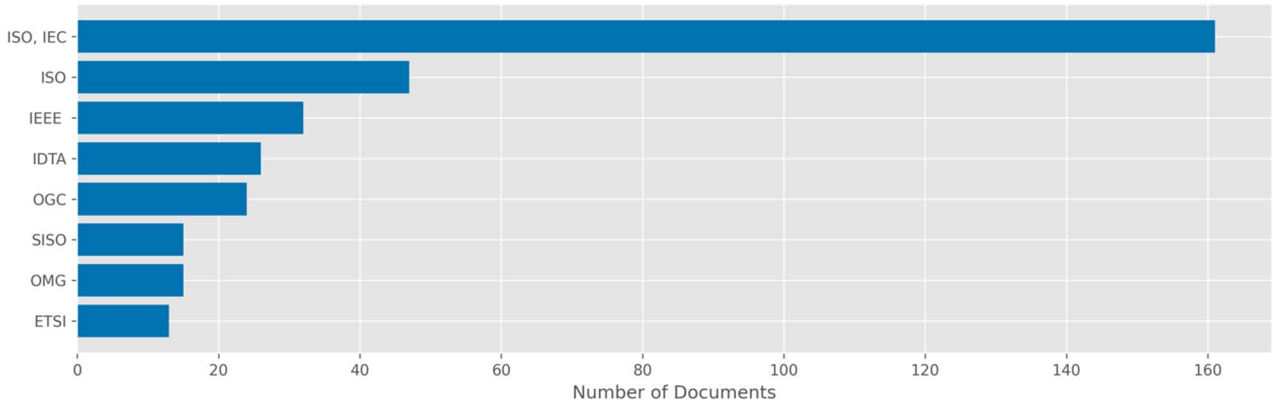

Figure 19: Number of standards published on Data Management domain by top seven SDOs

Due to the very large size of the data set and the details available for further study, the table containing information about the top standards in the virtual worlds data management domain is provided as a spreadsheet with the title "Top_standards_for_data_management_domain.xlsx" contained in archive gr_arf010v020101p0.zip.

7.5 Technical Reports

Figure 20 shows the number of technical reports with the highest ranking in the data management domain topics, published by the seven most prolific standards development organizations.

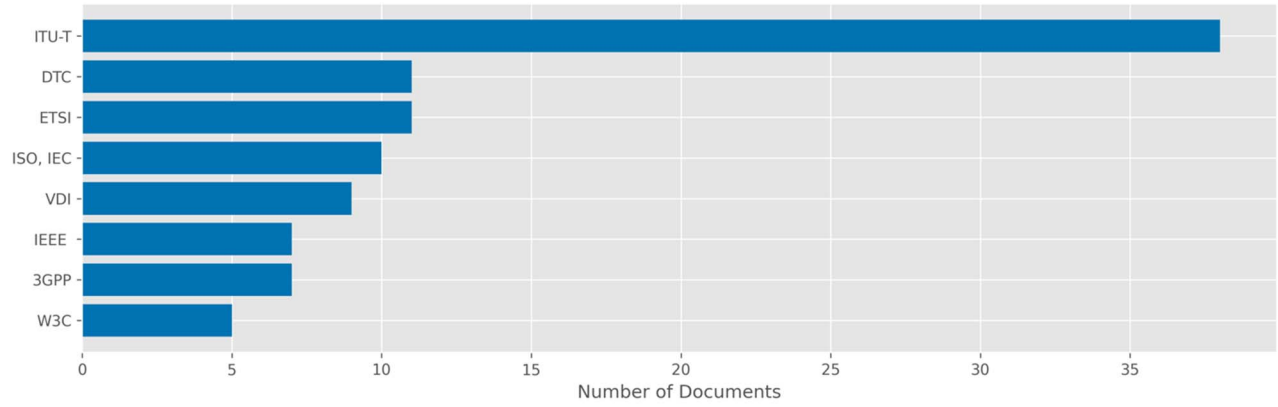

Figure 20: Number of technical reports published on data management domain by top seven SDOs

Due to the very large size of the data set and the details available for further study, the table containing information about the top technical reports in the virtual worlds data management domain is provided as a spreadsheet with the title "Top_technical_reports_for_data_management_domain.xlsx" contained in archive gr_arf010v020101p0.zip.

7.6 Conclusions

Data are abundant in virtual world technologies and vital for the smooth and automated understanding of users, their context, the worlds in which they live, work and entertain. Data are also processed by artificial intelligence algorithms and other processes to predict behaviours, detect anomalies and many other use cases. Standardization activities for data management in virtual worlds is difficult to clearly separate from the more general topic of data management, therefore, there are numerous data management standards in the data set for this project that are highly relevant but were conceived of and published well before the emergence of virtual worlds. This said, the importance of these standards to the smooth operation and management of virtual world society and economies, where the value of the data is exploited, cannot be overstated: data are the "raw materials" of virtual worlds and standards are the only scalable means to increase their exchange between virtual world components, users and systems that are outside the virtual world ecosystem.

These principles of data protection, interoperability, interchange and integration with systems operating in industries outside of virtual worlds have been widely adopted by companies and government agencies. To complement this landscape and to provide the target audiences with additional knowledge of standards outside of virtual worlds, the present document includes a dedicated clause on the topic of industry-specific standards. While it is not exhaustive of all standards in all industries, by choosing the top standards in multiple data management domains, it illustrates how deeply standards adoption is woven into the fabric of several leading industries already exploring virtual world use cases. Without integration and adoption of the industry-specific standards that are relevant for a use case, the adoption of virtual world technologies and growth of the ecosystem of virtual world businesses will be slow or fail to thrive.

8 Artificial Intelligence

8.1 Scope

8.1.1 Introduction

Artificial Intelligence in the context of this study refers to 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. AI in virtual world platforms and services lowers the cost and time for producing intelligent, adaptive, and immersive experiences. In combination with other technologies, AI enhances the realism, interactivity, and functionality of immersive experiences by analysing user context from sensor data and other sources, automating content creation, interpreting user inputs, and dynamically responding to real-time changes in the environment.

There are five components defined in this domain.

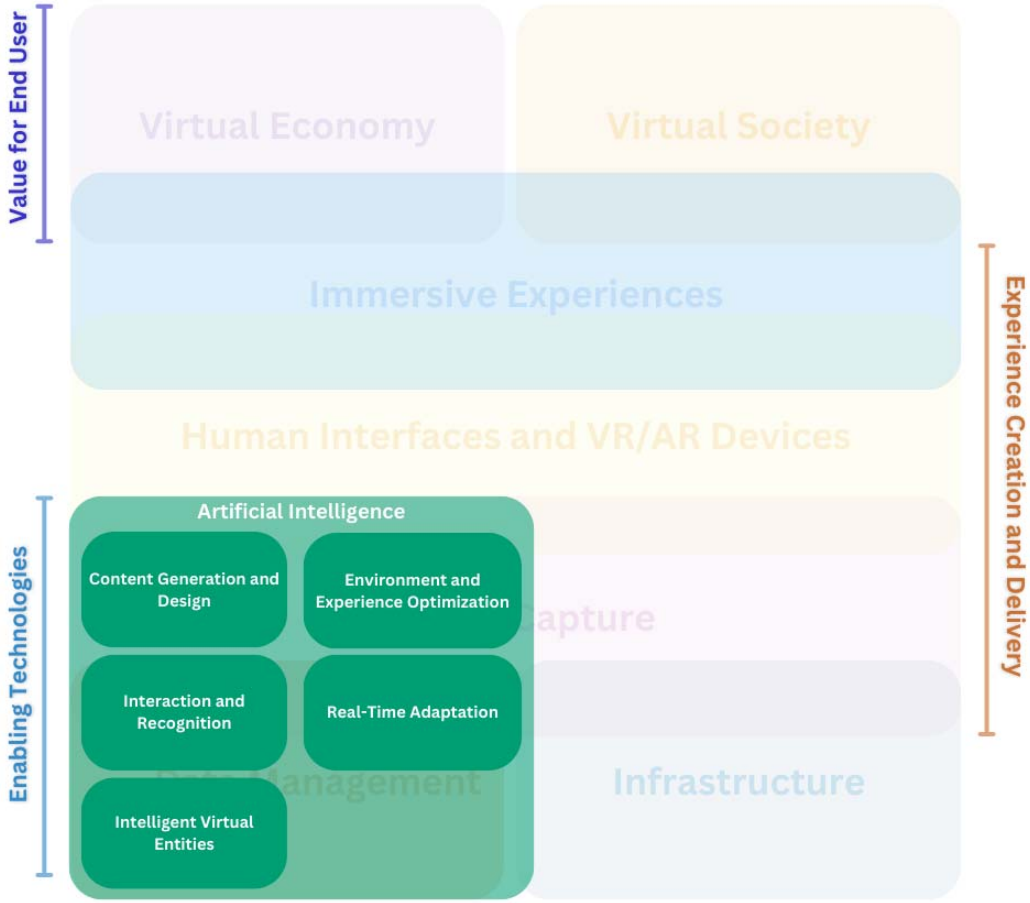

Figure 21: Components of the artificial intelligence domain

These components and the topics they include are described in clauses 8.1.2, 8.1.3, 8.1.4, 8.1.5 and 8.1.6.

8.1.2 AI-powered content generation and design

This component includes AI components, algorithms and technologies used to automatically create and enhance digital assets and other components of immersive experiences. This component includes these topics:

- AI-Driven Asset Generation: Algorithms that automatically generate digital object appearances and behaviours including their visual, auditory and haptic attributes, reducing development time and enabling richer experiences at lower cost than if performed manually.
- AI-Assisted 3D Model Reconstruction: Using AI to convert 2D data (e.g. images or videos) into detailed 3D models for virtual environments.
- Radiance Fields: Technologies that use neural networks for reconstruction of 3D scenes from a partial set of images or points in a 3D space viewed in aggregate.
- Environment Generation: AI-powered systems for creation and maintenance of dynamic and static virtual environments.

8.1.3 AI-powered interaction and recognition

The AI-powered interaction and recognition component includes AI components, algorithms and systems that interpret user behaviour and enhance interactivity. This component includes these topics:

- Machine Learning-Based Gesture, Posture, and Motion Capturing: AI algorithms that analyse body movements, gestures, and postures to provide precise motion tracking for avatars and interactions.

- Natural Language Processing (NLP) for Dialogue-Capable Avatars: AI systems enabling NLP interactions with environments and characters, including supporting avatars or virtual humans to understand and generate human-like dialogue, allowing for natural communication.
- Behaviour and Emotion Recognition: AI systems that analyse and recognize user emotions, facial expressions, voice tone, or body language to interpret and respond to user emotions in virtual worlds.

8.1.4 AI-powered intelligent virtual entities

The AI-powered intelligent virtual entities component includes AI algorithms and systems that create autonomous, adaptive characters and systems. This component includes these topics:

- AI Non-Playable Characters (NPCs): Virtual entities that can autonomously interact with users and adapt their behaviour based on context or goals, such as guides, teammates, or adversaries in XR environments.
- AI-Powered Agents: Intelligent agents designed to provide real-time support, navigation, or task management in XR applications.

8.1.5 AI-assisted environment and experience optimization

The AI-assisted environment and experience optimization component includes AI algorithms and technologies that enhance the functionality and performance of immersive environments. This component includes these topics:

- Crowd Simulation: Systems for realistic simulation of large groups of virtual characters.
- Predictive Analytics for User Behaviour: Using AI to anticipate user actions and tailor virtual world experiences accordingly.
- AI-Based Spatial Understanding: Algorithms that interpret spatial data and user context to refine object placement, navigation, and environmental interactions in virtual worlds or real world in real time.
- Semantic Scene Understanding: AI systems that comprehend the meaning and relationships of objects in spaces.
- Procedural Generation and Optimization: Automating the creation and optimization of virtual world environments or scenarios based on predefined parameters.

8.1.6 Real-time AI-assisted adaptation

The real-time AI-assisted adaptation component includes AI algorithms and systems that dynamically adjust environments to improve realism and usability. This component includes these topics:

- Dynamic Scene Rendering: Tools that adaptively create or modify scenes based on user behaviour or context, such as generating new environments in real-time.
- Adaptive AI Rendering: Algorithms that optimize rendering performance based on device capability and user focus, such as foveated rendering.
- Personalized AI Experiences: Tailoring assets and scenes used in immersive experiences to match individual preferences, behaviours, and learning styles using adaptive AI models.
- AI-Driven Physics: Artificial intelligence systems that manage physics simulations in virtual environments.

8.2 Standards Development Organizations

There are seven different standardization development organizations with working groups contributing to virtual world artificial intelligence standards in the data set. The internationally mandated SDOs have published 10 (approximately one third) out of the 29 standards identified as being relevant for this domain as defined above.

8.3 Standards Working Groups

Standards working groups are the units of a standards development organization that permit stakeholders and experts to contribute to standardization activities. Due to the large number of standards working groups and the detailed information about their year of formation and scope, it is necessary to provide these in a separate file for further study. The file containing descriptions of standards working groups in this domain are in a spreadsheet with the title "Top_standards_working_groups_in_artificial_intelligence_domain.xlsx" contained in archive gr_arf010v020101p0.zip.

8.4 Standards

Figure 22 shows the number of standards with the highest rankings in the artificial intelligence domain topics, that are published by the seven most prolific standards development organizations. This includes standards in the data set for artificial intelligence topics that are relevant to some stakeholders, however, do not rise to the highest ranking needed to be included in the table of top standards.

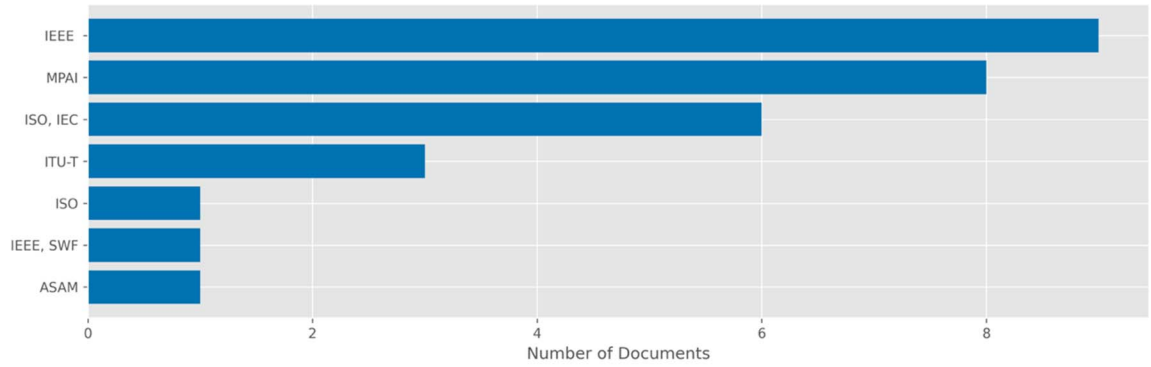

Figure 22: Number of standards published on the artificial intelligence domain by top seven SDOs

Due to the very large size of the data set and the details available for further study, the table containing information about the top standards in the virtual worlds artificial intelligence domain is provided as a spreadsheet with the title "Top_standards_in_artificial_intelligence_domain.xlsx" contained in archive gr_arf010v020101p0.zip.

8.5 Technical Reports

Figure 23 shows the number of technical reports with the highest ranking in the artificial intelligence domain topics, published by the seven most prolific standards development organizations.

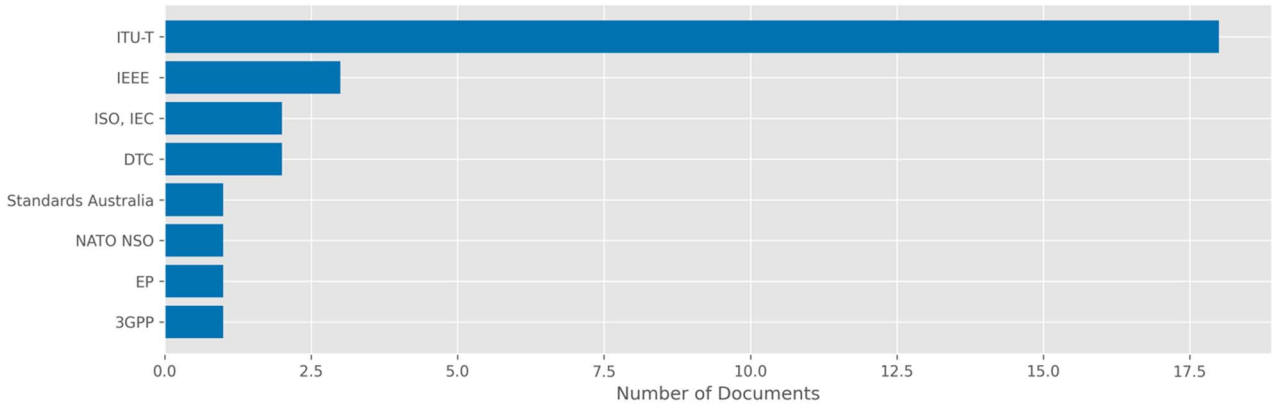

Figure 23: Number of technical reports published on artificial intelligence domain by top seven SDOs

Due to the very large size of the data set and the details available for further study, the table containing information about the top technical reports in the virtual worlds artificial intelligence domain is provided as a spreadsheet with the title "Top_technical_reports_in_artificial_intelligence_domain.xlsx" contained in archive gr_arf010v020101p0.zip.

8.6 Conclusions

By comparison with other domains, the domain of artificial intelligence in virtual worlds is relatively new. The rapidly evolving technologies and the challenges facing many of the stakeholders in this segment of the ecosystem prevent there from being a high number of published standards and technical reports. Nevertheless, there are many use cases and demonstrations to support the suggestion that artificial intelligence will play an important role in the success of virtual worlds.

It is evident from the data set for this project that there are efforts to gather requirements for possible interoperability standards for artificial intelligence, however, it is too early for there to be representatives of all the ecosystem segments involved in these efforts, and most of the technology innovators are investing heavily in innovation for the purpose of differentiation, not investing in standardization activities at the time of this project.

This domain will need to be carefully monitored for new developments and to align both requirements for virtual world technological innovation and the preservation of societal values.

9 Reality Capture

9.1 Scope

9.1.1 Introduction

Reality capturing refers to the process of digitizing physical environments, objects, humans and their interactions for further use in immersive, interactive, and virtual representations or by agents. 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. Reality capturing serves as the foundation for creating accurate and context-aware immersive experiences. It can happen in real time, for the purpose of context or situational awareness, as well as prior to experience design or delivery.

There are three components defined in this domain.

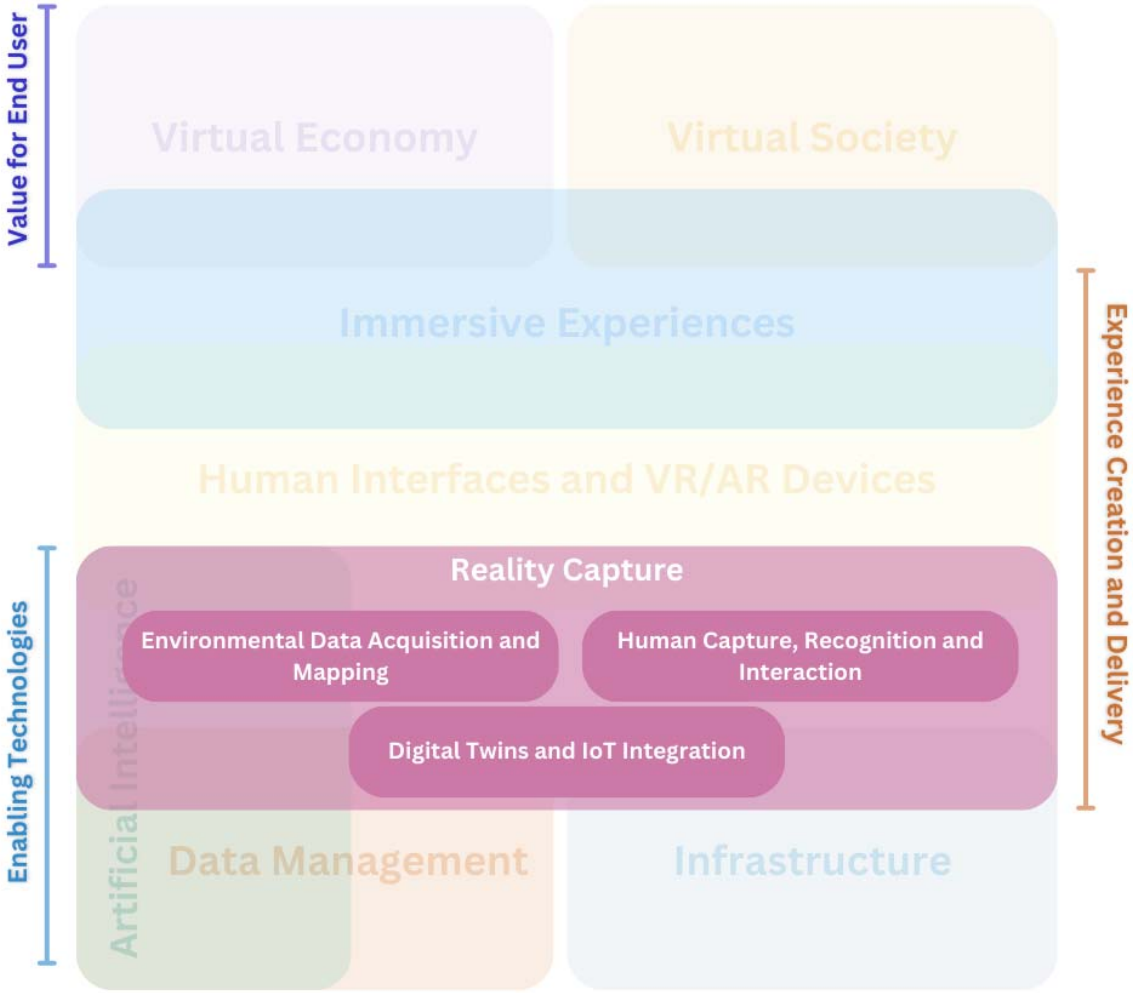

Figure 24: Components of the reality capture domain

These components and the topics they include are provided in clauses 9.1.2, 91.3 and 9.1.4.

9.1.2 Environmental data acquisition and mapping

This component covers all technologies used to capture spatially anchored or defined visual, auditory and haptic information about physical environments. This component includes these topics:

- Reality Capture Pipeline: End-to-end process for capturing, processing, and integrating real-world data into many other virtual world workflows.
- Spatial Mapping: Technologies that digitize 3D physical environments and are capable of anchoring the results in a coordinate reference system.
- Photogrammetry: Techniques for measuring characteristics of and relationships between real world objects in a mesh from images. Applied in different scales:
  - Aerial Photogrammetry: Capturing large-scale environments using drones or aircraft.
  - Terrestrial Photogrammetry: Ground-based imaging for detailed object and environment reconstruction.
  - Close-Range Photogrammetry: High-precision modelling of small objects or intricate details.
- Cameras: Devices for recording light signals emitting from objects and surfaces:
  - Monocular: A single lens used to detect and/or capture images and video.

  - Stereoscopic: Two or more lenses with separate image sensors or film frame for each lens, permitting.
  - Plenoptic: Multi-camera synchronized systems that capture the intensity and chromaticity of light observed from every position and direction in a 3D space.
- Volumetric Capture: Systems capturing real-time 3D recordings of any items in the real world for use in virtual environments.
- Spatial Audio: Use of microphones and special acoustic recording techniques to capture mono, stereo or ambisonic audio signals.
- Olfactory Sensing: Systems that capture particles in user proximity and use these to assess any scents as part of a user's context.

9.1.3 Human capture, recognition and interaction

Human capture, recognition and interaction systems capture and interpret human actions, gestures, and expressions in real time and serve as input for immersive experiences. This component includes these topics:

- Emotional Response Mapping: Systems that track and replicate subtle emotional expressions in virtual avatars.
- Body Scanning: Use of sensors to generate data with which to synthesize a 3D model of a user for simulation.
- Gesture and Action Capture Systems: Technologies that capture and classify hand and body movements for natural, touchless interactions.
- Face Recognition Systems: Tools that detect and analyse facial features for authentication, emotion recognition, or avatar representation.
- User Context: User's conditions in space and/or time that directly or indirectly, influence or shape perception, engagement and interaction with real or digital elements in a virtual experience.

9.1.4 Digital Twins and Internet of Things integration

This component incorporates any type of data received from connected devices and sensors and enhances the fidelity and interactivity of immersive experiences. This component includes these topics:

- Digital Twin: Digital and dynamic representations of real-world entities, systems, or processes created using data to reflect, simulate their behaviour and interactions in real time. Includes the control and management of actuators which can bring about changes in real world objects.
- Internet of Things (IoT): Real-time data collection and integration from smart, connected devices, such as temperature sensors, motion detectors, and cameras, to provide contextual awareness for uses in immersive experiences and environments.

9.2 Standards Development Organizations

There are 15 different standardization development organizations with working groups contributing to virtual world reality capture standards in the data set. The internationally mandated SDOs have published 38 (approximately one third) out of the 88 standards identified as being relevant for this domain as defined above.

9.3 Standards Working Groups

Standards working groups are the units of a standards development organization that permit stakeholders and experts to contribute to standardization activities. Due to the large number of standards working groups and the detailed information about their year of formation and scope, it is necessary to provide these in a separate file for further study. The file containing descriptions of standards working groups in this domain are in a spreadsheet with the title "Top_standards_working_groups_in_reality_capture_domain.xlsx" contained in in archive gr_arf010v020101p0.zip.

9.4 Standards

Figure 25 shows the number of standards with the highest rankings in the reality capture domain topics, that are published by the seven most prolific standards development organizations. This includes standards in the data set for reality capture topics that are relevant to some stakeholders, however, do not rise to the highest ranking needed to be included in the table of top standards.

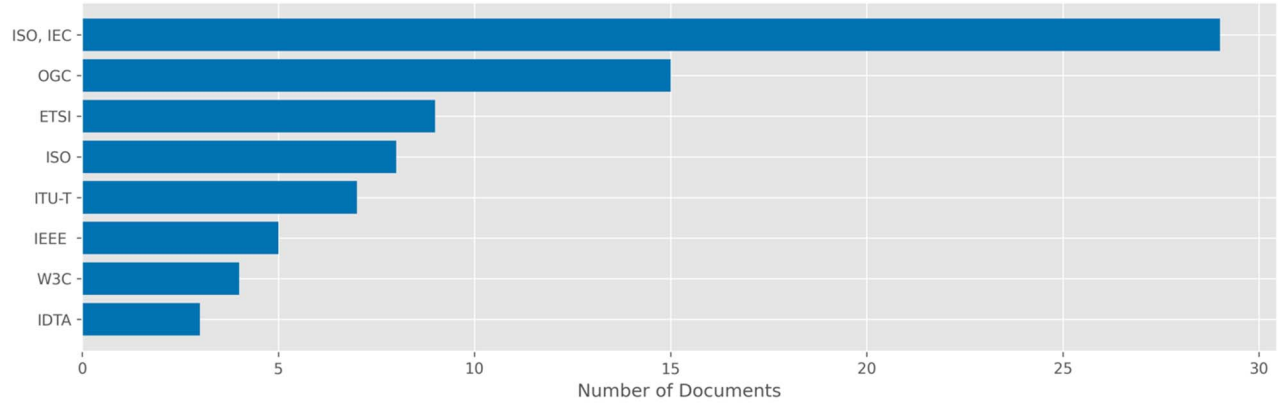

Figure 25: Number of standards published in the reality capture domain by top seven SDOs

Due to the very large size of the data set and the details available for further study, the table containing information about the top standards in the virtual worlds reality capture domain is provided as a spreadsheet with the title "Top_standards_in_reality_capture_domain.xlsx" contained in archive gr_arf010v020101p0.zip.

9.5 Technical Reports

Figure 26 shows the number of technical reports with the highest ranking in the reality capture domain topics, published by the seven most prolific standards development organizations.

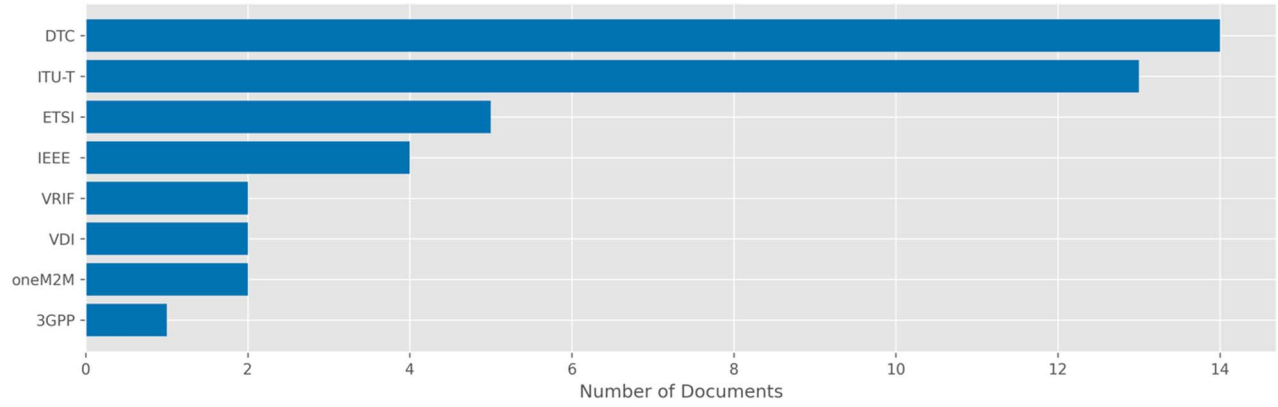

Figure 26: Number of technical reports published on reality capture domain by top seven SDOs

Due to the very large size of the data set and the details available for further study, the table containing information about the top technical reports in the virtual worlds reality capture domain is provided as a spreadsheet with the title "Top_technical_reports_in_reality_capture_domain.xlsx" contained in archive gr_arf010v020101p0.zip.

9.6 Conclusions

In some form, reality capture began with cave dwellers thousands of years ago. In modern times it began in Burgundy, France in 1826 when Joseph Nicéphore Niépce used a heliographic camera to take the world's first photograph. A lot has changed in two hundred years, and many things remain to be defined for the purpose of using reality capture in virtual worlds.

It is clear from the data set and expert knowledge in the field that many standards already exist and are widely adopted. For decades, ISO/IEC JTC1 Subcommittee 29 has dominated standardization activities in this field. The SC 29 standardization approach is as complete as possible, covering everything after the acquisition of the data, defining the encoding, file formats as well as data compression (and decompression). Its standards include the JPEG suite of standards for digital image data compression, .mp3 for audio compression and .mp4 as well as many other standards for video searching and management. SC 29 working groups involve and receive contributions from many leading technology companies and their efforts are aligned with industry direction.

EXAMPLE: SC 29 working groups have been working on and lead in the standardization of volumetric media types.

For this project, the acquisition of data about the real world is also important because it is happening very quickly using cameras from many new and diverse, including stereoscopic, points of view. Considering only cameras as an acquisition device, there are several active industry-driven groups standardizing the physical interfaces between the components and the calibration of the sensor. There is also active development of an application programming interface standard for the purpose of abstracting the detection of camera features and their control from the actual hardware, reducing the need for software developers to have intimate knowledge of camera intrinsics to use the camera.

Reality capture is also using new enabling technologies. Sensor technology is rapidly getting smaller and using lower power. Sensors are continuously providing new data about depth (distance from a detection point), vibration, velocity, pressure, temperature and other parameters of the world.

In the context of the present document and for the goals of this project, the standards for acquiring information about the real world that can be stored in digital formats for use in virtual worlds are, by comparison with infrastructure and data management domains, relatively immature. As noted above, this is due in part to the rapid pace of research, development and innovation in the field.

In addition to rapid innovation, one of the barriers to rapid standardization of reality capture is the right to privacy. Since the data may include personally identifiable information, the capturing device user may carry some responsibility for its safe use.

Despite these challenges, reality capture is a very promising field for future standardization activities. When more enabling technology advances are made and societal challenges are balanced with benefits, when the data are discoverable, accessible, efficiently compressed and transported between devices and analysed at low cost and risk, virtual worlds stakeholders will find many new ways to use reality capture.

10 Human Interface Systems and Devices

10.1 Scope

10.1.1 Introduction

Virtual world human interfaces are integrated systems of hardware and software components. 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. These systems enable users to perceive, navigate, and interact with digital content and other entities in intuitive and engaging ways, bridging the physical and virtual worlds to create seamless experiences.

There are five components defined in this domain.

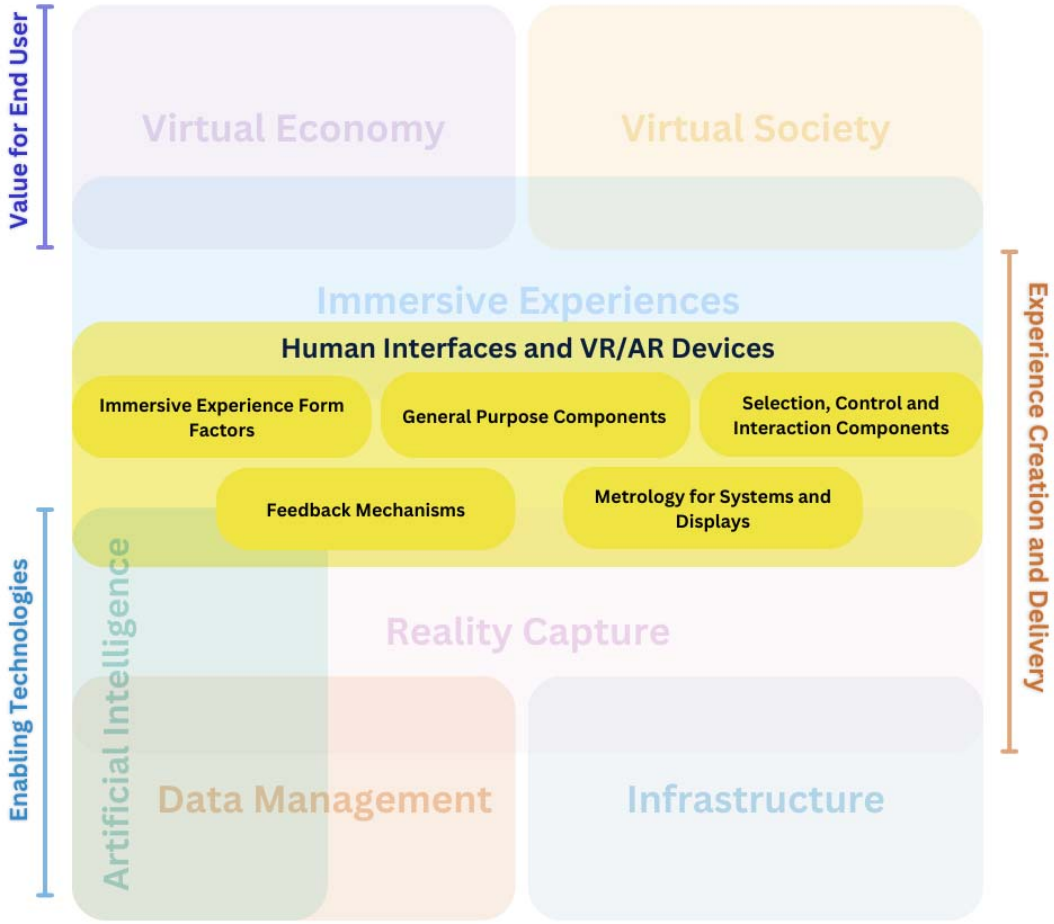

Figure 27: Components of the human interface systems and devices domain

These components and the topics they include are provided in clauses 10.1.2, 10.1.3, 10.1.4, 10.1.5 and 10.1.6.

10.1.2 Immersive experience form factors

There are many ways to integrate virtual world technologies such as sensors and displays into devices and environments that support the users' ability to consume, experience and interact with assets and other users in virtual worlds and/or in mixed physical-digital modality. This component includes these topics:

- Walk-in: Purpose-built spaces into which users enter for 3 dimensional experiences, including in some cases, audio, vibration, temperature and other signals detectable by user senses, in addition to vision.
- Projection Systems: Hardware that can be oriented to focus light on surfaces or in space. includes table-top systems, heads-up displays in automobiles and volumetric displays for multi-angle viewing without headsets.
- Hand-held: Smartphones and tablets that users hold or put in a support to consume immersive experiences on a screen.
- Head-worn: Devices that include a frame for resting on the user's head, nose and/or ears to provide visuals, including monocular systems for delivery of text in nearfield view and stereoscopic displays for 3D depth, usually with audio.
- Tethered Systems: A cable connects two or more components of a complete immersive experience system to distribute essential resources such as computational processing and power.
- Field of View: Extent of a user's observable world as provided by the device or display. Determined by optical and screen properties.

10.1.3 General purpose components

A delivery platform or device always includes some parts without which the user is unable to consume virtual world and immersive experiences. This component includes these topics:

- Sensors: Devices such as LiDAR sensors, motion trackers, microphones, cameras and molecular particle capture technologies (e.g. for olfactory) that acquire signals from the user's spatial environment and interactions and send the data into device processing and interaction systems.
- Application Programming Interfaces: Software that describes and permits access between the capabilities of an underlying or superior layer of technology, receives and sends requests between components in a manner that is predictable and consistent.
- Memory: Local data storage capacity used by sensors, applications and processors performing calculations and other required processes.
- Optics and Displays: Technologies that emit, focus, combine and disperse light beams by various means, and surfaces that reflect, magnify and diffract light into the user's eyes to produce immersive experiences.
- Data Processing: General purpose processors, Graphics Processing Units (GPUs) and other types of specialized processors incorporated into a display for executing software and generating immersive experiences.
- Frames, Brackets: Support structures into which optics, displays, microphones, cameras, processors, batteries and other components are attached or integrated.
- Power supply and storage: Technologies to supply and store electricity for use by other device or system components.

10.1.4 Selection, control and interaction components

In addition to general purpose, there can be elements of a delivery platform that support user's ability to select, control, navigate and interact with assets or spaces in virtual world experiences. This component includes these topics:

- Spatial Computing: Computing that uses space as an interface, enabling interaction with digital content in three dimensions.
- Speech Detection: Microphone and software for processing audio signals, usually commands, spoken by a user.
- Real or Simulated Keyboard: Surface with keys or projected in the user's field of view on which a user can enter text.
- 3D Controllers: Handheld or head worn devices that allow precise interaction with virtual objects using motion tracking and buttons.
- Hand and Gesture Tracking: Systems using cameras or sensors to detect and interpret hand movements for touchless interactions.
- Face and Eye Tracking: Technology that monitors gaze direction and facial expressions, useful for simulating natural navigation and adaptive rendering.
- Motion Capture: Tracking systems that detect and record (or mimic) user movements, gestures, and expressions in virtual environments.
- Multimodal Interaction: Combined use of multiple input methods (voice, gesture, touch) in virtual environments.

10.1.5 Feedback mechanisms

Optional components which, when integrated in a full immersive experience delivery system, automatically communicate with users about changes in status. This component includes these topics:

- Optical: Signals using light to transmit text or symbols to communicate achievement or current conditions to the user during an immersive experience.
- Auditory: Signals using sounds to communicate achievement or current conditions to the user during an immersive experience.
- Haptic: Devices like gloves, suits, or handheld tools that simulate touch, vibration, or pressure to replicate real-world sensations.
- Tactile: Mechanisms that provide physical responses to user interactions, such as button presses or simulated textures and vibrations.
- Cognitive Load Balancing and Optimization: Design principles and systems that dynamically adjust visual and interactive complexity based on user attention and processing capacity to reduce mental load.
- Spatial Audio Propagation: Advanced audio systems that simulate sound wave behaviour and acoustics in virtual spaces.
- Biometric Feedback: Systems that adjust virtual experiences based on users' physiological responses. This includes systems such as Brain-Computer interfaces.

10.1.6 Metrology for systems and displays

This component covers all technologies used for the measurement, calibration and validation of virtual world human interaction system characteristics to study and improve how users perceive and interact with digital content, ensuring accurate rendering, perceptual realism, and user comfort.

10.2 Standards Development Organizations

There are 31 different standardization development organizations with working groups contributing to virtual world human interface systems and devices standards in the data set. The internationally mandated SDOs have published 112 out of the 183 standards identified as being relevant for this domain as defined above.

10.3 Standards Working Groups

Standards working groups are the units of a standards development organization that permit stakeholders and experts to contribute to standardization activities. Due to the large number of standards working groups and the detailed information about their year of formation and scope, it is necessary to provide these in a separate file for further study. The file containing descriptions of standards working groups in this domain are in a spreadsheet with the title "Top_standards_working_groups_in_human_interface_systems_and_devices_domain.xlsx" contained in the archive gr_arf010v020101p0.zip.

10.4 Standards

Figure 28 shows the number of standards with the highest rankings in the human interface systems and devices domain topics, that are published by the seven most prolific standards development organizations. This includes standards in the data set for human interface systems and device topics that are relevant to some stakeholders, however, do not rise to the highest ranking needed to be included in the table of top standards.

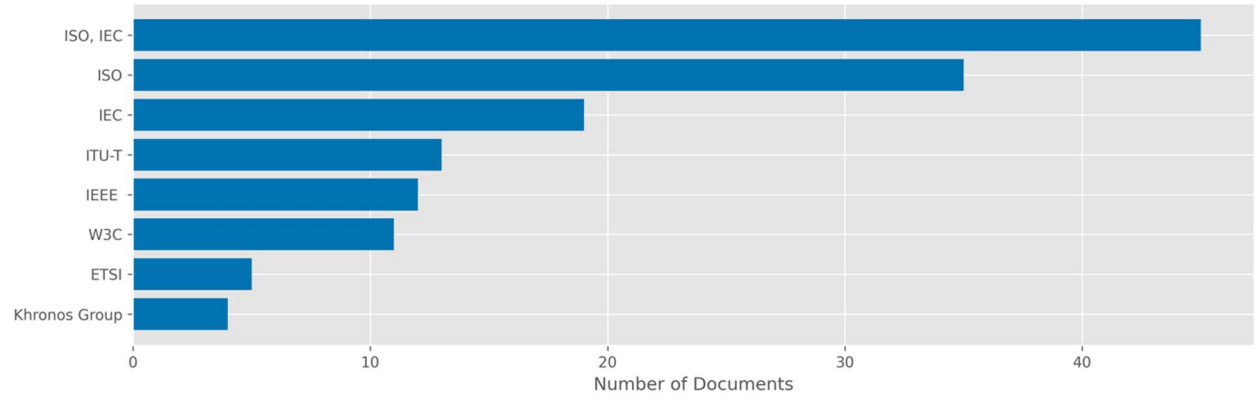

Figure 28: Number of standards published in the Human Interface Systems and devices domain by top seven SDOs

Due to the very large size of the data set and the details available for further study, the table containing information about the top standards in the virtual worlds human interface systems and devices domain is provided as a spreadsheet with the title "Top_standards_in_human_interface_systems_and_devices_domain.xlsx" contained in archive gr_arf010v020101p0.zip.

10.5 Technical Reports

Figure 29 shows the number of technical reports with the highest ranking in the human interface systems and device domain topics, published by the seven most prolific standards development organizations.

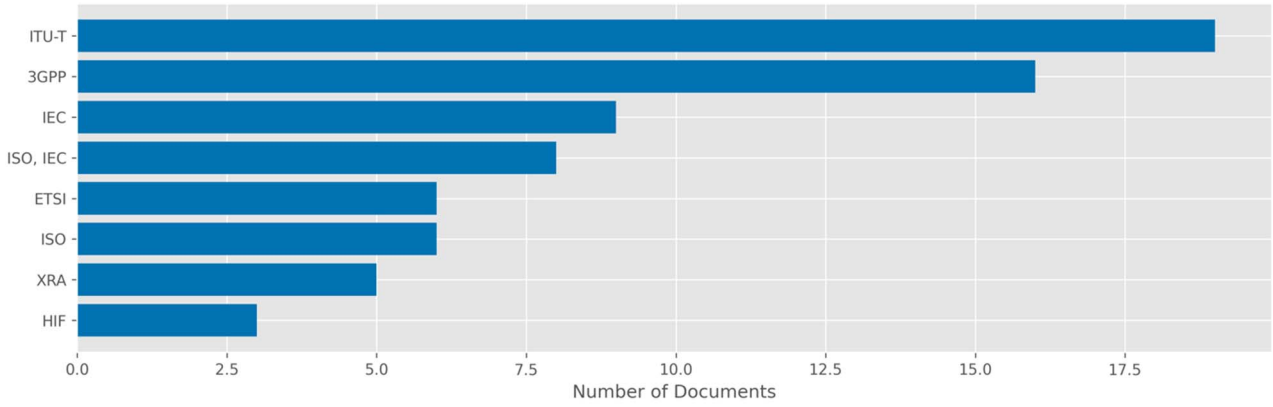

Figure 29: Number of technical reports published on human interface systems and device domain by top seven SDOs

Due to the very large size of the data set and the details available for further study, the table containing information about the top technical reports in the virtual worlds human interface systems and devices domain is provided as a spreadsheet in file "Top_technical_reports_in_human_interface_systems_and_devices_domain.xlsx" contained in archive gr_arf010v020101p0.zip.

10.6 Conclusions

Human interface systems and devices are rapidly evolving: every month there are new types of displays for delivering virtual world experiences and the providers of existing virtual world displays are introducing new features to attract customers and encourage developers. The features of highest interest to users and developers include higher display resolution, field of view, rendering power and robustness, while also reducing weight, power consumption and price.

In addition to the largest technology companies introducing new features and options for their products, there are many companies that have offered fully integrated human interface systems and devices in past years who were unsuccessful to gain market traction sufficient to be economically viable. Some of these virtual world investors and stakeholders may view standardization activities as being orthogonal to commercial success. Devices are a way for manufacturers to create customer lock-in. However, a case may be made that the adoption of standards can become a key enabler for companies seeking to find their unique value proposition in the ecosystem without needing to re-invent components and technologies that are stable and well understood.

Providing guidance on the positioning of standards as a strategic enabler of a successful long-term investment in human interface systems and devices is not within the scope or purpose of the present document. It is more likely that specific standards development organizations will need to take the leadership role in educating one or more virtual world segments about how and which standards would best serve a company's specific needs.

11 Immersive Experiences

11.1 Scope

11.1.1 Introduction

In the present document the term "immersive experiences" refers to 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. These experiences engage users through sensory inputs (e.g. visual, auditory, haptic, olfactory) 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.

There are five components of immersive experience domain.

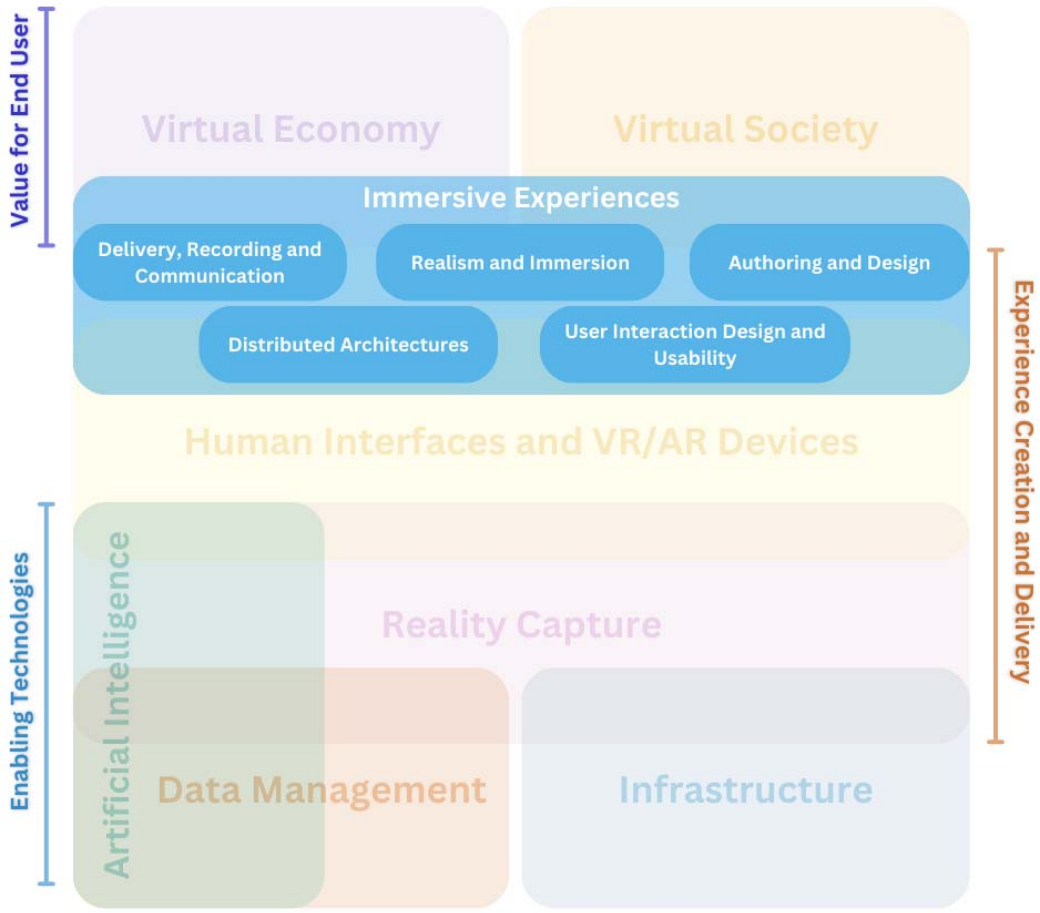

Figure 30: Components of the immersive experiences domain

They are described in clauses 11.1.2, 11.1.3, 11.1.4, 11.1.5 and 11.1.6.

11.1.2 Delivery, recording and communication

Software for the purpose of producing and recording immersive experiences in virtual worlds and mixed digital-real environments is the core of this component. It includes real time transmission of bi-directional 2- or 3-dimensional representations of and to users. This component includes these topics:

- Applications and Runtime Engines: Software and frameworks that when executed on a human interface device assemble components necessary to produce visual, auditory or haptic sensations defined by creators using an authoring environment and compiled to deliver the immersive experience to a user in real time.
- Middleware: Software running at an abstraction layer enabling operating system- and hardware-agnostic immersive experiences.
- Avatars: Digital representations of individuals or entities used to interact with virtual and mixed real-digital environments. They range from simple 2D icons to complex, customizable 3D humanoid models.
- Identity Expression: Personalization of avatars to reflect user preferences.
- Social Interaction: Enabling collaboration and communication in virtual spaces.
- Experience Recording and Playback: Tools and platforms enabling the capture and replay of scenes and actors, including their movement and interactions in virtual worlds.
- Telepresence and Teleportation: Real time interactive experiences between two or more entities connected over a network in which the live video or 3D scan of the user (teleportation) is perceived both visually and with audio by others in the experience.

11.1.3 Realism and immersion

This component is composed of protocols, formats, software tools and systems used to create, describe, manipulate, and render signals of three-dimensional objects, scenes and environments, enabling sensory-rich and immersive experiences that permit suspension of disbelief by mimicking and/or interacting with real world properties. This component includes these topics:

- Scene Description: Protocols, formats and ontologies to describe some or all elements in an immersive experience.
- Ambient Intelligence: Systems that adapt virtual environments based on user presence and behaviour patterns.
- Depth Perception: Techniques for measuring the distances between users and elements in a scene to reduce risks of asset obstruction and collisions.
- Real-Time and Stereoscopic Rendering: Generating shapes, sounds and tactile signals (touch) to enhance users' depth and 3D perception of digital assets through their visual, auditory and haptic senses.
- Physics Engine: Software systems for simulating physical world properties of any object or elements in an immersive experience.
- Animation Engine: Software systems for natural movement of digital objects including but not limited to avatars, in an immersive experience.
- Procedural Modelling: Algorithmic generation of 3D environments and objects.
- Dynamic Lighting and Visual Effects: Enhancing realism with techniques like ray tracing, radiance field technologies and global illumination.

11.1.4 Authoring and design

Software tools and technologies for creating, prototyping and compiling software for immersive experience delivery are the focus of this component. This component includes these topics:

- Asset Creation Pipeline: Workflow systems for developing and importing 3D assets into virtual environments.
- Authoring Platforms: Any software for designing visual, auditory and haptic assets and defining their behaviours for immersive experiences, including Software Development Kits or Frameworks, Application Programming Interfaces or Low Code/No Code platforms.
- Spatial Mapping, Experience Triggering and Optimization: Tools for managing spatial maps, spatial anchoring, visual positioning and programming of human-asset interactions, and performance within a 3D coordinate reference system.
- Collaborative Prototyping: Platforms allowing individuals or teams to iterate efficiently on the development of immersive and virtual world assets, tools and experiences.

11.1.5 Distributed architectures

This component includes all technologies and interfaces supporting the delivery of immersive experiences residing on two or more network-connected resources, ensuring distribution of computational resources, storage capacity and power consumption for scalability and reliability. This component includes these topics:

- Experience streaming: Protocols permitting experiences to include assets, scenes or environments originating from a server or headset and being transmitted in real time to another device such as a headset, or other display form factor.
- Hosted Experiences: Assets, scenes and interactions that remain active and accessible even when users log off, fostering ongoing interactions and economies.
- Synchronization Mechanisms: Systems to ensure consistency across two or more projectors, devices and users in collaborative XR experiences.

11.1.6 User interaction design and usability

Guidelines, frameworks and tests are used by experience developers to ensure consistent, intuitive, responsive, safe and accessible interactions in immersive environments, including interaction paradigms, interaction patterns and interaction metaphors. This component includes these topics:

- Control Components: Elements in an immersive experience user interface that permit the user to activate or deactivate features or to adjust parameters for their unique requirements or use cases, regardless of the display device or creator's authoring environment.
- Interaction Tracking: Tools that monitor and refine user inputs and interaction patterns, improving responsiveness and usability.
- Spatial Interface: User interface design principles specific to three-dimensional virtual spaces and interactions.
- User Profile Tracking: Monitoring user interactions, preferences, and engagement to enable personalized experiences and performance optimization.
- Usability Metrics: Methods and metrology for capturing user behaviours and feedback in order to evaluate and enhance user experience, including experience usability, safety, comfort, engagement, and satisfaction.

11.2 Standards Development Organizations

There are 36 different standardization development organizations with working groups contributing to virtual world immersive experiences standards in the data set. The internationally mandated SDOs have published 165 out of the 268 standards identified as being relevant for this domain as defined above.

11.3 Standards Working Groups

Standards working groups are the units of a standards development organization that permit stakeholders and experts to contribute to standardization activities. Due to the large number of standards working groups and the detailed information about their year of formation and scope, it is necessary to provide these in a separate file for further study. The file containing descriptions of standards working groups in this domain are in a spreadsheet with the title "Top_standards_working_groups_in_immersive_experiences_domain.xlsx" contained in archive gr_arf010v020101p0.zip.

11.4 Standards

Figure 31 shows the number of standards with the highest rankings in the immersive experiences domain topics, that are published by the seven most prolific standards development organizations. This includes standards in the data set for immersive experiences topics that are relevant to some stakeholders, however, do not rise to the highest ranking needed to be included in the table of top standards.

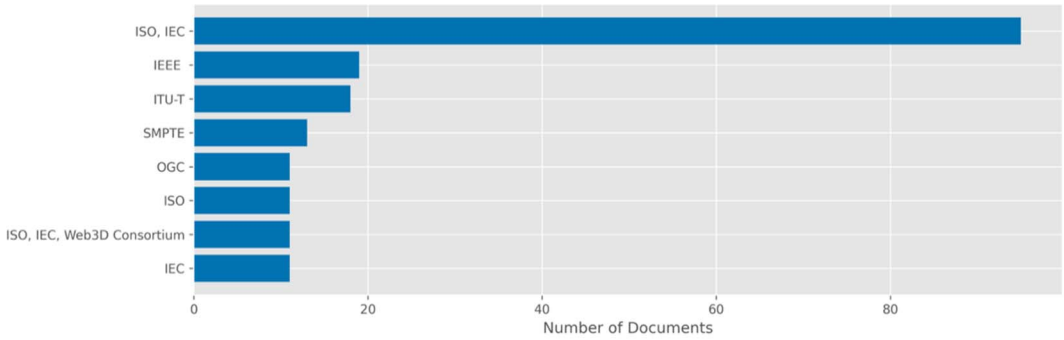

Figure 31: Number of standards published in the immersive experiences domain by top seven SDOs

Due to the very large size of the data set and the details available for further study, the table containing information about the top standards in the immersive experiences domain is provided as a spreadsheet in file "Top_standards_in_immersive_experiences_domain.xlsx" contained in archive gr_arf010v020101p0.zip.

11.5 Technical Reports

Figure 32 shows the number of technical reports with the highest ranking in the immersive experiences domain topics, published by the seven most prolific standards development organizations.

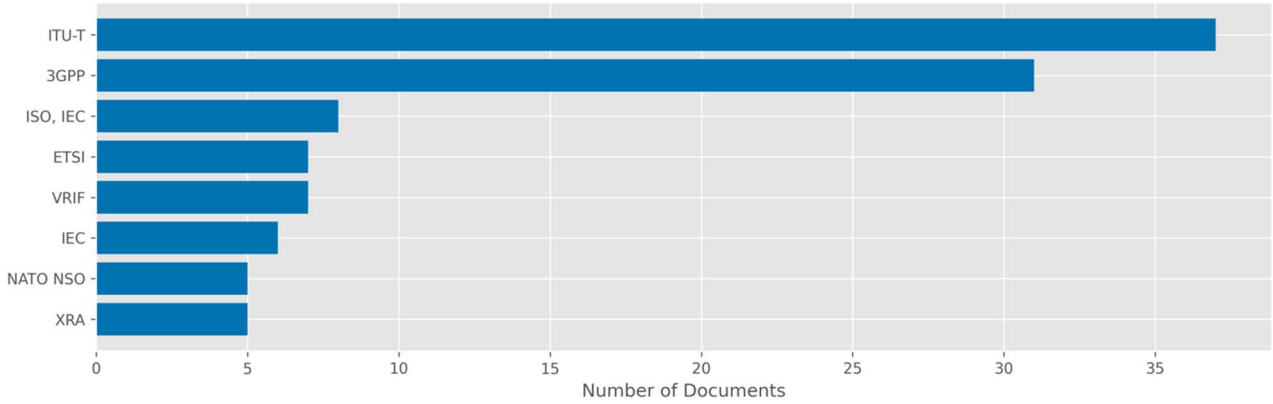

Figure 32: Number of technical reports published on immersive experiences domain by top seven SDOs

Due to the very large size of the data set and the details available for further study, the table containing information about the top technical reports in the immersive experiences domain is provided as a spreadsheet with the title "Top_technical_reports_in_immersive_experiences_domain.xlsx" contained in archive gr_arf010v020101p0.zip.

11.6 Conclusions

Two hundred and sixty-eight standards relevant to the immersive experiences domain are documented in the data set created for the present document. In addition, there are over a hundred technical reports about this domain. One of the patterns that emerges from their study is that the use cases and tools for developing experiences are highly diverse. The content developers most frequently involved in the creation of experiences are the ecosystem segment most directly impacted by the adoption (or the lack of) standards yet this group has not shown a strong interest in interoperability or invested in standardization activities [i.12]. Just learning to use their tools and study the requirements of their users is an important investment.

Engaging with and contributing to standardization activities is time consuming and involves learning the specific vocabulary and procedures of standards development organizations, competing with the time they might invest in their passions and delivering value for end users or customers. In other words, most content creators are more interested in experimentation with the technologies than taking on the overhead of standardization. In their place, academics studying this community of creators and user interaction paradigms have both the mandate and the financial support from projects and institutions for this activity. Therefore, many immersive experiences standards working groups are led by the academic research community. Until this group of standardization experts is ready to take on the task of technology transfer and evangelizing standardization to tools communities and their customers, the standards are likely to remain dormant at best or superseded by changes in usage trends.

12 Virtual Society

12.1 Scope

12.1.1 Introduction

A virtual society is composed of communities of individuals and organizations who share common interests and interact, collaborate, and engage in shared social activities within immersive environments or in the real world with assistance of immersive interfaces. A virtual society operates under social norms, governance structures, and ethical frameworks, often mirroring or adapting elements from physical societies.

There are three components in this domain.

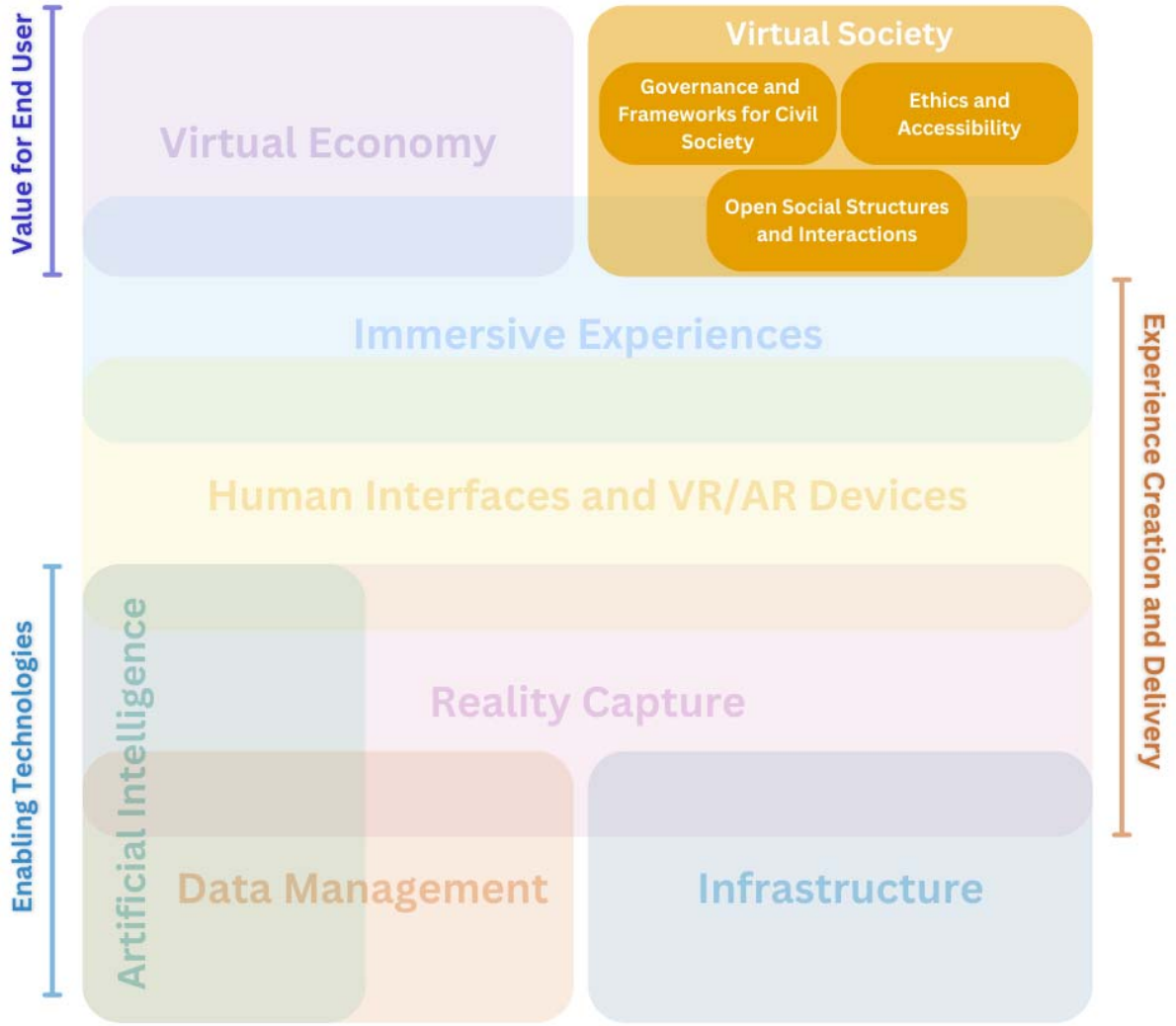

Figure 33: Components of the virtual society domain

They are described in clauses 12.1.2, 12.1.3 and 12.1.4.

12.1.2 Governance and frameworks for civil society

The adaptation or mirroring of physical-world legal principles in virtual environments is important to ensure legitimacy and accountability, such as enforcing property rights, citizenship, privacy laws, and due process. This component includes these topics:

- Digital Citizenship: Rights and responsibilities of individuals within virtual worlds, including behavioural standards and participation in virtual communities.
- Personal Identity Management: Secure data storage and editing systems for verifying and managing digital identities, preferences, avatars, and roles within society and across virtual platforms.
- Privacy Protection: Mechanisms that empower individuals to control who can access their personal and behavioural data within virtual environments, ensuring secure and ethical use.
- Protection Against Discrimination: Detection and means of preventing or correcting conditions that lead to discrimination on the basis of nationality, age, gender, language, sexual orientation or any other identifiable attributes of virtual world users.
- Right to Be Forgotten: The ability for users or avatars to erase their digital trail, maintaining autonomy and control over their participation in the virtual world.
- Data Sovereignty: Legal frameworks governing data ownership and control in virtual environments.

12.1.3 Ethics and accessibility

This component is for the guidelines for responsible behaviour, ensuring fairness, respect, and equality within the society. This component includes these topics:

- Anti-Harassment Standards: Policies and enforcement mechanisms to protect individuals from abusive or harmful behaviour, promoting inclusivity and safety in virtual communities.
- Age-appropriate guardrails: Systems to permit the definition and enforcement of terms and conditions related to the age of any user engaging in virtual world activities.
- Accessibility: Ensuring that virtual societies are inclusive and usable for individuals with diverse abilities and needs.

12.1.4 Open social structures and interactions

The tools and processes that foster engagement between users for a healthy and diverse society are the centre of this component. This component includes these topics:

- Community Development and Management: Platforms for users to engage in social networks, virtual neighbourhoods, and collaborative spaces for learning, education and entertainment.
- Social Graph Visualization: Systems for mapping and visualizing social connections and interactions in virtual spaces.
- Social Presence: The degree to which users feel psychologically present and connected with others in virtual environments.
- Cultural Representation: Ensuring diversity and inclusive representation of cultures, genders, languages, religious identities, and perspectives within virtual environments.
- Shared Experiences: Facilitating experiences, such as virtual conferences, concerts, or collaborative projects, for the purpose of strengthening social bonds and entertainment.

12.2 Standards Development Organizations

There are 18 different standardization development organizations with working groups contributing to virtual world virtual society standards in the data set. The internationally mandated SDOs have published 24 out of the 59 standards identified as being relevant for this domain as defined above.

12.3 Standards Working Groups

Standards working groups are the units of a standards development organization that permit stakeholders and experts to contribute to standardization activities. Due to the large number of standards working groups and the detailed information about their year of formation and scope, it is necessary to provide these in a separate file for further study. The file containing descriptions of standards working groups in this domain are in a spreadsheet with the title "Top_standards_working_groups_in_virtual_society_domain.xlsx" contained in archive gr_arf010v020101p0.zip.

12.4 Standards

Figure 34 shows the number of standards with the highest rankings in the virtual society domain topics, that are published by the seven most prolific standards development organizations. This includes standards in the data set for virtual society topics that are relevant to some stakeholders, however, do not rise to the highest ranking needed to be included in the table of top standards.

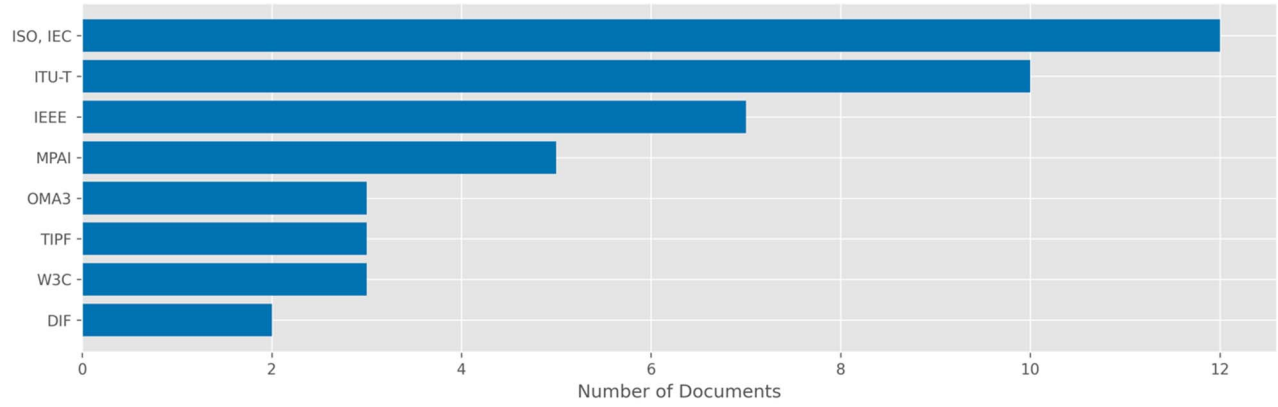

Figure 34: Number of standards published in the virtual society domain by top seven SDOs

Due to the very large size of the data set and the details available for further study, the table containing information about the top standards in the virtual society domain is provided as a spreadsheet with the title "Top_standards_in_virtual_society_domain.xlsx" contained in archive gr_arf010v020101p0.zip.

12.5 Technical Reports

Figure 35 shows the number of technical reports with the highest ranking in the virtual society domain topics, published by the seven most prolific standards development organizations.

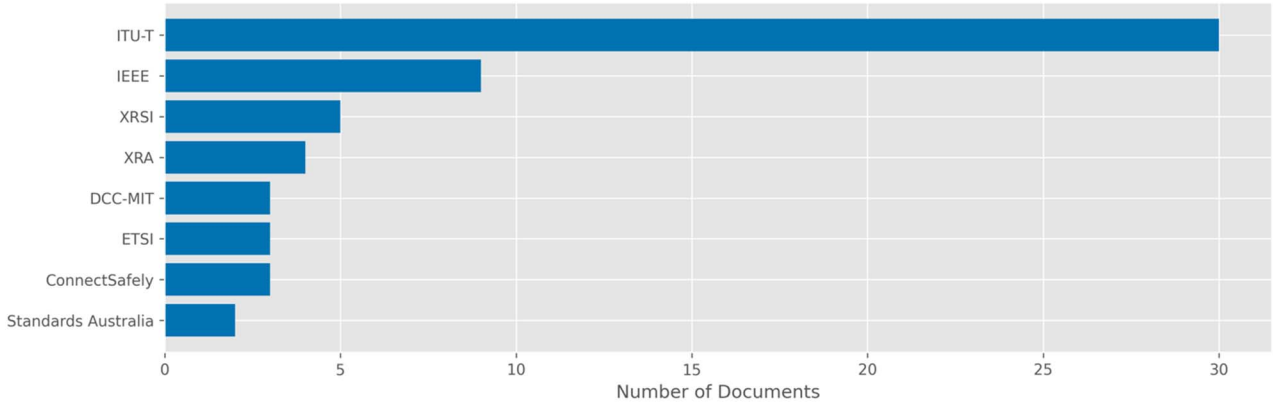

Figure 35: Number of technical reports published on virtual society domain by top seven SDOs

Due to the very large size of the data set and the details available for further study, the table containing information about the top technical reports in the virtual society domain is provided as a spreadsheet with the title "Top_technical_reports_in_virtual_society_domain.xlsx" contained in archive gr_arf010v020101p0.zip.

12.6 Conclusions

This is a domain that is and will continue to be rapidly evolving with the support of governments seeking to protect the rights as well as provide benefits to their people. The data set used in preparation of the present report reflects that there is widescale recognition of the needs for virtual society guidelines or standards (i.e. there are many new standards working groups identifying with this domain in this scope), however, there are few standards specifically defining solutions to address interoperability between communities.

Until greater experience is gained over time and in different cultures, it is highly likely that the rules and protocols in use outside of virtual worlds will gradually be reflected in norms within the virtual society. These may then be codified either in standards or in guidelines and technical reports.

13 Virtual Economy

13.1 Scope

13.1.1 Introduction

The Virtual Economy refers to the buying and selling of goods and services within virtual environments, including both digital and physical items. It uses systems of interconnected components that drive economic activities, transactions, and business models facilitated between entities (e.g. organizations, people and agents) within digital and mixed (digital-physical) environments. Participants can register with appropriate authorities and use tools to engage in exchanges of assets, experiences and services permitting the creation and fluctuations of value through a variety of immersive and decentralized platforms.

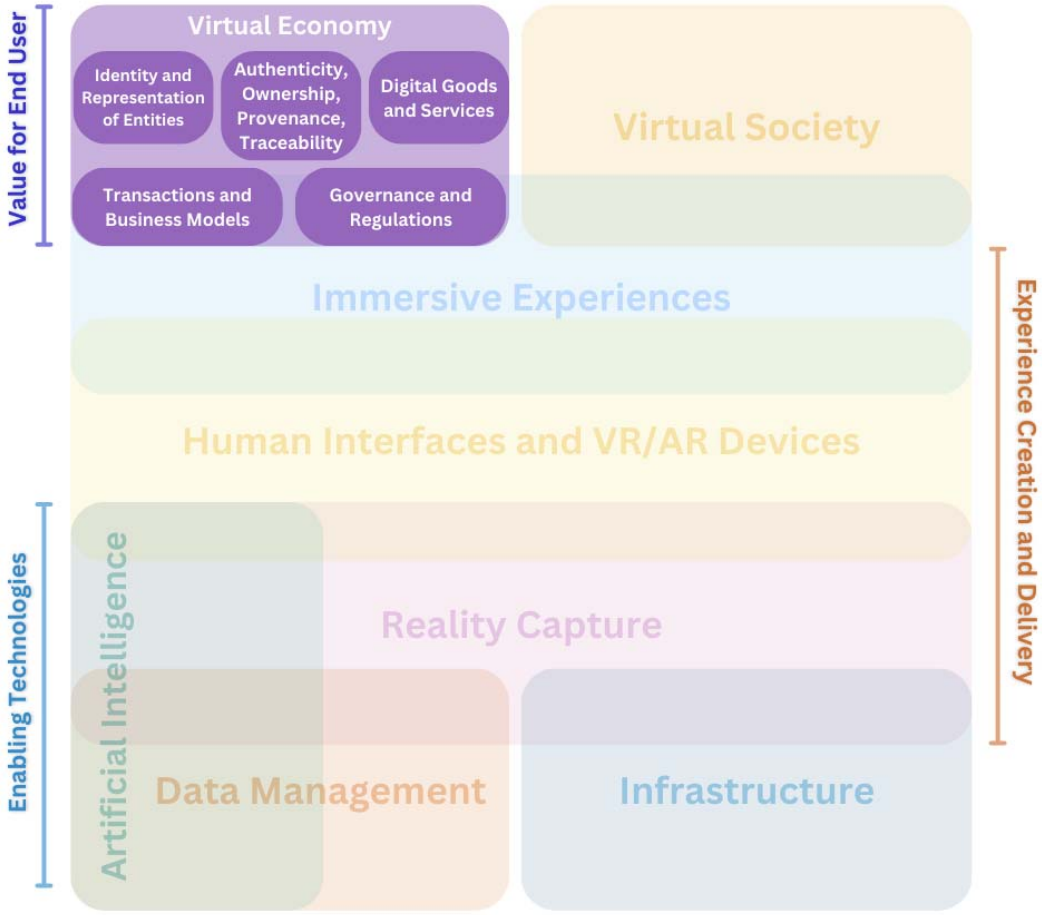

Figure 36: Components of the virtual economy domain

These components and the topics included in each are described in clauses 13.1.2, 13.1.3, 13.1.4, 13.1.5 and 13.1.6.

13.1.2 Identity and representation of entities

This component covers all technologies for the creation and maintenance of credentials and data that verifiably establish and maintain an entity's identity for the purpose of representation in one or more virtual world platforms, and in experiences where value can be exchanged. This component includes these topics:

- Digital Identity: A collection of attributes that uniquely define and represent individuals, entities, or other components in immersive environments. Users can choose tools to control access to personal identity information including but not limited to:
  - User Attributes: Information like username, account credentials, avatars and roles.
  - Asset Ownership: Ties users to digital goods, places, currencies, and NFTs.
  - Behaviours: Actions, transactions, and interactions within the virtual economy.
  - Identity Management: Systems for managing and verifying user identities across virtual platforms.
  - Portable Representations: Consistent, immutable and reusable components of an entity's identity that, once defined, remains valid, recognizable and traceable across multiple platforms.

13.1.3 Verification of authenticity, ownership, provenance and traceability

Any means of making assertions for the purpose of claiming or confirming authenticity, origins and transfer of digital assets, and preventing fraud or theft are included in this component. This component includes these topics:

- Digital Rights and Intellectual Property Management: Systems and protocols for managing and protecting intellectual property rights in virtual environments.
- Ledger Technology: A ledger ensures secure, transparent, and tamper-resistant records of status and activities. It provides crucial services for the virtual economy by facilitating secure transactions using cryptocurrencies, NFTs, and other digital assets.
- Non-Fungible Tokens: Unique, secure data (tokens) pertaining to entities, transactions and assets using Distributed Ledger Technology enabling verifiable digital scarcity and property rights in virtual worlds.
- Watermarks: Embedding visual data into digital assets for protection and verification.
- Certificates: Immutable metadata and digital signatures that accompany assets in the economy.

13.1.4 Digital Goods and Services

This component encompasses all digital assets and services that entities can buy, sell, or trade in virtual environments.

This component includes the following topics:

- Digital Goods: Uniquely identifiable digital items that can be owned, traded, or used within virtual environments. Includes clothing, tools, furnishings, art, weapons, skins, or avatars and other assets depicted as static or interactive in 2- or 3-dimensional formats.
- Gig Economy: Opportunities for freelancing and task-based work, such as consulting, training, designing digital goods, moderating communities, or creating virtual experiences.
- Digital Real Estate: Properties analogous to those in the real world that can be sold, purchased, traded, developed, and monetized in virtual worlds. Can also apply to rights to enhance or overlay physical property with digital assets.
- Virtual and Mixed Events: Production and sale of access to live or recorded concerts, education, training, other private and professional services delivered in virtual environments or with digital enhancements.

13.1.5 Transactions and Business Models

This component pertains to all aspects of buying, selling, and trading digital assets or services within immersive environments. This component includes these topics:

- Play-to-Earn (P2E): Economic model where users earn cryptocurrency or tradeable digital assets by participating in virtual world activities.
- Cross-Platform Value Transfer: Systems and protocols for moving digital assets and value between different virtual worlds and platforms.
- Decentralized Autonomous Organizations (DAOs): Community-governed entities that operate through smart contracts and blockchain technology to manage virtual world resources and decision-making.
- Marketplaces and Platforms: Infrastructure and applications where users can explore and engage with one another or merchants to exchange value for goods or services.
- Cybercurrencies: Tokens or coins specific to one or more virtual worlds, enabling economic exchanges within those environments.
- Digital Wallets: Applications permitting the user to receive, disperse and store value across multiple economic domains or transactions.

- Smart Contracts: Self-executing contracts with terms directly written into code, facilitating automated transactions in virtual environments.

13.1.6 Governance and Regulations

This component covers all rules and processes of decision-making that affect the way in which powers are granted, exercised and rescinded in virtual world platforms and experiences to protect financial instruments and support administrative structures established for economic activities. This component includes these topics:

- Virtual Justice System: Mechanisms for dispute resolution and rule enforcement within virtual communities.
- Smart Contract Law: Legal frameworks governing automated contracts in virtual environments.
- Jurisdiction: Concerns the legal regimes (rights and obligations) applicable to the activities within a geographically defined domain, and mechanisms to ensure governance is applied in cases of infraction.
- Dispute Resolution: Tools and procedures for resolving a dispute or conflict between entities, such as harassment claims or terms of service violations, that may mirror those established for physical world conditions.
- Taxation: The policies and acts leading to an authority, usually a government, levying a financial obligation on economically active entities to fund services for public benefits. Often leading to redistribution of value in society.
- Employment and Human Resources: Policies and practices pertaining to the management of hiring, protection and dismissal of employees in virtual worlds, including but not limited to guaranteeing safe working conditions, in compliance with labour laws, acts and regulations governing the activities of people and businesses.

13.2 Standards Development Organizations

There are 31 different standardization development organizations with working groups contributing to virtual world virtual economy standards in the data set. The internationally mandated SDOs have published 32 out of the 84 standards identified as being relevant for this domain as defined above.

13.3 Standards Working Groups

Standards working groups are the units of a standards development organization that permit stakeholders and experts to contribute to standardization activities. Due to the large number of standards working groups and the detailed information about their year of formation and scope, it is necessary to provide these in a separate file for further study. The file containing descriptions of standards working groups in this domain are in a spreadsheet with the title "Top_standards_working_groups_in_virtual_economy_domain.xlsx" contained in archive gr_arf010v020101p0.zip.

13.4 Standards

Figure 37 shows the number of standards with the highest rankings in the virtual economy domain topics, that are published by the seven most prolific standards development organizations. This includes standards in the data set for virtual economy topics that are relevant to some stakeholders, however, do not rise to the highest ranking needed to be included in the table of top standards.

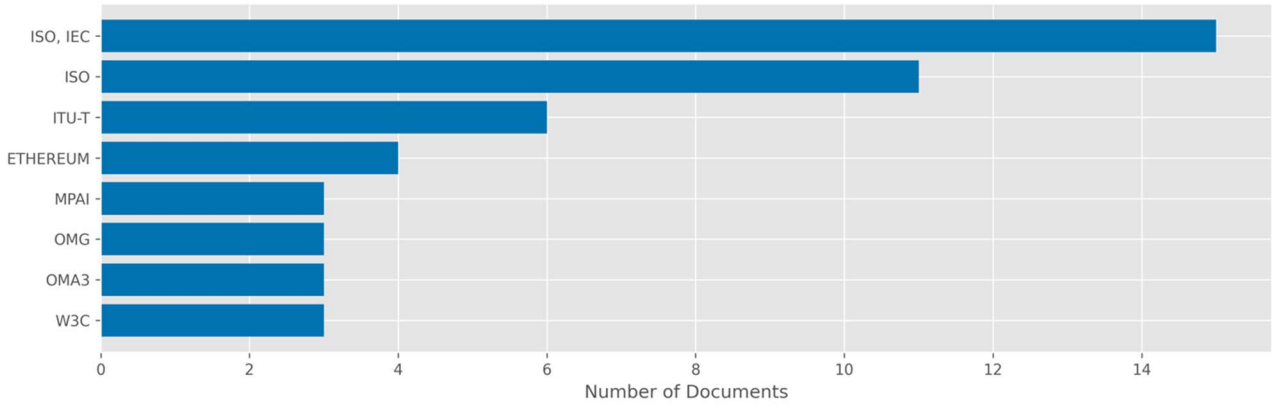

Figure 37: Number of standards published in the virtual economy domain by top seven SDOs

Due to the very large size of the data set and the details available for further study, the table containing information about the top standards in the virtual economy domain is provided as a spreadsheet with the title "Top_standards_in_virtual_economy_domain.xlsx" contained in archive gr_arf010v020101p0.zip.

13.5 Technical Reports

Figure 38 shows the number of technical reports with the highest ranking in the virtual economy domain topics, published by the seven most prolific standards development organizations.

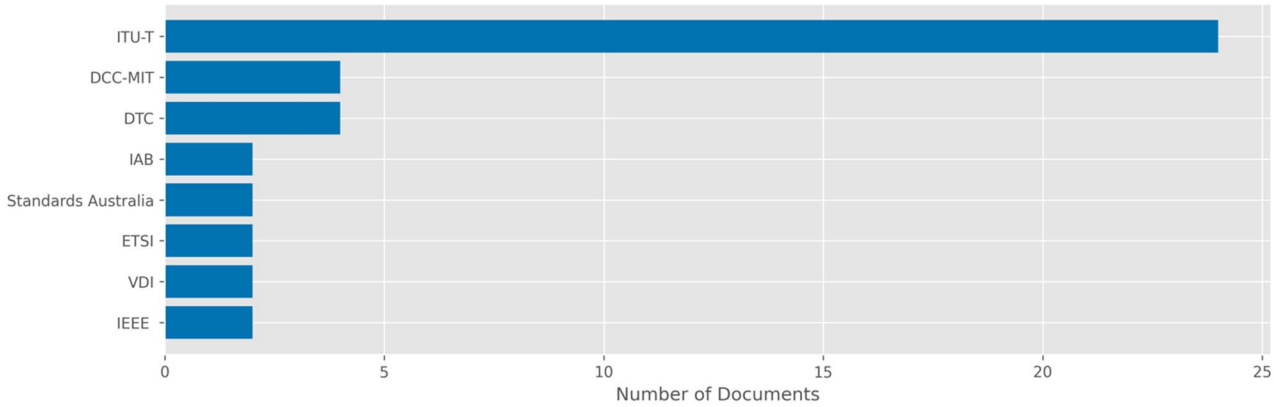

Figure 38: Number of technical reports published on virtual economy domain by top seven SDOs

Due to the very large size of the data set and the details available for further study, the table containing information about the top technical reports in the virtual economy domain is provided as a spreadsheet with the title "Top_technical_reports_in_virtual_economy_domain.xlsx" contained in archive gr_arf010v020101p0.zip.

13.6 Conclusions

As is the case for virtual society standards, the data set used in preparation of the present report reflects that it is still very early in the development of standards for virtual economy technologies. There is widescale recognition of the requirements for virtual economy standards (i.e. there are many new standards working groups identifying with this domain in this scope), however, there are several issues that confront those developing standards and technical reports for adoption by companies and governments with opportunities in this domain.

First, the legal jurisdictions in which standards can be applied are highly fragmented, meaning that each country represents a potentially new and different jurisdiction. There may emerge cross-jurisdictional policies and guidelines standards however, until that is clarified, standards developed for one jurisdiction may not be implemented in more than that jurisdiction. This constraint also raises questions about enforcement. The enforcement of standards, policies or protocols for virtual economy standards in a specific region may not be possible in the current geopolitical environment. An example of this is taxation on sales of goods and services sold on the Web. There are policies but they are not always enforced.

Another issue with the development of standards in this domain is the role of the private sector. While the data set for this project does not include all the specific organizations participating in a standards working group, it is the experience of the experts that academics working in universities are currently strongly represented in this segment of the virtual world ecosystem. There are also non-profit organizations but since public sector policies and protocols are usually defined in regulatory groups and approved in legislative bodies, not standards organizations, it is rare for there to be public sector participation in standards development in these domains.

Finally, there are the technological issues with standardization in this domain. It is highly likely that many research and development groups are rapidly innovating in this domain. As long as the technology is immature and not well proven in real world use cases, it is unlikely that standards developed in the recent years will be adopted by the largest technology companies.

14 Cross-Domain Standards

14.1 Scope

14.1.1 Introduction

A cross-domain standard is a document that describes architectures, conceptual models, protocols, interfaces, formats or other means for interoperability and standardization and is highly aligned with the definitions of components and topics provided in the clauses above within three or more virtual world domains. The virtual world domains used in the present document are defined in clause 5 above.

14.1.2 Benefits of cross-domain standards

Cross-domain standards can serve to provide a common language between different virtual world domains. When all the necessary experts contribute, they enable systems, processes and stakeholders from different areas of expertise to communicate and collaborate. From the point of view of users such standards may avoid duplication, reduce confusion and facilitate the integration of solutions across specialist boundaries.

For a digital avatar to function uniformly in different virtual worlds - such as in a gaming environment, a virtual conference room and an educational platform - standards that are not specific to or "neutral" about the use cases allow portability. Such standards enable interoperability and support seamless access to experiences without risk of exposing personally identifiable information.

14.2 Standards

It was found that 219 standards have two or more high (7 or greater) alignment with the domain definitions. Therefore, these 219 standards are considered highly relevant across multiple of the eight virtual world domains. A table containing these 219 standards in order of score is provided as a companion to the present document.

Due to the very large size of the data set and the details available for further study, the table containing information about the cross-domain standards is provided as a spreadsheet with the title "Top_cross-domain_standards.xlsx" contained in archive gr_arf010v020101p0.zip.

14.3 Conclusions

The challenge for contributors and publishers of cross-domain virtual world standards is to combine the complexity of requirements for multiple domains without losing precision. The contributors can do their best to ensure that the publications (standards and technical reports) recognize dependencies originating from diverse domains, reduce overlapping recommendations and balance the diverse interests of the virtual world ecosystem. If and when a well-designed, cross-thematic standard increases the acceptance and scope of the standard itself, then it can be used in multiple contexts and domains.

It is possible that, when balanced and provided that the required areas of expertise are well represented among the standards contributors, cross-domain standards promote interoperability, avoid redundancies and increase efficiency. They can create synergies for users and ensure relevance for publishers - in other words, they can become strategic aids for sustainable system design, especially in complex digital ecosystems such as the virtual worlds.

On the other hand, if a standard working group aims for its publications to cover multiple virtual world domains and it does not have the ideal composition of contributors it may fail to clearly designate the dependencies for success and the requirements it meets. If many stakeholders from different parts of the virtual world ecosystem are not participating, then there is higher risk of failure. Also, if a cross-domain standard contains implementation details, then the flexibility of those adopting may be reduced.

15 Industry-Specific Standards

15.1 Scope

Every industry is a unique and dynamic multi-layered ecosystem with specialized challenges which are managed through regulations and industry-specific standards. Some standards are based on established conventions, published by internationally recognized standards bodies, adopted at scale and constantly evolving to comply with modern requirements. New challenges continue to emerge for which market-based or standards-based solutions are in various stages of development and adoption, often with the involvement of industry-specific alliances and industry-driven standards development organizations.

Thought leaders in well-established, highly specialized industries are exploring where and how virtual world technologies can provide competitive advantages or add value, while stakeholders promoting virtual world technology adoption seek to expand their markets. These trends require integration of virtual worlds technology into existing IT ecosystems and the digitalization of industrial operations as a foundational activity. Figure 39 illustrates that the virtual world technologies will need to be integrated into existing IT systems and adopted by the developers of these industrial ecosystems. To ensure seamless interoperability, maintain regulatory compliance, enable key value generation and optimize performance within specific industrial contexts, specialized virtual world use cases require bi-directional cohesion between the core standardized systems of virtual world technologies and key industry-specific operational standards.

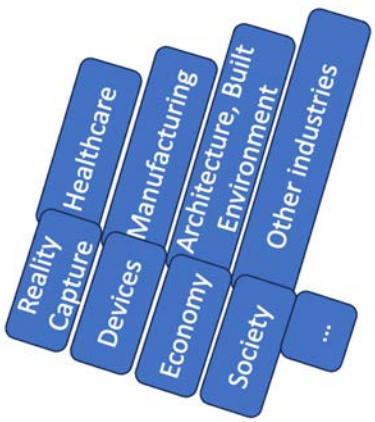

Figure 39: Virtual world technologies are being integrated into existing IT systems and ecosystems

Prior clauses of this standards landscape document focus on standards and activities that can advance the adoption of virtual world technologies and, as such, will provide value to those working in industry-specific standardization groups and activities seeking to be informed about existing and emerging standards for virtual world technology.

This clause seeks to achieve the reverse: to support those within the virtual world technology ecosystem that seek to assess if there are industry-specific standards they may wish to implement to integrate with industry-specific technologies and workflows. This integration will make virtual world technology components, services or solutions more attractive for customers and suppliers within the target industry.

Due to the limited resources in this project to examine industry-specific standardization, it is impossible to fully map standards in all the potentially important industries. The following clauses feature three industries with demonstrated interest in virtual world technologies and some relevant industry-specific standards: manufacturing, architecture, engineering and construction, and healthcare. These introductions to standards in the aforementioned industries are not exhaustive. They can only serve to illustrate how planners or policy makers could approach a deeper study of industry-specific standards to increase virtual world business and strategic value.

15.2 Manufacturing industry

15.2.1 Introduction

For decades, manufacturing industries have incorporated digitalization, robotics, and automation as part of the 'Fourth Industrial Revolution'. Concepts such as 'Industrial Internet of Things (IIoT)', Digital Twins and Virtual Factories have been core in this global movement. Manufacturing systems and supply chains rely strongly on the integration of many diverse technology providers and this integration contributes to system efficiency gains. In parallel with interoperability requirements, manufacturing industry stakeholders require cybersecurity and data transparency. These requirements are met by the widespread adoption of consensus-based standards.

The vision for Industry 5.0 formulated by the European Union hinges upon sustainability, human-centricity, and resilience with the Human-in-the-Loop. Important virtual world use cases cited by experts are to help people incorporate themselves into scenarios (such as design, planning, simulation and training) using avatars and then to integrate the virtual world with the real world. The use of virtual world technologies in industrial and manufacturing processes is a natural extension of the backbone of standardization for virtual factories, demonstrated by rising standards development activities and adoption by systems integrators and all members of the manufacturing ecosystem. These are highly aligned with initiatives from IEC, ISO, and manufacturing industry consortia.

15.2.2 Standards

There are hundreds of potentially important standards, however, the goal of the present document is solely to highly the most widely used standards. In the supplemental information attachment archive gr_arf010v020101p0.zip, a table with the title "Relevant_Manufacturing_Industry_Standards.xlsx" contains information about standards and frameworks on which global smart factories rely.

15.3 Architecture and Construction

15.3.1 Introduction

Architecture and construction industries have also experienced significant emphasis on standardization. Concepts like Building Information Modelling (BIM) have become core to modern practices, facilitating integrated workflows and data-driven decision-making across the lifecycle of built assets. Architects, engineers, contractors, and other stakeholders rely on a robust ecosystem of consensus-based standards for addressing various aspects of the built environment. These standards, developed by internationally recognized standards bodies as well as industry-driven standards development organizations, provide a unified framework for design, execution, data management, and environmental compliance. Drawing from the latest protocols, regulations, and industry practices, the present document identifies widely adopted standards, prioritizing those endorsed by leading organizations such as CEN, ISO, ASTM, and the International Code Council.

Key themes of these standards include structural integrity, digital data interoperability, environmental sustainability, and occupational safety, with lower level transport protocols like the Universal Data Protocol (UDP) reflecting the industry's shift toward decentralized, transparent systems. Furthermore, the rise of smart cities integrates these standards into urban planning and infrastructure, ensuring that digital technologies and data-driven solutions enhance the efficiency, sustainability, and liveability of modern urban environments.

15.3.2 Standards

Due to the nature of the data set and the details available for further study, the table containing information about the architecture, engineering and construction industry standards of greatest interest to the virtual world developer ecosystem is provided as a spreadsheet with the title "Relevant_Architecture_Construction_Industry_Standards.xlsx" contained in archive gr_arf010v020101p0.zip.

15.4 Healthcare

15.4.1 Introduction

The healthcare industry relies on a complex ecosystem of standards to ensure interoperability, data integrity, and quality of care. The present document identifies the 20 most widely adopted consensus-based standards, protocols, frameworks, and guidelines developed by internationally recognized consortia, associations, and standards bodies. These standards enable seamless data exchange, support clinical decision-making, and facilitate regulatory compliance across diverse healthcare systems. Drawing from authoritative sources such as the National Quality Forum (NQF), Health Level Seven International (HL7), and the International Consortium for Health Outcomes Measurement (ICHOM), this analysis highlights the technical specifications, applications, and real-world impacts of each standard.

15.4.2 Standards

Due to the nature of the data set and the details available for further study, the table containing information about the manufacturing industry standards of greatest interest to the virtual world developer ecosystem is provided as a spreadsheet with the title "Relevant_Healthcare_Industry_Standards.xlsx" contained in archive gr_arf010v020101p0.zip.

15.5 Conclusions

The diverse landscape of industry-specific standards plays a critical role in the potential integration and value creation of virtual world technologies across various sectors. As highlighted by the examples of manufacturing, architecture and construction, and healthcare, each industry possesses established conventions, regulations, and evolving standards that address their unique challenges. The integration of virtual world technologies into existing IT ecosystems and the digitalization of industrial operations provides a foundation for exploring competitive advantages. For virtual world technology to be successfully adopted and generate value within these industries, bi-directional cohesion between the core standardized systems of virtual worlds and key industry-specific operational standards is essential for seamless interoperability, regulatory compliance, value generation, and optimized performance. The examples provided illustrate the multitude of existing standards within each industry - ranging from interoperability and communication in manufacturing to BIM in architecture and construction and health data exchange standards in healthcare - that virtual world technology developers may consider and potentially integrate with to become truly valuable and widely adopted. Ultimately, a deeper understanding and implementation of relevant industry-specific standards will be crucial for virtual world technology providers seeking to offer attractive and effective solutions for customers, partners and suppliers within these target industries and others beginning to adopt virtual world technologies.

16 Conclusions

16.1 Introduction

The present document describes the scope of virtual worlds and purpose of the research. It then describes the current trends underpinning the emergence of virtual worlds and how interoperability will benefit the ecosystem of stakeholders. Details about interoperability standards, working groups and standards development organizations focusing on technology in eight virtual world domains are provided in subsequent clauses. Analyses performed on the largest data set of virtual world standards and information about standardization activities ever compiled offer insights into trends.

In order to provide stakeholders seeking specific details about standards and standardization activities within their topic of interest, this landscape uses a framework of eight virtual world domains. Each domain is the focus of a clause and each domain clause is supported by files in an attachment that accompanies the present document.

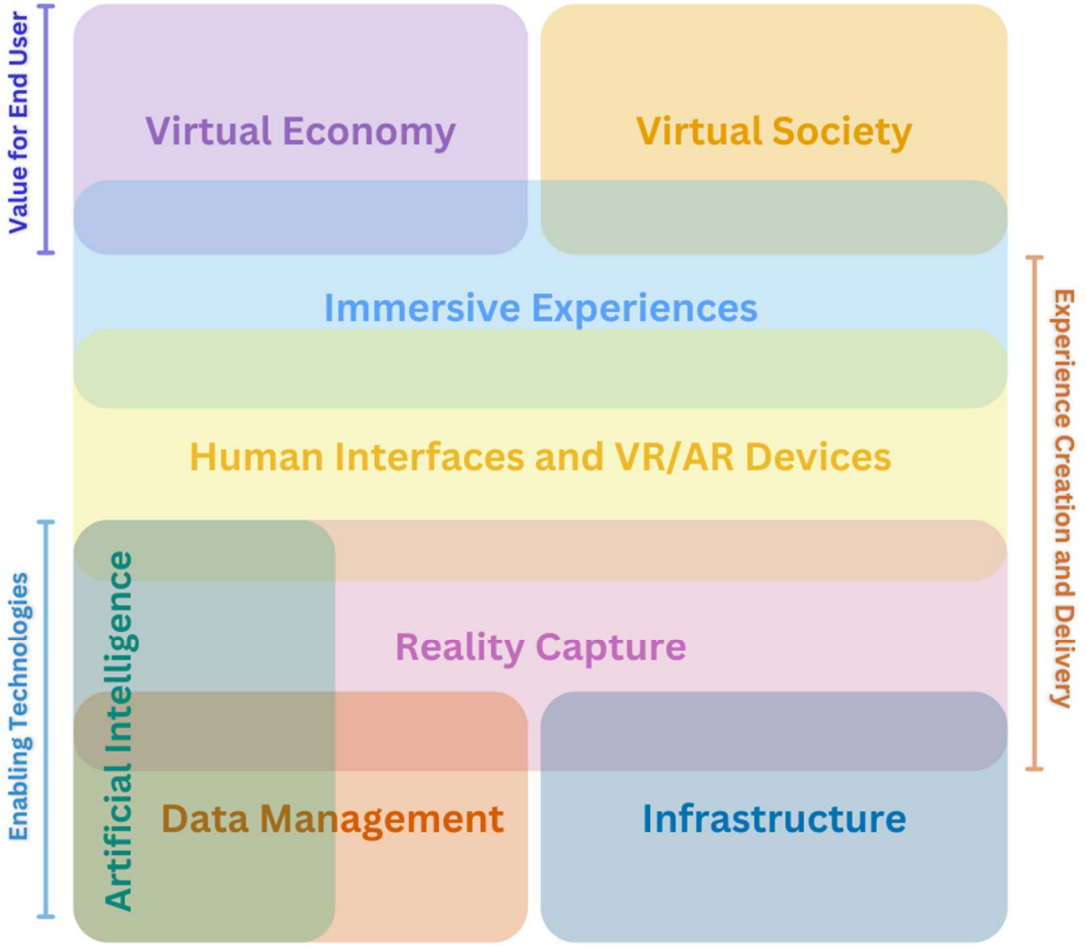

Figure 40: Eight virtual world domains form the framework for this standards landscape

16.2 High number and diversity

This standards landscape and the analyses conducted in its preparation make evident that many groups are developing or have published standards for virtual worlds. The data set contains standards that are very broad, covering three or more virtual world domains (see clause 14 about cross-domain standards), as well as standards that are highly focused on one component within one domain. There are conceptual models, and implementation standards. There are data format standards and physical interface protocols. These highly diverse approaches to standardization are not a priori negative or prevent adoption, however, they contribute to a highly heterogeneous set of options for those attempting to choose one or a few standards to solve a specific interoperability obstacle.

There are also standards in the data set that are very close to one another in terms of their target requirements. On the one hand this validates the requirements identified in the standardization activities. And, when two or more groups are working independently and in parallel in standards working groups without communicating with one another (see collaboration clause below), they may provide opportunities for different strategies for interoperability to be explored by experts with different experience. On the other hand, if neither or only one of the approaches is tested in real world settings to determine if they meet the requirements, the developer or potential adopter of these standards lacks evidence of value.

As noted in clause 4, reasons for this state of affairs are numerous and deeply engrained in the standardization activities and organizations. There will not be a rapid or single way to address the high proliferation of standards globally, however, some steps towards testing and validation, consolidation and rationalization of some work streams will be beneficial for many stakeholders.

16.3 Collaboration

One solution to the dilemmas described in clause 16.2 could be for diverse standards development organizations and standards working groups to increase their collaborative activities. Since the focus of the present document is on the standardization activities themselves and the results of these efforts, information about cross-SDO activities have not been heavily documented. This information is also not publicly available. However, standards experts as well as professionals in the virtual worlds field have recognized that there is a need for greater collaboration.

The need for coordination and collaboration between standards development organizations actively working on virtual worlds was so highly experienced by so many stakeholders as early as late 2021 that, in early 2022, the Khronos Group funded a 12-month project for the purpose of exploring potential solutions. The objectives of the project, the Metaverse Standards Forum, resonated so strongly across the virtual world ecosystem that over 2 600 companies joined in the first 18 months of the Forum's establishment. Today, the Metaverse Standards Forum members participate in over 15 working groups with the primary purpose to increase collaboration across standards development organizations.

While collaboration at organizational levels is highly desirable, it is not always possible due to the by-laws and policies of the standards development groups. Most of the organizations are explicitly prohibited from joining any other membership organization. Liaison statements focusing on specific objectives are a common way to establish communication channels that would not otherwise exist. But most standards activities are led by and receive support from passionate individuals who hold convictions about interoperability and expertise in a specific domain. In the future, it may be possible to create a standards activity landscape that is based on contributors. If contributors' names could be consistently published and their efforts recognized within documents, they could serve as a means to assess the participation of industry participants (companies) and establish trust.

16.4 Lack of standards for standardization information

Developing the associated data set and performing analyses for this project revealed a lack of consistency across standards and standards development organizations. The problems were identified when searching for standards about a topic, and when examining individual standardization documents for specific clauses, such as references or requirements.

When searching for standards or information about standards, there are many confusing or cryptic terms. Terminology specific to the virtual worlds domains can differ from standards organization and can even diverse between groups in the same standards organization (e.g. virtual worlds, metaverse). This suggests that although the subject of terms is frequently a starting point for standardization activities, one glossary of virtual world terms has not been widely adopted among those working on standardization activities. In fact, several standards development organizations have proposed their own glossaries without referring to those published by others.

For those who do not seek clarification on virtual world terminology another issue may arise. When describing the parts of a standard, type of document or stage of document development, every standards development organization has a different approach. This lack of consistency leads to confusion and impedes collaboration.

A closely related issue - inconsistency in the way that references are cited within standards-was identified when collecting metadata about documents for the associated data set for the present document. One of the goals was to collect references to other standards within the data set as an objective measure a standard's adoption or relevance in a domain. Unfortunately, the highly inconsistent appearance and format of references prevented the project from using this metric.

Taken as a whole, the lack of standard practices and methods of describing the content and the clauses and their contents across standards and standardization activities is an obstacle to more rapid and thorough study of standards and, more importantly, may in some cases, confuse or delay the work of those who would adopt standards but cannot find the best fit for their needs.

16.5 Standards adoption

Adoption of standards is the best metric for their contribution to the growth of the virtual world ecosystem. By comparison with the number of standards and the detailed data about them in the associated data set, there is relatively little high-quality information about their adoption. Lacking the records of implementations and adoption statistics, the standards experts had to rely heavily on their knowledge of industry trends when ranking standards of highest relevance by domain for this project.

Two themes arose. First, industry engagement during development of standards and dissemination of supporting materials contribute highly to adoption rates. Simply put, those who contribute do so based on one or more requirements and are motivated to implement the standards in their products or services to overcome interoperability challenges that they face. It is clear that standardization activities in industry-driven standards organizations are more often led by and receive contributions from industry stakeholders that perceive a real requirement than is the case in internationally mandated standards development organizations that do not have strong participation from the private sector. While this is a general trend, it is not a guarantee of adoption of industry-driven standards.

The industry-driven standards development organizations also support the developer ecosystem by producing more materials, such as technical reports, to communicate about the topics of standardization. They also develop tools for testing compliance and even porting code to meet standards.

One of the ways that industry-driven standards development organizations are bridging the gaps between standards documents and implementations in products and services is through use of collaborative coding platforms, such as GitHub, and using open source projects. Both of these are highly effective in providing sample code and resources for developers. For the present project, however, these repositories and tools were challenging to study and incorporate in the data set due to the lack of documentation in formats that lend themselves well to analyses performed in this project (e.g. PDF).

In conclusion, it is difficult to quantify but easy to illustrate how investments made by organizations and their members groups (prior to and following standardization activities) contribute to delivering the value of standardization activities.

Annex A: Methodology

A.1 Introduction

This annex describes the methodologies used for creating this standards landscape.

There are five clauses in this annex:

- definition of the virtual world domains;
- data collection;
- data processing;
- data analyses, and
- data presentation.

A.2 Definition of eight virtual world domains

In order to classify standards and technical reports (together the "documents") in a framework that meets the needs of its target audiences, preliminary information was extracted from reference documents provided by the European Commission. These included the Commission's Communication COM(2023) 442 "An EU initiative on virtual words" [i.13], and the Rolling Plan for ICT Standardisation.

Groups of concepts and key terms were assembled and a public large language model was used to generate the first draft of definitions from these basic building blocks. The machine generated definitions and components were refined in an iterative fashion, using the expert team's knowledge of the domains. The definitions of eight domains and their components and topics were also compared with frameworks published in third party standards landscapes and reports.

Once stabilized, the definitions were tested for robustness in matching with documents known to be examples of a domain (ground truth), fine-tuned and finalized.

A.3 Data collection

Gathering relevant information and metadata about standards, technical reports, working groups and standard development organizations is a highly time-intensive and iterative process. For the present project, a core data set of records was made available by the Virtual Dimensions Center. This served as a strong foundation for the development of our final data set.

Identification of new documents, working groups and standards development organizations with relevant projects to include was initiated from at least the following points:

- web site of a standards development organization;
- a standards landscape published by a third-party focusing on virtual worlds or adjacent technology areas;
- registers of documents maintained by industry associations or consortia; and
- normative or informative references within a standards document or a technical report.

Upon identification of a document, working group and standards development organization, it was first determined if it was new to the data set. If confirmed that it was new, metadata including the title of the document, relevant groups, location (url) of the document, headquarter location (if a standards development organization), date of publication or working group establishment, number of pages in the document and an abstract was manually entered.

Standards experts also assigned every document to one of five categories: standard, specification, technical report, guide and white paper. These categories were only used during data collection.

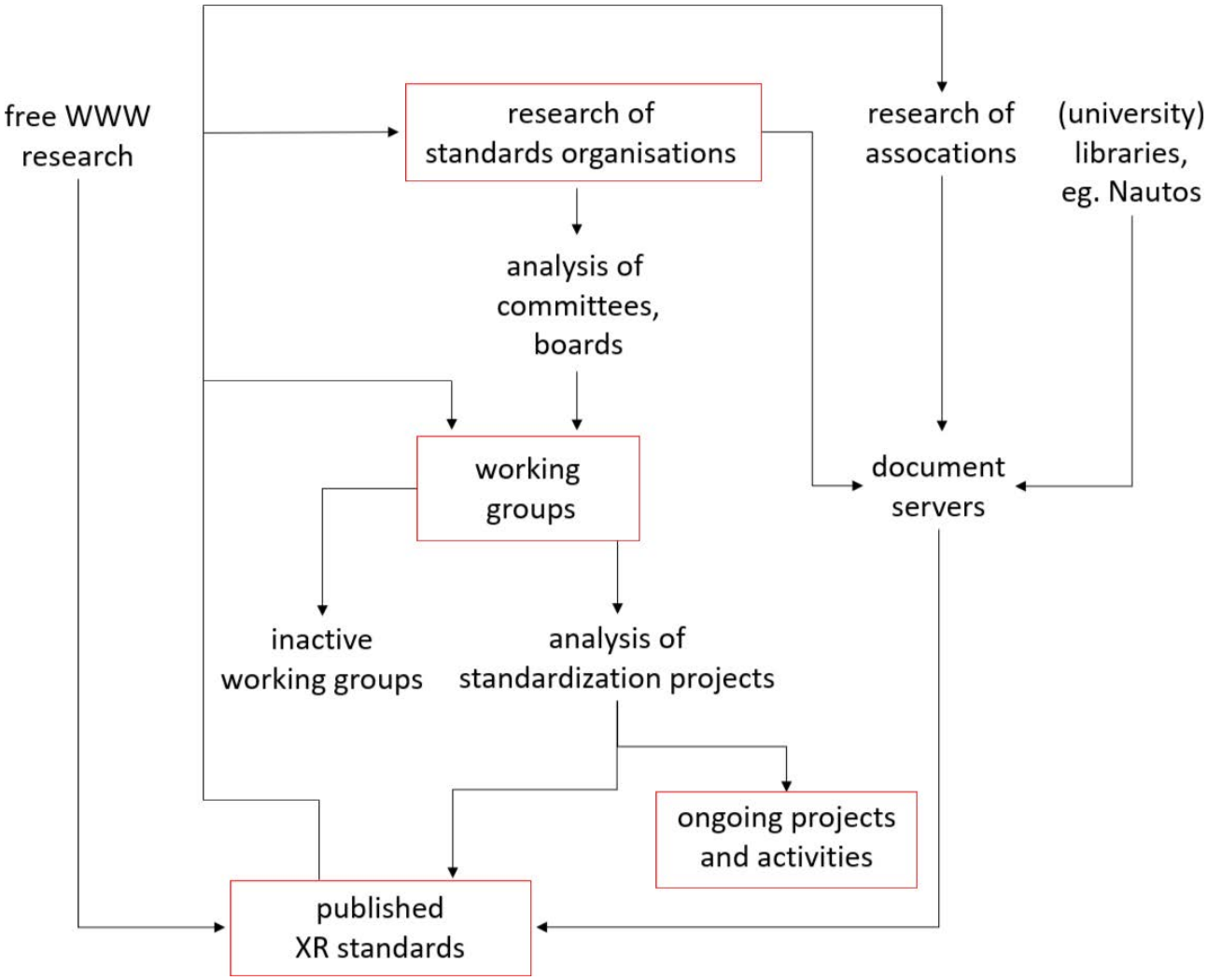

Figure A.1: Workflow used for searching for documents to include in the report data set

As shown in Figure A.1, when a new relevant working group or document was identified and its data entered, the search continued for any projects and publications in close proximity (e.g. cited in references clauses, published by another committee or working group of the same standards development organization).

English has become the dominant language for technology standards, including those relevant to virtual worlds standardization topics. The adoption of English as the primary language for international standards is driven by several factors. First is the emergence of English as a dominant language in science and technology during the 20th century. It serves as the common denominator among diverse linguistic groups, enabling effective information dissemination and collaboration across borders. The second driver of using English is that it promotes consistency and mutual understanding in the global arena. National standards bodies often produce documents first in their native languages, then these are translated into English before being submitted to ISO for international publication.

While most national standards are translated into English for international use, there are exceptions to this rule. Chinese standards related to virtual worlds are often published only in Mandarin by national organizations such as the China National Standardization Administration (SAC), Chinese Ministry of Industry and Information Technology (MIIT) and the Chinese Electronics Standardization Institute (CESI). Mandarin-only standards pose several challenges for the development of standards landscapes. Due to our lack of proficiency in Mandarin, it is impossible to identify all relevant Chinese standards or assess their significance comprehensively. Even when partial translations are available, there is no reliable way for the standards experts to determine whether these standards are being widely adopted within China or internationally. Finally, the target audiences for the present document + European Commission officers and technology professionals in Europe - cannot contribute to or provide feedback on these Mandarin-only standards due to language barriers. Consequently, the representation of non-English standards in the data set is very low (limited to a few German standards and four standards originally published in Mandarin that were machine translated).

If all the relevant metadata for a document or group was not available upon the first identification, then another examination of sources was needed. In almost all cases, the final source was the original document in either PDF or in HTML. For information about working groups, web pages provided varying details. In many but not all cases, an HTML page could produce a PDF file for further analysis.

All documents obtained for analysis were securely stored on premises and backed up in the cloud.

Edge cases were also identified. They include standards projects that working groups or committees develop in GitHub or another platform for collaboration and version control that does not lend itself to conversion to PDF.

For this project an agent was developed to perform additional research. The agent was instructed to follow high-quality research methods to identify new sources of objective information and documentation of standards adoption and trends. The agent gathered relevant publications, articles, white papers, and community references from the Web for subsequent analysis by the standards experts. One of the primary objectives for the agent development was to gather information and insights about adoption of individual standards by leading technology companies.

Upon completion of data collection, there were 920 standards, 354 technical reports and approximately 50 third-party landscapes in the data set. The data set also contains metadata about 240 standards working groups and 124 standards development organizations.

A.4 Data processing

For the present project, there were two phases of data processing:

- preparation of summaries of all clauses of all the documents; and
- extraction of additional information such as list of contributors' names, references, and other data from all the documents.

At no point in the project were any of the documents in the data set used for training any models or algorithms. Only platforms and tools trained independently of this project and made available to the public were used. The summaries of all clauses of all documents and the additional metadata extracted were stored with their respective documents and used in the analyses. Data processing also included verification of manually-entered metadata and subsequent data cleaning or alignment.

One of the manually-entered fields is the document type. There are many different definitions for standardization document types. In preparation for analyses, the experts studied many sources, including but not limited to the policies and procedures of the international standardization bodies including W3C®, ISO, IEC, ISO/IEC JTC1, OGC and IEEE™. The EU ICT and Standardisation web page simply defines all documents delivering ICT interoperability requirements as "specifications". Another important source is "Understanding ICT Standardization: Principles and Practice" [i.17], published by ETSI.

Due to the lack of agreement on document type definitions adopted by different international standardization activities, in the analyses performed and in the present document, the term "standard" includes all documents whose contents specify some conformance requirements that have reached wide consensus within a group of members with demonstrated expertise and experience in the topic. A standard only receives this designation once it has been approved by the members of the standards development organization publishing it using the most comprehensive and rigorous procedures the organization defines. This proved to be the most pragmatic definition as most standards development organizations do not distinguish between levels of consensus or stages of approval on their document covers, and, therefore, these cannot be easily determined manually or by the agent.

The term "technical report" is also an amalgam of document types. For the purpose of the analyses performed and in the present document, the term "technical report" is used for any document with explanatory material about a topic on which there has been discussion and consensus reached and lacking any conformance requirements. The explanatory material may be regarding requirements, use cases, implementation guides and any other information compiled by the standards working group and approved by its parent organization for the purpose of dissemination of knowledge about the topic in focus.

A.5 Data analysis

Data analysis for making the present document involved heavy use of natural language processing. Machine learning tools were used for comparing the eight virtual world domain definitions with:

- summaries of each document; and
- summaries of the description of each standards working group.

In addition, since every document in the data set was attributed to a standards development organization, and often a standards working group, it was possible to compare activities and rank those organizations for emphasis in one or more domains, and activity level based on number of relevant documents produced. This also permitted examination of the types of standards development organizations by headquarter location. Documents and metadata about them were inconsistent with regards to the standards working group in which they originated. Hence, the reliable detection of working group publication results and trends in this data set is not possible.

The dates of establishment of standards working groups and the publication dates of every document were used to study longitudinal trends from 1983 to the present.

From the comparison of document summaries with the domain definitions, those with the highest relevance (8 or above) for each domain based on natural language processing were selected. For each domain, the technical reports with the highest relevance were compiled in tables. Similarly, for the standards, a table with records with high relevance scores was generated. Finally, all the documents with the high relevance scores were, based on standards expert knowledge, carefully reviewed for the final tables. Documents in enabling technology domains (e.g. infrastructure, data management and artificial intelligence) that focused on a single use case were frequently not included as they lack applicability for the wide range of virtual world use cases. In the virtual society and virtual economy domains, the standards experts filtering kept more use case-specific documents.

Some criteria for establishing the relative relevance or importance of standards in a domain were proven impossible to measure objectively. The two criteria deemed to be highly desirable measures of importance are adoption by leading technology companies and the number of times a standard is included in normative or informative references by other standards. Research to quantify adoption by industry for each standard proved ineffectual due to a lack of publicly available information. Standards experts' experience and industry knowledge is a subjective measure that was used during the review and final assessment of all the standards and technical report lists (tables).

A.6 Data presentation

The analyses performed about the data set and the documents and activities relevant to each of the eight virtual world domains are presented in clause 4 of the present document and in spreadsheets provided in an attachment accompanying the present document. The visualizations in clause 4 permit deeper understanding of the present document types at a high level, the standardization activity trends over decades and the comparison of different standardization organization types.

In clause 4 and in the attachment, there are scatterplots. This visualization positions any standard or technical report in a two-dimensional space relative the eight virtual world domains. The visualization is essentially a force-directed layout where domain scores act as attractive forces, pulling standards toward relevant domain centroids. The X and Y axes in these plots do not represent specific variables or metrics in the traditional sense. Instead, they create a relational spatial coordinate system where domain centroids are positioned in a circle around the origin (0,0) and the documents are positioned based on their relationship to these domains. The documents are positioned through a weighted algorithm following these principles:

- Each standard has normalized scores (0-1) across all 8 domains.

- A document's position is calculated using weighted contributions from each domain centroid.
- Documents with higher scores in a particular domain are positioned closer to that domain's centroid than the centroids of other domains.

To interpret the visualization of these scatterplots, it is recommended to follow these guidelines:

- Proximity to a domain centroid indicates stronger relevance to that domain.
- Position between multiple domains shows relevance to multiple domains.
- Distance from centre represents the strength and clarity of domain relationships:
  - Items near or at the centre of the figure (equidistant from all the centroids) have either weak domain relationships or balanced relationships across two or more domains.
  - Items far from the centre of the figure have the strongest, clear relationships with specific domains.
- Colour coding shows each standard's top (highest-scoring) domain.

In clause B.2, radar charts generated about each of the top 20 standards development organizations permit evaluation of emphasis within the eight virtual world technology domains as measured by the total number of documents published and collected in the data set. Interactive versions of these radar charts are available in the archive.

Due to the size of the data to be presented for each domain and the details available for further study, results of most analyses and data have been compiled in an archive named "gr_arf010v020101p0.zip". The attachment contains a document (ReadMe) and 11 folders:

- Clause 4 - Emerging Virtual Worlds
- Clause 6 - Infrastructure
- Clause 7 - Data Management
- Clause 8 - Artificial Intelligence
- Clause 9 - Reality Capture
- Clause 10 - Human Interface Systems and Devices
- Clause 11 - Immersive Experiences
- Clause 12 - Virtual Society
- Clause 13 - Virtual Economy
- Clause 14 - Cross-Domain Standards
- Clause 15 - Industry-Specific Standards

Clause 4 folder contains:

- Interactive_all_documents_radar_chart.html
- Interactive_all_documents_scatterplot.html
- Interactive_standards_scatterplot.html
- Interactive_standards_SDO_radar_chart.html
- Interactive_technical_reports_scatterplot.html
- Interactive_technical_reports_SDO_radar_chart.html

Folders containing files for clauses 6 through 13 always contain the following files (these are the titles of the files):

- Top_standards_in_[appropriate folder]_domain.xlsx

- Top_standards_working_groups_in_[appropriate folder]_domain.xlsx
- Top_technical_reports_in_[appropriate folder]_domain.xlsx

Clause 14 folder contains one file:

- Top_cross-domain_standards.xlsx

Clause 15 folder contains three files:

- Relevant_Architecture_Construction_Industry_Standards.xlsx
- Relevant_Healthcare_Industry_Standards.xlsx
- Relevant_Manufacturing_Industry_Standards.xlsx

Annex B:
Standards Development Organizations

B.1 Introduction

The two clauses in this annex provide information about standards development organizations identified by the experts as having standards and/or technical reports included in the data set prepared for and used during the research and analyses performed to make this landscape report. The first clause, clause B.2, contains 20 radar charts ordered in alphabetical order.

Clause B.3 contains descriptions of activities for each of the 124 standards development organizations in the data set.

B.2 Radar charts for top 20 standards development organizations

This clause contains radar charts for 20 standards development organizations with the greatest activity in the virtual world standardization landscape as defined by the number of relevant documents in the data set. These charts are designed to quickly visualize how the documents in the data set published by the standards development organization of interest are distributed across the eight domains.

Each chart is based only on the standards and technical reports in the data set. The total number of documents used for generating the chart is provided in the caption for each chart.

Each axis on a chart represents one of the eight virtual world domains defined for this standards landscape. The values for the axes on each figure are normalized relative to the domain with the highest average score.

Figure B.1 shows the relative number of standards and technical reports published by 3GPP to address the requirements of stakeholders in each of eight virtual world domains.

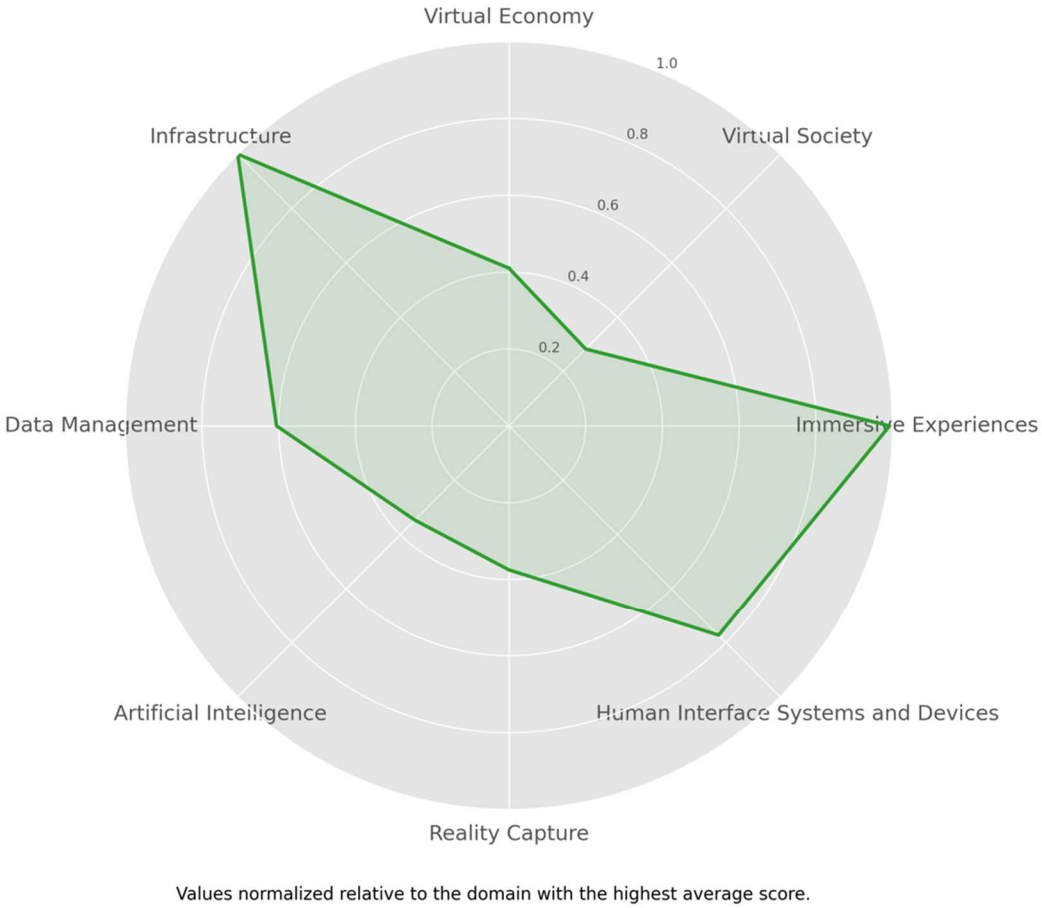

Figure B.1: 3GPP virtual world domain topic distribution based on 37 documents

Figure B.2 shows the relative number of standards and technical reports published by DIF to address the requirements of stakeholders in each of eight virtual world domains.

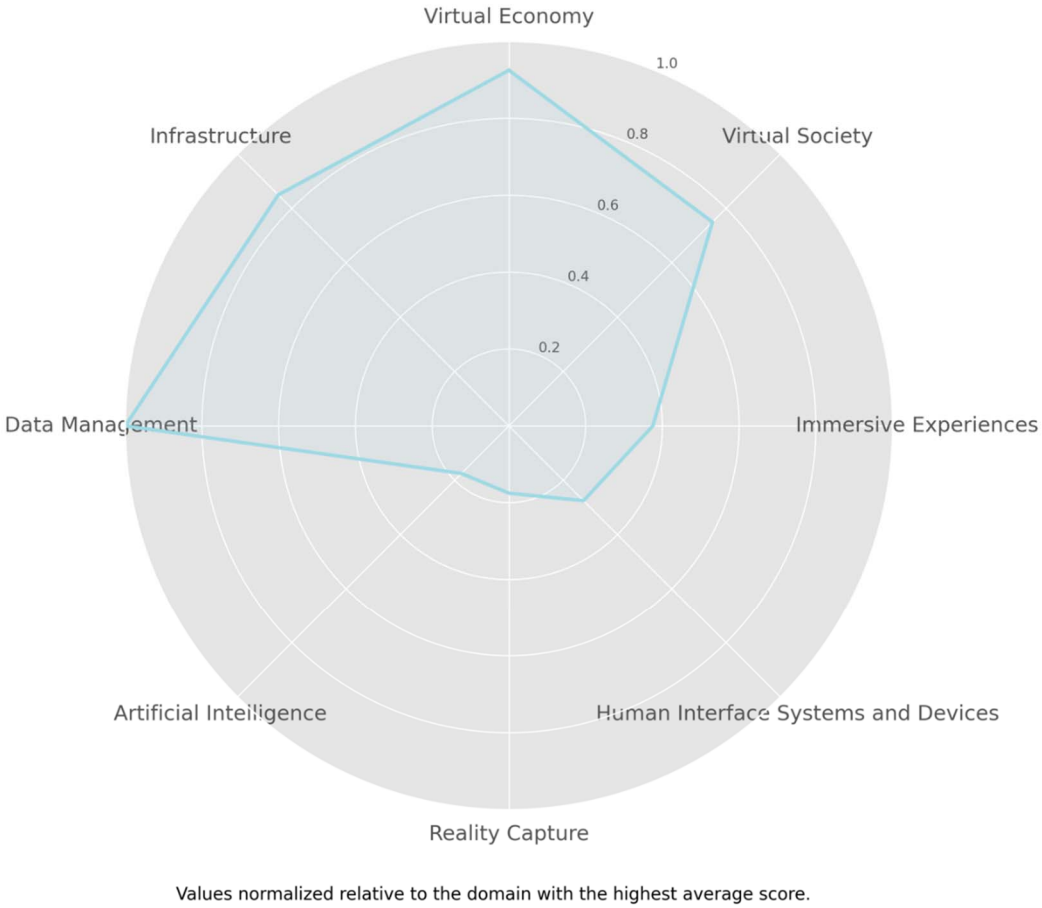

Figure B.2: DIF virtual world domain topic distribution based on 14 documents

Figure B.3 shows the relative number of standards and technical reports published by DTC to address the requirements of stakeholders in each of eight virtual world domains.

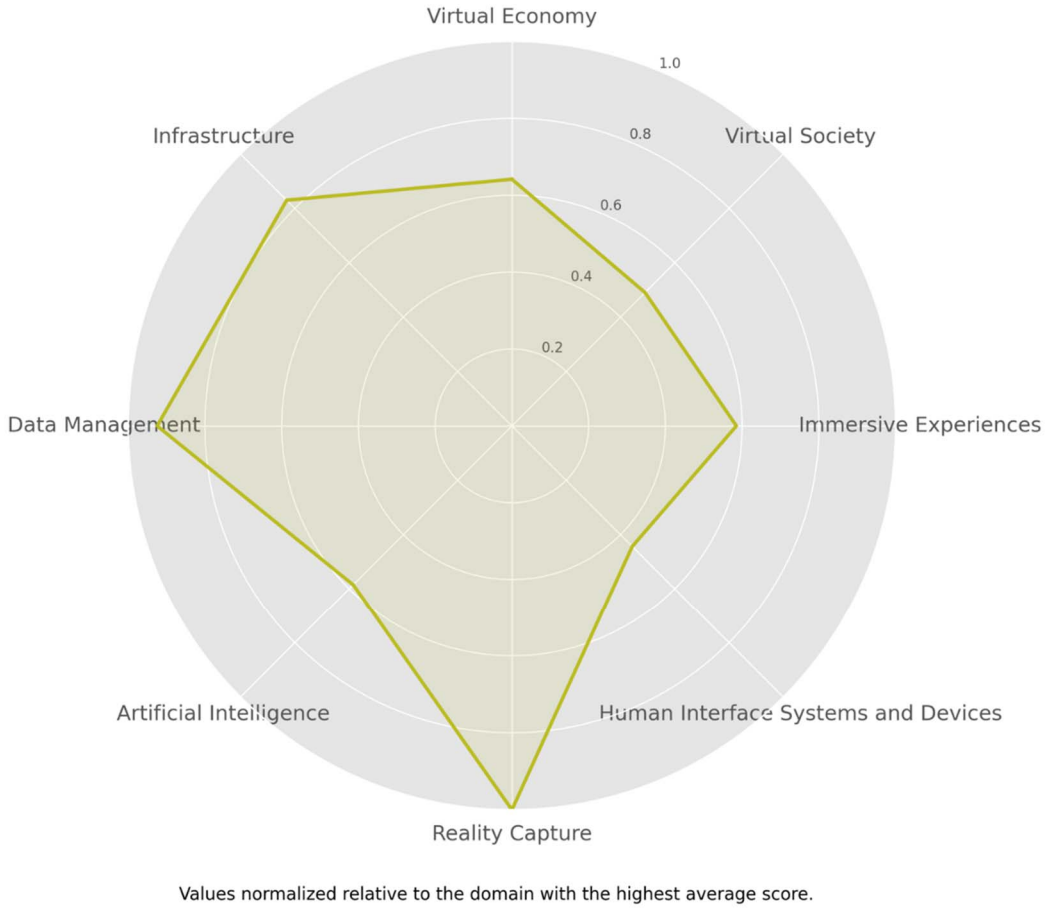

Figure B.3: DTC virtual world domain topic distribution based on 15 documents

Figure B.4 shows the relative number of standards and technical reports published by ETSI to address the requirements of stakeholders in each of eight virtual world domains.

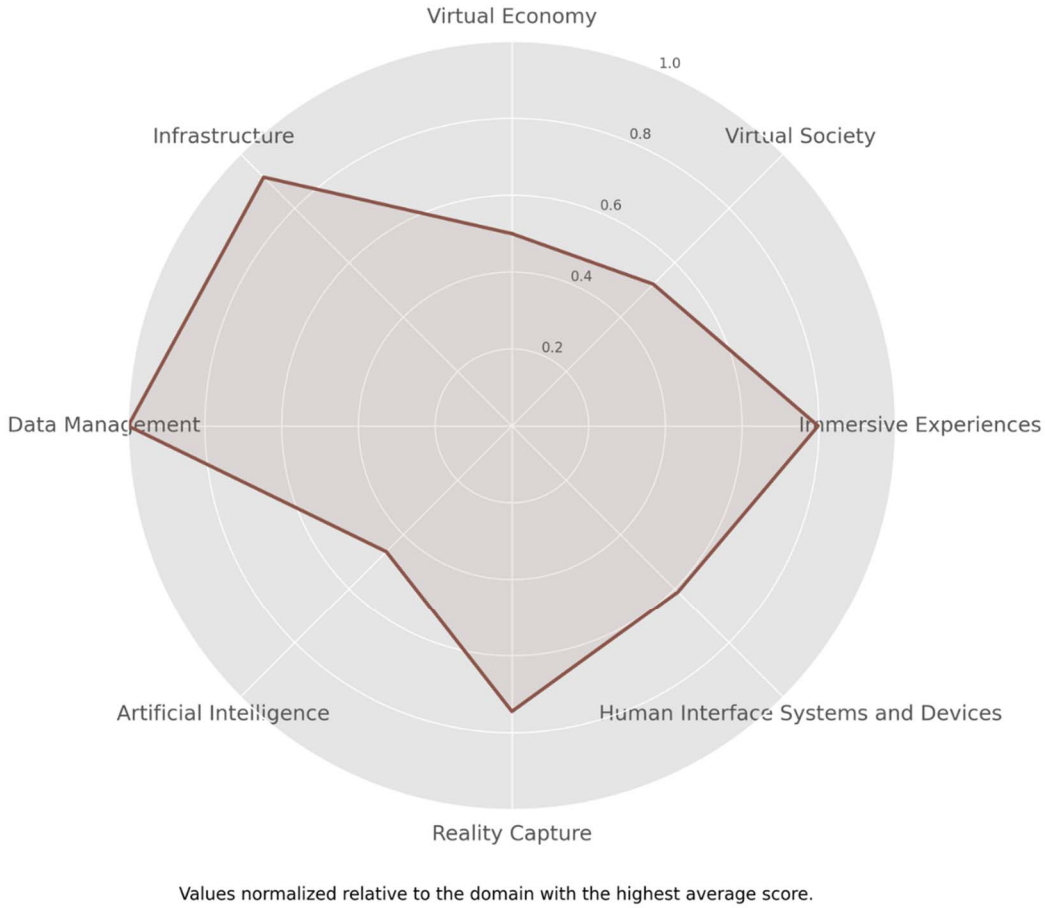

Figure B.4: ETSI virtual world domain topic distribution based on 27 documents

Figure B.5 shows the relative number of standards and technical reports published by IDTA to address the requirements of stakeholders in each of eight virtual world domains.

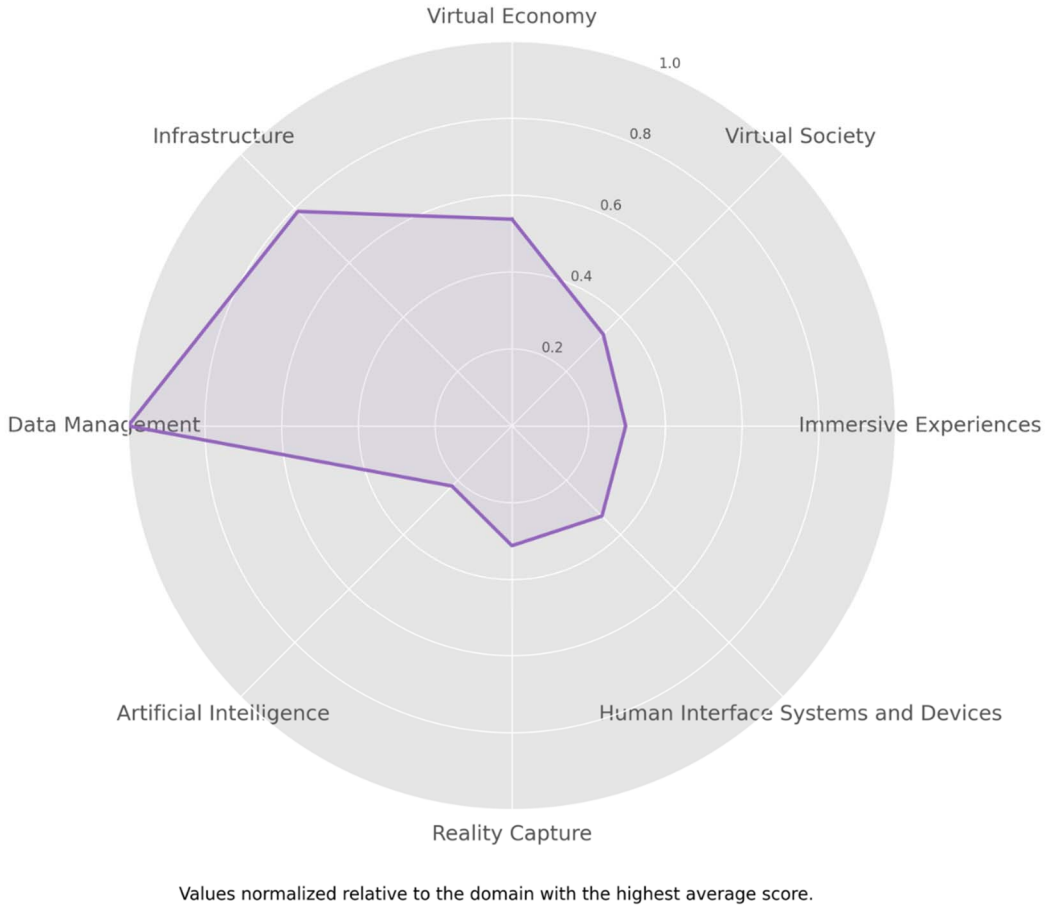

Figure B.5: IDTA virtual world domain topic distribution based on 28 documents

Figure B.6 shows the relative number of standards and technical reports published by IEC to address the requirements of stakeholders in each of eight virtual world domains.

Figure B.6: IEC virtual world domain topic distribution based on 37 documents

Figure B.7 shows the relative number of standards and technical reports published by IEEE™ to address the requirements of stakeholders in each of eight virtual world domains.

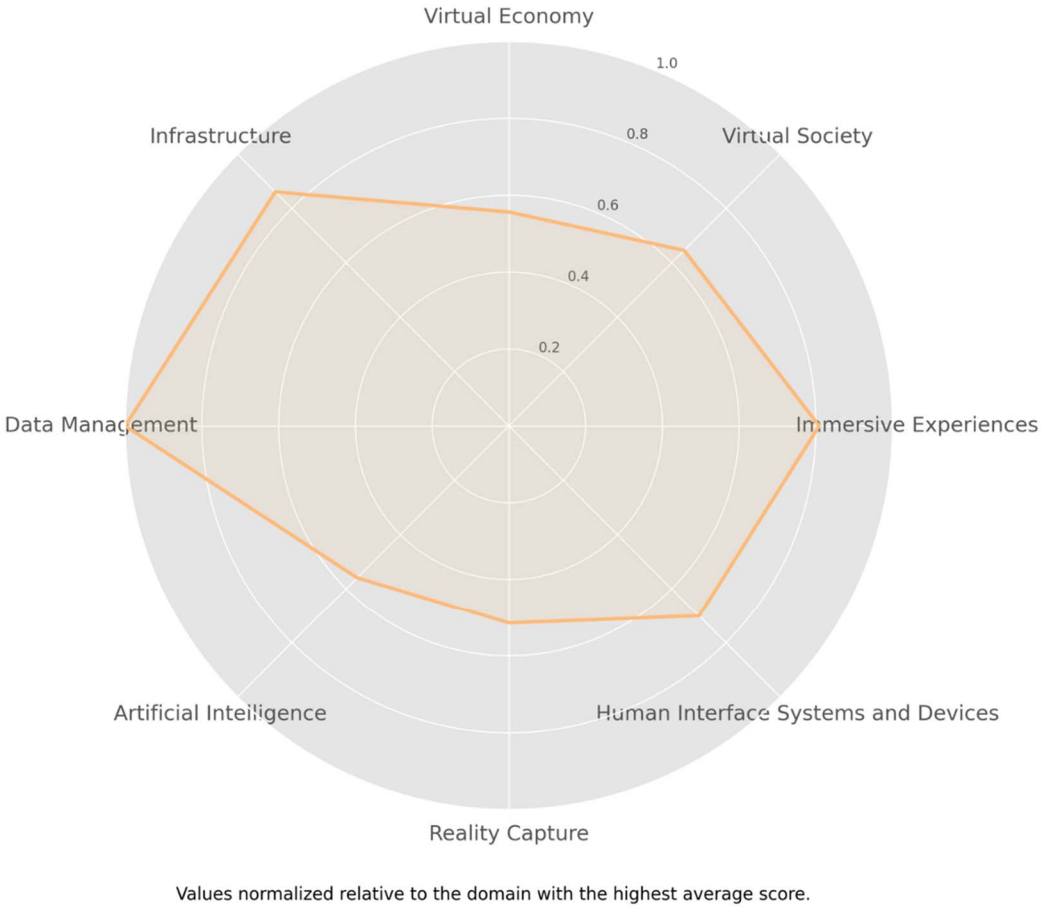

Figure B.7: IEEE virtual world domain topic distribution based on 66 documents

Figure B.8 shows the relative number of standards and technical reports published by IETF to address the requirements of stakeholders in each of eight virtual world domains.

Figure B.8: IETF virtual world domain topic distribution based on 14 documents

Figure B.9 shows the relative number of standards and technical reports published by ISO to address the requirements of stakeholders in each of eight virtual world domains.

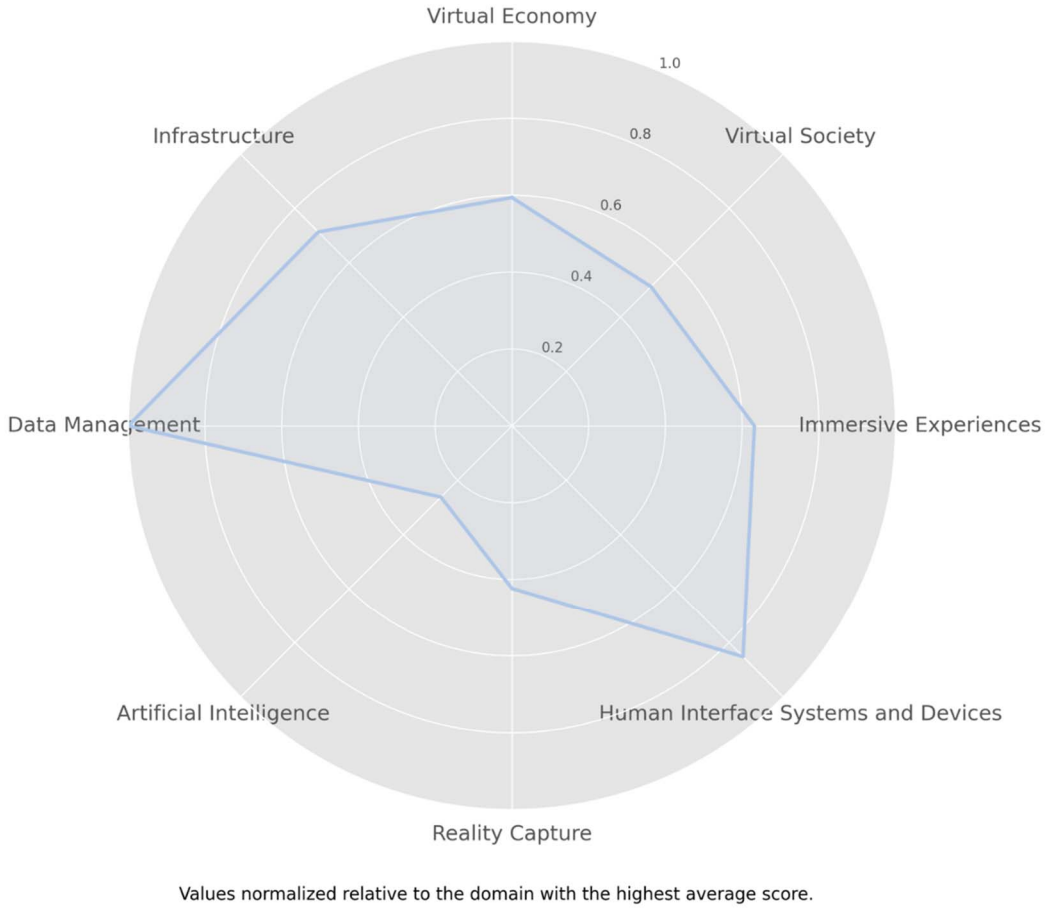

Figure B.9: ISO virtual world domain topic distribution based on 129 documents

Figure B.10 shows the relative number of standards and technical reports published by ISO/IEC to address the requirements of stakeholders in each of eight virtual world domains.

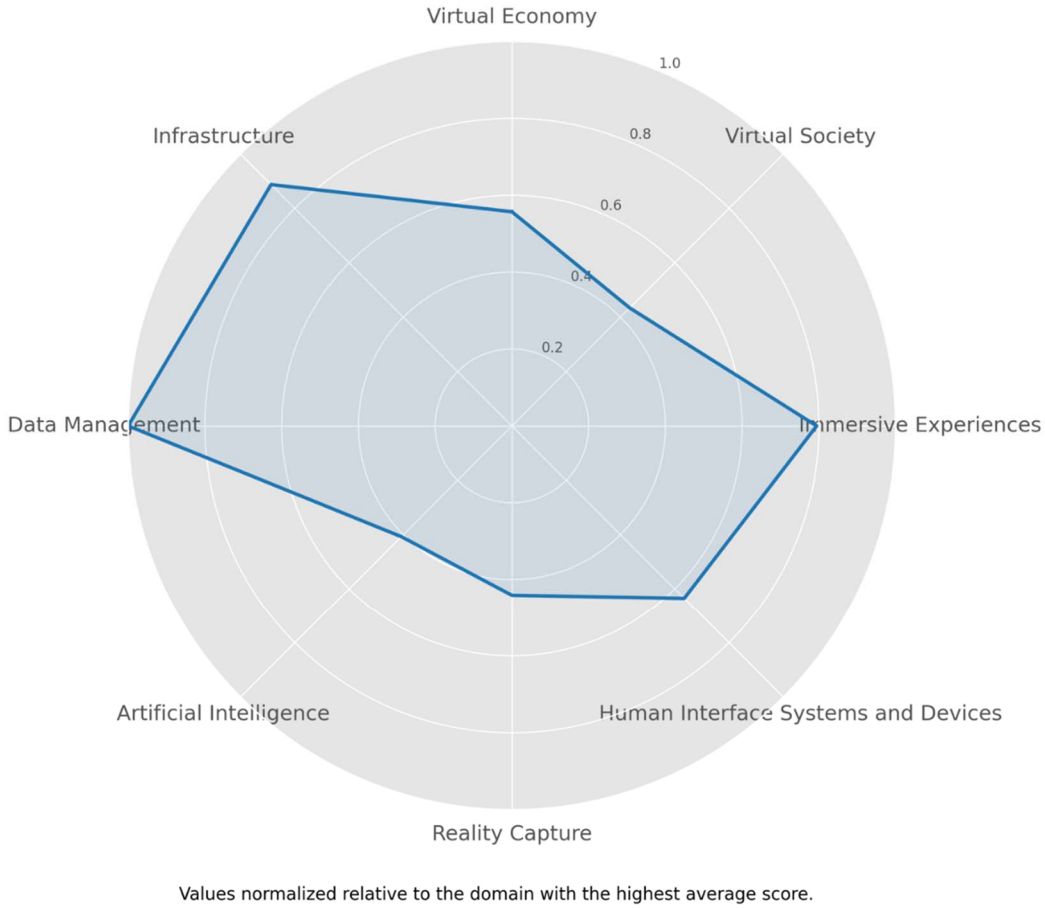

Figure B.10: ISO/IEC virtual world domain topic distribution based on 326 documents

Figure B.11 shows the relative number of standards and technical reports published by ISO/IEC/Web3D Consortium to address the requirements of stakeholders in each of eight virtual world domains.

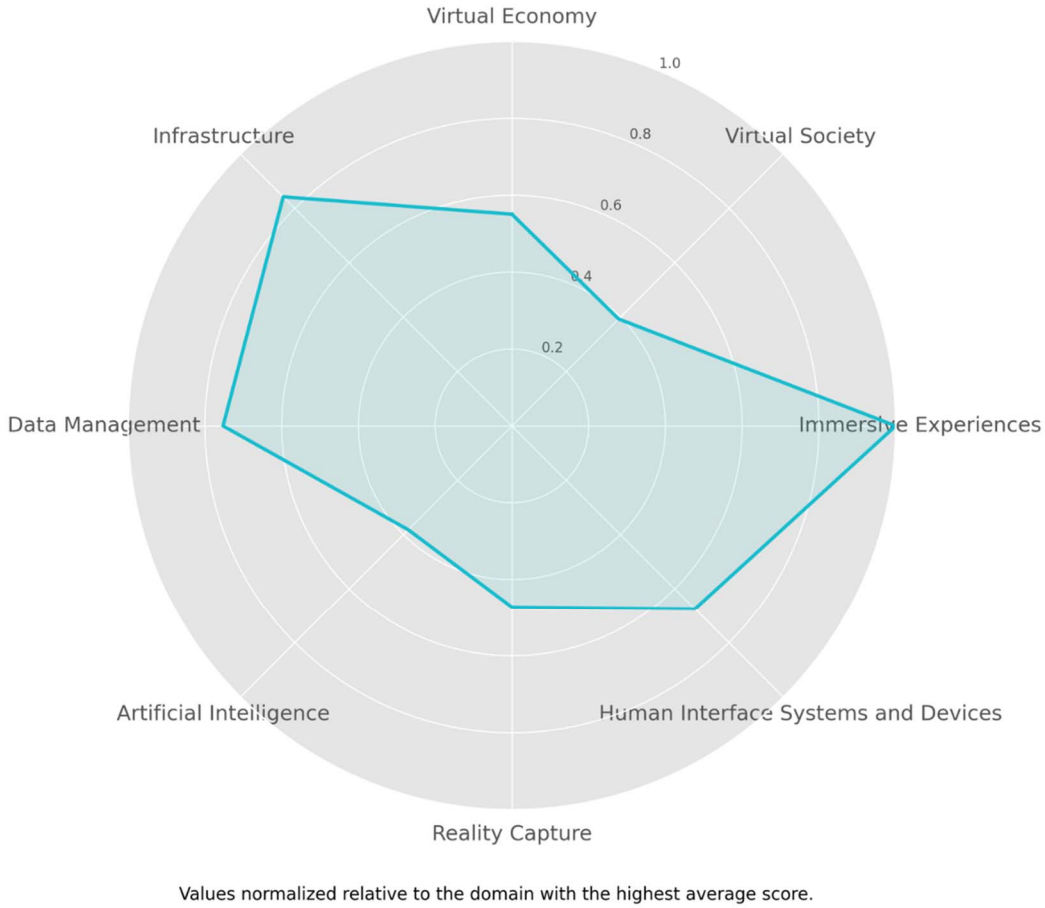

Figure B.11: ISO/IEC/Web3D Consortium virtual world domain topic distribution based on 14 documents

Figure B.12 shows the relative number of standards and technical reports published by ITU-T Consortium to address the requirements of stakeholders in each of eight virtual world domains.

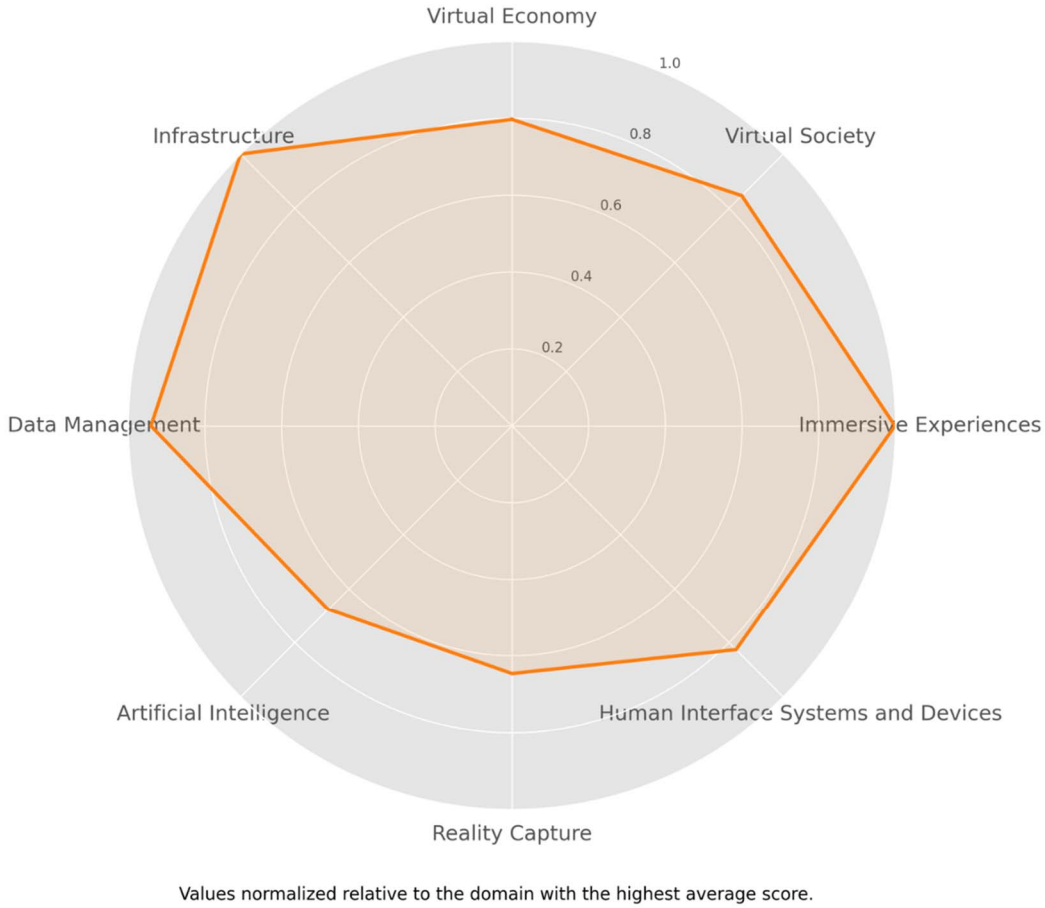

Figure B.12: ITU-T virtual world domain topic distribution based on 87 documents

Figure B.13 shows the relative number of standards and technical reports published by ITU-T VQEG to address the requirements of stakeholders in each of eight virtual world domains.

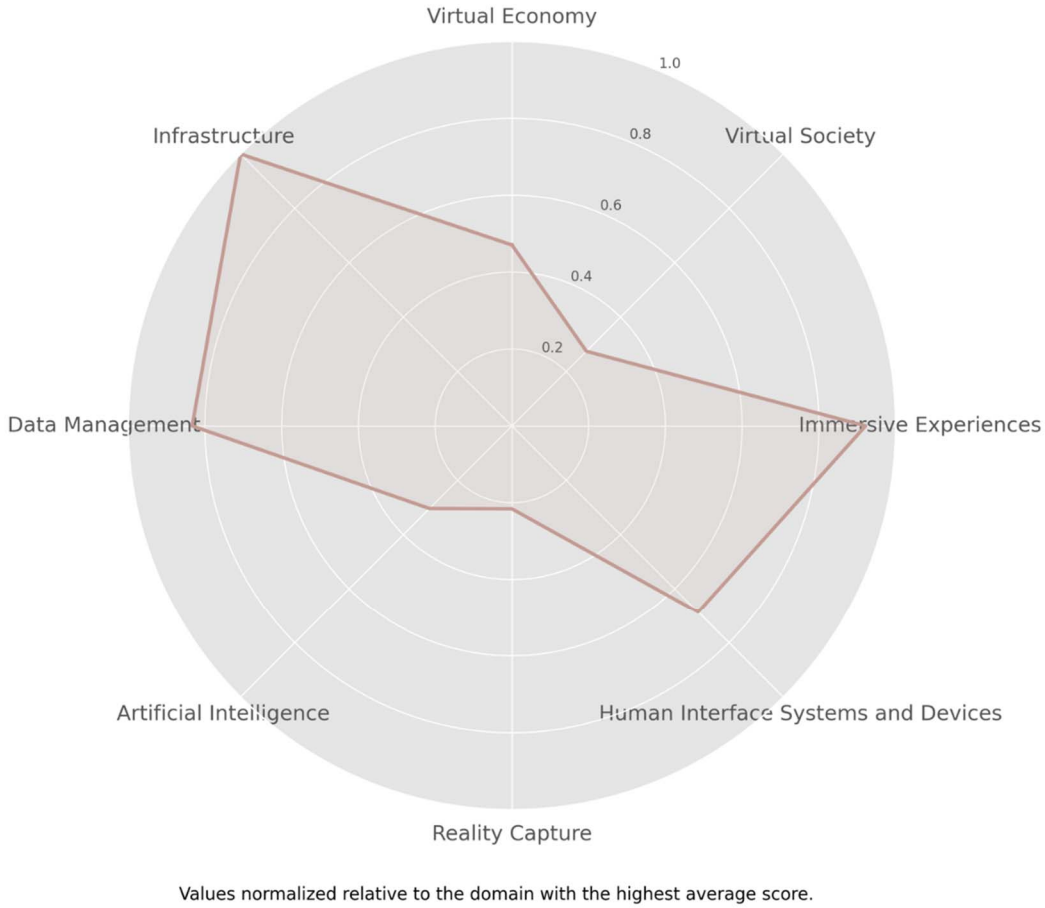

Figure B.13: ITU-T, VQEG virtual world domain topic distribution based on 26 documents

Figure B.14 shows the relative number of standards and technical reports published by the Khronos Group to address the requirements of stakeholders in each of eight virtual world domains.

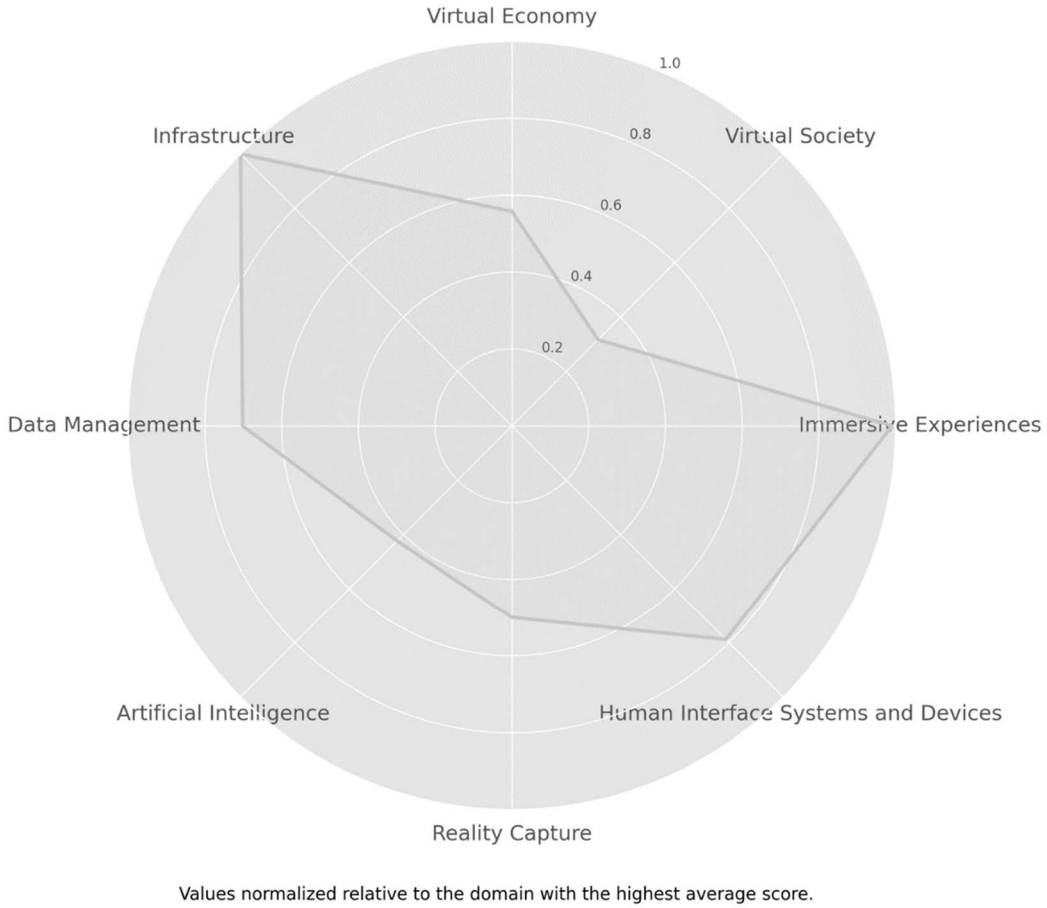

Figure B.14: Khronos Group virtual world domain topic distribution based on 18 documents

Figure B.15 shows the relative number of standards and technical reports published by OGC to address the requirements of stakeholders in each of eight virtual world domains.

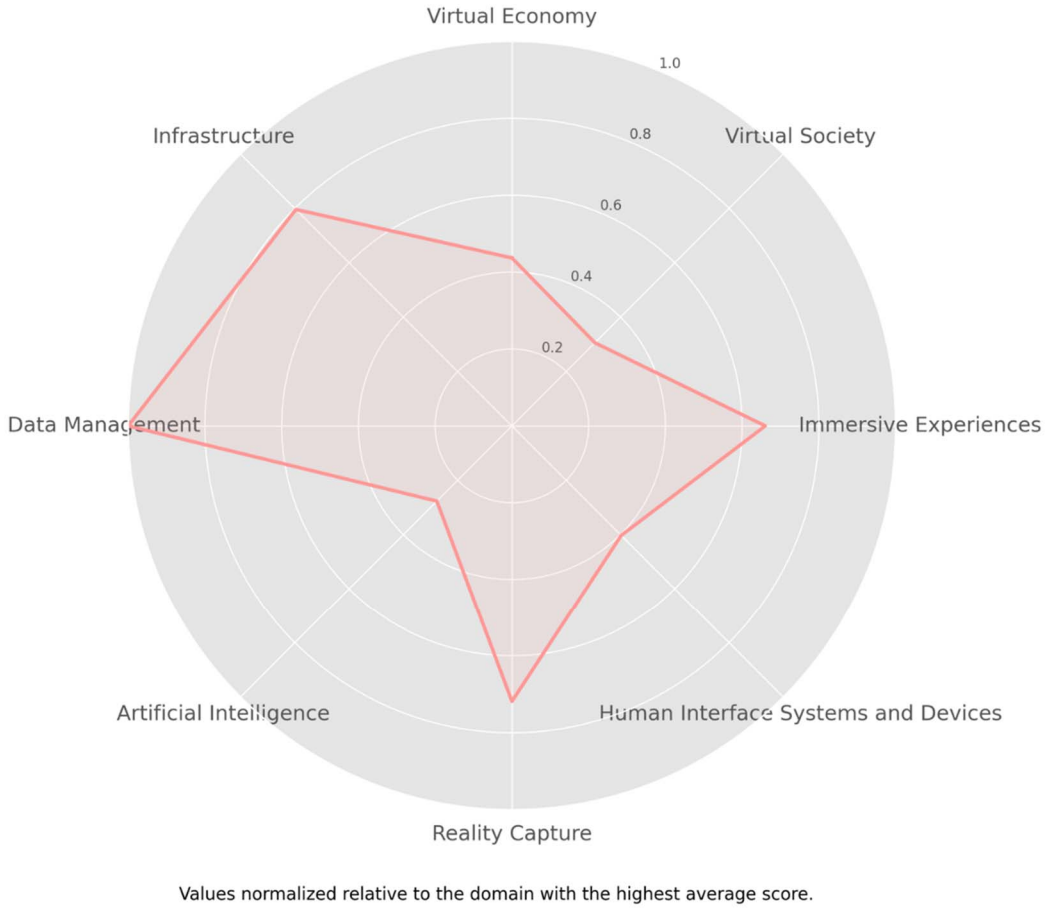

Figure B.15: OGC virtual world domain topic distribution based on 28 documents

Figure B.16 shows the relative number of standards and technical reports published by OMG to address the requirements of stakeholders in each of eight virtual world domains.

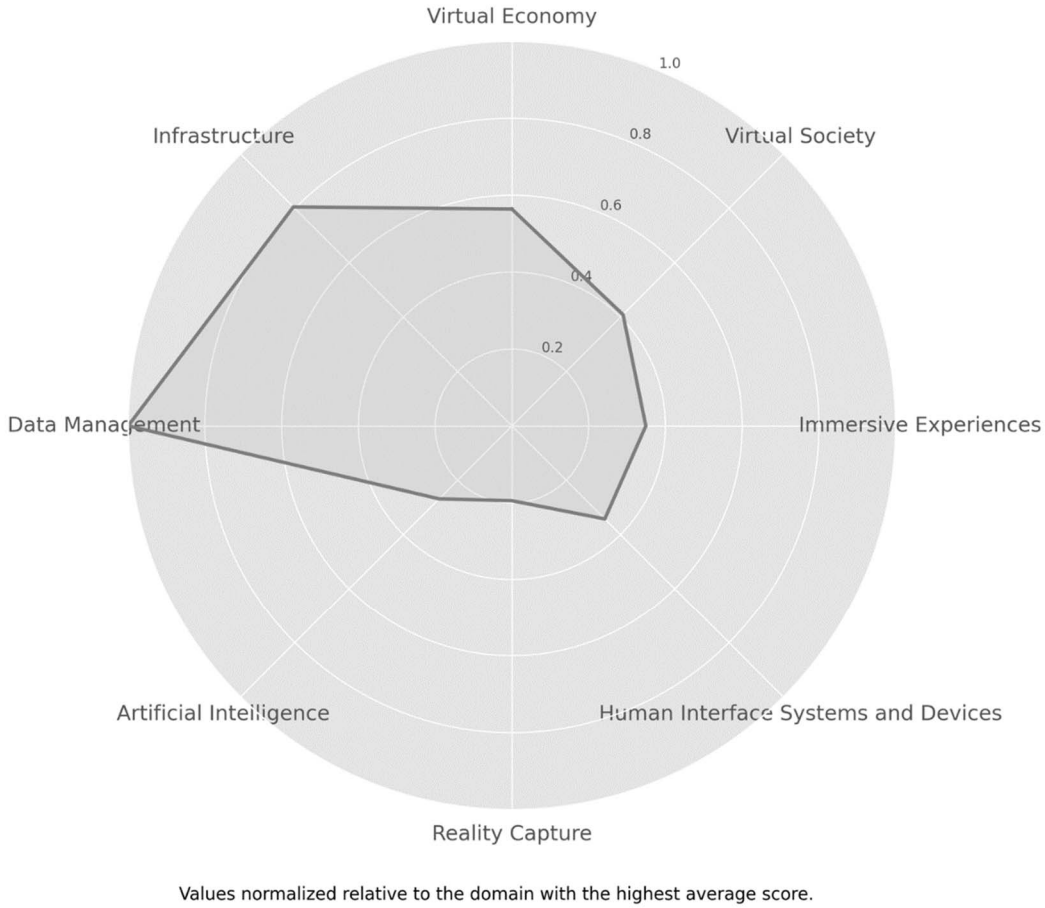

Figure B.16: OMG virtual world domain topic distribution based on 23 documents

Figure B.17 shows the relative number of standards and technical reports published by SISO to address the requirements of stakeholders in each of eight virtual world domains.

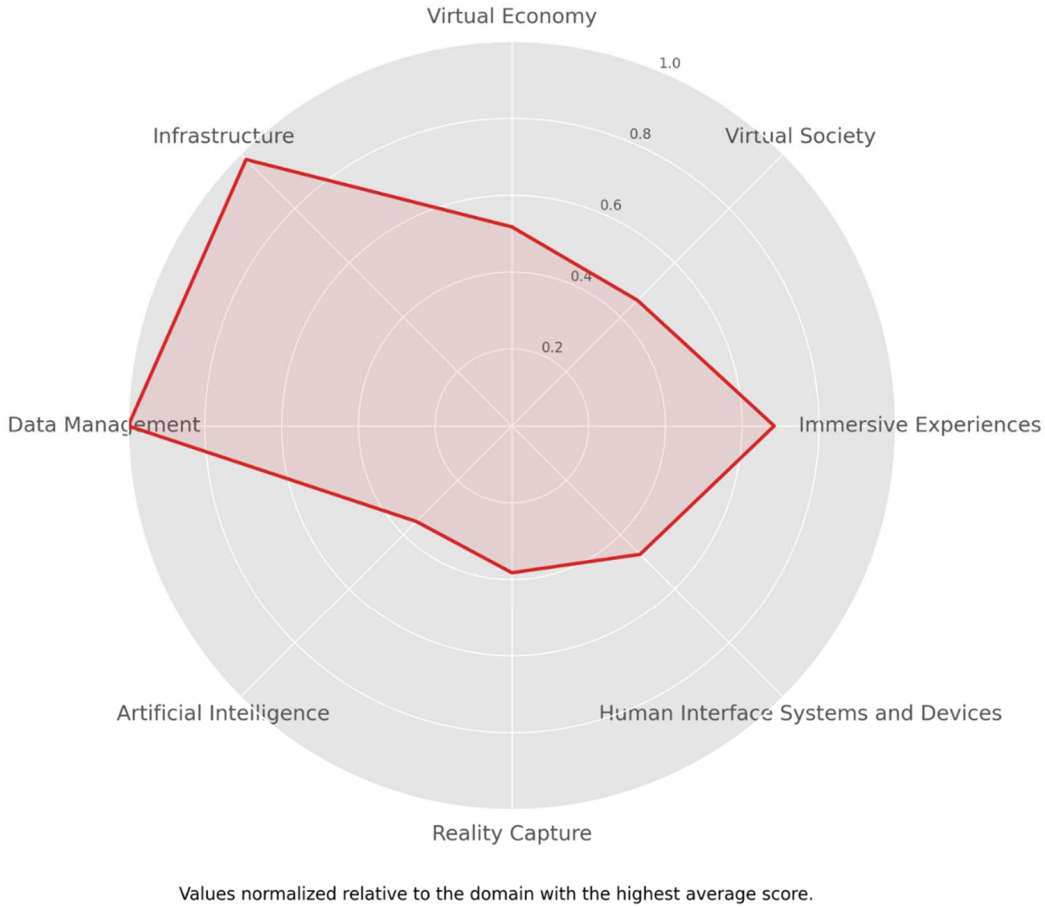

Figure B.17: SISO virtual world domain topic distribution based on 34 documents

Figure B.18 shows the relative number of standards and technical reports published by SMPTE to address the requirements of stakeholders in each of eight virtual world domains.

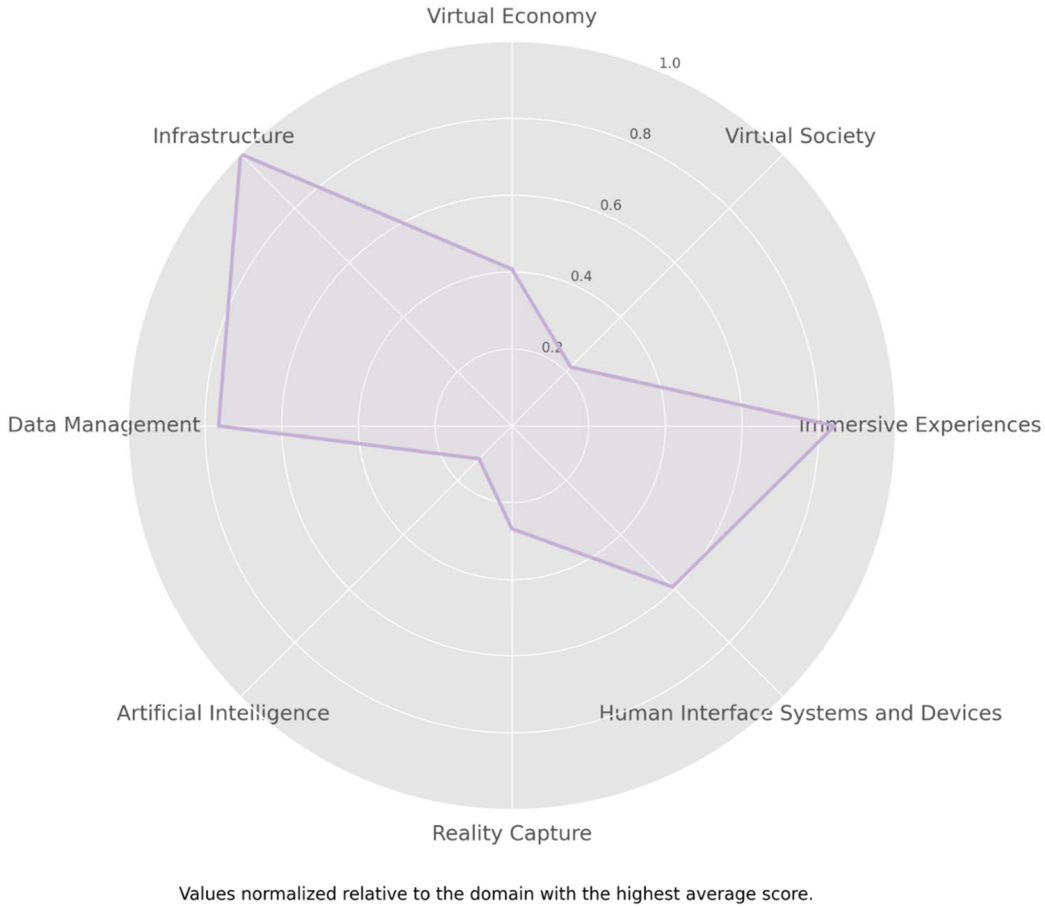

Figure B.18: SMPTE virtual world domain topic distribution based on 27 documents

Figure B.19 shows the relative number of standards and technical reports published by VDI to address the requirements of stakeholders in each of eight virtual world domains.

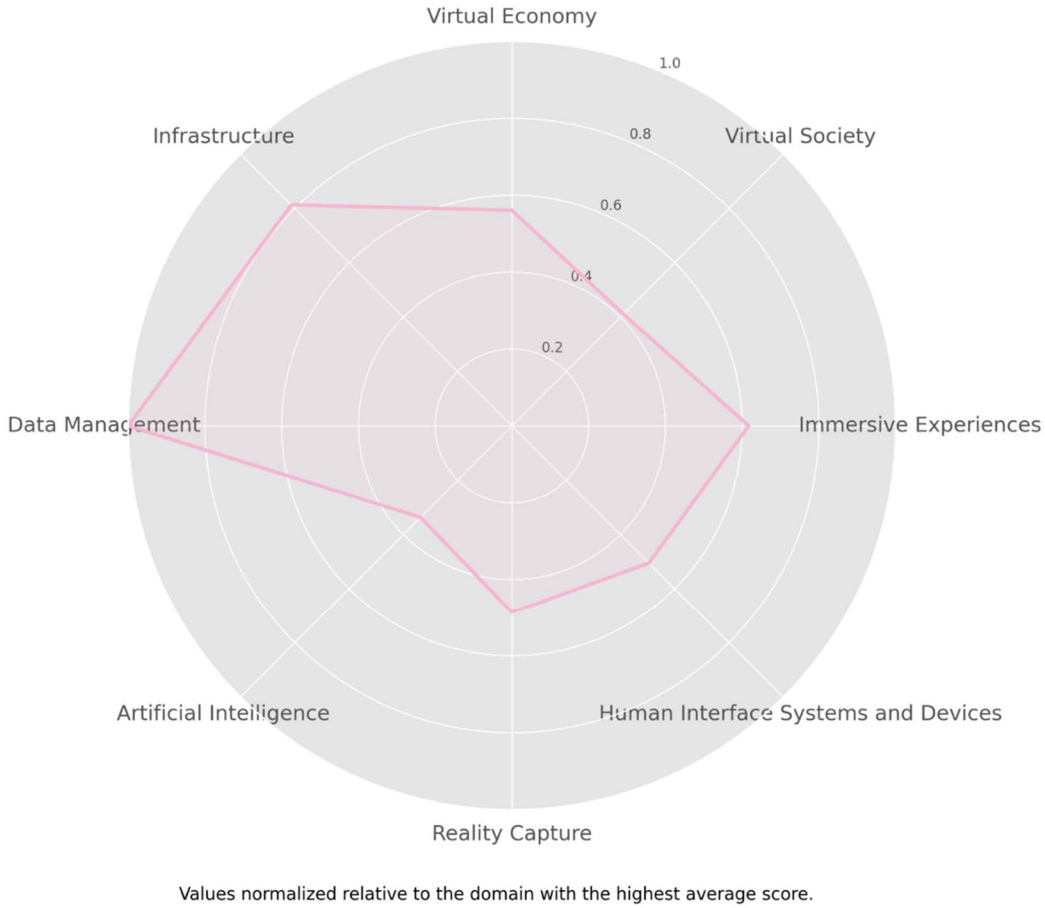

Figure B.19: VDI virtual world domain topic distribution based on 23 documents

Figure B.20 shows the relative number of standards and technical reports published by W3C® to address the requirements of stakeholders in each of eight virtual world domains.

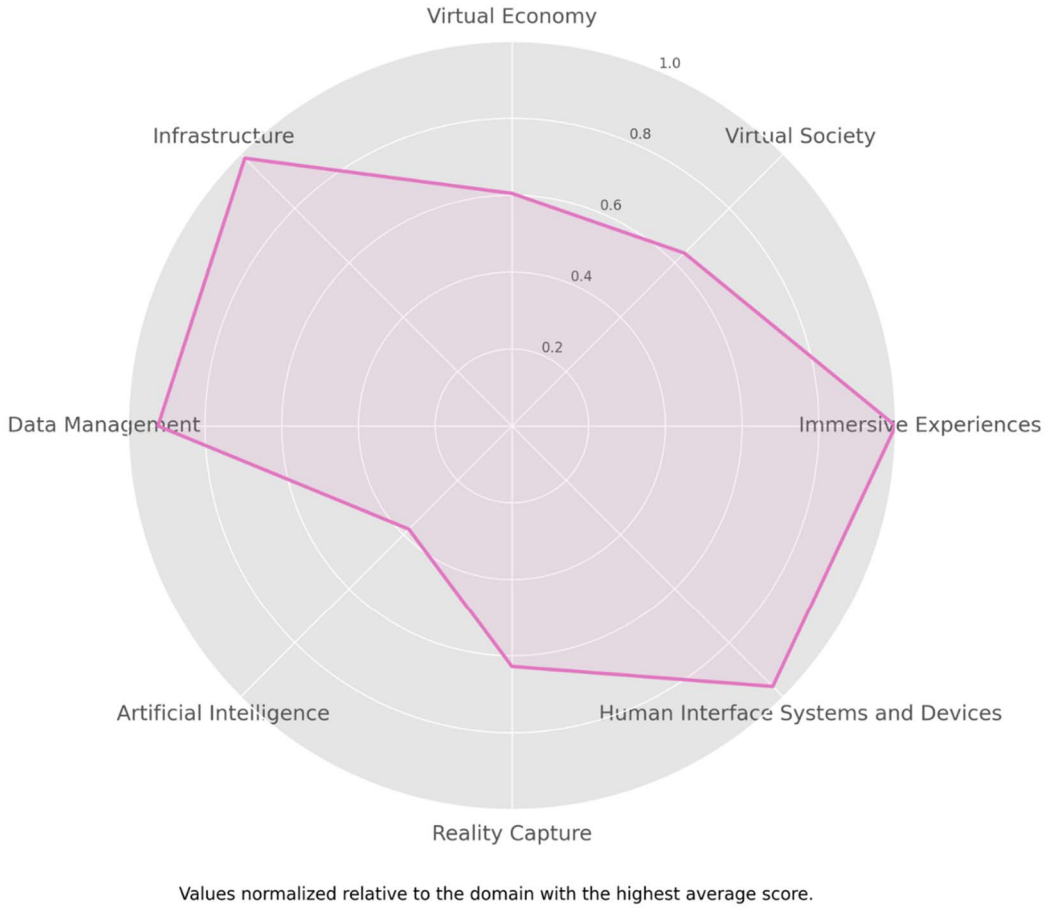

Figure B.20: W3C virtual world domain topic distribution based on 25 documents

B.3 Standards Development Organizations in the Data Set

This clause is organized alphabetically by the first letters in the name of the standards development organization. The name of each standards development organization is the linked to the home page of the organization. This information is followed by the year of establishment, and the headquarters location (city and country). Brief explanations of the standardization activities are provided for each of 130 organizations in the data set. The description of standardization activities of an SDO includes its purpose or scope and how these activities are or may be relevant for use by virtual world ecosystem stakeholders.

3rd Generation Partnership Project (3GPP), founded 1998, Sophia Antipolis, France

The 3rd Generation Partnership Project (3GPP), established in 1998, initially focused on developing global standards for 3G technologies, building on ETSI's 2G GSM work to unify global network operators under a single standards ecosystem. Today, 3GPP leads in mobile broadband standards for 5G and beyond, addressing ultra-reliable, low-latency communications, and IoT needs. As high priority 5G use cases like the virtual worlds and extended reality expand, 3GPP focuses on network slicing, edge computing, and immersive technologies. Technical Specification Groups and working groups, including Radio Access Network (RAN) and Service & System Aspects (SA), drive 3GPP's standardization efforts. Major players such as Nokia, Ericsson, Huawei, Qualcomm, and Samsung collaborate within 3GPP, advancing standards to meet evolving technological demands.

5G Media Action Group Association (5G-MAG), founded 2019, Le Grand-Saconnex, Switzerland

The 5G Media Action Group (5G-MAG) is a Geneva-based, not-for-profit association fostering collaboration between the media and ICT industries to implement advanced technologies in the connected media space. It focuses on leveraging global Internet and 5G technologies, facilitating the journey from use case conception to product implementation. 5G-MAG engages a wide range of stakeholders, including content providers, network operators, and technology developers, to build a robust ecosystem that enhances media consumption experiences. The group explores media-ICT convergence, particularly through 5G, examining potential in VR, AR, and XR. It hosts working groups and produces publications to drive innovations in media technology.

App Defense Alliance (ADA), founded 2019, San Francisco, California, USA

The App Defense Alliance (ADA) aims to enhance user protection by preventing threats from reaching devices and improving application quality. It establishes security standards, provides validation guidance, and implements a flexible certification scheme based on risk levels. Initially focusing on baseline security for developers, especially those handling sensitive data, ADA emphasizes secure coding, vulnerability mitigation, and security testing. In secure cloud configurations, it helps protect sensitive information from cyber threats. Key members, including Google, collaborate to create robust security practices. Though not focusing specifically on VR, AR, and XR, ADA's security initiatives indirectly benefit these technologies by ensuring secure foundations for application development.

Alliance for IP Media Solutions (AIMS), founded 2015, Bothell, WA, USA

The Alliance for IP Media Solutions (AIMS) is committed to promoting an IP-based, virtualized environment for broadcast and professional audiovisual industry industries by supporting open standards. AIMS collaborates with major standards bodies to ensure interoperability and prevent vendor lock-in, facilitating faster deployment of flexible media production, storage, and distribution solutions. The organization focuses on IP standards implementation, media content virtualization, and interoperability, benefiting industry leaders by ensuring access to cohesive standards. Comprising a diverse membership of engineers, technologists, and executives, AIMS fosters innovation through working groups and publications, indirectly supporting technologies like VR and AR.

European Association for the Coordination of Consumer Representation in Standardisation (ANEC), founded 1995, Brussels, Belgium

The European Association for the Coordination of Consumer Representation in Standardisation (ANEC) is committed to integrating consumer interests into the creation of technical standards in Europe. It aims to ensure that consumer perspectives are integral to standards that inform European legislation and public policies. ANEC addresses diverse topics related to consumer welfare, ranging from safety and sustainability to digital advancements like artificial intelligence. Although specifics about involvement in VR, AR, or XR are not detailed, ANEC's focus on digital technology implies potential engagement in these areas. ANEC collaborates with national consumer organizations and contributes to working groups, forming technical reports to uphold consumer interests in standardization processes. As technology evolves, ANEC's role in influences critical discussions, emphasizing consumer safety and accessibility in emerging technologies.

American National Standards Institute (ANSI), founded 1918, Washington, DC, USA

The American National Standards Institute (ANSI) is a private nonprofit organization that oversees standards and guidelines crucial for U.S. businesses across various sectors, focusing on quality, safety, and global competitiveness. Its primary goal is to develop voluntary consensus standards that enhance products, services, and processes. ANSI coordinates the U.S. private sector's standardization efforts, unifying stakeholders from diverse industries. Covering a wide range of topics from engineering to information technology, ANSI engages with emerging technologies like VR, AR, and XR, supporting initiatives to develop standards for interoperability and safety. ANSI collaborates with international bodies, promoting innovation while addressing cybersecurity and accessibility concerns.

Alliance for Open Media (AOM), founded 2015, Wilmington, Delaware, USA

The Alliance for Open Media (AOMedia) is a consortium focused on developing open, royalty-free multimedia technologies to enhance media delivery efficiency and standardization. Formed to address streaming media challenges like bandwidth, quality, and compatibility, AOMedia unites companies such as Google, Microsoft, Apple, and Netflix to drive innovation in media compression. Their open-source video codec, AV1, offers superior compression rates, benefiting traditional and emerging technologies like VR, AR, and XR by supporting high-resolution and low-latency content delivery. Through collaborative working groups, AOMedia advances media codecs and disseminates research to influence industry standards and seamless streaming experiences.

Alliance for Open Universal Scene Description (AOUSD), founded 2023, San Jose, California, USA

The Alliance for Open Universal Scene Description (AOUSD) is a non-profit organization aiming to standardize 3D content interoperability using OpenUSD (Universal Scene Description). Their goal is to enable developers and creators to efficiently work on large-scale 3D projects by establishing a unified standard. This facilitates the development of diverse 3D products and services, benefiting industries reliant on 3D technology. AOUSD focuses on technical standards, software compatibility, and best practices, particularly in virtual, augmented, and extended reality. Comprising technology and media leaders, AOUSD fosters collaboration through working groups and publications, shaping the future of 3D content in immersive environments.

Apache Software Foundation (ASF), founded 1999, Forest Hill, Maryland, USA

The Apache Software Foundation (ASF) is a decentralized community aimed at developing high-quality open-source software, supporting project communities, and maintaining legal and technical oversight for sustainable ASF projects. While ASF's technology range is vast, its projects are crucial for data processing, cloud computing, machine learning, and web applications, particularly in Extended, Virtual, and Augmented Reality (XR/VR/AR) fields. Apache Kafka aids real-time data processing for XR; Apache Spark supports big data analytics, and Apache MXNet and OpenNLP provide AI and natural language processing capabilities. ASF fosters community collaboration through meetups, conferences, and regular updates, providing essential frameworks for advanced XR development.

Association for Standardization of Automation and Measuring Systems (ASAM), founded 1998, Höhenkirchen, Germany

The Association for Standardization of Automation and Measuring Systems (ASAM) focuses on developing and coordinating technical standards for the automotive industry to ensure tool interoperability and seamless data exchange. ASAM standards cover protocols, data models, file formats, and APIs, enhancing compatibility across various tools and eliminating data converters. It addresses areas like simulation, measurement, calibration, and test automation, promoting compatibility with public standards like UML, XML, and CORBA. With members like Audi, BMW, and Volkswagen, ASAM leverages expert working groups to refine standards, staying current with technological advances. Collaborating with ISO and AUTOSAR, ASAM promotes a globally harmonious approach to automotive standardization.

Academy Software Foundation (ASWF), founded 2018, San Francisco, California, USA

The Academy Software Foundation (ASWF), founded in 2018 by the Academy of Motion Picture Arts & Sciences, serves as a neutral platform for developing open source software in the motion picture industry. It aims to improve open source contributions and enable collaboration, offering a structured environment for technological advancement in media and entertainment. ASWF supports the creation and deployment of open technologies crucial for visual effects, animation, and sound in filmmaking. As virtual, augmented, and extended reality grow, ASWF's scalable open source solutions are vital. Supported by leaders like Disney and Sony Pictures, it hosts working groups and events to foster collaboration and innovation.

Advancing Standards Transforming Markets (ASTM International), founded 1902, West Conshohocken, Pennsylvania, USA

ASTM International is a globally recognized leader in developing voluntary consensus standards to enhance quality and safety across various sectors. With approximately 12 575 standards, ASTM influences diverse industries, including consumer products, energy, chemicals, metals, and construction. In the rapidly evolving fields of virtual, augmented and extended reality, ASTM creates standards to address interoperability, user experience, and safety. The organization functions through collaborative efforts of industry professionals, academics, and government representatives. Technical committees and working groups focus on standards development, facilitating innovation and market access through research, conferences, and publications, ensuring that emerging standards meet industry demands.

b-com Technology Research Institute (B-COM), founded 2017, Cesson-Sévigné, France

b<>com Technology Research Institute specializes in advancing digital technologies, focusing on immersive technologies such as virtual, augmented and extended reality. Their goal is to enhance business competitiveness through innovative research and development. The institute bridges the gap between emerging technologies and market needs, fostering digital transformation across various sectors, including entertainment, healthcare, and smart industries. b<>com's team includes industrial and academic experts who drive projects. They emphasize collaborative efforts, practical solutions, and technology transfer to real-world applications, establishing leadership in the digital transformation landscape.

Bundesverband der Deutschen Sicherheits- und Verteidigungsindustrie (BDSV), founded 2009, Berlin, Germany

The Bundesverband der Deutschen Sicherheits- und Verteidigungsindustrie (BDSV) represents the German security and defense industry's interests, focusing on competitiveness, innovation, and ethical standards. It acts as a crucial intermediary between the industry and government, advocating for policy and regulatory interests. BDSV addresses topics like defense policy, export controls, and technological innovation, with a strong emphasis on cybersecurity and advanced technologies, including virtual, augmented and extended reality, for training and operational improvements. The association supports its goals by organizing working groups, conferences, and seminars to exchange ideas and inform members about trends. BDSV collaborates with major German defense companies and emphasizes digitalization in shaping defense capabilities.

BELIVVR INC (BELIVVR), founded 2021, Jeollanam-do, Korea

BELIVVR Inc., established in 2021 in South Korea, focused on advancing WebXR technology and AI to democratize the metaverse. Their mission was to make immersive environments accessible through open-source, WebXR-based platforms that function directly in web browsers, eliminating typical user barriers like specialized software requirements. BELIVVR contributed to projects like Mozilla Hubs and A-Frame, fostering community-driven innovations. Their work also included merging AI with storytelling, evident in their AI-generated webtoons. Although the company has folded, it continues to support global collaboration via GitHub. BELIVVR's code supports the virtual, augmented and extended reality community through open-source GitHub repositories for creating multi-user virtual spaces, enhancing both virtual experiences and AI-enhanced digital narratives.

Broadband Forum (BF), founded 1994, Fremont, California, USA

The Broadband Forum (BF) aims to accelerate broadband innovation, establish industry standards, and foster ecosystem development to support global broadband network growth. By setting benchmarks and creating standards, the Forum ensures broadband connectivity evolves to be smarter and faster, enabling robust services and a thriving ecosystem. Its work spans critical topics like broadband infrastructure, software evolution, testing, network optimization, and transitioning to new technologies. The Forum's activities, including developing technical specifications and organizing working groups, lay the groundwork for high-bandwidth, low-latency applications such as virtual, augmented and extended reality. Comprising key telecommunications members like AT&T and Nokia, the BF enhances network capabilities to support emerging technologies.

British Standards Institution (BSI), founded 1918, London, UK

The British Standards Institution (BSI) is the UK's national standards body, developing and promoting technical standards for diverse products and services. It aims to boost productivity, foster innovation, and enhance consumer and environmental protection. BSI influences industry specifications that support compliance and quality assurance across various sectors, including healthcare, construction, and emerging technologies like virtual, augmented and extended reality. By creating standards in these areas, BSI ensures innovations reach their potential while prioritizing safety and accessibility. Collaboration with experts and stakeholders allows BSI to establish guidelines, maintain quality, and drive global competitiveness. BSI's standards development facilitates the reliable deployment of transformative virtual technologies.

buildingSMART International (buildingSMART®), founded 1995, London, UK

buildingSMART® International is dedicated to advancing open standards for digital transformation in the built environment, primarily focusing on improving interoperability within the architecture, engineering, construction, and operations industries. By developing standards like Industry Foundation Classes (IFC), buildingSMART aims to enhance data exchange, collaboration, efficiency, and innovation. The organization emphasizes digital workflow optimization and explores technologies like Building Information Modelling (BIM), digital twins, and data-driven decision-making to transform traditional practices. Key members include industry leaders like Autodesk and Bentley Systems. buildingSMART conducts activities such as working groups and conferences to support its mission of aiding digital integration and collaboration.

Coalition for Content Provenance and Authenticity (C2PA), founded 2021, Washington, DC, USA

The Coalition for Content Provenance and Authenticity (C2PA) is dedicated to creating standards for verifying the source and integrity of digital media, enhancing trust in the digital ecosystem. C2PA develops open specifications that enable creators, publishers, and consumers to track digital media, ensuring its authenticity. The coalition's work includes creating guidelines and frameworks to integrate provenance data into digital content, addressing challenges in capturing and verifying content origins. Founding members, like Adobe and Microsoft, contribute expertise to develop standards benefiting digital content creators and consumers. C2PA's standards support content authenticity across platforms, including virtual, augmented and extended reality, promoting a transparent digital experience.

CableLabs®, founded 1988, Louisville, Colorado, USA

CableLabs® is an innovation lab focused on advancing broadband and telecommunications through collaborative industry efforts. Under CEO Phil McKinney, it aims to unify the sector and drive co-innovation by developing cutting-edge connectivity solutions. CableLabs emphasizes knowledge sharing to create faster, easier, and more profitable broadband infrastructure. A noteworthy focus is on integrating V virtual, augmented and extended reality into the broadband landscape to revolutionize entertainment, communication, and business. It facilitates industry collaboration through working groups, published research, and events, fostering understanding and consensus on immersive technologies in the broadband ecosystem.

Calendaring and Scheduling Consortium (CalConnect), founded 2004, McKinleyville, California, USA

CalConnect, the Calendaring and Scheduling Consortium, is a global non-profit organization established in 2004. It focuses on creating interoperable standards for calendaring and scheduling to enhance time management for individuals and organizations. By bringing together software developers, technology providers, and industry stakeholders, CalConnect promotes seamless communication across different systems, fostering collaboration and productivity. The consortium's primary aim is to develop open standards for seamless information exchange, enabling users to synchronize calendars and coordinate tasks efficiently. CalConnect collaborates with standards organizations like IETF, addressing technical challenges, standardizing protocols, and emphasizing interoperability. Its key members include major tech companies like Apple, Google, and Microsoft, and it organizes working groups and publishes guidelines for implementing interoperable calendaring solutions.

European Committee for Standardization (CEN), founded 1961, Brussels, Belgium

The European Committee for Standardization (CEN) unites 34 European countries' National Standardization Bodies to promote cohesion through standardized practices. It develops European Standards (ENs) and technical documents to boost trade, innovation, consumer safety, and environmental protection. CEN's core work involves creating standards for products, materials, services, and processes, ensuring market compatibility, interoperability, and efficiency. Covering sectors like construction, ICT, healthcare, and more, CEN meets diverse industrial and consumer needs, integrating new technologies into various sectors. Key members include BSI (UK), DIN (Germany), and AFNOR (France). CEN also advances standards in virtual, augmented and extended reality technologies, collaborating with ETSI and CENELEC, providing resources for the tech industry.

European Committee for Electrotechnical Standardization (CENELEC), founded 1973, Brussels, Belgium

Established in 1973, the European Committee for Electrotechnical Standardization (CENELEC) harmonizes electrotechnical standards across Europe, working with ETSI and CEN to create a unified framework. Its goals include facilitating global trade, removing technical barriers, and ensuring product interoperability and safety. By supporting economic growth and innovation, CENELEC helps enhance competitiveness and consumer trust. It addresses electrotechnical topics such as electromagnetic compatibility, electric vehicles, and energy management systems. CENELEC also focuses on standards for emerging technologies like virtual, augmented and extended reality, promoting interoperability and safety. Membership comprises national bodies contributing diverse perspectives. CENELEC collaborates internationally, influencing VR/AR/XR standards alongside global partners. Publications ensure electrotechnical product safety and reliability in Europe and beyond.

International Commission on Illumination (CIE), founded 1913, Vienna, Austria

The International Commission on Illumination (CIE) is a non-profit organization fostering global cooperation in lighting, colour, vision, photobiology, and image technology. Recognized by the ISO as an authoritative standardization body, the CIE sets international standards to advance lighting practices. It addresses topics such as colorimetry, vision, optical radiation metrology, and light's physiological and psychological impacts. With members from over 40 countries, the CIE comprises experts who develop standards and guidelines through technical committees. The CIE supports VR/AR development by exploring lighting and colour rendition, hosting conferences, and publishing reports to share innovations in lighting science and technology.

ConnectSafely (ConnectSafely), founded 2005, Palo Alto, California, USA

ConnectSafely, a non-profit founded in 2005 and based in Palo Alto, California, is dedicated to promoting safe, responsible technology use, with a focus on children, teens, families, and educators. Its mission is to foster digital citizenship and ensure online safety, privacy, and cybersecurity by collaborating with tech companies, educational institutions, and community groups. ConnectSafely develops resources like parental guides for apps, tips for managing screen time, and strategies to prevent cyberbullying. The organization addresses privacy, cybersecurity, and digital footprints while advocating for balanced technology use. Led by experts Larry Magid and Anne Collier, it also explores virtual reality technologies, offering guidance on safely navigating these spaces.

Cloud Security Alliance® (CSA), founded 2008, Seattle, Washington, USA

The Cloud Security Alliance® (CSA) is a global nonprofit dedicated to advancing security in cloud computing. Established in 2008, CSA unites industry experts, government agencies, and academia to address cloud security challenges. It develops frameworks like the Cloud Controls Matrix and offers certifications such as the Certificate of Cloud Security Knowledge to recognize cloud security expertise. CSA explores topics like compliance, identity management, and threat intelligence, emphasizing emerging technologies like virtual, augmented and extended reality. It forms working groups, publishes research, and provides best practices to help organizations integrate advanced technologies securely. CSA's collaborative efforts equip its members with knowledge to address modern digital security requirements.

Consumer Technology Association (CTA™), founded 1924, Arlington, Virginia, USA

The Consumer Technology Association (CTA™) represents over a thousand U.S. consumer technology companies, aiming to advance industry growth and innovation. By setting standards, offering market research, and advocating policy, CTA supports its members in overcoming industry challenges and driving economic progress. It addresses emerging technologies like virtual, augmented and extended reality, exploring their impact on sectors such as entertainment, education, healthcare, and retail. Gary Shapiro, CTA's president and CEO, leads the organization in shaping technology discussions. CTA organizes the Consumer Electronics Show (CES®) and working groups, promoting knowledge and collaboration among industry stakeholders.

CyberXR Coalition, founded 2020, Emeryville, California, USA

The CyberXR Coalition is committed to promoting diversity, equity, and inclusion in cybersecurity and Extended Reality (XR), encompassing Virtual Reality (VR) and Augmented Reality (AR). It seeks to eliminate social and technical biases in these technologies by encouraging representation and creating inclusive environments. The coalition focuses on societal impact, AI bias removal, and ethical guidelines, advocating for technologies that embrace diverse users. Key figures include Dr. Stephanie Dinkins and Professor Courtney Cogburn, who champion equitable AI and empathy-driven XR experiences. The coalition organizes working groups, produces reports, and holds events to advance principles of equality in technology development, ensuring safety and inclusivity.

DASH Industry Forum (DASH-IF), founded 2012, Beaverton, Oregon, USA

The DASH Industry Forum (DASH-IF) is a collaborative organization focused on promoting the adoption and interoperability of the MPEG-DASH standard. It aims to tackle challenges related to the standard's flexibility by providing guidelines and best practices, ensuring seamless integration and enhancing the streaming experience. Key topics include codec support, segment encapsulation, Digital Rights Management (DRM) signalling, and closed captioning harmonization. Key industry players, such as Microsoft, Qualcomm, Ericsson, and Netflix, contribute to its efforts. DASH-IF also explores emerging technologies like virtual, augmented and extended reality, adapting MPEG-DASH for these advanced formats to ensure its continued relevance in digital media delivery.

Digital Core™ Consortium (DCC), founded 2022, n/a, USA

The Digital Core™ Consortium (DCC) is an initiative focused on creating a standardized framework for digital representation of materials, known as 'digital twins,' to mirror physical materials accurately. These interoperable models serve industries like manufacturing, construction, automotive, and healthcare, enhancing efficiency and sustainability. The DCC establishes foundational standards and tools for digital materials, enabling virtual testing, product development, and sustainability assessments. Comprising industry leaders, technology providers, and research institutions, the consortium fosters collaboration and innovation, enhancing decision-making and driving continuous progress. By forming working groups and publishing research, the DCC actively shapes the digital innovation landscape, aligning with immersive technologies.

Digital Credentials Consortium (DCC-MIT), founded 2018, Cambridge, Massachusetts, USA

The Digital Credentials Consortium (DCC) is a global initiative of higher education institutions aiming to transform how academic credentials are managed digitally. The DCC seeks to create a secure, interoperable digital infrastructure for academic credentials, emphasizing transparency, security, and portability. It explores blockchain, digital identity, data privacy, and interoperability standards for reliable credential exchange. Advanced cryptographic techniques and decentralized networks are crucial to the system's integrity and scalability. The consortium, including MIT, Harvard, and others, also addresses ethical, inclusive, and user-centric design issues. While focused on digital credentials, its work may intersect with virtual, augmented and extended reality advancements.

Decentralized Identity Foundation (DIF), founded 2017, San Francisco, California, USA

The Decentralized Identity Foundation (DIF) is committed to fostering decentralized identity technologies, focusing on interoperability and global standards. Its efforts encompass research, development, and standardization of Decentralized Identifiers (DIDs), verifiable credentials, and identity hubs, emphasizing privacy and user control. Key members, including Microsoft, IBM, and MasterCard, collaborate to develop secure identity systems beyond centralized solutions. DIF operates through working groups drafting specifications and prototypes to encourage industry adoption. While not directly tied to VR or AR, DIF's work can enhance these areas with secure, verified identities, improving privacy and digital transaction trust. It supports universal standards for interoperable digital ecosystems.

Deutsches Institut für Normung e.V. (DIN), founded 1917, Berlin, Germany

The Deutsches Institut für Normung e.V. (DIN) is Germany's national standard-setting body and an influential member of the International Organization for Standardization (ISO). As a non-profit, DIN develops standards to enhance innovation, safety, and trade across industries. It establishes approximately 30 000 standards covering fields like manufacturing, IT, healthcare, and consumer products. Recently, DIN has expanded into emerging technologies such as virtual, augmented and extended reality, recognizing their growing importance. Collaborative working groups consisting of experts from various sectors draft standards to align with national and international interests. DIN actively supports technological advancement through initiatives, conferences, and partnerships, contributing significantly to global standardization efforts.

Deutsche Kommission Elektrotechnik Elektronik Informationstechnik in DIN und VDE (DKE), founded 1970, Offenbach am Main, Germany

The Deutsche Kommission Elektrotechnik Elektronik Informationstechnik im DIN und VDE (DKE) serves as Germany's central authority for developing standards in electrical engineering, electronics, and IT, under the joint management of DIN and VDE. Its primary aim is to harmonize technical standards and safety protocols, catering to national industries and contributing to global compatibility and interoperability, especially in information technology. DKE focuses on areas like virtual, augmented and extended reality, where it coordinates standardization efforts to ensure compatibility, safety, and innovation. DKE involves experts from various fields, forming working groups to address challenges and align German standards with international ones. Through publications and committee participation, DKE significantly influences the future of immersive technologies.

DOI® Foundation (DOIF), founded 1998, Chicago, Illinois, USA

The DOI® Foundation (DOIF) governs the Digital Object Identifier (DOI®) system to ensure persistently reliable identification of digital objects. As the ISO 26324 [i.7] registration authority, DOIF collaborates with Registration Agencies to manage DOI registries which serve diverse communities, from scholarly communications to entertainment. The foundation promotes global infrastructure for digital content management, focusing on identifier standards and best practices. Their work supports technology fields like virtual, augmented and extended reality by enabling consistent resource identification. Through a collaborative network, DOIF aligns the DOI system with international standards, engaging in global partnerships to improve the system's application and integration in digital ecosystems.

Digital Object Numbering Authority (DONA), founded 2014, Geneva, Switzerland

The Digital Object Numbering Authority (DONA), a non-profit based in Geneva and established by the Corporation for National Research Initiatives in 2014, manages the Digital Object Architecture (DOA) and the Handle System, which assigns persistent identifiers to digital objects. By providing a neutral, global alternative for digital object management, DONA facilitates international cooperation and advances digital ecosystems. While its focus is not explicitly on VR, AR, or XR, its identifier technology supports interoperability in these fields. DONA collaborates globally on the handle system's governance but is not directly involved in metaverse standardization, though its work remains crucial for digital infrastructure.

Digital Twin® Consortium (DTC), founded 2020, Boston, Massachusetts, USA

The Digital Twin® Consortium (DTC) is an international organization focused on promoting and advancing digital twin technologies across various sectors. It operates under the Object Management Group® and collaborates with its members to foster technology development, raise awareness, and improve interoperability in digital engineering projects. DTC serves as a hub for innovation, helping organizations create efficient, sustainable products by enhancing decision-making and product performance. The consortium addresses digital twin lifecycle management, standards, and best practices, exploring their use in IoT, AI, and smart cities. Founding members include Ansys, Dell, Lendlease, and Microsoft, combining industry, academia, and government efforts. DTC supports its mission through working groups, events, and publications to enhance the scalability of digital twins in virtual reality, augmented reality, and extended reality contexts.

Digital Video Broadcasting (DVB®), founded 1993, Geneva, Switzerland

The Digital Video Broadcasting (DVB®) Project, established in 1993, is an industry-led consortium focused on developing open technical specifications for global digital media delivery. Collaborating with major media and tech companies, DVB's specifications become international standards, largely through the European Telecommunications Standards Institute (ETSI). Their aim is to ensure efficient media distribution across satellite, cable, terrestrial, and broadband networks. The consortium addresses digital TV systems, media delivery technologies, broadcasting, and internet integration, ensuring global interoperability and innovation. DVB® now explores emerging technologies like UHD TV, HEVC, virtual, augmented and mixed reality, enhancing viewer experiences and informing standards through strategic working groups.

European Computer Manufacturers Association (ECMA), founded 1961, Geneva, Switzerland

ECMA International is a leading industry association focused on standardizing information and communication systems to promote global interoperability. It provides a collaborative platform for developing high-quality technical standards that enhance compatibility and functionality across ICT products. ECMA covers diverse areas, including programming languages, data formats, multimedia, and telecommunications. Although it has not published specific standards for the metaverse, VR, AR, or XR, ECMA plays a crucial role in related technologies. Through the Metaverse Standards Forum, ECMA contributes to interoperability standards for virtual environments. Its diverse membership, including major tech companies and startups, drives standardization efforts to meet evolving industry needs.

Eclipse® Foundation (EF), founded 2004, n/a, n/a

The Eclipse® Foundation is a non-profit organization that promotes open-source software collaboration and innovation across diverse technological fields, including enterprise, cloud, AI, IoT, and automotive. It provides infrastructure, frameworks, and tools to foster global cooperation in developing open-source solutions, while upholding open standards and interoperability crucial for digital advancements such as the metaverse. Notably, the Foundation supports over 410 projects and is involved in IoT, edge computing, and systems engineering. It contributed the Sparkplug specification for industrial IoT, now an ISO/IEC standard, and engages in the Metaverse Standards Forum. Led by Mike Milinkovich, the Foundation hosts working groups, facilitating projects like Jakarta EE and Eclipse Adoptium.

Entertainment Identifier Registry Association (EIDR), founded 2010, Redwood City, CA, USA

The Entertainment Identifier Registry Association (EIDR) provides a universal ID system for audiovisual content, simplifying the entertainment industry's supply chain. As digital technologies create complex challenges, EIDR addresses them by offering universally accepted IDs for all types of audiovisual materials, such as films and TV shows. These IDs streamline asset management, enhance integration, and ensure seamless content interaction across platforms, including virtual and augmented reality. Major media and tech companies, key EIDR members, drive industry-wide adoption and standardization. EIDR's system supports the tracking and monetization of content, ensuring efficient management through evolving technology landscapes.

Express Language Foundation (ELF), founded 2022, Claymont, Delaware, USA

The Express Language Foundation (ELF) focuses on developing frameworks for seamless data model interchangeability across information systems, emphasizing interoperability and data exchange in complex environments such as manufacturing. A major contribution is to ISO 10303 [i.8] (STEP), standardizing product data sharing in lifecycle management, enhancing consistency and precision. ELF addresses interoperability challenges in design and engineering, supporting standards that minimize digital discrepancies and fostering collaboration. Their work impacts digital twins and simulations, intersecting with VR, AR, and XR advancements. ELF operates collaboratively, engaging experts to develop and disseminate standards. They produce resources to aid organizations in adopting these standards, driving digital innovation.

European Machine Vision Association (EMVA), founded 2003, Barcelona, Spain

The European Machine Vision Association (EMVA), established in 2003 in Barcelona, is a non-profit organization dedicated to advancing machine vision technology across Europe. It serves as a network for stakeholders such as manufacturers, integrators, research organizations, and academia. The EMVA's goals include fostering collaboration, innovation, and knowledge exchange, while representing the industry's interests at the European level. It addresses machine vision topics such as computer vision and imaging technologies, intersecting with areas like artificial intelligence and deep learning. The association's activities, including conferences and workshops, explore applications in augmented reality, virtual reality, and extended reality, enhancing human-computer interaction.

Enosema Foundation (Enosema Foundation), founded 2022, n/a, USA

The Enosema Foundation is a US-based non-profit dedicated to advancing terminology, ontology, and semantics. Its main goals include developing best practices and tools for managing and sharing concepts across domains. Enosema promotes semantic interoperability, particularly in digital realms like the metaverse, by addressing challenges in technologies such as VR, AR, and XR. By fostering a user community and participating in initiatives like the Metaverse Standards Forum, it aims to create unified standards for virtual interactions. Comprised of experts, Enosema drives innovation and sets international standards to ensure consistent understanding and efficient use of concepts in virtual environments.

Ethereum (ETHEREUM), founded 2015, Zug, Switzerland

Ethereum is a decentralized platform allowing developers to build and deploy smart contracts and decentralized applications (dApps) without centralized control. It serves as a global open-source platform for secure applications in various fields, such as financial services and identity systems. Ethereum addresses smart contract development, decentralized finance (DeFi), and blockchain interoperability, and is evolving with solutions like Ethereum 2.0, transitioning to proof-of-stake for enhanced efficiency. Co-founded by Vitalik Buterin, Ethereum's development is supported by contributors and the Ethereum Foundation. It intersects with virtual realities through projects like Decentraland and Cryptovoxels, encouraging innovation and interoperability in digital environments.

European Telecommunications Standards Institute (ETSI), founded 1988, Sophia-Antipolis, France

The European Telecommunications Standards Institute (ETSI) is dedicated to developing globally relevant standards for information and communications technology systems, focusing on interoperability, quality, and effectiveness. Founded in 1988, ETSI functions as an independent, not-for-profit organization and is designated by the European Union as a European Standards Organization. It plays a crucial role in aligning EU regulations with standards acknowledged worldwide, particularly in technologies like GSM and 5G. ETSI addresses diverse ICT dimensions and increasingly emerging technologies such as virtual, augmented and extended reality. It comprises over 900 member organizations and promotes collaboration among various stakeholders. ETSI's Industry Specification Groups (ISGs) define standards for seamless AR solutions, facilitating workshops and forums to align market needs with technological advancements.

FIWARE Foundation e.V. (FIWARE), founded 2016, Berlin, Germany

FIWARE Foundation e.V. aims to establish open standards for smart solutions, enhancing interoperability and preventing vendor lock-in. It supports an ecosystem fostering innovation through open source components across smart domains like cities, agriculture, and energy. A key element, the FIWARE Context Broker, utilizes the NGSI API for dynamic data management, aligning with ETSI NGSI-LD standards. This ensures real-time data processing crucial for timely decision-making. FIWARE's community includes tech leaders like Atos and Telefonica, collaborating to expand its technology's reach. Although not exclusively focused on VR/AR/XR, FIWARE's standards and tools can support immersive applications and smart technology integration.

Global Human Body Models Consortium (GHBMC), founded 2006, Rochester Hills, USA

The Global Human Body Models Consortium (GHBMC) focuses on advancing computational human body models for automotive safety, medical research, and biomechanics. Aiming to improve crash testing and injury analysis, GHBMC enhances vehicle safety, reducing injuries and fatalities. The consortium's work also impacts medical research, refining anatomical simulations and biomechanics understanding, which benefits surgical practices and rehabilitation. Comprising experts from automotive, healthcare, and academic sectors, GHBMC collaborates on research projects and human model development. Their models, grounded in engineering and biomechanics, are valuable for designing safer vehicles and can inform virtual and augmented reality safety training, virtual medical scenarios, and educational experiences.

Global Standards 1 (GS1®), founded 1974, Brussels, Belgium

GS1® is an international, not-for-profit organization dedicated to creating and maintaining global standards to enhance supply chain efficiency and visibility across sectors. It primarily facilitates accurate information exchange between businesses to support seamless global commerce. Central to its offerings is the barcode system, which aids in tracking goods and managing inventory. GS1® assigns unique identifiers and company prefixes for effective barcode implementation. The organization's focus areas include supply chain management, data synchronization, and product tracking, with standards like EPC and RFID enhancing traceability and consumer safety. Its vast network includes over 2 million businesses from various industries, reflecting its global impact. Although GS1 does not focus specifically on VR, AR, or XR technologies, it engages with emerging technologies like RFID and IoT, which could intersect with AR applications in logistics. The organization's ongoing efforts aim to integrate technological advancements into global standards, supporting innovation in digital landscapes.

Global Tech Advocates Metaverse Group (GTAMG), founded 2013, Rotterdam, Netherlands

The Global Tech Advocates Metaverse Group (GTAMG) is committed to advancing the metaverse and Web3 technologies such as DeFi, blockchain, and cryptocurrency. As part of the Global Tech Advocates network, GTAMG aims to develop and promote metaverse innovations by connecting thought leaders and professionals across diverse sectors. The group focuses on collaboration, knowledge sharing, and technology adoption, believing in their potential to transform gaming, entertainment, finance, and social interaction. GTAMG addresses topics like decentralized ecosystems and digital identity, emphasizing societal impacts and ethics. The group organizes forums, working groups, and publishes insights to support best practices in virtual technologies.

Human Factors and Ergonomics Society (HFES), founded 1957, Santa Monica, California, USA

The Human Factors and Ergonomics Society (HFES) focuses on enhancing the interaction between humans and systems through understanding and applying human factors and ergonomics. It advances safety, performance, and well-being by providing education, fostering connections, and advocating for the profession. HFES's diverse membership includes students, researchers, and practitioners dedicated to bridging research and practical application. The Society addresses topics such as cognition, human-computer interaction, and usability, with a growing focus on emerging technologies like VR, AR, and XR. HFES organizes events and publications to share research and insights, promoting collaboration and integrating human factors into technology development to ensure safe and effective user experiences.

Hyperledger Foundation (HHerledger), founded 2015, San Francisco, California, USA

The Hyperledger Foundation, part of LF Decentralized Trust and hosted by the Linux® Foundation, promotes enterprise-grade blockchain technologies via global collaboration. It aims to grow adoption of scalable, secure, and interoperable systems by developing open-source tools across industries like finance and healthcare. Hyperledger creates permissioned blockchain networks for enhanced security, privacy, and regulatory compliance, emphasizing interoperability for diverse sector adoption. Members include IBM, Intel, and Accenture, contributing to strategic project guidance. While not focusing on VR, AR, or XR, Hyperledger's technologies support digital identity and secured transactions applicable in virtual environments through blockchain solutions, with Special Interest Groups exploring industry-specific applications.

Haptics Industry Forum (HIF), founded 2019, San Francisco, California, USA

The Haptics Industry Forum (HIF) aims to advance haptic technology by establishing standards to ensure interoperability and enhance user experiences across gaming, automotive, and virtual reality sectors. Its main goals include creating a universal framework for haptic content and defining 'haptic primitives,' fundamental components for diverse interactions in hardware and software. HIF promotes widespread adoption of haptic technologies in XR, touchpads, and other applications, supporting ecosystem growth. The forum consists of diverse industry members collaborating through working groups to develop and apply haptic standards. HIF also publishes guidelines to integrate haptic feedback into virtual environments, enhancing immersive user experiences.

The Healthcare Standards Institute (HSI™), founded 2021, Texas, Texas, USA

The Healthcare Standards Institute (HSI™) enhances healthcare management by collaborating with global experts to improve healthcare delivery through its System of Excellence. Working with organizations like ANSI, ANAB, and ISO, HSI sets benchmarks for healthcare excellence, focusing on quality management, risk assessment, patient safety, and performance improvement. The institute explores integrating innovative technologies, such as virtual, augmented and extended reality, into healthcare to boost training, patient care, and operational efficiencies. HSI organizes working groups and publishes research and guidelines on standardizing these technologies, fostering innovation and improving care through healthcare standards development.

International Advertising Bureau (IAB), founded 1996, New York, NY, USA

The International Advertising Bureau (IAB) aims to advance the digital advertising industry by developing standards, conducting research, and advocating for policies. It supports a sustainable, innovative, and trusted digital ads ecosystem by establishing best practices and addressing complex issues like data privacy and technology integration. Covering topics from programmatic advertising to AI and immersive technologies such as AR, VR, and XR, the IAB helps members leverage new innovations. Its global branches address regional needs, and membership includes key industry leaders. The IAB offers guidelines, educational events, and insights to integrate emerging technologies into digital strategies, enhancing industry impact.

Immersive Digital Experiences Alliance (IDEA), founded 2019, Bothell, WA, USA

The Immersive Digital Experiences Alliance (IDEA) is a non-profit organization focused on developing royalty-free technical specifications to ensure interoperability in immersive media. By standardizing the capture, distribution, and display of volumetric and light field content, IDEA supports consistent quality across devices and systems. The alliance emphasizes creating end-to-end solutions for emerging technologies like VR, AR, and XR. It involves industry leaders in working groups to develop standards and guidelines, while organizing events to share insights and gather feedback. IDEA aims to overcome barriers in the immersive media landscape, facilitating innovation and robust immersive multimedia applications.

Industrial Data Spaces Association e.V. (IDSA), founded 2016, Dortmund, Germany

The International Data Spaces Association (IDSA) is a non-profit dedicated to developing standards for secure data sharing, aiming to foster a fair data economy through principles of trust, transparency, and sovereignty. IDSA's key initiatives include the IDS Reference Architecture Model (IDS-RAM) and the IDSA Rulebook, which offer frameworks for secure data ecosystems. Their efforts in standardization, such as the Dataspace Protocol and IDS Certification, ensure trusted exchanges without compromising privacy. Comprising diverse members like Fraunhofer, SAP, and IBM, IDSA supports innovation in sectors including VR, AR, and XR by providing secure data sharing infrastructure, enabling interconnected and trustworthy environments.

Industrial Digital Twin Association (IDTA), founded 2020, Frankfurt am Main, Germany

The Industrial Digital Twin Association (IDTA) was founded in September 2020 by 23 organizations from diverse industries to advance digital twin technology. Now with 63 members across 8 countries, IDTA aims to promote interoperability through the Asset Administration Shell and open-source solutions, driving digital transformation. The association focuses on digital twin integration, standardization, and scalability, exploring augmented, virtual, and extended reality to visualize complex data and simulate industrial scenarios. Key members include significant industrial and technology companies. Over 250 representatives in working groups develop standards and publish resources to guide digital twin adoption and innovation.

International Ergonomics & Human Factors Association (IEA), founded 1959, Geneva, Switzerland

The International Ergonomics & Human Factors Association (IEA), established in 1959, is dedicated to enhancing safety, performance, and user experience by promoting ergonomics and human factors science. It focuses on understanding human interactions with systems and products to improve design and implementation practices. The IEA advocates for effective ergonomics in various industries, emphasizing workplace design, product usability, and human-computer interaction. It explores the benefits of emerging technologies like VR, AR, and XR in enhancing human-system interaction. Through a global network of professionals and experts, the IEA organizes conferences and publishes research, ensuring alignment with ergonomic principles for usability and safety.

International Electrotechnical Commission (IEC), founded 1906, Geneva, Switzerland

The International Electrotechnical Commission (IEC) develops global standards for electrical, electronic, and related technologies to enhance safety, efficiency, and interoperability, promoting innovation and international trade. It addresses technical and safety issues across various domains, including power generation, consumer electronics, sustainable technologies, cybersecurity, and emerging areas like electric vehicles and smart grids. The IEC also focuses on standards for information security, privacy, and system resilience. It comprises national committees and industry experts worldwide, such as ANSI, BSI, and DIN, collaborating to create these standards. The IEC also engages in standardizing virtual, augmented, and extended reality technologies, emphasizing security and interoperability.

Institute of Electrical and Electronics Engineers Standards Association (IEEE™ SA), founded 1963, Piscataway, New Jersey, USA

The IEEE™ Standards Association (IEEE SA) develops and promotes global technology standards to ensure innovation, compatibility, safety, and reliability. Part of the IEEE, it enables collaboration among industry experts, government agencies, and stakeholders to tackle current and emerging technological challenges. IEEE SA plays a critical role in advancing technologies like 5G, AI, and cybersecurity by providing a framework for interoperability and safety. Notably, it addresses complex challenges in VR, AR, and XR, developing standards for safe and effective integration. Through working groups and partnerships, IEEE SA produces reports and publications, fostering innovation and responsible use in immersive technologies and virtual worlds.

Internet Engineering Task Force (IETF®), founded 1986, Wilmington, Delaware, USA

The Internet Engineering Task Force (IETF®), founded in 1986, develops high-quality, voluntary standards to enhance Internet design, use, and management, emphasizing openness and fairness. It influences global Internet development through engineering documents, promoting decentralized control, user empowerment, and resource sharing. Though the IETF does not control the Internet, it encompasses a wide range of topics like Internet protocols and cybersecurity. Even as it seldom targets VR, AR, and XR, IETF's work improves protocol efficiency and network capabilities, supporting these technologies. Comprising global volunteers organized into working groups, the IETF shapes Internet infrastructure via meetings and RFC publications, fostering advancements in network protocols and performance.

Industrial Ontologies Foundry (IOF), founded 2016, n/a, USA

The Industrial Ontologies Foundry (IOF) focuses on creating interoperable ontologies for the digital manufacturing sector to enhance cross-system integration within factories, enterprises, and product life cycles. By emphasizing interoperability and standardized data representation, the IOF is pioneering foundational technologies crucial for industrial metaverse applications. It addresses key topics like standardized ontology development and semantic interoperability, enabling the creation of digital twins and virtual manufacturing systems. Collaborating with academic, industrial, and governmental partners, the IOF develops robust ontological frameworks. Its initiatives, like the IOF Core Ontology and connectSpec, adhere to international standards, supporting comprehensive data integration for future immersive industrial environments.

International Society of Automation (ISA™), founded 1945, Durham, NC, USA

The International Society of Automation (ISA™), founded in 1945, is a leading global nonprofit focused on advancing automation technologies and industrial control systems. It aims to develop industry standards, offer technical education, and promote best practices to enhance safety, efficiency, and innovation in automation. ISA impacts diverse sectors, like manufacturing and energy, by improving industrial network integration and protection. Key standards developed include ISA-88, ISA-95, and ISA-99/IEC 62443, bolstering process automation and cybersecurity. While not emphasizing VR, AR, or XR, ISA explores Industry 4.0, smart manufacturing, and IIoT. It offers training, certification, and events, fostering continual learning and adaptation.

International Organization for Standardization (ISO), founded 1947, Geneva, Switzerland

The International Organization for Standardization (ISO) is an independent, non-governmental international body that promotes innovation and global solutions through standardization. Its key objectives are facilitating international trade, assuring product quality, enhancing safety, and improving efficiency via harmonized standards across industries. ISO assembles global experts to refine and create standards for emerging needs, supporting innovation and continuity. While not handling electrical engineering, ISO covers broad topics like industrial products, IT, and specialized areas like VR, AR, and XR. Its membership includes national bodies from 167 countries, offering diverse expertise. ISO's Joint Technical Committees and groups like MPEG develop standards for VR, AR, and XR, ensuring alignment with global expectations.

International Telecommunications Union (ITU), founded 1865, Geneva, Switzerland

The International Telecommunication Union (ITU) is a UN agency focused on global cooperation in Information and Communication Technologies (ICT). Established in 1865, its ITU sector develops international technical standards to enhance global communication infrastructure. Key goals include promoting radio spectrum use, coordinating satellite orbits, and boosting telecom interoperability. ITU-T supports telecom systems improvement in developing countries and enhances broadband access. It addresses emerging tech areas such as mobile communication, VR, AR, and XR. With 193 countries and 900 private and academic members, ITU facilitates innovation. It also issues guidance and hosts symposiums to tackle challenges and enhance global connectivity.

Khronos® Group, founded 2000, Beaverton, Oregon, USA

The Khronos® Group, founded in 2000, is a key industry consortium creating open standards for multimedia, enabling cross-platform interoperability. Comprising over 100 technology companies, including AMD, Intel, NVIDIA, and Microsoft, Khronos® focuses on API standards for graphics rendering, VR, AR, and XR technologies. Its work in 3D graphics, parallel computing, and vision processing advances immersive experiences. Notable standards like OpenGL, Vulkan, and WebGL enhance high-performance graphics. Led by Neil Trevett, the group promotes efficient system integration and innovation. Khronos supports XR through initiatives like OpenXR, uniting VR and AR development across platforms, driving technological growth in immersive applications.

Mobile Industry Processor Interface Alliance (MIPI®), founded 2003, Bridgewater, New Jersey, USA

The MIPI® Alliance is a global organization that develops interface specifications to enhance device connectivity and interoperability across mobile and mobile-influenced industries, such as tablets, automobiles, and XR technologies. It aims to optimize technology integration within devices, supporting innovation and improving user experiences. MIPI® focuses on high-performance interfaces for cameras, displays, and sensors essential for VR and AR applications. It also addresses wireless connectivity issues, promoting energy efficiency and low electromagnetic interference. Key industry players like Intel and Samsung contribute to MIPI's standards, which facilitate advancements in XR, robotics, and more. The Alliance uses working groups and publications to advance its mission, fostering innovation and ensuring compatibility across devices.

Mozilla, founded 2003, San Francisco, California, USA

Mozilla is a prominent organization dedicated to maintaining an open and accessible internet by advocating for privacy, innovation, and user control. It is known for developing open-source software like the Firefox browser and participating in policy initiatives. Mozilla emphasizes transparency, security, community-driven development, web standards, privacy rights, and internet health. The organization is committed to preserving the web as a public resource and focuses on emerging technologies, including virtual and augmented reality. Mozilla Foundation has played a significant role in developing web-based XR standards, furthering innovation and accessibility.

Moving Picture, Audio and Data Coding by Artificial Intelligence (MPAI), founded 2020, Geneva, Switzerland

The Moving Picture, Audio and Data Coding by Artificial Intelligence (MPAI) is a Swiss non-profit organization advancing data utilization through AI-driven technical specifications for data encoding. MPAI aims to integrate these specifications into broader ICT systems, bridging technical and practical application via Intellectual Property Rights guidelines. The organization focuses on AI's role in VR, AR, and XR, enhancing system performance and interoperability. MPAI collaborates with diverse experts to drive its mission across ICT domains. Organized into working groups, MPAI develops and refines standards, supporting technologies through outreach efforts like publications and conferences, shaping future data coding in emerging realities.

MSquared Inc. (M^2), founded 2020, New York, USA

MSquared Inc. (M^2) is committed to building the infrastructure for a seamless, interconnected metaverse, focusing on integrating virtual worlds and digital assets. Their goal is a unified ecosystem allowing users to move across digital realms without compatibility issues. They establish technologies and standards, such as the Metaverse Markup Language (MML), to enhance interoperability. MSquared also addresses digital asset management, identity verification, and data security, ensuring reliability and trust. The team, likely experts in technology and immersive environments, tackles the metaverse's challenges. MSquared engages in activities like MML development, collaborations, research, and knowledge sharing to advance the metaverse community.

North Atlantic Treaty Organization (NATO) Standardization Office (NSO), founded 1951, Brussels, Belgium

The NATO Standardization Office (NSO) is essential for ensuring NATO forces' interoperability and effectiveness by developing standards across member states. It aims to facilitate successful multinational operations through standardization agreements that harmonize military practices, enhancing cooperation and resource sharing. The NSO supports NATO's strategic goals by boosting readiness, collective defence, and addressing emerging security challenges. It covers various military operation topics, integrating technologies like virtual, augmented and extended reality in training and planning. Collaborating with NATO agencies and partners, the NSO ensures these technologies are considered in standards, enhancing modern warfare capabilities.

New European Media (NEM) initiative, founded 2008, Brussels, Belgium

The New European Media (NEM) initiative is a leading European network dedicated to advancing media and creative industries by fostering collaboration across multiple sectors such as Media, Content, Broadcasting, and Consumer Electronics. Its goal is to create a unified innovation environment to shape the future European media landscape, emphasizing the integration of interactive technologies like virtual, augmented, and extended reality. NEM facilitates partnerships and promotes innovation by organizing workshops and conferences. It relies on the collective expertise of its diverse member organizations rather than specific leaders. Through publications and strategic initiatives, NEM ensures Europe remains at the forefront of global media technology advancements.

National Electrical Manufacturers Association (NEMA), founded 1926, Arlington, Virginia, USA

The National Electrical Manufacturers Association (NEMA) supports the electrical and medical imaging industries in the U.S. through standardization, advocacy, and innovation, enhancing interoperability, safety, and efficiency. Established in 1926, NEMA develops standards, influences policy for energy-efficient products, and improves regulations across various sectors. It publishes technical standards for diverse electrical products and is involved in DICOM standards for medical imaging. NEMA's 350+ member companies, from sectors like lighting and imaging equipment, collaborate on standards, advocacy, and innovation. NEMA also explores emerging technologies like VR, AR, and XR, assessing their potential impact on design, manufacturing, and industry standards.

National Institute of Standards and Technology (NIST), founded 1901, Gaithersburg, Maryland, USA

The National Institute of Standards and Technology (NIST) advances innovation and industrial competitiveness through measurement science, standards, and technology. Its goals include ensuring product reliability, accuracy, and interoperability across industries. NIST develops standards, conducts research, and provides tools to address technological challenges. The agency supports innovation, national security, and economic growth in areas like cybersecurity, advanced manufacturing, quantum science, AI, and healthcare. Efforts include the Cybersecurity Framework and quantum computing research. NIST's experts collaborate with government, academia, and industry to enhance technologies like VR, AR, and XR by developing measurement tools, standards, and guidelines, improving user interaction and system performance.

Open3D Foundation (O3DF), founded 2021, San Francisco, California, USA

The Open3D Foundation (O3DF) is a non-profit organization established in 2021 under the Linux Foundation, dedicated to promoting the Open3D library for 3D data processing and visualization. Its mission is to support researchers, developers, and organizations by advancing fields like computer vision, robotics, digital twins, AR, and VR. O3DF enhances the Open3D library's capabilities in 3D geometry processing, point cloud manipulation, and rendering, making these tools accessible and interoperable. By engaging with industry experts and developers through working groups and collaborative projects, the foundation fosters innovation and expands the library's capabilities, contributing significantly to immersive and interactive 3D technologies.

Open AR Cloud (OARC), founded 2018, Delaware, USA

Open AR Cloud (OARC) is a non-profit organization focused on advancing open, interoperable spatial computing technologies that integrate the physical and digital worlds, benefitting all users. They aim to establish universal standards for augmented and mixed reality, ensuring accessibility and security. By fostering industry collaboration, OARC seeks to prevent fragmentation and enhance the seamless integration of virtual elements into real environments. Key focus areas include interoperability, graphics software, and mobile XR technologies. OARC's experts lead initiatives, working groups, and research. The organization hosts events to encourage innovation and develop cohesive augmented reality solutions.

Organization for the Advancement of Structured Information Standards (OASIS Open), founded 1993, Burlington, Massachusetts, USA

OASIS Open is a global non-profit consortium established in 1993, focused on developing open IT standards to enhance interoperability, security, and innovation. It addresses areas such as e-commerce, cybersecurity, cloud computing, blockchain, and IoT. OASIS collaborates with businesses, government agencies, academic institutions, and individuals to create vendor-neutral and freely available standards. Significant contributions include XML, SAML, TOSCA, and UBL, supporting web technologies and simplifying electronic commerce. Its diverse membership participates actively, ensuring standards meet global demands. While not exclusively focused on VR, AR, or XR, OASIS's work on interoperability and IoT can influence these technologies.

Open3D Foundation (ODn), founded 2021, San Francisco, California, USA

The Open3D Foundation, established under the Linux Foundation in 2021, focuses on advancing the development and adoption of Open3D, an open-source library for 3D data processing and visualization. It aims to drive innovation in areas like computer vision, robotics, AR, VR, and digital twins by supporting researchers, developers, and businesses. Key topics include 3D geometry processing, point cloud manipulation, and visualization, essential for 3D scanning, mapping, and scene reconstruction. The foundation thrives on community collaboration, involving contributors from academia and industry, to enhance the library and ensure continuity. Its initiatives foster collaboration and innovation, providing a platform for shared progress in 3D technologies.

Open Geospatial Consortium (OGC), founded 1994, Wayland, Massachusetts, USA

The Open Geospatial Consortium (OGC), founded in 1994, focuses on enhancing geospatial data interoperability and accessibility through open standards. These standards enable seamless geospatial information exchange, crucial for fields like urban planning, transportation, and disaster management. Key contributions include standards like Web Map Service (WMS), Web Feature Service (WFS), and Geography Markup Language (GML). OGC supports open geospatial APIs, enhancing data accessibility in areas such as agriculture, defense, and smart cities. Its diverse membership, comprising industry leaders and academic institutions, collaborates on these initiatives. OGC also explores 3D geospatial data integration in VR and AR to enhance immersive applications.

OpenID® Foundation (OIDF), founded 2007, San Ramon, California, USA

The OpenID® Foundation (OIDF), founded in 2007, is a non-profit organization dedicated to developing open identity standards that promote security, interoperability, and privacy. Its primary aim is to lead the global effort in providing robust identity solutions that are widely recognized and adopted across various applications. OIDF focuses on simplifying digital identity management and enhancing trust and privacy in online interactions through secure identity verification and management specifications. Key areas include single sign-on and privacy-enhanced login systems. The foundation benefits from diverse contributions, including leaders from major tech firms, and hosts working groups to advance identity technology while considering emerging fields like VR and AR. It also publishes reference materials and organizes global events to foster stakeholder collaboration and innovation.

Open Mobile Alliance (OMA), founded 2002, San Diego, CA, USA

OMA SpecWorks, formerly the Open Mobile Alliance, aims to develop global standards that facilitate mobile services and the Internet of Things (IoT). A key goal is enhancing IoT interoperability, security, and management through protocols like Lightweight M2M. This enables smooth device communication, integrating IoT with mobile tech across networks and regions. Key to this mission is collaborating with industry leaders to foster innovation and adoption of their standards. While focusing on mobile and IoT, OMA SpecWorks also supports XR technologies by maintaining essential communication standards. It engages in collaborative working groups, publications, and webinars to advance technology integration and dissemination.

Open Metaverse Alliance for Web3 (OMA3), founded 2022, Zug, Switzerland

The Open Metaverse Alliance for Web3 (OMA3) is committed to building an interconnected and transparent metaverse ecosystem, focusing on interoperability of virtual lands, digital assets, and services across various platforms. Its main objective is to empower creators and users by providing them control over their data. OMA3 aims to establish universal standards and protocols for seamless interaction between Web3 metaverse platforms, promoting a cohesive digital environment. The alliance underscores the importance of data interoperability, user control, and decentralized governance. Comprising members like The Sandbox, Animoca Brands, and Decentraland, OMA3's working groups develop standards to support open metaverse principles, and the organization fosters community growth through publications, events and outreach.

Open Metaverse Foundation (OMF), founded 2023, Denver, Colorado, USA

The Open Metaverse Foundation (OMF), established under the Linux Foundation in 2023, focuses on fostering an open, interoperable, and inclusive metaverse ecosystem. It brings together developers, businesses, researchers, and technologists to develop standards and tools that promote a decentralized, interconnected virtual world, emphasizing open-source principles to break proprietary silos. OMF prioritizes interoperability across platforms and decentralization, utilizing blockchain for user control over digital identities and assets. It also emphasizes accessibility, inclusivity, privacy, and security in the digital space. Through collaborative working groups and events, OMF aims to advance open standards and drive the adoption of open metaverse principles, ensuring a user-centric digital future.

Object Management Group (OMG®), founded 1989, Milford, Massachusetts, USA

The Object Management Group (OMG®) is a non-profit standards development organization with over 230 members from 27 countries, focusing on creating technology standards that provide value across diverse industries. OMG® brings together end-users, researchers, and vendors from academia, government, and industry to develop and update standards as technologies evolve. Key areas include agriculture, autonomous vehicles, finance, healthcare, and space exploration. OMG® also focuses on virtual, augmented, and mixed reality technologies, creating frameworks and guidelines to enhance their development and application, ensuring interoperability and innovation across sectors.

Open Metaverse Interoperability Group (OMI), founded 2021, n/a, n/a

The Open Metaverse Interoperability Group (OMI) is an open-source community dedicated to creating an inclusive and interoperable metaverse. It aims to develop technology standards that integrate various virtual environments by fostering industry collaboration. OMI emphasizes input from industry professionals, creators, and enthusiasts to establish shared technological foundations for metaverse expansion. The group focuses on technical interoperability aspects, including graphics software and open communication protocols for seamless platform interaction. Key members include industry leaders like Neil Trevett and Tim Sweeney. OMI organizes working groups to tackle VR, AR, and XR challenges, facilitating collaboration and innovation to enhance user experiences.

oneM2M®, founded 2012, Memphis, Tennessee, USA

oneM2M, established in 2012, is an international initiative focused on creating technical specifications for Machine-to-Machine (M2M) communication and the Internet of Things (IoT). Comprised of standards organizations like ETSI and TIA, it develops a common M2M service layer for seamless connectivity among various devices and application servers. Targeting diverse domains such as smart homes, healthcare, and smart cities, oneM2M addresses interoperability, security, and data management in IoT. It comprises over 200 members, including major corporations and small tech firms, enhancing its standards' adaptability. While not directly focused on VR or AR, oneM2M supports these fields through IoT infrastructure improvements.

The Open Group®, founded 1996, San Francisco, California, USA

The Open Group® is a global consortium established in 1996, aiming to develop open standards and certifications to enhance technology innovation and interoperability across various industries. It provides a collaborative platform for companies, government entities, and individuals to create and implement standards in enterprise architecture, IT management, security, and cloud computing. The Open Group also addresses emerging technologies like virtual reality, augmented reality, and extended reality by adapting existing frameworks to incorporate these immersive technologies. Its diverse membership includes large corporations and tech specialists, working collectively to foster open standards and integrate immersive experiences into IT ecosystems.

Open Source Virtual Reality Movement (OSVR), founded 2015, Columbia, Maryland, USA

The Open Source Virtual Reality Movement (OSVR) advances VR and AR by offering an open-source platform for easy discovery and operation of various devices, avoiding proprietary system lock-ins. Its aim is to boost innovation and collaboration by ensuring device interoperability and standardization. OSVR supports integration across game engines and OS for developers, enhancing creativity and user experiences. Key technologies include asynchronous time warp and direct mode, reducing latency for smoother, immersive VR interactions. Founded by Sensics and Razer, OSVR promotes resource sharing and community engagement through documentation, libraries, and forums. It fosters innovation via the Apache 2.0 license, aiding VR, AR, and XR growth.

Open Worldwide Application Security Project (OWASP®), founded 2001, Wilmington, DE, USA

The Open Worldwide Application Security Project (OWASP®) is a non-profit foundation dedicated to enhancing global software security. Its core aim is to foster a community that aids organizations in creating secure applications. Through open-source projects and extensive chapter networks, OWASP offers tools, documents, and resources for anyone interested in application security. It focuses on secure coding, vulnerability assessments, and threat modelling, and is renowned for the OWASP Top Ten, highlighting major web application security risks. OWASP operates as a decentralized community with notable contributions from figures like Jeff Williams. Its dynamic, volunteer-driven approach ensures responsiveness to security challenges across all software domains, including emerging technologies like VR and AR.

ProfiBus Nutzerorganisation e.V. (PI), founded 1989, Kaiserslautern, Germany

PROFIBUS & PROFINET International (PI), founded in 1989, promotes the standardization and advancement of industrial communication technologies, specifically focusing on the PROFIBUS and PROFINET protocols, essential for real-time data exchange and process optimization in automation. PI aims to enhance communication and interoperability across sectors such as manufacturing, energy, and pharmaceuticals. The organization integrates cutting-edge technologies like VR, AR, and XR into industrial applications, improving operational efficiency and safety. Comprising industry-leading members, PI conducts working groups, publishes resources, and hosts global events to facilitate the adoption of these standards and encourage innovation in industrial communication networks.

ProSTEP iViP e.V. (ProStep iViP), founded 1993, Darmstadt, Germany

ProSTEP iViP e.V. is a leading German organization focused on driving digital transformation across professional services and technology sectors. It aims to improve business processes and efficiency through technologies like virtual and augmented reality, and immersive digital environments. By bringing together experts from diverse industries, the organization fosters collaboration and innovation to integrate these technologies into business operations effectively. It emphasizes developing and promoting industry standards for digital solutions, ensuring adaptive technology advancements. With members from sectors such as automotive, aerospace, and IT, ProSTEP iViP e.V. conducts events, workshops, and publishes guidelines, shaping interactive virtual technology's future in professional contexts.

Responsible Metaverse Alliance (RMA), founded 2022, Sydney, Australia

The Responsible Metaverse Alliance (RMA) is dedicated to creating an ethical, sustainable, and inclusive metaverse. Its goals include ensuring privacy, equity, security, and societal well-being in the digital landscape. The RMA focuses on user safety, digital rights, and data privacy, promoting diversity and inclusivity. It addresses risks like data misuse and digital addiction while leveraging the metaverse for human connection and innovation. The RMA is a collaborative effort involving industry leaders, technologists, legal experts, and social advocates. It organizes working groups and publications to drive transparency and accountability, establishing guidelines for metaverse governance and promoting responsible innovation.

Standards Australia (SA), founded 1922, Sydney, Australia

Standards Australia (SA) is a vital non-governmental organization that develops standards to enhance safety, quality, and efficiency across various industries, including manufacturing, construction, energy, and IT. Its mission is to collaborate with industry stakeholders to formulate standards that promote innovation and fair competition aligned with global benchmarks. SA is instrumental in strengthening Australia's global industrial competitiveness. It addresses emerging technologies like VR, AR, and XR, focusing on interoperability, data security, user safety, and system reliability. Through its committees, SA engages experts from industry, academia, government, and consumer groups to ensure diverse, balanced standards. SA collaborates with international bodies to harmonize standards and regularly updates guidelines to drive innovation and protect stakeholder interests in emerging technologies.

Society of Automotive Engineers (SAE), founded 1905, Warrendale, Pennsylvania, USA

SAE International® is a global association with over 128 000 engineers and technical experts in aerospace, automotive, and commercial vehicle industries, dedicated to advancing mobility knowledge and solutions. Committed to lifelong learning and voluntary consensus standards, SAE aims to lead in educating mobility professionals and promoting safe, clean, and accessible mobility. It covers topics like VR, AR, and XR, vital for designing and testing automotive systems. These technologies enhance visualization and interaction, improving safety and efficiency. SAE hosts conferences, webinars, and maintains a library of technical papers and standards, fostering collaboration and innovation in next-generation mobility solutions.

Society for Information Display (SID), founded 1962, Campbell, California, USA

The Society for Information Display (SID) advances electronic display technology by uniting top scientists, engineers, researchers, and business professionals. Valued at over $120 billion annually, the display industry benefits from SID's push for innovation and collaboration. SID focuses on the development and integration of display technologies in virtual, augmented and extended reality, enhancing resolution, latency, and colour accuracy. Prominent members from academia and industry contribute to research and standards. SID supports its mission through working groups, conferences like the Display Week Symposium, and publications, offering insights into VR, AR, and XR advancements crucial for future immersive experiences.

Simulation Interoperability Standards Organization (SISO) Standards Activity Committee (SAC), founded 1997, St. Petersburg, Florida, USA

The Simulation Interoperability Standards Organization (SISO) Standards Activity Committee (SAC) focuses on enhancing interoperability and integration of simulation systems across various platforms by developing and managing standards critical for fields like defense, aviation, training, and research. SAC ensures simulation systems operate effectively together by overseeing technical standards in distributed simulations, Modelling and Simulation (M&S) architecture, and data exchange. These efforts improve communication and data sharing between simulations, fostering realism and utility. SAC's work involves forming working groups addressing virtual, augmented and extended reality, and organizing conferences and workshops to advance simulation technologies worldwide.

Society of Motion Picture and Television Engineers (SMPTE), founded 1916, White Plains, New York, USA

The Society of Motion Picture and Television Engineers (SMPTE) is a global organization committed to advancing motion imaging and media technology. With over 5 000 members, SMPTE promotes technological innovation and global media interoperability through setting industry standards. It has developed about 800 engineering standards, vital for integrating diverse media technologies. SMPTE supports member growth with educational programs and networking opportunities. It focuses on emerging fields like Virtual, Augmented, and Extended Reality (VR, AR, XR), developing standards for immersive media to ensure quality and consistency. SMPTE facilitates expert collaboration, publishes research, and hosts events to lead in industry innovation and immersive media development.

Solana Foundation (Solana), founded 2020, Zug, Switzerland

The Solana Foundation is dedicated to advancing the Solana blockchain by enhancing scalability, speed, and reducing transaction costs, making it ideal for decentralized applications, finance, NFTs, and broader blockchain innovations. It aims to create a robust ecosystem for developers and startups by providing resources, funding, and guidance, ensuring technological, security, and user experience improvements. The Foundation focuses on scalability and performance, enhancing sectors like finance, gaming, and supply chain, and also explores emerging technologies like VR, AR, and XR. Key figures include Co-Founders Anatoly Yakovenko and Raj Gokal. Activities include grants, educational programs, and partnerships fostering blockchain innovation.

Streaming Video Technology Alliance (SVTA), founded 2014, Fremont, California, USA

The Streaming Video Technology Alliance (SVTA) aims to advance the streaming video industry by developing standards and best practices to enhance video quality and interoperability across platforms. It focuses on video compression, streaming protocols, low-latency streaming, and both live and on-demand video delivery. SVTA also explores emerging technologies like 4K, 8K, VR, AR, and XR. Key industry participants, including Apple, Comcast, and Netflix, are members. They collaborate to address challenges and set guidelines for efficient content delivery. The SVTA manages working groups and produces publications to support innovations in streaming technology, maintaining a forward-thinking perspective in the industry.

Spatial Web Foundation (SWF), founded 2017, Los Angeles, California, USA

The Spatial Web Foundation (SWF) is dedicated to establishing socio-technical standards for the Spatial Web, a digital landscape integrating the physical and virtual worlds. SWF prioritizes secure, interoperable, and ethical technological advancement, ensuring it aligns with societal norms. The foundation explores VR, AR, and XR integration, aiming for seamless technology interoperability while upholding privacy and security. SWF's community-driven efforts involve developers, scientists, and innovators who collaboratively tackle VR, AR, and XR challenges. Through working groups and research, SWF addresses interoperability, security, and ethics, contributing to publications that guide stakeholders. SWF's work shapes a responsible and sustainable digital future.

The International Future Computing Association (TIFCA) (formerly: Immersive Technology Alliance), founded 2009, Whitby, Canada

The International Future Computing Association (TIFCA), formerly the Immersive Technology Alliance, is a non-profit network uniting technology, media, and standards leaders to promote technology adoption. Its main goal is creating frameworks to facilitate new technology integration, focusing on virtual, augmented, and extended reality, as well as virtual world development. TIFCA's collaborative ecosystem addresses user needs and technological challenges. It involves members from various sectors, like semiconductor and software industries, to enhance immersive technology viability. By organizing working groups and events, TIFCA fosters communication on interoperability, content creation, and experiences to ensure seamless technology integration.

Trust over IP Foundation (ToIP), founded 2020, San Francisco, California, USA

The Trust over IP Foundation (ToIP) is a global initiative established in 2020 to create open standards for decentralized digital trust. Its mission is to develop a secure, privacy-focused framework to support trustworthy digital interactions, emphasizing identity, privacy, and trust. By utilizing decentralized technologies like blockchain and self-sovereign identity, ToIP aims to enhance online engagement for individuals and organizations. It defines protocols, standards, and practices to manage trust, focusing on verifiable credentials, decentralized identifiers, and trust frameworks. Although not directly focused on virtual environments, ToIP's work supports secure and authentic interactions across digital and emerging platforms, fostering innovation in finance, healthcare, and governance.

The Linux Foundation (TLF), founded 2000, San Francisco, California, USA

The Linux Foundation (TLF), established in 2000, is a non-profit organization focused on promoting the growth of the Linux operating system and enhancing the open-source ecosystem. It serves as a neutral collaboration platform for individuals, corporations, and communities, providing resources like funding, legal support, and infrastructure for critical projects. TLF manages significant open-source initiatives, including Kubernetes and the Cloud Native Computing Foundation, and covers sectors like cloud computing, AI, and blockchain. In 2023, TLF launched the Open Metaverse Foundation (OMF) to develop open-source standards for a global metaverse, supporting VR, AR, and XR technologies through collaborative efforts across industries.

TeleManagement Forum (TM Forum) (TMF), founded 1988, Parsippany, New Jersey, USA

The TM Forum is a global industry association that supports digital transformation in telecom, media, and technology sectors through collaboration. Since 1988, it has united service providers and vendors to develop best practices, frameworks, and standards for digital business transformation. TM Forum focuses on emerging technologies like 5G, AI, IoT, and cloud computing, facilitating discussions that enhance operational efficiency and innovation. It is known for fostering interoperability and innovative business models, with contributions from major industry players like AT&T, China Mobile, and Ericsson. The Forum's Catalyst Projects and events encourage cross-industry collaboration and exploration of new digital services, including immersive technologies.

Telecommunications Technology Association (TTA), founded 1988, Seonnam-city, Korea

The Telecommunications Technology Association (TTA) is a key South Korean organization focused on advancing and standardizing telecommunications. It fosters innovation in ICT through collaboration among service providers, manufacturers, and government entities. TTA develops national and international standards, crucial for technologies like 5G, IoT, AI, and cloud computing, and ensures interoperability and new service creation. It explores emerging fields like VR, AR, and XR, playing a role in their standardization, indicated by its inclusion in the Metaverse Standards Register. Comprising telecom providers, manufacturers, and government agencies, TTA hosts events and offers certifications to promote technological advancement and global ICT leadership.

Underwriters Laboratories (UL), founded 1894, Northbrook, Illinois, USA

Underwriters Laboratories (UL) is dedicated to ensuring product safety, quality, and environmental sustainability by developing rigorous safety standards and testing procedures. UL conducts comprehensive testing for potential hazards and provides certifications for compliance, helping industries minimize risk and enhance safety practices. The organization addresses safety standards across diverse sectors, including electronics, automotive, construction, and healthcare, while also focusing on emerging technologies like renewable energy, smart homes, and cybersecurity. Under the leadership of President and CEO Jennifer Scanlon, UL advances strategic initiatives and global influence. In the realm of VR, AR, and virtual worlds, UL develops safety standards, offers certifications, and publishes research to promote safe adoption and implementation of these technologies.

Verband der Automobilindustrie e.V. (VDA), founded 1901, Berlin, Germany

The Verband der Automobilindustrie e.V. (VDA) is a prominent German association promoting automotive industry advancement. Its goals include boosting German automotive innovation, global competitiveness, and fostering supportive policies. The VDA represents vehicle manufacturers, suppliers, and related entities, facilitating dialogue to create a favourable regulatory environment. Key focus areas include sustainability, digitalization, autonomous vehicles, and mobility solutions. The VDA advocates integrating extended reality technologies into automotive design for enhanced prototyping and user experiences. It organizes forums on digital advancements, collaborating with academia and tech firms to push research and development for industry innovation and sustainability.

Verein Deutscher Ingenieure e.V. (VDI), founded 1856, Berlin, Germany

The Verein Deutscher Ingenieure e.V. (VDI), the Association of German Engineers, has supported engineers for over 160 years by advancing their interests and representing them across various levels. VDI strengthens the engineering community and drives technological progress globally by providing networking opportunities and guidance on industry standards. It addresses a broad range of engineering topics, focusing on interdisciplinary fields like XR (extended reality) technologies, exploring management, regulation, and technical aspects. VDI, comprising industry experts, hosts forums and publishes insights to promote innovative practices and ethical use of immersive technologies, fostering collaboration and setting industry standards in engineering.

Video Electronics Standards Association (VESA), founded 1989, San Jose, California, USA

The Video Electronics Standards Association (VESA) is a key organization focused on standardizing video display interfaces to ensure compatibility and performance across consumer electronics. With around 340 member companies, including major players like AMD, Intel, NVIDIA, and Microsoft, VESA creates uniform specifications to enhance interoperability between graphics, video hardware, optics, and displays. The organization develops standards such as DisplayPort for seamless communication between devices and addresses emerging topics in Extended Reality (XR) technologies. Through working groups and participation in conferences like SIGGRAPH, VESA refines and develops new standards, driving advancements in VR, AR, and other immersive digital experiences.

Volumetric Format Association (VFA), founded 2021, Dover, DE, USA

The Volumetric Format Association (VFA) is an international consortium dedicated to developing open specifications for volumetric video, aiming to create a unified ecosystem that enhances collaboration, reduces fragmentation, and promotes interoperability. By establishing standards, the VFA facilitates the integration and use of volumetric video across various platforms, crucial for applications in virtual, augmented, and mixed reality. The association addresses topics like capture technology, data compression, and real-time streaming, advancing immersive media technologies. Comprising industry leaders from entertainment, technology, and telecommunications, the VFA conducts working groups, publishes technical papers, and hosts events to foster collaboration and disseminate knowledge, driving the industry forward.

Video Quality Experts Group (VQEG), founded 1997, n/a, Sweden, USA

The Video Quality Experts Group (VQEG) is an international consortium focused on advancing video quality assessment across diverse platforms. Originally centred on subjective and objective evaluation within known distribution methods, VQEG now emphasizes a comprehensive understanding of Quality of Experience (QoE), covering visual and audio aspects. As multimedia technology evolves, including VR, AR, and XR, VQEG develops new assessment methodologies. The group comprises industry and academic experts collaborating to establish standards and share findings through research and conferences. VQEG's holistic and innovative approach to QoE ensures its continued leadership in multimedia quality assessment and support for industry standardization.

VRM Consortium, founded 2019, Chūō-ku, Japan

The VRM Consortium aims to foster interoperability and open standards within virtual reality, augmented reality, mixed reality, and related virtual world technologies. Its primary goal is to define and promote 3D model formats based on glTF. This includes the VRM avatar representation file format (VRoid Model) which is designed for human-like 3D avatars. It addresses interoperability issues related to character rigging, animation, and metadata, ensuring that avatars can be consistently rendered and interacted with across different virtual world environments. The consortium also works on related areas like glTF integration for broader 3D asset interoperability. The VRM Consortium is composed of a diverse group of contributors from primarily Japanese. Key members and contributors include representatives from Pixiv, the company behind VRoid Studio, which is a major driving force behind the VRM standard. The community also includes individual contributors who participate in discussions and development.

Video Service Forum, Inc. (VSF), founded 1997, San José, California, USA

The Video Services Forum, Inc. (VSF) is an international association dedicated to enhancing interoperability and establishing quality metrics in media networking technology. It aims to address challenges related to the development, deployment, operation, and security of media technologies through forums and contributions to standards development. VSF educates industry stakeholders and covers topics like professional video transport and media network integration. While it traditionally does not focus on VR, AR, or XR, these areas might offer future opportunities. Key members from the media industry collaborate within VSF to advance media networking, contributing to standards like SMPTE 2110. Currently, no projects target immersive media domains.

Virtual World Society® (VWS), founded 2019, Seattle, Washington, USA

The Virtual World Society® (VWS) is dedicated to using immersive technologies like VR, AR, and XR to foster societal improvement. It builds a community addressing global issues, promoting education, and encouraging cross-disciplinary collaboration. VWS focuses on setting ethical foundations for the responsible, equitable use of virtual worlds, exploring regulation, ethics, and governance. Key contributors include Tom Furness, a VR pioneer, and Jim Chabin, an industry leader. VWS hosts workshops, conferences, and working groups to share knowledge and inspire innovation, emphasizing user-centred design and ethical frameworks. Through research dissemination and partnerships, VWS aims to shape immersive technology's future for societal benefit.

World Wide Web Consortium (W3C®), founded 1994, Cambridge, Massachusetts, USA

The World Wide Web Consortium (W3C®), founded on October 1, 1994, at MIT, is crucial for standardizing web technologies to create a universal internet. It operates through a cooperative, transparent process to develop widely-endorsed technical standards like HTML, CSS, and WCAG, enhancing the modern web. Addressing cutting-edge topics like virtual, augmented and extended reality, W3C's 'Immersive Web Community Group' integrates these technologies into web browsers to boost accessibility and user engagement. Key figures, including web founder Tim Berners-Lee, drive these initiatives. Their work on APIs, protocols, and guidelines furthers immersive, interoperable web experiences.

Wabi Foundation (Wabi), founded 2017, Austin, Texas, USA

The Wabi Foundation aims to enhance supply chain transparency, efficiency, and trust in the consumer goods sector through blockchain technology. By enabling consumers to authenticate product origins and quality, it addresses issues like fraud and counterfeiting, with a focus on sensitive areas such as food safety, luxury items, and pharmaceuticals. The foundation's Wabi platform lets businesses track product lifecycles using blockchain, ensuring authenticity and fostering consumer trust. Operating as a key player in blockchain-driven supply chain innovation, Wabi Foundation collaborates with various stakeholders to advance ethical commerce. It focuses on developing digital solutions to improve traceability and transparency, promoting a more sustainable supply chain.

World Broadband Association (WBA), founded 2022, London, UK

The World Broadband Association (WBA) works to promote global broadband access and the development of high-speed broadband technologies like Wi-Fi, 5G, and fibre-optics. Since its founding in 1996, the WBA has aimed to enhance connectivity, digital inclusion, and urban development. It represents stakeholders such as network operators and technology vendors. Key objectives include fostering innovation, ensuring broadband interoperability, and addressing the digital divide. Members like BT Group and Google collaborate to advance broadband infrastructures and best practices. The WBA also explores the integration of virtual, augmented and extended reality into broadband applications and invests in research on these technologies' impacts and innovations.

Web3D Consortium, founded 1997, Salinas, California, USA

The Web3D Consortium promotes open standards for 3D graphics on the internet, focusing on the ISO-certified X3D standards. Established in 1997 as a non-profit organization, its diverse members, including tech companies and academic institutions, collaborate to advance 3D technology. The Consortium prioritizes interoperability, mobile XR integration, and creating APIs for seamless communication across systems. Key activities include organizing working groups in areas like Web Architecture and Medical, and publishing research and technical documents. These efforts ensure high-quality, interactive, and accessible 3D graphics across platforms, shaping the future of VR, AR, and XR technologies through innovation and collaboration.

World Intellectual Property Organization (WIPO), founded 1967, Geneva, Switzerland

The World Intellectual Property Organization (WIPO) aims to create a balanced global Intellectual Property (IP) system that promotes innovation and creativity, contributing to sustainable development. It focuses on developing international IP laws, providing services, and supporting inventors, artists, and businesses in protecting their IP rights. WIPO addresses various IP topics, including patents, trademarks, and copyrights, and is exploring the implications of emerging technologies like the metaverse, VR, AR, and NFTs on IP. Led by Director General Daren Tang, WIPO's member states drive its policies. In March 2023, WIPO held discussions on IP and the metaverse, highlighting challenges and opportunities.

XR Association (XRA), founded 2016, Washington, DC, USA

The XR Association (XRA) is focused on promoting the responsible development of the Extended Reality (XR) industry, which includes virtual, augmented, and mixed reality. XRA's goal is to bring together diverse stakeholders to establish industry standards and best practices, emphasizing ethical and innovative integration of XR into society. By advocating for its members, including major companies like Meta, Microsoft, and Google, XRA ensures the alignment of developmental goals with ethical strategies. Key focus areas include privacy, safety, accessibility, and ethics, exploring XR's impact across various sectors such as education and healthcare. XRA leads initiatives like working groups, publishes research, and hosts events to encourage collaboration and knowledge-sharing towards responsible XR adoption.

XR Guild (XRG), founded 2022, Los Angeles, California, USA

The XR Guild is an industry collective focused on advancing and standardizing Extended Reality (XR) technologies, including VR, AR, and MR. It aims to foster innovation by creating a collaborative platform for developers and stakeholders across sectors, facilitating the sharing of knowledge and resources. The Guild emphasizes ethical practices and inclusivity while advocating for robust XR standards. It engages in discussions and provides educational resources to address technical, ethical, and accessibility aspects. By organizing events, workshops, and forming working groups, the Guild promotes the responsible development of XR technologies and supports innovation in diverse industries like entertainment, education, and healthcare.

X Reality Safety Intelligence (XRSI), founded 2019, San Francisco, California, USA, Turino, Italy

X Reality Safety Intelligence (XRSI) is a leading organization focused on ensuring the ethical development of emerging technologies like VR, AR, and XR. With offices in the San Francisco Bay Area and Torino, XRSI offers intelligence and advisory services emphasizing safety, privacy, security, and responsible innovation. The organization collaborates with experts to prioritize human welfare in technology through standardization, certification, and policymaking. XRSI addresses significant topics such as medical XR, child safety, and diversity via initiatives like the Medical XR Advisory Council and the CyberXR Coalition. Their frameworks, including the XRSI Privacy and Safety Framework, guide stakeholders and lawmakers worldwide toward safer, inclusive technology ecosystems.

Annex C: Bibliography

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