STRATEGIC RESEARCH & INNOVATION AGENDA

SOLVING REAL WORLD PROBLEMS

JUNE 2025

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Chapter 0

INTRODUCTION

Introduction – Virtual Worlds, solving real world problems

Virtual Worlds (VW) represent a transformative convergence of physical and digital realities, creating immersive environments where users can interact, work, learn and play in unprecedented ways. This Strategic Research and Innovation Agenda identifies the required foundational concepts and technological advancements driving VW, highlighting their potential to revolutionise various sectors, including industry, entertainment, education, and commerce. By examining the interplay between Augmented Reality (AR), Virtual Reality (VR), or Mixed Reality (MR) and other emerging technologies like Digital Twins (DT) and Artificial Intelligence (AI), we aim to provide a comprehensive overview of VWs' prospects and associated research and innovation gaps. A deeper exploration of VWs' impact on society and the economy gives context to the application and technology perspectives.

VW are persistent, immersive environments, based on technologies including 3D and extended reality (XR), which make it possible to blend physical and digital worlds in real-time, for a variety of purposes such as designing, making simulations, collaborating, learning, socialising, carrying out transactions or providing entertainment[1]. They encompass a wide range of digital experiences, from fully immersive VW to AR overlays on the physical world, that enable new ways to solve real world problems.

Vision of the future

Imagine a world where VW are fully established, seamlessly blending physical and digital realities to create immersive environments that redefine our daily lives and are key enablers to solve real world problems. Consumers experience unparalleled levels of engagement and personalisation, with virtual shopping and cultural experiences that enridge real-world interactions and entertainment options that transport them to fantastical realms. Workers benefit from enhanced collaboration and productivity, leveraging virtual workspaces that transcend geographical boundaries and enable real-time interaction with DT and collaboration with colleagues worldwide. Moreover, VW enable us to upskill labour forces safely and fast through virtual training, closely mimicking real world scenarios.

Defence and security personnel train in hyper-realistic simulations, preparing for diverse scenarios with unprecedented precision and adaptability. Civil servants utilise VW to streamline public services, offering virtual consultations and interactive platforms that improve accessibility and efficiency. Doctors and nurses get access to enhanced medical training and can provide better patient care and collaborative diagnostic. VW foster a new era of social inclusion, where individuals from all walks of life

[1] https://digital-strategy.ec.europa.eu/en/library/eu-initiative-virtual-worlds-head-start-next-technological-transition

can connect, share experiences, and build communities in virtual spaces that reflect their interests and identities.

Enabling technologies such as AI, 5G/6G connectivity and blockchain play a role in realising this vision. This research agenda will rely on associated partnerships' agendas and leverage these technological advancements to explore and develop VW. It will consider other ongoing associated research activities within the EU landscape increasing the synergies and maximizing the benefits.

Europe's strategic imperative for competitiveness, autonomy, and societal well-being is increasingly intertwined with its leadership in VW. By proactively investing in the development of a human-centric European VW ecosystem, the continent can unlock substantial economic growth, create new high-value jobs, and drive innovation across key sectors like manufacturing, healthcare, and education. This pursuit of digital autonomy within virtual spaces ensures that European values of privacy, transparency, and inclusivity are embedded by design, preventing reliance on external actors and fostering an open, interoperable, and ethically sound digital future that truly empowers its citizens and strengthens its global standing.

The outline of the Strategic Research and Innovation Agenda

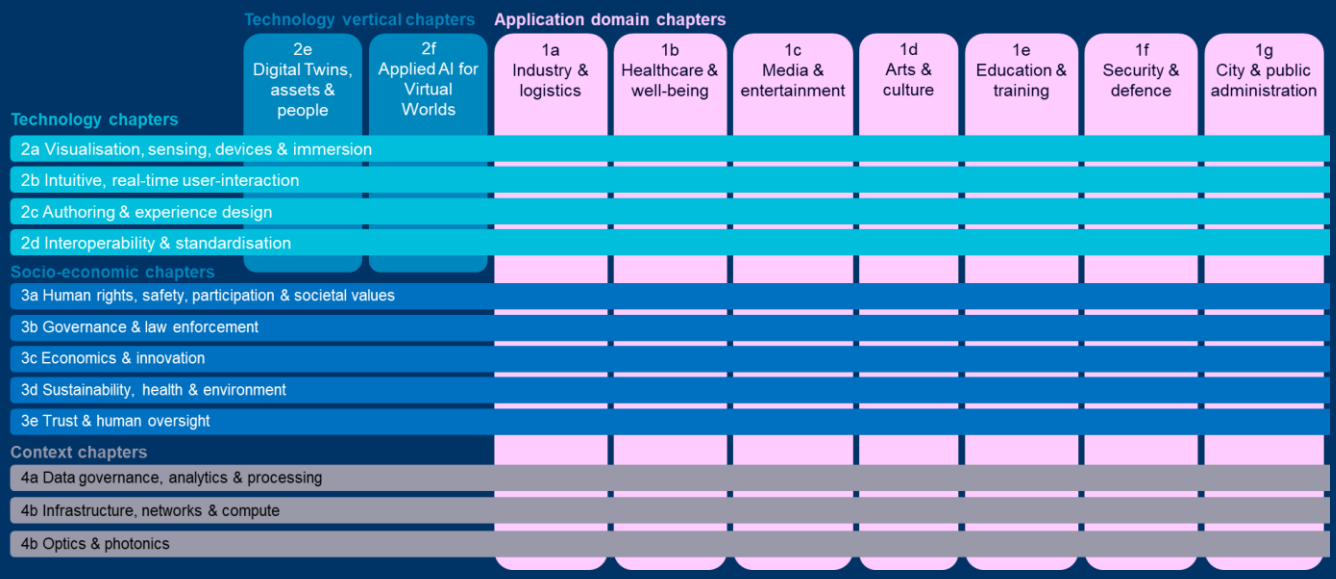

Figure 1. The structure of the Strategic Research and Innovation Agenda

Applications and opportunities in 7 key sectors

The development and expansion of Virtual Worlds (VW) involve a diverse array of stakeholders, including technology companies, content creators, and end-users. The key players in the VW ecosystem range from major corporations to independent developers, user communities, research institutes and public services. In Chapter 1 we address seven domains and identify key use cases to drive associated technology development priorities:

a. Industry and logistics
b. Healthcare and well-being
c. Media and entertainment
d. Arts and culture
e. Education and training
f. Security and defence
g. Cities and public administration

We explore the roles and interests of various stakeholders per use case, highlighting the collaborative efforts required to build and sustain value adding VW. By mapping out the landscape of key players, we gain insights into the dynamics shaping VW' growth and evolution.

Technical outlook and challenges

The identified VW use cases, present several technical challenges that must be addressed to realise their full potential. Chapter 2 examines these challenges, grouped into the following categories:

a. Visualisation, sensing, devices and immersion
b. Real-time user interaction
c. Authoring and experience design
d. Standardisation and interoperability
e. Digital Twins, assets, and people
f. Applied Artificial Intelligence for Virtual Worlds

By identifying and analysing the research topics, we provide a comprehensive understanding of the research gaps in the path towards a European competitive positioning for VW.

Socio-economic outlook and challenges

VW have far-reaching implications for society and the economy, influencing how we live, work, and interact. Chapter 3 delves into the potential societal and economic impacts of VW, from changes in social behaviour and communication to new business models and economic opportunities. We discuss both the positive and negative aspects of these implications, considering issues such as digital divide, privacy, health, legal and ethical concerns. By examining the broader consequences of VW, we aim to provide a balanced perspective on their transformative potential and the needs for European autonomy in specific technologies. The following sections are presented:

a. Human rights, safety, participation and societal values
b. Governance and law enforcement
c. Economics and innovation
d. Sustainability, health and environment
e. Trust and human oversight

The European research and innovation context

The European Commission is advancing a comprehensive strategy to position Europe as a leader in the development and governance of VW and Web 4.0. These technologies represent the next stage in digital transformation, merging physical and digital realities to create immersive, intelligent, and interconnected environments with broad societal, economic, and industrial implications.

The strategy, adopted in July 2023, aims to ensure these emerging technologies develop in alignment with EU values, supporting a human-centric, open, secure, and fair digital environment. Structured around the pillars of the Digital Decade policy program, the initiative addresses skills, infrastructure, innovation ecosystems, and global governance. It commits to supporting citizens with a dedicated guidance toolbox and talent development programs, including actions to boost female participation and digital literacy. To bolster the industrial ecosystem, the Commission is backing a candidate Horizon Europe Partnership on VW and promoting regulatory experimentation through sandboxes. Public sector applications are already underway via major initiatives such as Destination Earth, Local Digital Twins, and the European Virtual Human Twin. These efforts are complemented by global standardisation and governance engagement to ensure interoperability and openness.

Under Horizon Europe, concrete actions are already being taken to translate the strategy into research and innovation. Research on Extended reality technologies and applications have been funded throughout the first part of HEurope (2021-2024). Two key topics under the 2025 Work Program illustrate the depth and direction of these initiatives. First, the GenAI4EU Innovation Action supports the use of generative AI for enhancing the performance, personalisation, and inclusiveness of VW. It aims to support the creation of safe, immersive environments, intelligent digital assistants, and human-centred interfaces, with a strong focus on social sciences and humanities to ensure societal impact. Second, the Research and Innovation Action on Core Technologies for Virtual Worlds focuses on advancing multimodal interaction through optics and photonics. The call encourages the development of immersive systems incorporating touch, vision, haptics, and olfactory feedback, and prioritizes high-performance microdisplays, waveguides, and sensor integration. It emphasizes the importance of human perception, interoperability, and EU values such as privacy, diversity, and accessibility.

These research actions are anchored in co-programmed European Partnerships, notably in AI, Data and Robotics (ADRA), Big Data Value Association (BDVA), Virtual Worlds, and Photonics. They aim to bridge technological excellence with ethical responsibility and real-world applications, including health, education, cultural heritage, and urban planning.

Overall, the EU's initiatives on VW are designed not only to develop innovative technologies but also to shape the regulatory and social landscape that surrounds them. Authorities and academic institutions are encouraged to engage with these initiatives, contribute expertise, and collaborate across disciplines and sectors to co-create an inclusive, secure, and globally competitive European digital future. The proposed Strategic Research and Innovation Agenda (SRIA) aims to function as continuation and built on the ongoing of activities of the European Commission, while targeting to leverage key developments from associated partnerships as described in Chapter 4.

A scientific roadmap for technological developments

This document aims to present a scientific roadmap that outlines a strategic path for the responsible, inclusive, and innovative development of VW that would enable Europe to tackle real world challenges. By systematically addressing technological, ethical, social, and governance challenges across these horizons, Europe can ensure its leadership in shaping sustainable, equitable, and secure digital future

VW represent transformative digital environments where immersive technologies, advanced AI systems, and interconnected data ecosystems converge. This roadmap synthesizes key technological developments outlined in recent research agendas and policy documents, categorizing them into short-term, mid-term, and long-term horizons. As the technologies described in Section 2, such as visualization, sensing, devices, and immersion, evolve and mature along this strategic timeline, they will underpin the realization of the diverse application use cases as described in Section 1. These advancements are critical for enhancing the fidelity and interactivity of virtual environments, making them more suitable for real-world problem-solving across various sectors. For instance, improvements in XR hardware and real-time user interaction will directly enable more effective training simulations in healthcare and defence, as well as richer cultural and entertainment experiences. The continued progress in these foundational technologies, across short-term, mid-term, and long-term horizons, is essential for unlocking the full potential of VW in addressing complex societal and economic challenges. While certain technologies might mature faster than others, it's in the convergence and synergies between them that the vision of VW of the future will fully deploy. The proposed clustering of these horizons represents a preliminary estimation, grounded in the current technical maturity of the various requisite technologies, alongside their observed evolution in recent years. The horizons presented below represent the time needed to harvest the full potential of the developments as they have diverse

Technology Readiness Levels today and it is important to start investing and investigating from early stage in all the three horizons.

Short-term technological developments (3-5 Years)

In the short term, real-time user interaction and immersion will be enhanced through the development of ergonomic extended reality XR hardware and adaptive systems that mitigate motion sickness and physical strain. To promote inclusivity and creativity, accessible authoring environments such as low-code and no-code platforms are being introduced alongside comprehensive accessibility standards. Concurrently, AI-driven content creation is advancing with the implementation of generative models that streamline immersive content generation and AI-assisted moderation tools to govern these environments. Addressing regulatory and ethical obligations, adaptive governance frameworks aligned with the GDPR, AI Act, and Data Act are being implemented, including certification mechanisms to ensure robust data governance and protection practices. Efforts are underway to finalize and adopt interoperable standards for DT and VW ecosystems to facilitate cross-platform experiences and seamless asset exchange.

Mid-term technological developments (5-7 Years)

Looking to the mid-term horizon, development focuses on integrating advanced XR hardware with improved optical systems and rich sensory experiences, as well as deploying scalable cloud-edge infrastructure to support immersive content delivery. Human-centric AI interaction is also gaining traction, marked by the creation of multimodal interaction frameworks and context-aware virtual avatars capable of adaptive responses. Parallel to this, work is progressing on transparent and ethical AI frameworks, including the development of explainable AI tailored for immersive environments and the adoption of ethics-by-design approaches to support responsible content generation.

Long-term technological developments (7-10 Years)

Over the long term, research will explore next-generation immersive technologies such as neuromorphic computing and bio-integrated sensors, alongside brain-computer interfaces (BCIs) for seamless integration of neural input, smart haptics and device-free interaction. Future virtual environments are envisioned to be adaptive and context-aware, with AI models capable of self-evolution, leveraging edge computing and DT ecosystems. Environmental and economic sustainability will be prioritized through circular economy models for immersive hardware and frameworks that link sustainability performance to funding and resource management.

Socio-economic impact of Virtual Worlds

Expected economic impact of Virtual Worlds in Europe

VW are expected to significantly reshape Europe's economic landscape, offering substantial growth and job creation opportunities across various sectors. The global market for VW is projected to experience substantial growth, expanding from an estimated €27 billion in 2022 to over €800 billion by 2030[2]. The European Commission is ready to play a pivotal role in accelerating the development and widespread adoption of VW across member states. By fostering a robust European Web 4.0 industrial ecosystem and investing in critical infrastructure and skills, the Commission can significantly contribute to the increased GDP of member states through new economic opportunities and enhanced productivity across various sectors.

[2] https://digital-strategy.ec.europa.eu/en/factpages/virtual-worlds

Job creation

Beyond GDP growth, the proliferation of VW is set to generate significant employment opportunities. Forecasts indicate the creation of approximately 860,000 new jobs related to XR technologies in Europe by 2025. These new roles will span various fields, including virtual world architecture, content creation, and specialized technical development, necessitating substantial investment in reskilling and upskilling initiatives for the existing workforce.

Sectoral impact and opportunities

VW are poised to revolutionize numerous sectors, driving efficiency, innovation, and new service models:

- **Industry and logistics:** VW applications will enable intelligent, resilient, and connected operations, fostering more efficient, cost-effective, and sustainable digital processes. Industries can leverage virtual environments for product design, development, simulation, testing, inventory optimization, and immersive staff training, reducing risks and accelerating innovation cycles.
- **Healthcare and well-being:** VW will facilitate advancements in health services, supporting clinical decisions and personalized treatments through technologies like the European Virtual Human Twin.
- **Education and training:** Immersive virtual environments offer more engaging and effective learning experiences, particularly for developing soft skills and foreign language proficiency.
- **Public services:** VW can enhance public services, with initiatives like "CitiVerse" aimed at improving urban planning and management, and the development of Local Digital Twins.
- **Arts and culture:** VW will enable immersive cultural experiences, allowing access to virtual museums and galleries, thereby broadening reach and engagement.
- **Agriculture:** Virtual solutions can provide remote assistance for machinery operation and more precise animal treatment, boosting productivity and safety.

A more detailed presentation of the **socioeconomic impact** of VW will be the exclusive focus of Chapter 3. This dedicated section will thoroughly explore the economic opportunities, societal shifts, and potential challenges associated with their widespread adoption.

Chapter 1

APPLICATIONS

Applications and opportunities in 7 key sectors

1a Industry and logistics

Scope and introduction

Industrial Virtual Worlds (VW), using a variety of immersive technologies, have significant potential to transform industry and logistics. These digital environments, accessible on multiple devices, allow for the creation and use of Digital Twins. By leveraging these VW, businesses can simulate and analyse complex manufacturing and supply chain processes, improving forecasting, efficiency, and reducing costs. These technologies also support predictive maintenance, optimized workflows, and data-driven decision-making. As they evolve, their cross-platform capabilities foster collaboration and innovation, making them essential for the future industrial landscape in various domains.

Industrial processes comprise several areas where VW can confer significant benefits. These include design and engineering, virtual testing, planning and manufacturing, operations (including training), and maintenance, repair, and overhaul (MRO). Logistics is an intrinsic component of all these stages and processes. All these processes involve interactions both within a single company and across inter-company networks. Consequently, ensuring that future industrial VW are structured on interoperable rather than proprietary platforms is a critical step to facilitate information flow across organisational boundaries.

Figure 2. The product lifecycle

The industrial VW market is experiencing considerable growth, with recent reports projecting a compound annual growth rate of approximately 35%, a notable figure compared to traditional technology sectors. Forecasts for the global market value in 2030 range from 100 billion USD (source: ABI Research[3]) to 395 billion USD by 2034 (source Precedence Research[4]). Regardless of the precise figures, it is evident that industrial VW are anticipated to be one of the fastest-growing sectors in the forthcoming decade. This trend is corroborated by studies indicating increased investments in VW technologies, with 62% of participants augmenting their spending from 2023 to 2024, and the number of

[3] https://www.technologyreview.com/2023/03/29/1070355/the-emergent-industrial-metaverse/
[4] https://www.precedenceresearch.com/industrial-metaverse-market

large companies investing over 10 million USD in these technologies doubling within the same period. This trajectory underscores the rapidly increasing relevance of VW in industrial contexts. The adoption of VW in the industrial sector has notably accelerated, driven by concrete results and clearly defined use cases. Early deployments have demonstrated substantial improvements, including productivity increases of 15–20% through digital twins like in the Siemens Electronic Factory in Erlangen, reductions in product development cycles by 20–50%, and decreased downtimes. Additionally, virtual technologies significantly contribute to sustainability by reducing emissions through virtual prototyping, remote operations, and minimized physical resource usage.

The fundamental technology underpinning the effective utilisation of industrial VW is the integration of standardised DT/shadows/models. This applies to a diverse array of assets, including machinery, buildings, environments, processes, and materials. It is imperative not only to standardise the representation of real-world assets within virtual environments but also to standardise their interactions and connections with each other and with the real world. While various standards and normative efforts are currently underway, their development must accelerate and encompass a broader range of application fields to propel industrial VW forward. Different approaches can be employed, such as achieving interoperability through a combination of automated application programming interface integrations and a layered approach to standards, as detailed in the "Interoperability and Standardisation" chapter of the broader SRIA.

Use cases

This section outlines key research areas within the industrial and logistics domain, detailing their significance, current challenges, and proposed objectives for future innovation.

1a.1 Rapid prototyping through collaborative design, editing and simulations

This approach aims to enhance the cost and resource efficiency of prototype design cycles for designers and developers. By facilitating virtual experiences and testing of product and service versions and functions collaboratively with colleagues worldwide, it reduces the need for physical prototypes or expensive 3D printing. Furthermore, it enables secure co-development of innovative products and services with external partners and customers, thereby improving early-stage acceptance and feasibility. This method allows distributed development teams to collaborate on virtual prototypes, adapt designs in real-time using immersive technologies like Augmented Reality (AR) or Virtual Reality (VR), and interact with complex products or services at a 1:1 scale, with immediate visualisation of changes. This interdisciplinary approach can integrate various data and information layers of virtual models, providing shared and contextual experiences in realistic VW environments throughout the product lifecycle. It also supports interactive simulation and testing of all possible configurations with diverse customer groups.

Challenges and opportunities: Current practices often involve various development departments, frequently geographically dispersed, collaborating either virtually or on-site, but high transaction costs often lead to work division and limited collaboration. Prospective customers and end-users are typically engaged late in the development process, which can result in significant error costs and a risk of inadequate market acceptance. Currently, the adoption rate of VW solutions for rapid prototyping is low, with only initial proofs of concept and isolated lighthouse solutions available, indicating a limited presence of industrialised solutions in the market.

Research and Innovation Objectives: Industry-grade head-mounted displays and multi-user platforms (2a). Back-end platforms, integration of context and usage data, and utilisation of physical geometric virtual models (2d, 2e). Distributed-ledger technologies and AI for enhanced collaborative design and prototyping (2d, 2f).

1a.2 Virtual integration of factory planning and simulation of series start-up

This scenario aims to minimise the time required for production line start-up and reduce downtime for existing lines by enabling factory planners and systems engineers to plan and simulate production line modifications in advance. It offers a cost-efficient solution by saving time during the ramp-up and testing phases due to comprehensive prior simulation. Moreover, it mitigates the risk of errors and the need for re-planning, as diverse scenarios can be tested that are difficult to visualise and comprehend in a two-dimensional environment. The outcomes can be made accessible on mobile devices, further enhancing flexibility.

Challenges and opportunities: While some very large companies already utilise VW for planning new facilities, access to the necessary know-how and, crucially, a sufficient DT base of production equipment and building information modelling models are not readily available for small and medium-sized enterprises. The current adoption rate of VW solutions for virtual factory and production line planning remains low, primarily confined to a few very large companies.

Research and Innovation Objectives: DTs for comprehensive factory and production equipment (2e). Interoperability with enterprise resource planning systems (2d). End-to-end integration and interoperability among simulation tools (2d, 2e).

1a.3 Model-Based Systems Engineering (MBSE)

This approach aims to efficiently coordinate development teams, end-users, and other key stakeholders, thereby accelerating feedback loops and ensuring that project outcomes align with expectations. Virtual world-based project models, leveraging extended reality (XR) technologies, offer an accessible, highly visual, and interactive unified language applicable across different engineering disciplines. This facilitates a shift from conventional linear, rigid, and document-centric models towards a more collaborative, non-linear, and agile digital information-based methodology. Through fully immersive VR environments or context-aware AR overlays, teams can engage with project data in intuitive and flexible ways, significantly enhancing communication.

Challenges and opportunities: Engineering projects currently often revolve around various models that capture key aspects by highlighting important subsystems and elements while simplifying or omitting less relevant features. MBSE approaches exhibit considerable variation across different engineering disciplines, and the optimal method for conveying a model remains a frequent subject of debate. Despite the relative popularity of MBSE approaches, the utilisation of VR as a means of facilitating them remains underutilised, indicating a low adoption rate for VW solutions in this area.

Research and Innovation Objectives: Real-time 3D rendering engines (2c). XR head-mounted displays (2a). Collaborative multi-user VW for project coordination (2b).

1a.4 System control interfaces

This research topic focuses on enabling workers to remotely operate various machinery systems XR head-mounted displays facilitate a shared, real-time spatial context between remote workers and on-site machinery, which is often crucial for effective remote control. This capability addresses challenges in many industrial contexts, such as production, medical surgeries, and construction, where integrating spatial information in real-time is vital for shared understanding among users. Remote operation reduces project costs and delays that can arise from the unavailability or high demand for key on-site personnel.

Challenges and opportunities: Current industrial practices frequently necessitate on-site presence and co-located interaction for system operation and control, which can lead to increased project costs and delays. While some -mainly- large companies are developing and employing XR solutions across their value chains, the adoption rate of VW solutions for system control interfaces is currently medium.

Research and Innovation Objectives: Advanced XR head-mounted displays (2a). Low-latency network connectivity to support real-time remote operation (2d).

1a.5 Manage and maintain intralogistics (AGVs, humanoids, forklifts)

This use case aims to minimise downtime and errors in intralogistics operations, ensuring that available resources are used efficiently. In photorealistic virtual environments, it is possible to train and simulate the behaviour of automated guided vehicles and humanoids. The interaction between tracked manual entities and robots like Automated Guided Vehicles (AGV) can be safely monitored, allowing robots to plan and simulate their future actions within the virtual world. Workers can visualise the real-time planned actions, safety zones, or trajectories of these robots using AR devices. In the event of errors, a rollback function with real track data can be used to locate missing goods within an interconnected system.

Challenges and opportunities: Currently, intralogistics operations are handled by a multitude of proprietary tools, each managing specific aspects such as automated guided vehicle guidance or warehouse maintenance. Manual labour, such as forklift transport, is often not tracked at all, and humanoids are largely confined to test cases rather than widespread production use. While some aspects like automated guided vehicle management or smart warehouses are well-established in two-dimensional environments, interoperable and integrated VW solutions for the entire intralogistics fleet, encompassing training, planning, and predictive maintenance, are not yet available. The adoption rate of VW solutions in this area is medium, indicating a gap in comprehensive integrated solutions.

Research and Innovation Objectives: DTs for intralogistics assets (2e). Interoperability with enterprise resource planning systems (2d). 3D photorealistic training environments (2b). Advanced tracking and mapping technologies (2a, 2b). It is acknowledged that this use case benefits from collaboration with the ADRA partnership and that any double work is to be prevented.

1a.6 Training and onboarding in a virtual work environment

This research aims to enable employers to comprehensively train new employees and specialists at the earliest possible stage when new products and services are introduced, preparing them for new tasks. This ensures that theoretical concepts can be effectively implemented in practice. It particularly focuses on simulating critical operational situations in advance to enhance employee confidence and mitigate errors. VW provide flexible and experience-based learning opportunities for new activities and tasks. By simulating various scenarios, different courses of action can be tested and their consequences assessed. The inclusion of avatars and AI agents facilitates the training of social interactions and soft skills. Critical operations can be jointly trained by multiple participants in advance and on a case-by-case basis, especially for situations in hazardous environments.

Challenges and opportunities: Currently, when new products and services are introduced, employees often receive training late in the process, on the job, or are provided with product sheets, process descriptions, and design plans that are difficult to comprehend. Critical situations or processes in hazardous environments are typically only discussed theoretically and cannot be experienced or simulated in advance. The adoption rate of VW solutions for training and onboarding is currently medium, indicating that while offers exist in the market, they are not yet broadly adopted across industries.

Research and Innovation Objectives: Advanced XR head-mounted displays (2a). Creation of DTs and human DT's (2e). Collaborative platforms with the capability to manipulate and interact with virtual environments (2b, 2c). It is acknowledged that this use case benefits from collaboration with the ADRA partnership and that any double work is to be prevented.

1a.7 Virtual dashboards

This research focuses on enabling shopfloor managers to access relevant data and collaboratively monitor and analyse the shopfloor in a virtual world, utilising services and applications including AI. This approach ensures that data and DT of assets and processes are available to all authorised individuals, everywhere, with correct access rights. Beyond shopfloor managers, other stakeholders can also benefit from this data. Managers can inspect error cases within a virtual environment to gain a better understanding of bottlenecks, crashes, and other issues. This allows for real-time analysis from anywhere in the world, reducing downtime and facilitating effective communication of necessary changes to higher management by providing them with virtual experiences of the issues.

Challenges and opportunities: Currently, shopfloor managers access different enterprise resource planning or evaluation tools, typically displayed in tables, spreadsheets, or two-dimensional environments. The primary challenge lies in providing available shopfloor data in real-time within a virtual environment to anyone with access rights on demand. There are currently no widely adopted virtual applications for shopfloor integration that facilitate real-time, AI-assisted analytics on shopfloor data and collaborative access. The adoption rate of VW solutions for this purpose is low.

Research and Innovation Objectives: DTs and robust interoperability with enterprise resource planning systems (2d, 2e). End-to-end integration and interoperability of simulation tools (2d, 2e). Enabling real-time data access and real-time streaming capabilities (2b, 2d, 2e).

1a.8 Public outreach for energy grid extensions and generation units planning

This research aims to allow citizens to visualise planned power grid lines, new wind or photovoltaic parks, and power plants before construction, enabling them to understand the environmental impact on their living surroundings. For planners, it provides a means to effectively demonstrate planned assets to citizens, better address objections and concerns, and support and accelerate communication and public outreach during the planning process. This approach facilitates ad-hoc visualisation of planned assets in real environments on mobile devices, for instance, through applications. This offers citizens low-threshold access to dynamic visualisations and improves communication between citizens and planners during project planning and projection.

Challenges and opportunities: Current methods rely on static photoshopped images from specific viewpoints or animations in virtual environments, which offer a more abstract and less tangible impression of the actual impacts of new assets. These methods also lack the ability to provide visualisations from various viewpoints and under different conditions, such as weather or seasonal changes. The adoption rate of VW solutions for public outreach in energy planning is low, with only initial proofs of concept and isolated lighthouse solutions available.

Research and Innovation Objectives: AI for enhanced visualisation capabilities (2f). Mobile applications that integrate georeferenced planning data and virtual models of assets to be built.

1a.9 Life cycle continuity in structural and civil engineering projects

This research aims to provide infrastructure project stakeholders, such as architects, engineers, and construction managers, with a more comprehensive understanding of their project space and its main components throughout its entire lifecycle, from design and construction to maintenance. Multi-user, multi-location XR tools can be utilised to display relevant infrastructure models, enhancing spatial perception, improving communication, and reducing errors. Additionally, Mixed Reality (MR) and AR tools can be employed during actual construction and maintenance work to display relevant parts of the Building Information Modelling (BIM) model to field technicians and facility managers. The integration of a virtual assistant, such as a dedicated large language model, can provide real-time guidance,

particularly during construction and maintenance phases, especially in non-nominal or unexpected situations.

Challenges and opportunities: Currently, a 3D digital representation of a project is developed and distributed among key stakeholders for tasks such as asset tracking, space planning, and Internet of Things data. While BIM is already well-established in the construction and infrastructure sector, the adoption of VW solutions built on top of this for lifecycle management is high for distinguished use cases. However, the full potential for immersive, collaborative experiences and advanced real-time guidance throughout the entire project lifecycle remains a research gap.

Research and Innovation Objectives: AR/VR/MR head-mounted displays and large XR displays (2a). AI and large language models for real-time guidance and assistance (2f).

1a.10 Virtual showrooms and product customisation in real-time

This research aims to enable sales representatives to clearly demonstrate innovative products and services and their benefits to potential customers. The objective is to help customers recognise the advantages and high quality of technically complex products and intangible services before making a purchase decision, thereby differentiating from competitors. VW allow for the presentation of virtual models of products and services within their virtual application environment, with concrete added value demonstrated using real data. In collaboration with customers, various application scenarios can be simulated, and, at least in part, immediate adjustments can be made.

Challenges and opportunities: Current methods involve elaborate presentations, trade fair appearances, films, and prototypes that often only abstractly illustrate the tangible benefits in a working or living environment. Communicating the direct benefits to a customer is particularly challenging for technically complex products, market innovations, and intangible services. Direct feedback and adjustments can typically only be made retrospectively. The adoption rate of VW solutions for enhanced customer experience is currently medium; while static virtual models for technical products exist, dynamic models or the ability to simulate usage in a customer's environment are limited.

Research and Innovation Objectives: 3D DTs with predictive and prescriptive analytics capabilities (2e). Physical places for presentation and interoperable virtual platforms.

1a.11 AI generated industrial Digital Twins and visualisations

This research aims to enable software engineers and 3D artists to generate 3D assets and DT of industrial machines and goods with the assistance of AI and scanning/mapping technology, thereby reducing manual development time and democratize the creation of DT. In an industrial virtual world, new objects could be placed on the fly with minimal integration effort. For example, an AI assistant could generate a 3D model based on available Computer-Aided Design (CAD) data from an enterprise resource planning system, cloud network, or marketplace, and then individually generate the DT of the necessary component, machine or process according to specific requirements. This process can be coupled with low-resolution scanners from widely available hardware, such as smartphones, to create digital assets from real environments with minimal effort and to make it affordable even for Small-Medium Enterprises (SMEs).

Challenges and opportunities: Currently, industrial 3D assets are typically created using CAD data and discipline-oriented software that can be operated only by few experts. Thus, the adoption is very limited and expensive. The challenge lies in integrating AI and large language model tools to generate assets with less manual integration work or even in automated workflow. Additionally, the current state of scanning and mapping technology needs improvement to build more detailed models more cost-efficiently. While tools exist that combine visual 3D models with software functionality, manual labour is still extensive.

The AI generation of standardised DTs is still in an early research state, and while scanning and mapping technology is used for digitalising environments, it remains expensive for achieving detailed results. The adoption rate of VW solutions in this area is currently medium.

Research and Innovation Objectives: Integration of computer-aided design, AI, large language models, and 3D technology/game engines (2b, 2c, 2e, 2f). Development of advanced DTs. (2e). Advancement of scanning and mapping technologies (2d, 2e).

1a.12 Collaborative remote maintenance and operations support

This research focuses on allowing technicians and remote engineering teams to visualise machines and relevant equipment in high-fidelity 3D to support activities such as remote inspection and collaboration. This addresses the challenge that maintenance and operations support typically require on-site presence, which can lead to downtime and project delays. VR enables remote teams to visualise machines, equipment, or infrastructure in 3D, at full scale, and with high fidelity. This aids in maintenance planning, troubleshooting, and reviewing inspection reports that are difficult to interpret in two dimensions. Through AR or MR, on-site workers can receive real-time information from expert teams, even overlayed on real machines or components. Additionally, connection to a virtual assistant, such as a dedicated Large Language Model (LLM), can guide both the remote expert and the on-site worker in non-nominal situations. Human factors are crucial, ensuring that information is provided in the most suitable format, particularly for on-site workers.

Challenges and opportunities: Normally, maintenance and operations support necessitate on-site presence, which is not always feasible, resulting in downtime and project delays. While organisations in the industry are integrating VW into their workflows, for instance, to simulate and monitor complex factory systems, the practice still has considerable untapped potential. The adoption rate of VW solutions for collaborative remote maintenance and operations support is currently medium.

Research and Innovation Objectives: XR head-mounted displays and low-latency network Connectivity (2a, 2d). Consideration of human factors and User Experience (UX) in system design (2b, 3a, 3d). AI for enhanced support (2f).

1a.13 Exchange of complex industrial data

This research aims to enable manufacturing systems engineers to securely share DTs and Internet of Things data with suppliers and partners. This collaborative approach facilitates real-time optimisation of production, predictive maintenance, and supply chain operations. It allows for immersive and collaborative interaction with DTs within a shared virtual space, utilising blockchain-based access control for secure data sharing and decentralised digital asset ownership. Furthermore, it supports real-time simulation and data fusion from multiple sources.

Challenges and opportunities: Currently, data exchange predominantly occurs through centralised platforms or manual file transfers (e.g., email, FTP). Proprietary platforms often exhibit poor interoperability, and there are significant concerns regarding security and intellectual property (IP) protection. Data silos hinder real-time collaboration, and there is limited traceability and access control. The adoption of VW solutions in industrial applications remains in an early stage, with implementation primarily observed in pilot projects and testbeds rather than full-scale rollouts. While DTs are more mature, collaborative environments are still fragmented.

Research and Innovation Objectives: Interoperable DT standards, such as Asset Administration Shell and DT Definition Language (2d, 2e). Decentralised data exchange mechanisms, including IPFS, blockchain, and Solid Pods (2d). AI and machine learning for semantic data translation (2d, 2f). XR

interfaces for immersive collaboration (2b). Integration of edge AI and federated learning for privacy-preserving computation (2d, 3b).

1a.14 Training AI systems and autonomous agents

This research focuses on enabling engineers and developers to train and test AI and machine learning models and autonomous systems, including robots and humanoids, within high-fidelity, multi-user virtual environments. These environments simulate complex physical and socio-technical systems, allowing for validation of performance, safety, and adaptability under diverse conditions prior to real-world deployment. The proposed scenario leverages the availability of a DT of a complex system within a virtual world. This DT embeds various layers, encompassing realistic 3D visualisation and models that define its behaviour from multiple perspectives (e.g., physical level for process configuration and control, discrete event level for high-level behaviour and integration within a manufacturing system). This DT can generate synthetic data at scale under diverse and customisable conditions, facilitating robust AI training and testing. Robots and vehicles can be virtually deployed in detailed factory scenarios or urban environments, leading to reduced costs, safety risks, and faster time-to-market. Multi-user capabilities support interdisciplinary collaboration and scenario co-design.

Challenges and opportunities: Current training methods for AI and autonomous systems heavily rely on physical prototypes, limited-scale simulations, or domain-specific datasets. These approaches often lack scalability and struggle to fully account for diversity and safety issues, particularly in scenarios involving rare edge cases or high-risk situations. Existing simulation tools are frequently siloed, with limited multi-user interaction or cross-disciplinary integration. The adoption of VW solutions for this purpose remains in an early stage, with uptake primarily in academia or pilot industrial applications for very large companies. Barriers include high development costs, a lack of standardisation, technical complexity, and the advanced use of heterogeneous software libraries and tools.

Research and Innovation Objectives: High-fidelity 3D simulation engines (2c). DTs with real-time physics modelling (2e). Synthetic data generation pipelines and integration with real-world sensor and control data (2f). UX design for immersive collaboration (2b). Sim-to-real transfer and domain adaptation (2d, 2e). Development of governance frameworks for virtual experimentation (3b).

Recommendations

To advance the integration and impact of VW within the industry and logistics sectors, a series of strategic recommendations are proposed, addressing the identified challenges and research gaps.

Firstly, a concerted effort is needed to develop and promote interoperable standards for DTs and VW platforms. The current fragmentation, characterised by proprietary tools and siloed data, significantly hinders widespread adoption and seamless collaboration across supply chains and industrial networks. Standardisation initiatives, such as Asset Administration Shell must be accelerated and broadened to cover a wider range of industrial applications. This will facilitate secure, decentralised data exchange, crucial for real-time optimisation and predictive maintenance.

Secondly, investment in advanced hardware and software solutions specifically tailored for industrial applications is paramount. This includes the development of robust, cost-effective, and user-friendly XR head-mounted displays and large XR displays, alongside low-latency network connectivity. Furthermore, the creation of high-fidelity 3D simulation engines with real-time physics modelling is essential for accurate virtual testing, factory planning, and the training of AI systems and autonomous agents.

Thirdly, there is a critical need to enhance the accessibility and usability of VW solutions for small and medium-sized enterprises. This involves developing low-code or no-code content authoring tools that enable subject-matter experts to create and customise immersive environments without extensive

programming knowledge. Furthermore, fostering knowledge transfer and providing clear demonstrations of measurable benefits will encourage broader adoption beyond large corporations.

Fourthly, the integration of AI and LLMs across the industrial VW ecosystem should be prioritised. This includes AI-assisted generation of DTs and machine visualisations, intelligent assistants for remote maintenance and operations support, and AI-driven analytics for virtual dashboards. These advancements will reduce manual development time, enhance decision-making, and improve the efficiency of complex industrial processes.

Finally, a strong emphasis should be placed on human factors and UX design. Ensuring that VW interfaces are intuitive, inclusive, minimise cognitive load, and provide information in the most suitable format is crucial for effective training, remote operations, and collaborative design. Research into user acceptance, long-term retention, and the transfer of skills from virtual to real-world contexts will be vital for successful implementation.

1b Healthcare and well-being

Scope and introduction

Virtual worlds (VW) are rapidly emerging as a transformative force in healthcare, offering unprecedented opportunities to revolutionise patient care, medical education, and public health initiatives. These immersive, interactive digital environments provide a dynamic platform for a wide array of applications, from sophisticated medical training simulations and advanced therapeutic interventions to engaging patient education tools. The integration of virtual models, often referred to as Digital Twins (DT), enables highly personalised treatment plans and predictive analytics, allowing for a proactive approach to health management. Beyond clinical applications, VW are also instrumental in enhancing well-being and fostering social inclusion, offering innovative solutions for mental health support, combating social isolation, and improving accessibility for individuals with diverse needs. This chapter delves into specific research topics, outlining their importance, defining existing challenges, and proposing key objectives for future research and innovation within this evolving landscape.

The application of VW in healthcare and social inclusion spans prevention, advanced diagnostics, personalised care, surgical assistance, rehabilitation, and the broader aspects of well-being and social integration. Each of these areas presents unique challenges and opportunities for leveraging immersive technologies to improve health outcomes and quality of life. The strategic importance of these applications lies in their potential to democratise access to healthcare services, provide cost-effective interventions, and offer highly personalised and engaging experiences for patients and healthcare professionals alike.

Use cases

This section details key research areas within healthcare and social inclusion, outlining their significance, current challenges, and proposed objectives for future innovation.

Prevention

1b.1 Reduction of disorders and syndromes

VW offer an accessible and cost-effective method for administering preventive programmes for several disorders (i.e. musculoskeletal, dietary, ...) or syndromes (i.e. pain) with gamification elements potentially boosting user motivation to engage in training and daily practice. This approach facilitates widespread adoption and can help reduce the incidence of related diseases. For example, keeping an active life will prevent musculoskeletal pain (i.e. back pain) as well as nutrition awareness will prevent metabolic syndromes (i.e. bulimia, anorexia, obesity).

Challenges and opportunities: Sedentary lifestyles and eating disorders often lead to sever diseases. Current research on prevention is bringing the attention on awareness and engagement of the target population. VW are suitable tools for providing preventative strategies, participation and engagement.

Research and Innovation Objectives: Develop ad-hoc applications with scalable difficulty levels that promote comprehensive and focused awareness and habits, tailored to user age and characteristics for long term engagement (2c). Ensure the technology is widely available and affordable (3a, 3b, 3c) and create a user-friendly and motivating applications (2b).

1b.2 Prevention of accidents (while driving, working, at home, …)

Continuous, passive health monitoring of users in their living environments or while using any mean of transportation or work through the use physiological sensors (better if contactless) supports personalised nudges, enhancing safety, well-being, and contextual health assessment. This system complements existing monitoring systems (i.e. driving assistant) and support the monitoring and the pre-alert for possible dangerous situation for the people providing augmented feedback (visual, sonorous, haptic).

Challenges and opportunities: an augmented world connected with environment (or transportation means) as well as with contactless (or non-invasive wearable) physiological sensors would provide a better comprehension of the people (general health, attention, stress, tiredness, cognitive load, …) and it can provide more extensive feedback preventing accidents. While regulatory interest is growing, adoption remains low due to technological feasibility, interoperability and data privacy concerns.

Research and Innovation Objectives: Develop an augmented VW collecting information, data and knowledge from contactless (on non-invasive wearable) physiological sensors and from the environment (or means of transportation) able to provide a holistic feedback system (2a, 2b, 2d, 2f). Develop AI algorithms for inferring heart rate, heart rate variability, respiration rate, and stress levels (2f). Create intuitive feedback interfaces, including head-up solution, AR, and mobile applications (2b).

Early disease detection

1b.3 Age-related or progressive diseases

VW facilitate screening for several age-related and progressive diseases (i.e. cognitive decline) without the need for a continuous specialised clinical personnel supervision, enabling widespread and cost-effective deployment in local communities and volunteer associations. This approach provides a more naturalistic and ecologically valid environment for screening, allowing for the collection of detailed data such as error rates, accuracy, efficacy, and behavioural outputs, thereby enabling early detection and intervention to slow disease progression.

Challenges and opportunities: Current age-related and progressive decline (like the cognitive one) often identifies pathology only when it significantly impacts daily activities. The ability to perform occasional screenings (e.g., bi-annually after age 50, annually after 65) could enable earlier detection. However, large-scale VW applications for general population screening are not yet widely adopted.

Research and Innovation Objectives: Develop an augmented VW collecting information, data and knowledge from user of any age and able to provide a holistic feedback system (2a, 2b, 2d, 2f). Develop AI algorithms for inferring possible diseases in advance (2f).

1b.4 Early prediction of diseases

Integration of VW, Digital Twins (DT) of people, combined with continuous biosensor (in general wearable physiological sensors), can predict the development of diseases (e.g. heart failure). The VW offers individuals an advanced and easily accessible feedback and warning system highlighting the potential

high risk, allowing for lifestyle adjustments to prevent disease progression, and provides a more accurate and continuous information flow for the doctors. The full environment can also be beneficial for athletes experiencing cardiac stress.

Challenges and opportunities: Individuals often lack awareness of their health and risk in the absence of symptoms. Currently, the data provided by wearable devices are often not very intelligible and uncomprehensible to the individuals. Providing an augmented VW connected with own DT can works as early detection system for the medical doctors and for creating awareness and change-life-style driver for the people.

Research and Innovation Objectives: Develop specific monitoring technics that can integrate DT and wearable sensors able to provide a continuous surveillance on users' parameters (2e, 2d). Advance data analysis and risk prediction modelling (2f). Implement augmented warning systems for changes in physiological parameters (i.e. linked to future cardiac disease or heart failure) (2a, 2b).

Personalised care

1b.5 Personalised treatment through patient Digital Twins

Developing accurate patient-specific DT using advanced system identification and modelling techniques can assist clinicians in predicting disease progression, personalising treatments, and optimising healthcare outcomes. This allows for virtual testing and refinement of different treatments, leading to optimised therapeutic strategies, reduced uncertainty, minimised side effects, and improved patient engagement in their care decisions. A specific case can be represented using the DT for virtual inspecting the specific patient body district better understanding the extent of the illness and simulate the effects of various therapeutic strategies.

Challenges and opportunities: Current illness treatment planning heavily relies on general clinical guidelines, population-level statistical outcomes, and limited patient-specific data, leading to clinical uncertainty, trial-and-error methods, and non-optimal therapeutic outcomes. Existing patient-specific modelling methods often lack accuracy, adaptability, and scalability for clinical practice. Gaps exist in utilising advanced identification methods, augmented sensing, and integrating physics-inspired data blocks crucial for patient-specific DT development in healthcare. Moreover, a specific “care” companion can support in understanding the care and providing support on care- adherence.

Research and Innovation Objectives: Develop specific patient DT integrate in a full personal care VW connected to a network of sensors wearable and in the living environments (2a, 2d, 2e, 2f). Manage the personalised data in a security system providing privacy while maintain the whole medical chain informed and updated on patient condition (2d, 3b). Need of a specific interfaces for clinical staff and eventually a customised one for explaining the care to the patient (2b).

1b.6 Adaptation of Virtual Worlds according to patient needs (AI and DT-Supported)

Digital twins, as virtual replicas of patients, are transforming personalised healthcare by enabling real-time monitoring, predictive modelling, and tailored treatment plans. Increased computational power facilitates the merging of various domains to address all aspects of a patient's health and clinical issues. Moreover, XR technologies can enhance personalisation, emotional engagement, and accessibility for all users and specifically for elderly individuals with cognitive impairment or children/adults with special needs. This approach has the potential to reduce reliance on sedatives and improve overall therapeutic outcomes also improving the therapy adherence, while promoting emotional well-being and (cognitive) engagement.

Challenges and opportunities: Existing patient DT examples often focus on specific topics and lack interoperability for clinical specialists from diverse backgrounds. The integration of DTs into routine

clinical practice is still in its early stages. For example, elderly individuals often receive sedatives to manage discomfort or participate in traditional group-based reminiscence therapy, which is often less personalised and engaging. Conventional methods face limitations including reduced accessibility, limited individualisation, dependence on facilitator skills, low sensory stimulation, and difficulties for participants with cognitive or communication impairments. While solutions exist in the market, they are not widely adopted as a standard of care.

Research and Innovation Objectives: Develop specific patient DT integrate in a full personal care VW connected to a network of sensors wearable and in the living environments (2a, 2d, 2e, 2f). Manage the personalised data in a security system providing privacy while maintain the whole medical chain informed and updated on patient condition (2d, 3b). Need of specific and different interfaces for individuals and clinical staff (2b).

Surgery

1b.7 Real-time intraoperative Digital Twin for surgical assistance

This system receives real-time sensor data during surgery and continuously predicts tissue response, suggesting optimal surgical paths. It acts as a closed-loop assistant, providing warnings and suggesting adjustments, and can be visualised in XR to give surgeons intuitive feedback, ultimately enhancing surgical safety and precision.

Challenges and opportunities: Current surgical workflows primarily rely on static pre-operative imaging and intraoperative visual interpretation. While some robotic and image-guided tools offer updated navigation, they lack dynamic, patient-specific physiological models that adapt to surgical events. Real-time feedback or predictive control based on continuously updating DTs remains an early research stage, with most intraoperative decisions still heavily reliant on surgeon experience. Gaps exist in using real-time identification methods, developing hybrid models, fusing sensory data, and creating predictive control loops.

Research and Innovation Objectives: Develop hybrid and data-driven modelling techniques for real-time surgical support (2d, 3b). Advance system identification and dynamic modelling of soft tissues and implement real-time control loops, model updates, and feedback mechanisms with new sensor fusion capabilities (2a, 2e, 2f). Create XR visualisation with low-latency interaction for surgical environments provided by a safety-critical systems with fail-safe modes for surgical applications (2b, 2c).

1b.8 Endoscopic inspection as a diagnostic procedure

Enhancing information available to physicians through advanced image sensors and multi-modality imaging systems, potentially combined with smart pill cameras, paves the way for patient-specific treatment planning. The integration with XR can make procedures faster, more accurate, and with fewer side effects, by improving surgical and endoscopic outcomes, providing intraoperative guidance, and monitoring smart pill passage.

Challenges and opportunities: Challenges include the miniaturisation of imaging sensors, the integration of multi-modal data facilitated AI, and the provision of AI-based decision support for diagnostics and treatment planning. Embedding real-time information during diagnostic and therapeutic interventions and combining it with previously collected data (e.g., live endoscopic imaging with smart pill images) remain key hurdles. While endoscopic procedures are widely adopted, these enhancements represent significant improvements within existing practices.

Research and Innovation Objectives: Develop miniaturised imaging sensors, including hyperspectral imaging, to provide high-quality imaging and video at relevant wavelengths and integrate multi-modal sensor data fusion for enhanced decision support (2a). Create XR-enhanced, intuitive visualisations and

interfaces for surgeons and physicians (2b, 2c). Develop AI models and DTs for training, learning, and surgery planning (2f).

Rehabilitation – Therapy monitoring

1b.9 Extended Reality technology to support rehabilitation intervention

Personalised and adaptive XR environments can support rehabilitative interventions, even without constant therapist supervision. This allows for longer training periods, potentially in a combined modality where XR acts as an add-on to standard therapy, enabling more patients to receive intervention simultaneously, eventually at home. Multi-user environments could further enhance adherence and motivation.

Challenges and opportunities: Currently, therapists typically provide one-to-one sessions, often limited by strict patient schedules and time constraints and forcing the therapist to be present throughout the session. While some XR solutions are applied in research hospitals, they are not widely adopted, and patients often receive a limited number of scheduled sessions before discharge.

Research and Innovation Objectives: Develop ad-hoc designed applications specifically for rehabilitation (2b). Create lightweight, wearable hardware devices (2a). Design user-friendly interfaces (2c). Implement adaptive mechanisms to adjust task and task difficulty based on patient progress (2f).

Well-being

1b.10 People with specific needs

VR offers a complementary approach to traditional therapy for individuals with special needs (i.e. children with the autism spectrum disorder) by providing simulated scenarios that help them better handle social (and working) situations strengthening the inclusion in the day life activities. VR environments can be easily implemented and replicated, allowing for repeated practice and personalised settings, which is often challenging in real-life conditions. The use of VR scenarios as serious games can also enhance engagement and therapy adherence where needed.

Challenges and opportunities: Traditional procedures and support activities (in same case therapies) for individuals with special needs, like the one based on cognitive behavioural strategies, social skills programmes or motor training, often involve exposing individuals to real-life scenarios to teach autonomy. While effective, this can be challenging to implement and replicate consistently in real life. Current VR solutions for this purpose are primarily initial proofs of concept and are not yet widely adopted as a standard of care.

Research and Innovation Objectives: Develop commercial head-mounted displays (and widely interaction devices) suitable for therapeutic applications and addressing the special needs of individuals (2a). Create VR and mixed reality (MR) customised applications specifically designed for strengthening social, emotional and cognitive skills (2b, 2c). Establish robust back-end platforms to support these applications (2d, 3b).

1b.11 Virtual communities for individual recovering from temporary illness

XR technologies can create shared virtual spaces where patients recovering at home from temporary illnesses can connect with others, participate in social and meaningful activities, and mitigate feelings of isolation, boredom, or emotional distress. XR fosters a sense of presence and normality, thereby enhancing recovery motivation and psychological well-being.

Challenges and opportunities: Individuals recovering at home from temporary illnesses often rely on limited social support from family or friends, leading to feelings of disconnection and reduced mood or motivation. Current passive entertainment options offer minimal interaction or stimulation. While some

rehabilitation programmes use basic applications or video calls, immersive community-based XR platforms for short-term recovery are not yet widely adopted.

Research and Innovation Objectives: Develop lightweight, easy-to-use XR systems suitable for home environments (2a, 2b). Design intuitive onboarding processes for users experiencing temporary fatigue or pain (2c). Incorporate asynchronous participation options to accommodate varying patient schedules and energy levels (2f, 2d).

1b.12 Education for clinical personnel

Technology-based education aims to raise awareness among clinical personnel regarding the current possibilities offered by the market and research centres in XR and VW. This enables informed decision-making regarding technology, solutions, and their application in patient care, ensuring that healthcare professionals are equipped to integrate innovative approaches.

Challenges and opportunities: While initial courses on innovative technologies are emerging, they are often elective and not widely integrated into standard curricula across European Union countries. A dedicated education pathway for XR and VW technologies is currently lacking in standard medical training, and there is an absence of specific "hybrid" professional roles within hospitals that combine clinical expertise with technological understanding.

Research and Innovation Objectives: Develop educational programmes that inform clinical personnel about the opportunities, barriers, and ethical implications of new technologies. Establish mechanisms for continuous professional development to ensure healthcare providers remain updated on evolving technological advancements (1e, 3b, 3d).

Recommendations

To fully realise the transformative potential of VW in healthcare and well-being, a multi-faceted approach addressing technological, educational, and ethical considerations is essential.

Firstly, there is a pressing need for the development of highly accessible and affordable VW hardware and software solutions. This includes lightweight, user-friendly XR devices suitable for diverse user groups, from elderly patients to individuals with specific needs. The widespread adoption of these technologies' hinges on their ease of use and economic viability, particularly for home-based applications and community-level interventions.

Secondly, significant investment is required in the creation of high-fidelity, evidence-based VW applications for prevention, diagnosis, personalised care, surgery, and rehabilitation. These applications must be rigorously validated against established clinical standards to ensure their efficacy and safety. A focus on gamification and engaging user experiences will be crucial for maintaining user motivation and adherence, particularly in long-term preventive and rehabilitative programmes.

Thirdly, the integration of AI and DT technologies is paramount for advancing personalised healthcare. Developing patient-specific DTs capable of real-time monitoring, predictive modelling, and tailored treatment recommendations will revolutionise clinical decision-making. This necessitates robust data integration from various sources, including wearable sensors and ingestible devices, alongside the development of intuitive XR interfaces for healthcare professionals.

Fourthly, addressing the educational gap among clinical personnel regarding XR and VW technologies is critical. Comprehensive educational programmes should be developed and integrated into standard medical curricula to ensure healthcare professionals are equipped to understand, evaluate, and apply these innovative approaches in patient care. The establishment of "hybrid" professional roles combining clinical expertise with technological understanding could further accelerate adoption.

Finally, ethical considerations, particularly concerning data privacy, consent, and the responsible use of AI in healthcare, must be embedded into the design and deployment of all VW solutions. Transparent data governance frameworks and robust safety-critical systems are essential to build trust and ensure that these technologies serve the public interest without exacerbating inequalities or causing harm.

1c Media and entertainment

Scope and introduction

Over the past decade, the European media sector has undergone a major transformation, marked by the breakdown of traditional boundaries between content formats, markets, and distribution channels. Accelerated by the Covid-19 crisis, this shift is driven by five interconnected trends: the rise of new digital technologies, the emergence of digital-native creators and platforms, changing consumption habits, evolving monetisation models, and shifting societal expectations of media's role. A second wave of digital disruption is now unfolding, led by generative AI, Large Language Models (LLMs), Virtual Worlds (VW), immersive media, and virtual production technologies. These advances are reshaping how content is created, distributed, and experienced, blurring the lines between entertainment, gaming, shopping, and social interaction in what is increasingly referred to as "liquid media."

However, this innovation surge occurs within a global media landscape dominated by U.S.-based platforms that control streaming, video sharing, and social networks. Despite efforts by European broadcasters to adapt, structural challenges—such as fragmented infrastructure, limited access to investment, and a still-incomplete Digital Single Market—hinder Europe's ability to compete at scale. European start-ups, while numerous, struggle to grow in a capital environment that remains less supportive than in the U.S. or China. At the same time, changing audience preferences—especially among younger generations—are favouring short-form, interactive, and personalised content accessed via social platforms and virtual spaces, leaving traditional media models increasingly sidelined.

These changes present both existential threats and powerful opportunities. Europe's media ecosystem is under pressure from declining revenues, eroding public trust, and the loss of influence among digital-native audiences. To regain strategic autonomy and remain relevant, the EU must invest boldly in innovation, cross-sector collaboration, and European-owned infrastructures. VW, in this context, offer a transformative opportunity—both as a creative frontier and as a testbed for inclusive, rights-based digital futures. The European Commission views VW as a cornerstone for economic dynamism and digital autonomy but insists they must be shaped by European values: inclusion, accessibility, cultural diversity, and public interest.

To guide this transformation, the Strategic Research and Innovation Agenda (SRIA) outlines seven interconnected use cases that reflect Europe's technological priorities: AI-driven virtual production, volumetric media and avatars, XR stage tracking, immersive events, virtual education and health, adaptive gaming, and secure media ecosystems. These domains reflect the convergence of cutting-edge tools—such as real-time 3D engines, generative AI, volumetric capture, and cloud-native XR platforms—with the creative demands of immersive storytelling and interaction.

Yet innovation must go hand in hand with robust governance. Safeguards like real-time image harmonisation, blockchain-based rights management, and explainable AI are essential to ensure privacy, security, and user trust. Inclusive system design, hardware-neutral access, and strong ethical frameworks are equally vital to ensure equitable participation. Europe's media future must be built not only on technical excellence but on democratic principles. By aligning regulatory foresight with strategic investment and a commitment to cultural and social values, Europe can lead in building immersive, intelligent, and human-centric virtual media ecosystems.

Use cases

This section outlines key research areas within the media and entertainment domain, detailing their significance, current challenges, and proposed objectives for future innovation.

Media production

1c.1 Artificial intelligence -driven virtual production and rendering

AI-driven tools and real-time rendering engines are set to revolutionise media production by automating and streamlining content creation. These technologies enable instant generation of 3D environments from natural language descriptions, provide intelligent assistance for tasks like colour grading and scene layout, and offer creative suggestions. This approach aims to reduce reliance on expensive hardware, shorten production timelines, and accelerate feedback cycles, ultimately democratising cinematic-quality virtual scene production for smaller teams and independent creators.

Challenges and opportunities: Current production processes are often characterised by physical set building, extensive post-production for visual effects, and fragmented, manually coordinated workflows. Existing AI applications are typically narrow and not integrated across the full production pipeline. Key challenges include long iteration cycles, high costs associated with skilled labour and hardware, a lack of automation in critical areas like colour grading and lighting, complexity in coordinating remote or hybrid teams, limited real-time feedback for creative decisions, and issues with AI explainability and interoperability.

Research and Innovation Objectives: AI-Driven Virtual Production and Rendering integrates foundational technologies from across 2a–2f, leveraging advanced visualisation and real-time rendering systems (2a) to produce high-fidelity virtual scenes. It draws on interaction models (2b) for intuitive content control using voice, gesture, and predictive inputs, while authoring tools (2c) support collaborative, AI-assisted scene creation and real-time co-design workflows. Interoperability standards (2d) are critical to ensure compatibility across distributed creative pipelines and platforms. Digital assets and virtual environments (2e) form the backbone of scalable scene elements and enable adaptive reusability in diverse production settings. Applied AI (2f) plays a central role, powering generative content creation, lighting and scene layout suggestions, version control, and embedded explainability to preserve creative intent.

On the socio-technical side (3), key intersections include transparency, explainability, and human oversight (3e)—essential for maintaining trust in AI-assisted creative processes—and innovation, IP, and creativity (3c), which are central to defining rights and ownership in AI-generated media.

1c.2 Volumetric media and avatar presence

The ability to capture and reconstruct people volumetrically in real-time allows for their realistic representation as avatars in immersive environments. This facilitates rich human presence, interaction, and emotional expressiveness across entertainment, sports, training, and social XR applications. Furthermore, real-time volumetric capture enables the seamless integration of remote individuals into live virtual productions or broadcasts, supporting interactive interviews, performances, and collaborative segments.

Challenges and opportunities: Currently, volumetric capture is largely confined to specialised studios, requiring expensive and complex multi-camera systems. Most avatars rely on hand-modelled rigs or low-fidelity motion capture. Challenges include high costs, limited scalability and portability, significant hardware requirements, restricted emotional realism, reliance on marker-based facial tracking, and technical barriers for small teams or live applications. While interest is growing in various sectors, widespread adoption is hindered by these technical and cost barriers.

Research and Innovation Objectives: Volumetric Media and Avatar Presence spans all core technology areas (2a–2f), integrating advanced visualisation and sensing (2a) for lifelike avatars and real-time volumetric capture. It leverages real-time interaction models (2b) for social presence and embodiment, and authoring tools (2c) for designing, animating, and customizing avatars and experiences. Standardisation (2d) ensures interoperability of avatars and volumetric formats across platforms, while digital humans' frameworks (2e) enable identity, behaviour, and emotional realism. Applied AI (2f) supports avatar animation, emotion recognition, data compression, and ensures ethical use and explainability. In addition to these technical layers, the use case intersects with key Section 3 socio-technical areas: privacy and data governance (3b) are critical in managing captured biometric and behavioural data; identity, autonomy, and agency (3a) relate to how users control their digital representations; and inclusion and accessibility (3a) are essential to ensure that avatar-based interactions are usable and representative for diverse populations.

1c.3 Camera tracking and smart Extended Reality stages

Precise and automated tracking of physical cameras and actors within modular XR stages ensures perfect synchronisation between physical and digital environments. This allows for seamless blending of real and virtual scenes, crucial for immersive storytelling and live production. Leveraging visual analysis methods also enhances the overall coherence between physical displays and virtual environments, addressing alignment, geometry, and visual consistency, and harmonising lighting and colour for believable integration.

Challenges and opportunities: Current camera tracking often involves manual configuration and custom solutions. XR stage setups typically rely on proprietary integrations of displays, sensors, and game engines, often requiring recalibration for each production, which increases setup time and limits portability. Key challenges include a lack of standardisation, hardware fragmentation, tracking drift or latency, high calibration costs, reliance on specialist crews, and difficulty adapting to changing set configurations. While high-end productions utilise these technologies, broader adoption is constrained by their technical complexity and cost.

Research and Innovation Objectives: Camera Tracking and Smart XR Stages integrates key technologies across areas 2a–2f, combining advanced sensing and visualisation (2a) for precise real-time alignment of physical and digital environments, with interaction models (2b) to support seamless spatial coherence during live production. Authoring tools (2c) facilitate efficient setup and calibration of XR stages, while interoperability standards (2d) ensure compatibility across diverse hardware systems. Digital Twins and spatial models (2e) contribute by enabling dynamic, responsive representations of physical stage elements, allowing for real-time adaptation and accurate synchronisation between physical and virtual components. Applied AI (2f) enhances camera tracking, lighting consistency, and automated scene adjustments.

From the socio-technical perspective in Section 3, key intersections include safety, security, and consumer protection (3b), which are essential for maintaining reliability and system integrity in high-stakes production environments, and inclusion and accessibility (3a), to ensure XR stages support a wide range of user needs and collaborative workflows.

Domain specific research topics are the development of open XR tracking protocols to promote interoperability and the establishment of plug-and-play calibration standards for easier setup and reduced reliance on specialist crews.

Immersive experiences

1c.4 Immersive interactive events

Immersive interactive events allow digital-native participants to experience real-time, shared entertainment in virtual environments, such as virtual concerts or film festivals. This enables social engagement, interaction with content, and even co-creation of performances, moving beyond passive viewing towards active participation and connection. These events are persistent, globally accessible, and layered with live social interactions, fostering meaningful fan-to-fan and fan-to-creator connections.

Challenges and opportunities: Current practices largely involve passive livestreaming or in-game events with limited interactivity. Existing VR social platforms host niche community events. Key challenges include predominantly passive audience experiences, limited scalability and social richness, poor integration of user-generated content, fragmented tools for cross-platform access and creator monetisation, and high technical barriers combined with a lack of standards for real-time shared XR events. While experimentation is growing, particularly among younger generations, widespread use is limited by technical constraints, platform fragmentation, and XR device adoption.

Research and Innovation Objectives: Standardisation on infrastructure, system and runtime interoperability (chapter 2d). Sensing devices for audience input (chapter 2a). Real-time co-creation frameworks, need for real-time user interaction (chapter 2b) and interactive experience design tools (chapter 2c). The need for new (AI-assisted) storytelling models (2f18) and novel human-AI interaction paradigms (2f.33).

1c.5 Immersive educational and health applications

Immersive educational and health applications enable students and mental health service users to engage with content in interactive formats, promoting more effective learning and emotionally resonant support. These experiences are designed to be informative, enjoyable, and motivating, leveraging immersive environments and game-based interactions to deliver personalised and effective services.

Challenges and opportunities: Current educational games are often two-dimensional with limited interactivity, and virtual classrooms rely on basic video conferencing. Mental health tools typically include basic telehealth services and chatbot therapy, lacking deep immersion or personalisation. While some simulation-based medical training exists in VR or AR contexts, it often lacks gamification and adaptive feedback. Challenges include low emotional engagement, limited personalisation, a lack of embodiment and social presence in remote services, generic one-size-fits-all designs, difficulty sustaining motivation, insufficient integration of biometric or behavioural data, and ethical and accessibility concerns within XR settings.

Research and Innovation Objectives: The requirement on accessibility in games and game mechanics (3a) and the technological realisation of this (2f). The need for personalisation frameworks and adaptation to user contexts (2c).

1c.6 Innovative and adaptive game design

Game developers and creative studios seek to design and deploy games that dynamically adapt to diverse user contexts, including cultural, linguistic, physical, and technological variations. This is achieved through modular tools, AI-driven personalisation, and accessible motion capture. This approach aims to broaden audience reach, facilitate experimentation with inclusive mechanics, and reduce production costs while maintaining creative flexibility and quality.

Challenges and opportunities: Most games are currently designed with a limited number of languages and cultural contexts, with localisation often added as a post-development step. Integrating advanced personalisation and accessibility features is costly and complex. Motion capture remains resource-

intensive, requiring specialised studios or significant budgets. Co-located multiplayer experiences are rare and technically fragmented across platforms. Challenges include a lack of integrated frameworks for dynamic cultural or linguistic adaptation, limited availability of low-cost motion capture tools for independent developers and educators, fragmentation in tools supporting accessibility, multiplayer, and content reuse, and barriers to creative experimentation due to steep learning curves in XR and AI integration.

Research and Innovation Objectives:

The mitigation of cultural bias and working on diversity in content and representation (chapter 3a.1). The requirement on accessibility in games and game mechanics (chapters 3a.1, 3a.2). The need for personalisation frameworks and adaptation to user contexts (Chapter 2c.9). The need for standards and codes for transparent and ethical XR design (chapter 3e.4).

1c.7 Secure, scalable and strategic media ecosystems

Ensuring that digital media production and distribution are secure, interoperable, and aligned with European values is crucial for protecting creators' rights, enabling cross-platform innovation, and building resilient infrastructures. This supports long-term cultural and economic sustainability by adopting open standards and decentralised infrastructures within VW. Blockchain-based content authentication and licensing ensure transparency and traceability, while AI governance frameworks align algorithms with ethical and legal norms. Interoperable metadata schemas enhance portability and discoverability across platforms, and decentralised identifiers and verifiable credentials protect identity and consent.

Challenges and opportunities: Current content rights and metadata are often managed in proprietary, siloed systems, with licensing and access handled manually. Platform ecosystems frequently lack transparency and portability. Key challenges include rights fragmentation, data silos, a lack of cross-border interoperability, piracy, platform dependency, weak monetisation channels, and the absence of comprehensive AI governance frameworks and ethical safeguards. While some media platforms are exploring blockchain-based licensing or interoperable metadata, widespread and standardised adoption remains limited.

Research and Innovation Objectives: Secure, Scalable, and Strategic Media Ecosystems draws on all key technology areas 2a–2f to establish resilient and ethically grounded infrastructure for media production and distribution. It integrates immersive content systems and device-level safeguards (2a) to support trusted media environments and applies interaction models (2b) to maintain secure, user-centric experiences across platforms. Authoring and distribution frameworks (2c) enable creators to manage content securely and flexibly, while interoperability standards (2d) are essential for cross-platform metadata, rights management, and secure licensing mechanisms. Digital assets and infrastructure models (2e) support persistent identity, verifiable credentials, and scalable content portability. Applied AI (2f) enhances metadata generation, content moderation, and algorithmic governance, while embedding ethics-by-design principles to ensure accountability and fairness.

From the socio-technical perspective (Section 3), this use case intersects most strongly with privacy, data protection, and data governance (3b) (ensuring user data and digital rights are protected across distributed infrastructures) and democracy and fundamental rights (3a), which underpin the development of media ecosystems that respect freedom of expression, transparency, and European digital autonomy.

Recommendations

To cultivate a robust, innovative, and ethically sound media and entertainment ecosystem within VW, a strategic framework encompassing technological advancement, infrastructure development, and regulatory alignment is essential.

Firstly, a concerted effort is needed to advance AI-driven virtual production and rendering. This involves developing sophisticated tools for voice- and gesture-based scene control, predictive scene layout, and lighting design, which can significantly reduce production timelines and democratise access to cinematic-quality virtual content. Integration of embedded explainability into AI models is crucial to preserve creative intent and foster trust among creators.

Secondly, significant investment should be directed towards volumetric media and avatar presence technologies. This includes developing efficient compression algorithms for volumetric data to enable seamless streaming and establishing clear privacy and ethical guidelines for the use of avatars and captured volumetric information. The creation of scalable real-time pipelines for volumetric capture and rendering will enhance human presence and emotional expressiveness in immersive environments.

Thirdly, the development of open standards and plug-and-play calibration for camera tracking and smart XR stages is paramount. This will facilitate seamless blending of real and virtual scenes, crucial for immersive storytelling and live production, by ensuring perfect synchronisation between physical and digital environments. Integrating dynamic Digital Twin technology for XR stages will further enhance real-time synchronisation and adaptability.

Fourthly, fostering immersive interactive events requires the development of adaptive, multi-user storytelling models that respond to audience input and behaviour. Establishing interoperable standards for XR events and environments will facilitate cross-platform access, while creating real-time audience engagement and co-creation frameworks will empower participants to influence performances, moving beyond passive viewing to active participation.

Fifthly, in the realm of immersive educational and health applications, a focus on personalisation frameworks and the investigation of game mechanics' impact on mental health and cognitive development is crucial. Establishing XR design principles tailored for neurodiverse and vulnerable populations will ensure these applications are effective, informative, and emotionally resonant for all users.

Sixthly, for innovative and adaptive game design, efforts should concentrate on mitigating cultural narrative bias to ensure broader appeal and inclusivity. Developing adaptive game mechanics that cater to diverse physical and cognitive abilities and establishing ethical frameworks for AI personalisation in interactive media, will promote responsible and inclusive game development.

Finally, to build secure, scalable, and strategic media ecosystems, it is vital to develop ethics-by-design AI approaches, research the sustainability of distributed ledgers, and align regulatory frameworks for interoperable standards. This will ensure transparency, traceability, and protection of creators' rights, fostering long-term cultural and economic sustainability within VW.

1d Arts and culture

Scope and introduction

The European arts and cultural sector demonstrates a significant capacity to engage with complex societal challenges, aligning with the European Union’s mission-oriented policy objectives under frameworks such as Horizon Europe, the Green Deal, Digital Europe and the New European Bauhaus.

Cultural actors contribute not only through dissemination and public engagement but also as co-developers of transformative practices. From a policy perspective, initiatives like the New European Agenda for Culture and Creative Europe as well as the Council Resolution on the EU Work Plan for Culture 2023–2026, underscore the integration of culture and the arts within cross-sectoral innovation ecosystems. This reflects a growing recognition of the arts as a horizontal enabler in achieving Europe's green, digital, and inclusive goals. By embedding artistic approaches into research and innovation pipelines, the European Union leverages the sector's ability to foster critical reflection, prototype alternative futures, and generate engagement beyond disciplinary silos.

Virtual Worlds (VW) offer a powerful platform for bringing arts and culture to a broader audience, showcasing its importance and impact on society and life in general. By leveraging VW, cultural institutions can reach global audiences, preserve heritage, and foster a deeper understanding of diverse cultures. The ability of VW to enrich arts and culture lies in their capacity to create engaging, educational, and accessible experiences for all. Immersive technologies such as Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) will likely see increasing use, most commonly in the museum sector to provide more dynamic and engaging forms of visitor experiences. Other applicable technologies include 3D experiences, audio augmentation, gaming, holograms, and avatars for immersive storytelling and education.

Almost 8 million people fall in the context of cultural employment, through 1.2 million firms, 99.9% of which are small and medium-sized enterprises. On average, 22% of heritage collections in Europe have been digitally reproduced. Regarding the European Commission's support for the digitisation of cultural heritage, from 2014-2020, 70 million euros were invested in projects focused on digital cultural heritage through Horizon 2020, with the Commission starting the European Collaborative Cloud for Cultural Heritage (ECCCH), the Data Space for Cultural Heritage and the EIT Culture and Creativity to advancing the digital transition of these cultural resources and providing data and application scenarios. As a business sector, cultural and creative industries are not only essential for Europe's cultural diversity but also in strengthening social cohesion and enhancing the European Union's global attractiveness. According to Eurostat figures (2024), cultural and creative industries employ 7.9 million people in the European Union, equivalent to 3.8% of the total workforce, and represent 2 million cultural enterprises, in 2022.

Use cases

This section outlines key research areas within the arts and culture domain, detailing their significance, current challenges, and proposed objectives for future innovation.

Cultural heritage and museums

1d.1 User-centred Extended Reality experiences

User-centred XR experiences enable museum curators to develop engaging, informative, and high-quality interactions for visitors, thereby increasing engagement. This approach facilitates co-design processes, allowing for enhanced interaction and communication with audiences, including their involvement in co-creation tasks. It also supports the customisation of experiences to meet the diverse needs of different audiences and promotes the sustainability of XR content through archiving and adaptation for various purposes.

Challenges and opportunities: Current museum practices often rely on custom-built XR experiences tailored to individual institutions, limiting re-use and adoption opportunities. Co-design efforts typically involve non-XR or analogue methods, with social XR largely confined to prototyped or blended experiences. Customisation for specific users is rare, except for child-focused content. These limitations

hinder scalability, increase costs, and restrict the widespread implementation of immersive cultural experiences.

Research and Innovation Objectives: Develop content templates and no-code content creation tools for XR applications, enabling museum curators to define high-quality experiences for various devices without coding (2c). Create multi-user platforms and back-end systems that support collaborative interaction and content sharing among museum visitors (2b). Ensure interoperability with existing collection management systems to facilitate seamless content integration and archiving (2d).

Performing arts in virtual spaces

1d.2 Enabling immersive and interactive performing arts experiences

The integration of VR and AR technologies into performing arts productions allows creators to develop novel and engaging experiences. This approach facilitates the creation of entirely new digital performance spaces, enables avatar embodiment and unique audience perspectives, and offers the potential for highly interactive and personalised narrative experiences. It also opens avenues for remote collaboration and global audience reach, fostering new forms of artistic expression and storytelling.

Challenges and opportunities: The integration of immersive experiences in performing arts not only offers new means to extend the experience but also allows for exploring new ways to perform. However, integrating XR on a large scale is costly and technically complex, exacerbated by a lack of standardised workflows and interoperability between technologies. Challenges include ensuring reliable real-time interaction, low latency, managing complex integrated systems, optimising high-fidelity digital assets for real-time XR environments, and ensuring stable network infrastructure for hybrid and multi-user experiences. While adoption is growing in theatre and large live productions, it remains relatively niche compared to traditional performing arts.

Research and Innovation Objectives: Develop seamless integration solutions for XR hardware and software in live performance contexts (2a). Create real-time, cost-effective motion capture and avatar control systems (2e). Establish standardisation protocols for XR performance assets and data to promote interoperability (2d).

Cultural events and festivals

1d.3 Expanding outreach and digital archiving of cultural events

VW solutions allow cultural events and festivals to expand their outreach by providing year-round, interactive access to past events through virtual walkthroughs and digital archives. This extends the life of cultural work, enriches artistic content, strengthens knowledge and curiosity, engages new generations, and facilitates the sharing of best practices. VW solutions can take various forms, such as 360-degree video virtual tours or capturing and storing metadata for future regeneration of experiences.

Challenges and opportunities: Most cultural events and festivals are ephemeral, with their digital presence often limited to static web pages, images, and videos. There are few opportunities for the public to fully experience events retrospectively or as remote participants, largely due to a lack of simple tools for digital storage. Current adoption of VW solutions for this purpose is low, with traditional media being the common method for documentation.

Research and Innovation Objectives: Develop methodologies for capturing and storing heterogeneous cultural event experiences, including audiovisual works, physical installations, and virtual components (2c). Promote the sharing of content among artistic entities through universally accessible platforms (2d). Implement measures for inclusion, such as considering the needs of persons with impaired eyesight and other accessibility requirements (3a).

New media art and creativity

1d.4 Artistic creation for embodied research

Artists are leveraging emerging and interactive technologies, including XR and AI, to create immersive, participatory experiences that challenge conventional thinking and speculate on future possibilities. This approach transforms how we perceive the physical world by enabling global access, embodied interaction, and the exploration of alternative narratives. Audiences are engaged as co-creators, fostering a dynamic relationship between artwork and participant.

Challenges and opportunities: New media art is currently realised through diverse digital installations, online exhibitions, and XR platforms. However, artists face challenges such as technical complexity, fragmented ecosystems, limited institutional support, funding issues, and preservation difficulties due to rapid technological obsolescence. There is also an issue of "sameness" in artistic output, suggesting a need for more innovative approaches. While adopted in niche art festivals and research institutions, widespread mainstreaming remains limited.

Research and Innovation Objectives: Develop AI-based generative tools and multimodal analytics for artistic creation, fostering unique and diverse outputs (2f). Integrate blockchain technology for provenance and ownership tracking of digital artworks (2d). Establish transdisciplinary co-creation methods to facilitate collaboration between artists, technologists, and audiences (2c). Enable artistic research to explore new formats (2d).

1d.5 AI curated or generated art in virtual environments

Next-generation platforms leverage AI to enhance curatorial storytelling, spatial design, and artwork creation within hybrid physical-digital environments. This enables curators and artists to explore multiple narrative and spatial exhibition scenarios, moving beyond static tools to dynamic, intelligent systems. VW provide added value through real-time simulation of visitor behaviour, multilingual storytelling, and generative layout suggestions tailored to exhibition goals.

Challenges and opportunities: Current design practices often rely on static software or manual methods, lacking narrative intelligence, AI integration, or inclusive simulation tools. Artists frequently use generative AI tools without the capability to automatically explore how their artwork would be presented within a physical or virtual space. Adoption of VW solutions in this area is low, with existing tools lacking semantic AI and integrated audience feedback simulation or contextualisation.

Research and Innovation Objectives: Develop generative AI capabilities for text-to-scene conversion and curatorial narrative modelling (2f). Integrate visitor behaviour simulation to inform spatial layouts and exhibition flow (2b). Establish collaborative cloud infrastructure to support multi-user design and curation processes (2c). Establish methods to ensure high-quality checks for the generated content with a focus on storytelling (2f).

Cultural tourism

1d.6 Virtual visits for cultural tourism

Immersive virtual visits allow tourists to explore heritage sites and cultural locations remotely, offering a highly immersive and interactive experience that goes beyond static images or videos. This approach broadens access to culture for individuals who may be geographically or physically restricted, supports sustainable tourism by reducing the environmental impact of physical travel, and creates new value streams for cultural institutions and virtual tour providers through mechanisms like remote guiding and entrance fees.

Challenges and opportunities: Current remote experiences of cultural locations primarily rely on images, prerecorded, or live videos, which offer limited immersion and interactivity. Existing business

models for remote tourism are often confined to basic travel guides or video tours. Adoption of VW solutions for cultural tourism is currently low, with only initial proofs of concept and limited industrialised solutions available in the market.

Research and Innovation Objectives: Develop high-quality head-mounted displays and back-end platforms to support realistic VW representations (2a). Ensure high-quality content recording and streaming capabilities for immersive virtual tours (2e). Investigate and develop sustainable business models for virtual cultural tourism, including remote guiding and virtual entrance fees (3c). Ensure high quality content recording, including scanning and AI tools (2a).

1d.7 Enhanced experiences in cultural tourism

Tourists can enhance their on-location experiences by gaining access to additional content through wearable devices or smartphones. This includes virtual time travels or augmented experiences that overlay digital information onto physical spaces. This approach enriches the visitor experience by providing deeper insights and interactive elements, such as location-based services, virtual tours into hidden areas, or gamified experiences.

Challenges and opportunities: Existing enhanced experiences, such as virtual time travels or AR applications, are often limited to specific, pre-defined scenarios. The adoption rate of VW solutions for on-location enhanced tourism is currently low, with only initial proofs of concept and limited industrialised solutions available. Challenges include the seamless integration of digital content with physical environments and the development of engaging, context-aware applications.

Research and Innovation Objectives: Develop high-quality content for wearables and smartphones that seamlessly integrates with physical locations (2e). Create robust back-end platforms to support the streaming and delivery of enhanced content (2b). Design engaging gamified experiences that leverage AR and location-based services (2c).

Collection and site management

1d.8 Integrated information and monitoring for heritage collections and sites

VW solutions for collection and site management enable the integration of diverse information sources, such as sensors, Internet of Things devices, and social media platforms, into digital or memory twins of specific objects or sites. This provides managers and restorers with comprehensive, tailored insights, allowing for real-time monitoring of decay and change, assessment of potential threats, and prediction of consequences by overlaying time-series data. It also facilitates the previsualisation of restoration outcomes, enabling better assessment and communication with stakeholders.

Challenges and opportunities: Current collection management often involves fragmented information across different databases, lacking full integration and direct access to all relevant data for a specific asset. Monitoring is typically tailor-made, with data available primarily via charts without direct correspondence to the specific site or object, often focusing on limited parameters. Previsualisation of restoration actions is traditionally done through physical or digital mock-ups, which are less dynamic. While many prototypes exist, few industrialised solutions offer broad interoperability.

Research and Innovation Objectives: Develop connectors to integrate data from heterogeneous sources, including sensors, Internet of Things devices, and social media platforms, into Digital Twins (2e). Create industry-grade head-mounted displays and AR applications that provide tailored data views for monitoring and assessment (2a). Ensure interoperability and retrieval capabilities from various data sources to facilitate comprehensive data integration into spatial, temporal, and semantic contexts (2d).

Architectural design

1d.9 Integration into architectural workflows

The integration of VW and XR technologies into architectural design and construction workflows significantly improves client interaction, design presentations, and experimentation with new architectural styles. This enables architects to create and evaluate designs in various XR interaction spaces, including head-mounted displays, caves, and holographic devices, with live manipulation and high-fidelity visualisation. It also allows construction engineers to simulate structural loads from DT, plan and review cost, and manage manufacturing processes, thereby accelerating planning and supporting rapid manufacturing and facility management.

Challenges and opportunities: Current architectural workflows primarily rely on digitised processes with a strong emphasis on 2D outputs, and while Building Information Modelling standards are prevalent, XR is only occasionally used. Industrialised XR solutions for architects are available but are in an early adoption state. Challenges include integrating XR seamlessly into existing computer-aided design/computer-aided manufacturing systems and ensuring that high-fidelity visualisations can be verified and documented within standard planning processes.

Research and Innovation Objectives: Develop industry-grade visualisation tools, including head-mounted displays, caves, and holographic devices, for multi-level visualisation and interaction in architectural design (2a). Create multi-user platforms and back-end systems that support collaborative design and review processes (2c). Ensure robust interoperability with existing computer-aided design/computer-aided manufacturing systems to facilitate seamless data exchange and workflow integration (2d).

Fashion

1d.10 Immersive digital fashion experiences

The fashion industry is embracing VW to revolutionise design, presentation, and consumer engagement by leveraging immersive technologies. This enables designers to host virtual runway shows, create digital garments for avatars, and reduce waste through digital prototyping. Virtual fashion offers global access, promotes sustainable practices, and creates new digital revenue streams through non-fungible tokens and avatar fashion, while providing interactive consumer engagement and creativity beyond physical constraints.

Challenges and opportunities: Traditional fashion events are often physical, costly, and exclusive, and prototyping generates significant waste. Online shopping lacks realistic virtual try-ons, contributing to high return rates. Existing digital initiatives in fashion are fragmented with low interoperability. While interest is rapidly growing, particularly among younger demographics, the adoption rate of VW solutions by end-users is currently low.

Research and Innovation Objectives: Develop advanced 3D modelling and real-time rendering capabilities specifically for digital garments and virtual fashion environments (2a). Establish robust avatar and DT systems that accurately represent physical apparel in virtual spaces (2e). Create interoperability standards and blockchain/non-fungible token infrastructure to support digital ownership and cross-platform use of virtual fashion assets (2d). Enable creation tools for virtual fashion (2c).

Gaming

1d.11 Inclusive game design for cultural and creative organisations

Cultural and creative organisations are seeking to engage wider and more diverse audiences through immersive, accessible, and meaningful game experiences. VW offer co-creation platforms that allow cultural actors to collaborate with developers in designing heritage or socially meaningful games,

thereby preserving and sharing diverse cultural stories in an engaging and accessible format. This approach provides visual, no-code interfaces for collaborative game creation, integrates explainable AI for cultural narrative branching, and ensures accessibility-by-design through built-in standards.

Challenges and opportunities: In cultural experiences game design is frequently outsourced, costly, and lacks participatory elements. End-users typically have no input in the cultural stories being told, and digital accessibility is often an afterthought. There is a significant lack of game design knowledge and guidance within cultural institutions, and few links exist between the game industry and cultural organisations. Most existing initiatives lack continuity and struggle with maintenance or scalability, leading to low accessibility compliance and risks of cultural misrepresentation.

Research and Innovation Objectives: Develop VR and XR ready co-creation environments that support multiplayer collaboration (2c). Create open-source design tools with integrated explainable AI for adaptive storytelling (2f). Establish ethical and inclusive game design frameworks, along with accessibility testing tools for developers and curators (3a).

Intangible heritage, crafted artifacts, safeguarding, preservation, posterity

1d.12 Documenting and preserving intangible cultural heritage

Leveraging advanced 3D digital technologies, such as 3D scanning, motion capture, and volumetric video, enables the accurate documentation, preservation, and communication of knowledge, skills, and cultural context related to Intangible Cultural Heritage, particularly traditional crafts. This approach allows for the visualisation and interaction with Intangible Cultural Heritage in immersive 3D environments, the preservation of movement-based traditions in a comprehensive way, and enhanced accessibility for remote users. It also creates interactive educational experiences, new possibilities for analysing practices, and opportunities for community participation in digital preservation.

Challenges and opportunities: Traditional methods of documenting Intangible Cultural Heritage (text, audio, video) often lack the nuance required to capture embodied practices like craftsmanship or dance, and struggle with documenting movement and spatial relationships in 2D media. Access to Intangible Cultural Heritage can be geographically limited, and the preservation of living traditions requires ongoing effort. Digital preservation demands specialised skills and infrastructure, and technological limitations hinder the capture of full sensory and social context. Interoperability issues between digital formats and technologies, along with a lack of standards for volumetric video data, pose significant challenges. Oral transmission is at risk of being lost, and museums often focus on objects rather than lived experiences, struggling with community involvement.

Research and Innovation Objectives: Develop high-resolution 3D scanning and modelling techniques for artefacts and environments, alongside accurate and cost-effective motion capture systems (2e). Create accessible volumetric video capture solutions for realistic recording of performances and practices (2a). Develop AR/VR platforms for online access and sharing of digital Intangible Cultural Heritage assets, supporting experiential interaction with cultural practices (2b).

Cross-cutting enablers

1d.13 Co-creation and participatory art for stakeholder engagement

Using art as an enabling technology through co-creation and participatory processes in VW can significantly increase stakeholder engagement and acceptance of XR technologies. This approach fosters emotional attachment between people and complex problems, enabling stakeholders to collaboratively propose, discuss, and prototype art and culture solutions with high impact. It brings together diverse ideas and resources to create value, addressing specific needs and fostering tailored

service experiences, ultimately enhancing community action, social engagement, and citizen involvement.

Challenges and opportunities: Traditional stakeholder engagement methods, combining analogue and basic digital tools, often lack the interactivity and engagement of physical presence. A key challenge is creating engaging and collaborative VW that are easily accessible to diverse groups, from experts to untrained citizens. There is a notable lack of toolkits and best practices for utilising VW for co-creation and participatory art. While the shift from physical to online meetings has begun, digital interaction formats often remain less interactive than in-person encounters.

Research and Innovation Objectives: Develop multi-stage methodologies that integrate co-creation, community participation, and innovation, supported by frameworks like the Place by Design Playbook (2c). Create toolkits and best practices for implementing co-creation and participatory art within VW (2c). Research and develop functionalities that enable easy access and intuitive collaboration for diverse user groups in virtual environments (3a).

1d.14 User accessibility to immersive cultural experiences

Ensuring user accessibility to immersive cultural experiences in VW allows individuals with physical, sensorial, intellectual, or learning disabilities, as well as the elderly, to participate in cultural life that might otherwise be inaccessible due to socio-economic, physical mobility, or other restrictions. By incorporating accessibility features and services, the range of users is widened, fulfilling human rights and enabling individuals to enjoy new experiences, represented with or without disabilities as per their preferences.

Challenges and opportunities: Current VW often have limited alternative access options because accessibility services are not consistently considered during development. Challenges include ensuring access through different devices and alternative authentication methods (speech, written text, haptics), managing roles and permissions, and guaranteeing interoperability with assistive devices. Self-representation through avatar choices, content perception, navigation, and interaction require alternative options tailored to user needs. Additional challenges include catering for multilingualism and adapting to user needs in accessible, responsive, multilingual, and intuitive environments with contextual help guidelines.

Research and Innovation Objectives: Develop accessible VR applications with accessible authentication and platform features, ensuring interoperability with assistive technologies (2d). Integrate access services such as subtitling, audio description, and sign language interpreting directly into AR/VR/XR experiences (3a). Conduct further research to understand the most effective ways to integrate access services within AR/VR environments (3a).

Recommendations

To foster a vibrant, inclusive, and sustainable participation/engagement of the cultural and artistic sector within VW, a comprehensive set of recommendations is proposed, addressing critical challenges in infrastructure, accessibility, sustainability, ethics, and creative collaboration.

Strengthening technical infrastructure, tools, and standards is essential. A coordinated effort is needed to develop shared specifications for content formats, metadata, avatar behaviour, and interaction models—building on frameworks like BIM, GLTF, and the European common data space for cultural heritage. Investment in modular, possibly open-source, authoring tools, including no-code and low-code options, will empower non-technical users. Additionally, regional or national “Virtual World Labs” could provide access to advanced technologies, forming a distributed European Cultural Extended Reality Infrastructure.

Establishing scalable pipelines for creation, testing, and distribution is vital to move beyond fragmented prototypes and bridge the digital divide. This involves shared authoring standards, modular, possibly open-source tools, and networked environments accessible to diverse organisations. These pipelines should support the full content lifecycle—from concept to cross-platform deployment. Coordinated investment in interoperable tools, evaluation frameworks, and accessible repositories will reduce redundancy, build capacity, and accelerate broad public impact.

Enhancing sustainability, funding, and institutional support is key to the long-term impact of immersive cultural experiences. This requires funding models that support full project lifecycles and integration of VW into national and European cultural policies. Dedicated resources and capacity-building in XR workflows, storytelling, asset management, and ethical AI are essential for the digital transition of cultural institutions.

Accessibility, inclusion, and reach must be built into VW from the start. This means designing for users with disabilities and vulnerable groups, ensuring access services like subtitles and audio description, and inclusive avatar representation. Broader access requires lightweight, mobile-friendly XR applications and support for audience development to reach diverse, global users.

Co-creation and collaboration are key to unlocking the participatory potential of VW. Priority should be given to tools for real-time, multi-user content creation and adapted participatory design methods. Training digital facilitators will support inclusive and impactful community engagement.

Safeguarding content integrity and ethics is crucial as immersive and AI-generated content grows. Clear frameworks must address authorship, consent, and data sovereignty, especially for underrepresented communities. Validation, explainability, and human oversight are key, along with preserving cultural context through metadata, multilingual narration, and rich storytelling.

1e Education and training

Scope and introduction

Virtual Worlds (VW) possess the potential to revolutionise learning and teaching by offering immersive and interactive environments that are valuable across multiple levels of education and training. At the institutional level, virtual classrooms and campuses can simulate complex, real-world scenarios, provide hands-on learning experiences, and facilitate collaboration across geographical boundaries. At the teacher/trainer level, VW enable personalised learning paths, immediate support, real-time adaptive assessments, and innovative methods tailored to individual needs. At the student/trainee level, VW can enhance engagement, improve learning and training outcomes, and better prepare future generations for a digital world.

Thus, VW offer significant value for both educational and training purposes, each with distinct yet complementary goals. While education is primarily concerned with the acquisition of knowledge—concepts, theories, and critical thinking—training focuses on the development of practical skills and competencies necessary for performing specific tasks. VW are uniquely suited to support both: they can host rich, contextualised content for cognitive learning as well as realistic, interactive simulations for skill acquisition.

For education, VW offer opportunities to explore abstract concepts through visualisation, engage in collaborative problem-solving, and immerse learners in historical, scientific, or mathematical contexts that foster deeper understanding. They also provide dynamic and authentic settings for language learning and intercultural exchange, enabling students to practise in real-time, interact with virtual agents or peers, and receive immediate feedback, including AI-assisted language analysis. For training,

they provide safe, controlled, and repeatable environments in which learners can practice procedures, decision-making, and situational awareness—especially valuable in high-stakes and technically complex domains such as healthcare, engineering, emergency response, or technical maintenance. In such contexts, hands-on training opportunities are often limited, real-life practice may be costly or logistically unfeasible, and the margin for error is minimal. By simulating realistic scenarios, VW enable trainees to learn from mistakes without real-world consequences, build competence through repetition, and gradually transfer their skills to authentic professional settings.

By combining education and training in shared virtual environments, institutions and organisations can create holistic learning ecosystems that address both knowledge and skill development. This integration not only supports lifelong learning, teaching, and training but also ensures that learners and trainees are both informed and capable—ready to meet the demands of an increasingly complex, technology-driven world.

The strategic importance of VW in education lies in their ability to democratise access to high-quality, experiential learning. Learners can conduct virtual experiments, explore historical events, practise languages, or interact with complex 3D models—regardless of geography, mobility, or resource constraints. These environments adapt to individual progress and learning preferences, enabling personalised and differentiated instruction that promotes equity, engagement, and inclusion. In training contexts, particularly in high-risk or technically demanding professions, VW offer unparalleled opportunities for safe and effective skill development. From healthcare to energy, logistics, aviation, and manufacturing, immersive simulations allow workers to rehearse procedures, navigate emergency scenarios, and develop professional confidence without real-world risks. Increasingly, embodied AI agents enhance these experiences by providing context-aware guidance, feedback, and performance monitoring.

VW also support scalable, cost-effective delivery of education and training—critical in the context of global teacher shortages, shifting labour market demands, and the urgent need for upskilling and reskilling. They enable real-time data collection and adaptive feedback, which drive continuous improvement in teaching, training, and institutional performance. Investing in the development and responsible adoption of VW is a strategic priority for countries and institutions seeking to lead in innovation, economic competitiveness, and digital sovereignty. This requires coordinated action in technology development, interoperability, curriculum integration, pedagogical design, accessibility, and professional development. As VW evolve, they will be central to building more inclusive, agile, and future-ready education and training ecosystems.

Thematic areas within education and training in VW span a wide range of learners, contexts, and institutional needs—from early schooling to corporate learning and technical upskilling. These immersive environments provide new ways to deliver knowledge, foster skill development, and support inclusive, adaptive education. Key thematic areas include primary and secondary education, higher education and research, intercultural learning and integration, lifelong learning and adult education, vocational education and training, immersive and adaptive training for high-risk technical professions, corporate/professional training, inclusive and emotionally adaptive learning for special education, teacher training and professional development, remote and distance education, and trainee-controlled adaptive support via embodied AI in VW. These thematic areas form the foundation of this chapter and guide the identification of challenges, research priorities, and technological enablers.

Use cases

This section outlines key research areas within the education and training domain, detailing their significance, current challenges, and proposed objectives for future innovation.

School education and academics

1e.1 Primary and secondary education

VW transform how students learn by providing immersive, interactive, and dynamic environments that support both conceptual understanding and hands-on learning across a wide range of subjects. They facilitate the support of individual learners' progress and needs, thereby enhancing learning efficiency within an integrated blended learning approach. Simultaneously, these environments inclusively prepare all learners for a digitised society where physical and digital experiences seamlessly converge, allowing dynamic assessment through open, adaptive tasks that mirror 21st-century complexities.

Challenges and opportunities: Current primary and secondary education primarily relies on classroom instruction, textbooks, and limited access to labs or field trips, making it difficult to provide personalised and deep learning experiences, especially for abstract or dynamic concepts. Widespread integration of VW remains low due to high costs, limited high-quality software and hardware, insufficient teacher training, and challenges with curriculum integration. Pedagogically, many VW lack strong instructional design, underrepresent 21st-century skills, and underutilize AI and machine learning for content creation or dialogue-based learning.

Research and Innovation Objectives: Develop pedagogically grounded content designed with strong instructional principles that align with effective teaching practices (2c). Create safe, child-friendly AR/VR/XR hardware and subject-specific interactive modules aligned with national curricula (2a). Conduct research into developmental effectiveness, cognitive load, and equity of access in virtual learning environments (2f, 3a).

1e.2 Higher education and research

VW transform how students and university staff engage with complex learning topics by providing immersive, interactive environments that support theoretical understanding and applied learning. They create new opportunities for advanced teaching and collaborative research by offering immersive access to complex systems, simulations, and real-world data. In higher education, these environments serve as interfaces to live databases, computational models, and scientific infrastructure, addressing individual learner needs through real-time feedback and personalised support, and providing instructors with insights into learning patterns via analytics dashboards.

Challenges and opportunities: Higher education typically relies on lectures, textbooks, and static digital resources, with limited access to hands-on labs or real-world applications. Instructors face constraints such as large class sizes and limited tools for personalised support. Advanced research often requires costly equipment, limited lab access, and fragmented collaboration tools, with large datasets and complex models often visualised in 2D. Co-design is mostly conducted via in-person workshops or 2D platforms, lacking immersion and embodiment. Adoption of VW solutions remains low to medium, primarily experimental, with limited integration into institutional systems and research data pipelines.

Research and Innovation Objectives: Develop pedagogically sound content with advanced instructional design principles aligned to higher education teaching and learning strategies (2c). Create secure, user-friendly AR/VR/XR hardware suitable for adult learners and complex academic use, with robust instructor dashboards for managing virtual classrooms and assessments (2a). Research usability, learning efficacy, cognitive load management, impact on scientific productivity, and ensuring equitable access for all students (2f, 3a)

1e.3 Supporting intercultural learning and integration

VW support foreign student integration in host institutions by facilitating language and culture learning and providing access to cultural experiences adapted to different language levels. Students can access immersive environments that reproduce cultural experiences, catering to the rich diversity of European cultures, including minority ones, and facilitating engagement and language learning in meaningful contexts. Students can navigate and interact with objects in multiple situations, enhancing engagement and language acquisition.

Challenges and opportunities: There is a need for less costly equipment and easy-to-use authoring tools that allow for the integration of customised assets into truly interactive experiences. Professional upskilling of existing educators and integration into teacher education curricula are also required. A universal design approach, including accessibility services for diverse users, and increased awareness of the VR potential are crucial. Adoption remains low, particularly in language and culture learning within higher education.

Research and Innovation Objectives: Develop intuitive user interface design for XR environments (2b). Create content templates and AI-based tools for easy content creation (2c, 2f). Conduct research into usability and impact on learning and integrate accessibility services for a universal design approach (3a).

Lifelong and professional learning

1e.4 Lifelong, vocational, and corporate learning

VW offer powerful opportunities for adult learning across lifelong education, vocational training, and corporate development by enabling immersive, interactive, and practice-oriented experiences. These environments transform how adult learners engage with knowledge—whether they are acquiring foundational skills, preparing for technical roles, or advancing professional expertise—by simulating complex real-life scenarios. They support both individualised and collaborative learning, reinforce technical and soft skills, and provide contextualised feedback, enhancing knowledge retention and workplace readiness. For companies, they enable experiential, task-specific, and collaborative learning that supports onboarding, leadership development, operational excellence, and cross-functional communication. By facilitating the transfer of tacit knowledge across roles, departments, and locations, VW strengthen institutional knowledge and foster organisational adaptability.

Challenges and opportunities: Adult education—across lifelong learning, vocational education, and corporate training—continues to rely heavily on static resources (e.g., lectures, PDFs, or slide-based e-learning), with limited opportunities for experiential learning or hands-on application. Vocational learners face restricted access to specialised equipment, while corporate learners often lack time, support, or immersive tools that reflect complex workplace realities. Challenges include high costs, fragmented access to training infrastructure, limited personalisation, and the absence of scalable systems for peer learning and situated expertise transfer. Despite growing interest, institutional adoption of VW remains low to medium.

Research and Innovation Objectives: Develop content grounded in adult learning principles, aligned with real-world tasks, occupational standards, and collaborative work practices (2c). Create user-friendly and ergonomic AR/VR devices tailored for extended use in diverse settings, including workshops, offices, and homes (2a). Implement adaptive learning pathways, scenario editors with conditional logic, and analytics for individual and team performance tracking (2d, 2f, 3a). Develop high-fidelity 3D models of equipment and environments to support hands-on training and safety-critical rehearsal (2e). Conduct research on the effectiveness, inclusion, engagement, tacit knowledge transfer, and return on investment of immersive training approaches (3a, 3b).

1e.5 Immersive and adaptive training for high-risk technical professions

Immersive and adaptive VW support training in high-risk technical professions by combining realistic simulations with AI-driven personalisation. These environments replicate complex workspaces and procedures while responding dynamically to individual learners' performance, enabling scalable, safe, and effective skill development. This accelerates skill acquisition, increases engagement, and allows high-fidelity practice of emergency or failure conditions impractical in the real world.

Challenges and opportunities: Traditional training relies on physical mock-ups, classroom theory, and supervised hands-on practice, which are costly, limited in scope, and hard to scale, especially for dangerous scenarios. Trainers struggle to personalise support, and learners may not receive timely or objective feedback. Equipment access, instructor availability, and learner safety remain key barriers. Fully adaptive, AI-enhanced systems are still in early stages or pilot use, with hardware cost, integration complexity, and content obsolescence hindering scaling.

Research and Innovation Objectives: Develop high-fidelity 3D models of industrial equipment and facilities (DTs) and real-time behaviour tracking (e.g., gaze, hesitation, error type) (2e). Create AI agents for adaptive tutoring and procedural guidance, along with scenario editors featuring conditional logic and semantic workflows (2f, 2c). Conduct research into long-term retention, trust AI tutors, and transfer of training from virtual to real-world contexts (3a, 3e).

1e.6 Teacher training and professional development

Training teachers using VW that simulate real classroom settings enables them to develop teaching skills, classroom management strategies, and student engagement techniques through active, experiential learning. These environments support personalised growth by monitoring individual progress and tailoring experiences, accordingly, preparing educators for modern classrooms. They allow teachers to interact with student avatars in realistic simulations, practice techniques, and receive immediate feedback, enhancing pedagogical flexibility and confidence.

Challenges and opportunities: Teacher training typically relies on lectures, limited classroom observation, and short practicum periods, leading to restricted access to diverse teaching situations, limited feedback opportunities, and high variability in training quality. Complex classroom dynamics and uncommon situations are difficult to simulate. Adoption of VW solutions remains very low, primarily due to cost, lack of awareness, and limited integration into teacher education curricula.

Research and Innovation Objectives: Develop immersive classroom simulation platforms with behavioural AI for dynamic student interaction (2b, 2f). Create scenario creation and customisation tools, along with learning analytics and feedback systems (2c). Conduct research into skill transfer, pedagogical impact, and user experience in virtual teacher training environments (2f, 3a).

Special education

1e.7 Inclusive and emotionally adaptive learning for special education

VW support inclusive, adaptive learning for students requiring special education, such as those with cognitive, sensory, emotional, or physical challenges. These environments offer personalised instruction, adjustable pacing, and multimodal content tailored to diverse learning needs. With real-time biometric feedback and AI adaptation, they respond to stress or disengagement, helping learners stay motivated and confident. Educators and therapists gain valuable insights to tailor support and monitor emotional and cognitive development.

Challenges and opportunities: Special education often relies on observation alone to assess student stress and engagement, with limited support for real-time adaptation. Many schools lack the tools, training, or funding to offer consistent, inclusive experiences for complex needs like emotional regulation

or executive functioning. Feedback is often delayed, subjective, and difficult to personalise at scale. Adoption of VW solutions remains low to very low, limited by hardware cost, accessibility limitations, and lack of integration with Individualised Education Programmes and national frameworks.

Research and Innovation Objectives: Develop AI-powered content personalisation engines and wearable biosensors for emotional state monitoring (2f, 2a). Create real-time affective computing and multimodal input analysis, along with universal design features such as text-to-speech, speech-to-text, visual simplification, and alternative inputs (2b, 3a). Conduct research into adaptive learning for neurodiverse users, cognitive load, and long-term impact of VW interventions (2f, 3a).

1e.8 Remote and distance education

In remote and distance learning, VW transform how learners engage with content by providing immersive and interactive settings that bring lessons to life beyond traditional screens. These environments encourage active participation and collaboration despite physical separation, offering hands-on experiences and real-time feedback. VW also support personalised learning paths and continuous progress tracking, making distance education more flexible and effective, and preparing learners to thrive in a world, where digital and physical experiences merge seamlessly.

Challenges and opportunities: Remote education heavily relies on digital platforms and self-directed learning, often with limited real-time interaction between instructors and learners. Teachers face challenges in maintaining learner engagement and ensuring equitable access to technology. Learners encounter distractions and varying degrees of support at home, hindering motivation and progress. The absence of hands-on experiences and immediate feedback makes it harder to grasp complex ideas or practical skills, and overall integration of VW solutions remains low.

Research and Innovation Objectives: Develop instructional content with proven pedagogical methods suitable for virtual, self-directed learning (2c). Create reliable, user-friendly AR/VR hardware optimized for home or remote settings, ensuring accessibility and comfort (2a). Conduct research into remote learning effectiveness, learner motivation, technology accessibility, and minimising cognitive overload in virtual environments (2f, 3a).

1e.9 Trainee-controlled adaptive support via embodied AI

VW empower trainees in technical and vocational training programmes to control their learning experience by selecting their desired level of AI support. An embodied AI agent, a virtual tutor powered by a LLM, interacts with learners in natural language, allowing them to negotiate the degree of guidance, hints, and feedback they receive. This human-AI dialogue fosters autonomy, builds metacognitive awareness, and adapts to individual learning preferences and confidence levels, ensuring optimal challenge and support.

Challenges and opportunities: Traditional training often follows a "one-size-fits-all" approach, with predefined levels of guidance that may not suit all learners, potentially limiting critical thinking or leaving some without enough support. Human instructors may lack the bandwidth to individualise support in real-time, and trainees have limited agency in directing their own learning. While intelligent tutoring systems exist in VR training, they rarely allow dynamic adjustment of support through natural conversation, and large language model-powered avatars are largely unexplored at scale in technical training.

Research and Innovation Objectives: Develop large language models integrated with lifelike, emotionally responsive avatars capable of dialogue management to interpret requests for varying support levels (2f, 2b). Create training task modularity for adjustable guidance levels and implement learning analytics to track interaction patterns and performance impact (2c). Conduct research into

learner agency, metacognition, and trust in AI tutors, alongside usability studies on dialogue clarity, frustration reduction, and effectiveness (3a, 3e).

Recommendations

To fully leverage the transformative potential of VW in education and training, a strategic approach encompassing technological development, pedagogical innovation, and inclusive design is essential.

Firstly, a concerted effort is needed to develop pedagogically sound and instructionally robust content for virtual learning environments across all educational levels. This includes creating subject-specific interactive modules aligned with national curricula for primary and secondary education, as well as professionally grounded content for vocational and corporate training. The content should support both conceptual understanding and practical skill acquisition, with a focus on active, experiential learning.

Secondly, significant investment is required in the development of accessible, user-friendly, and cost-effective AR/VR hardware. These devices must be suitable for diverse learning contexts, from child-friendly designs for primary education to ruggedised, industry-compliant equipment for vocational training, and ergonomic devices for prolonged use in professional settings. Ensuring accessibility features are embedded by design will be crucial for inclusive learning environments.

Thirdly, the integration of AI and large language models into virtual learning environments should be prioritised. This includes developing AI agents for adaptive tutoring, personalised feedback, and dynamic student interaction in classroom simulations. AI-powered content personalisation engines and real-time affective computing will enable more responsive and emotionally adaptive learning experiences, particularly for special education.

Fourthly, fostering research into the effectiveness and impact of VW on learning outcomes is paramount. This includes studies on developmental effectiveness, cognitive load, skill transfer from virtual to real-world contexts, and the long-term retention of knowledge. Research into learner agency, metacognition, and trust in AI tutors will also be vital for optimising human-AI collaboration in learning.

Finally, addressing the professional development needs of educators and trainers is critical for widespread adoption. This involves integrating VW technologies into teacher education curricula and providing opportunities for professional upskilling in XR workflows, immersive storytelling, and digital asset management. Creating scenario creation and customisation tools accessible to educators will empower them to tailor learning experiences to specific needs, thereby enhancing pedagogical flexibility and confidence.

1f Security and defence

Scope and introduction

This section explores the critical research topics within the domain of security and defence in Virtual Worlds (VW), highlighting their strategic importance, defining existing challenges and research gaps, and outlining key objectives for future innovation to safeguard these emerging digital frontiers.

The application scenarios for VW in security and defence are diverse, ranging from training and simulation environments to advanced mission planning, on-field operational assistance, situational awareness for operational command, remote maintenance and technical support, and medical support and recovery. Each of these areas leverages the unique capabilities of VW to enhance preparedness, improve decision-making, and increase the safety and efficiency of personnel in high-stakes environments.

However, the effective deployment of VW technologies in security and defence is contingent upon addressing several key challenges. These include ensuring technological autonomy to mitigate reliance on non-European providers, developing robust hardware designed for demanding operational conditions, the ability to create cost-effective and customisable immersive content and the responsible integration of AI. Finally, while offering immense potential, the convergence of advanced digital technologies and decentralised systems also creates new attack surfaces and necessitates novel approaches to cybersecurity.

Use cases

This section outlines key research areas within the security and defence domain, detailing their significance, current challenges, and proposed objectives for future innovation.

1f.1 Training and simulation

VW offer unparalleled opportunities for realistic and cost-effective military and civil protection training and simulation. This enables personnel to practice complex operations, including intervention, combat, piloting vehicles, behavioural skills, command, equipment maintenance, and medical interventions. Training can occur in shared, persistent virtual environments that replicate operational theatres, allowing users to connect via XR headsets, haptics, and voice systems from multiple locations. This leads to improved learning curves, enhanced on-field efficiency, greater diversity of training scenarios, and reduced training time and costs.

Challenges and opportunities: Traditional training systems often lack adaptability and immersion, with cost limiting the frequency and scope of exercises. While some simulators, especially for aviation, leverage VR or MR devices, many still rely on legacy means, such as screens or actual equipment. Overall adoption of VW solutions is modest, with full integration remaining at the research and development stage. Challenges include the expense and immaturity of XR hardware and ensuring user acceptance.

Research and Innovation Objectives: Create cost-effective, low-code/no-code content authoring tools that allow subject-matter experts to create training content by themselves (2c). Develop Live-Virtual-Constructive interoperability frameworks. Create cost-effective and user-friendly XR devices with extended battery life (2a). Develop AI-controlled virtual agents and adversaries (2f).

1f.2 Mission planning

VW provide immersive environments for team-based mission planning, typically supported by mixed reality setups. This allows commanders, field operators, and specialised units to test and plan missions before engagement, leveraging Digital Twins (DT) and simulations. The enhanced immersion and access to comprehensive data within these environments help to reduce cognitive overload and improve understanding of mission challenges.

Challenges and opportunities: Current mission planning relies on a combination of paper and digital tools, such as integrated Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance systems. While these tools utilise DTs and simulations, they often lack the immersive qualities needed to fully convey the complexities and challenges of a mission, potentially leading to cognitive overload and difficulties in understanding the operational environment.

Research and Innovation Objectives: Develop high-fidelity 3D environments for detailed mission visualisation (2a). Create cost-effective and user-friendly XR devices for planning (2a). Establish secured interoperability XR frameworks to facilitate collaboration (2d).

1f.3 On-field operational assistance

XR technologies can overlay mission-critical information directly into a user's field of view, providing contextual real-time guidance. This allows field personnel, such as soldiers or firefighters, to receive data on maps, threat indicators, biometrics, environmental alerts, friendly unit positions, and even facial or object recognition, while maintaining hands-free situational awareness. Coupled with AI-based assistants, these devices can filter and prioritise information and generate local analysis, significantly improving situational awareness, decision-making, coordination, and overall operational safety.

Challenges and opportunities: Current operational support relies on radios, handheld devices, or tablets, often leading to cognitive overload, distraction, degraded reactivity, poor coordination, and fragmented data visualisation. There is a growing need for real-time contextual data delivered to personnel on the ground. Adoption in operational contexts remains low, with pilot programmes facing setbacks due to hardware limitations.

Research and Innovation Objectives: Develop lightweight, ruggedised AR headsets with extended battery life suitable for field conditions (2a). Create AI-based context-aware assistants for real-time decision support (2f). Establish secure, high-bandwidth communication networks (4b).

1f.4 Situational awareness for operational command

XR enables commanders to visualise battlefield scenarios in real-time using 3D operational maps and immersive simulations, improving coordination between tactical and strategic levels. Virtual presence technologies XR allow for seamless collaboration between in-person and remote participants. Ultimately, this aims to create virtual spaces for advanced command and control centres accessible from anywhere, providing all stakeholders with relevant data and reducing the need for centralised physical locations.

Challenges and opportunities: Traditional command centres rely on in-person locations with multiple monitors and personnel, which can limit collaboration. While virtual presence and XR technologies are gaining traction in Europe, widespread deployment requires improved headsets, along with better integration with legacy systems. Holographic display adoption is also in early stages.

Research and Innovation Objectives: Develop high-fidelity 3D environments for comprehensive situational awareness (2a). Create cost-effective and user-friendly XR devices (2a). Establish secured interoperability XR frameworks to facilitate collaboration (2d).

1f.5 Remote maintenance and technical support

XR enables immersive and contextual support for maintenance tasks. Through AR/MR goggles, technicians can receive over-the-shoulder assistance, view 3D holographic models overlaid on physical components, and even access local, step-by-step procedures without connectivity. AI assistants, connected to camera streams, can aid in troubleshooting and prevent manipulation errors. This improves speed, accuracy, and safety, while reducing downtime and the need to deploy experts in the field.

Challenges and opportunities: Current maintenance relies on paper manuals and fragmented expert support via phone or videoconferencing, leading to slow troubleshooting, high error rates, and lengthy downtime for critical systems. Challenges include the need for improved XR goggles with high precision spatial anchoring, and the high cost of content creation for mixed reality-guided procedures. While AR-based remote assistance is used in civil aerospace and adapted for military use, widespread adoption in European defence forces remains low to moderate.

Research and Innovation Objectives: Develop high-fidelity AR/VR/XR goggles with low latency and high precision spatial anchoring, ensuring device security and ruggedisation (2a). Create cost-effective, low-

code/no-code content authoring tools that allow subject-matter experts to reuse training content (2c). Establish secure and low-bandwidth remote collaboration protocols and ensure numerical continuity through integration with asset management systems and DTs (2d).

1f.6 Medical support and recovery

VW enable comprehensive medical and psychological intervention training, including combat trauma care, field surgery, post-traumatic stress disorder therapy and operational decompression. Shared immersive scenarios, dynamic emotional stress simulations, and scenario branching based on user biometrics enhance realism, leading to improved memory consolidation and procedural fluency. Empathetic and emotionally adaptive therapy scenarios enhance post-traumatic stress disorder treatment outcomes, while real-time adjustment based on stress and muscle activation signals further refines interventions. This also reduces training costs and increases accessibility for remote and underserved units.

Challenges and opportunities: Traditional medical training relies on role-playing and screen-based trainers, which offer limited realism and adaptability to stress or skill levels. Physical simulations are costly and lack emotional realism. While virtual reality-based post-traumatic stress disorder therapy and trauma simulation are gaining traction, full virtual world-based Live-Virtual-Constructive integration for medical support remains at a low adoption level.

Research and Innovation Objectives: Develop real-time biofeedback systems (e.g., heart rate variability, electroencephalography, galvanic skin response) and stress modelling for personalised trauma scenarios (2a). Develop low-code authoring tools and representative 3D environments (2c). Develop AI-driven virtual avatars for guidance and support, along with adaptive multimodal interfaces (voice, gesture, haptics) (2f).

1f.7 Human-Machine Interaction (HMI)

Using XR technologies, operators can "become" the drone or robot, controlling autonomous systems through immersive 3D interfaces and natural gestures or voice commands. Situational data, drone feeds, or robot status can be overlaid directly onto the real environment, improving contextual awareness and decision-making. Haptic controllers can simulate forces and resistance, such as wind, recoil, collisions, or uneven terrains, enhancing the realism and precision of remote operations. This approach aims to reduce cognitive load and improve navigation in complex terrains, while increasing the precision of robotic arms for delicate tasks.

Challenges and opportunities: Current unmanned systems are often controlled via rugged tablets, joysticks, or dedicated stations, which require significant training and limit situational awareness. First-person goggles used for drone control typically provide only an immersive video feed with limited spatial awareness, lacking depth perception and haptic feedback. These interfaces contribute to high cognitive load and difficulty in navigating complex terrains. While some advanced first-person view systems are evolving towards XR by integrating overlays or gesture-based control, overall operational use of XR interfaces remains at a low adoption level.

Research and Innovation Objectives: Develop intuitive multimodal human-machine interfaces (2b). Create real-time data fusion and visualisation capabilities (2a). Implement AI-assisted decision support and target recognition (2f).

Key challenges

1f.8 Ensuring technological autonomy

Europe faces a critical strategic dependency on non-European providers for core XR technologies, including processors, sensors, and software for authoring and rendering. Pursuing technological

autonomy in the XR domain is crucial for safeguarding data security and integrity, mitigating supply chain vulnerabilities, and ensuring that European forces are not locked into non-sovereign ecosystems. This requires strategic efforts across the full XR value chain to develop European-designed components, open software platforms, and secure frameworks.

Challenges and opportunities: The XR market is dominated by non-European hardware and software providers, leading to concerns regarding cybersecurity, technological and data autonomy, and long-term autonomy in critical sectors for the European Union. This reliance poses risks of surveillance or manipulation of sensitive defence data, potential restrictions on access to key XR components during geopolitical tensions, and the risk of being locked into non-European standards. This situation also entails a significant dependence on states imposing export control through extraterritorial laws, such as the US.

1f.9 Hardware for Extended Reality systems

The deployment of VW technologies in security and defence settings necessitates the development of hardware that goes beyond consumer-grade solutions. This includes creating cost-effective, user-friendly, and lightweight XR devices with low-latency displays and high-precision spatial anchoring. Specifically for this application domain, ruggedised and secured XR headsets are crucial for achieving operational readiness and scale in demanding environments.

Challenges and opportunities: Current XR hardware often lacks the specific characteristics required for security and defence applications, such as ruggedisation, enhanced security, and extended battery life.

Research and Innovation Objectives: Develop cost-effective and user-friendly, lightweight XR devices with low latency displays and high precision spatial anchoring. Create ruggedised and secured XR headsets suitable for harsh operational environments. (2a)

1f.10 Immersive content authoring

Enabling cost-effective content creation accessible to subject-matter experts, through low-code/no-code editors, is crucial for the widespread adoption of VW technologies in security and defence. This allows for the rapid development and customisation of mission-relevant interactive environments and the reuse of content across different use cases. Such tools empower operational personnel to create tailored training scenarios and mission plans without extensive programming knowledge, significantly reducing development time and costs.

Challenges and opportunities: The creation of high-fidelity immersive content for security and defence applications is currently expensive and requires specialised technical expertise. There is a lack of user-friendly authoring tools that allow subject-matter experts to directly contribute to content development, limiting the agility and relevance of training and simulation environments.

Research and Innovation Objectives: Develop cost-effective low-code/no-code content authoring tools that are accessible to subject-matter experts. Design tools facilitating the reuse of immersive content across various use cases, such as training and field support. (Section 2c Authoring and experience design)

1f.11 User interaction and ergonomics

Effective deployment of XR systems in security and defence requires advanced user interfaces and user experiences that enable rapid cognition without distraction. Adaptive multimodal interfaces, incorporating voice, gesture, and haptics, are essential for intuitive and efficient interaction in high-stress environments. Ensuring ergonomic comfort for prolonged use in harsh and variable field conditions is also critical to prevent fatigue or injury and enhance human performance.

Challenges and opportunities: Current XR interfaces may not be optimised for the rapid decision-making and high-pressure scenarios typical of security and defence operations, potentially leading to cognitive overload

Research and Innovation Objectives: Develop advanced user interface/UX designs that facilitate rapid cognition in XR environments. Create adaptive multimodal interfaces that seamlessly integrate voice, gesture, and haptics for intuitive control. Conduct human factors research to ensure ergonomic comfort for prolonged use. (2b)

1f.12 Artificial Intelligence (AI) and agents

The integration of AI and intelligent agents is vital for enhancing the realism and effectiveness of VW in security and defence AI-based context-aware assistants can provide real-time decision support, while AI-controlled virtual agents and adversaries (constructive participants) enable highly dynamic and realistic training scenarios. AI-assisted content creation streamlines the development of complex environments, and AI-monitored performance with adaptive tutoring can tailor scenarios on the fly, improving learning outcomes. Furthermore, AI and computer vision-based object recognition and guidance automation enhance operational assistance in the field.

Challenges and opportunities: The development of highly intelligent and adaptable AI agents for realistic simulation in security and defence contexts remains a significant challenge. Ensuring that AI systems provide reliable and trustworthy decision support in high-stakes situations requires robust validation and ethical considerations. There is also a need for more efficient AI-assisted content creation tools to keep pace with the demand for diverse and complex virtual environments.

Research and Innovation Objectives: Develop AI-based context-aware assistants for real-time decision support. Create AI-controlled virtual agents and adversaries that exhibit realistic and adaptive behaviours for training and simulation. Develop AI-assisted tools to streamline the content creation process. Implement AI-monitored performance assessment and adaptive tutoring systems to personalise training scenarios. (2f)

1f.13 Systems integration, networks, and infrastructure

Secure and robust communication networks are foundational for the effective deployment of VW technologies in security and defence, enabling seamless data exchange and real-time collaboration across distributed teams. Establishing a distributed and secured collaborative XR framework, including Live-Virtual-Constructive interoperability, is crucial for integrating diverse operational elements into a unified environment.

Challenges and opportunities: The integration of VW technologies into existing security and defence infrastructures presents significant challenges, particularly concerning network bandwidth, latency, and cybersecurity. Ensuring secure and robust communication in contested environments is paramount.

Research and Innovation Objectives: Develop secure and robust communication networks capable of supporting high-bandwidth, low-latency XR applications in challenging environments. Create distributed and secured collaborative XR frameworks, including Live-Virtual-Constructive interoperability protocols. Ensure numerical continuity through seamless integration with asset management systems and DTs (2d).

1f.14 Human monitoring

Integrating human monitoring capabilities, such as biometrics and cognitive load monitoring, into VW is essential for enhancing human performance and ensuring the well-being of operators in high-stress security and defence environments. Multimodal biometric fusion for scenario adaptation allows training environments to dynamically respond to an individual's physiological and cognitive state, optimising

learning and performance. Emotion recognition via facial, gaze, and vocal analysis provides valuable insights into an operator's psychological state, enabling timely intervention and support.

Challenges and opportunities: The effective deployment of XR technologies in security and defence depends fundamentally on their acceptance and impact on human operators. Systems must be designed to enhance human performance without causing cognitive overload or unintended psychological harm. Ethical considerations, particularly regarding the use of AI-driven virtual agents, biometric monitoring, and behavioural data, raise concerns about surveillance, autonomy, and consent, necessitating transparent data governance.

Research and Innovation Objectives: Develop advanced biometrics and cognitive load monitoring systems for real-time assessment of operator state in XR environments. Create multimodal biometric fusion techniques for dynamic scenario adaptation in training and operational support. Research and implement emotion recognition capabilities via facial, gaze, and vocal analysis for enhanced human-machine interaction. (2a)

1f.15 Economic and market challenges

Europe's fragmented defence market, characterised by diverse national requirements and procurement rules, creates significant economic barriers to the adoption of XR technologies, in contrast with countries with a very large domestical marker such as China and US. Fostering greater cooperation between member states, harmonising procurement processes, and promoting coordinated investments can create larger, integrated markets. Developing common standards and certification frameworks will facilitate interoperability and reduce duplication, ultimately lowering costs and enhancing the competitiveness of European industries globally.

Challenges and opportunities: The fragmentation of the European defence market complicates joint procurement and increases costs. This makes it more difficult for the European industry to foster global leaders.

Research and Innovation Objectives: Therefore, it is suggested to foster greater cooperation among member states to harmonise procurement processes and promote coordinated investments to create larger, integrated markets. Development of common standards for interoperability and duplication reduction will further contribute here (2d).

Recommendations

To ensure the effective, secure, and sovereign deployment of VW technologies in security and defence, a comprehensive set of recommendations is proposed, addressing key challenges across technology, economics, and human factors.

Firstly, a strategic imperative is to achieve technological autonomy in XR. This necessitates a concerted European effort to develop and manufacture core XR components, including processors, sensors, and headsets. Furthermore, the creation of open, certifiable, and high-performance software platforms, such as rendering engines, authoring tools and simulation frameworks, is crucial to reduce reliance on non-European providers and ensure the long-term autonomy and resilience of European security and defence capabilities.

Secondly, significant investment is required in the development of purpose-built hardware for XR systems. This includes creating cost-effective, user-friendly, lightweight, and ruggedised XR devices with low-latency displays and high-precision spatial anchoring, suitable for harsh operational environments.

Thirdly, enabling cost-effective and accessible immersive content authoring is crucial. This involves developing low-code/no-code editors that empower subject-matter experts to create and customise

interactive, realistic, mission-relevant environments. Designing frameworks that facilitate the reuse of immersive content across various use cases will significantly reduce development time and costs.

Fourthly, a strong focus on user interaction and ergonomics is essential. Advanced user interface/UX designs that facilitate rapid cognition and minimise distraction in high-stress XR environments must be developed. Creating adaptive multimodal interfaces incorporating voice, gesture, and haptics will ensure intuitive and efficient control, while human factors research will guarantee ergonomic comfort and minimise cognitive load for prolonged use.

Fifthly, the responsible integration of AI and intelligent agents is paramount. This includes developing AI-based context-aware assistants for real-time decision support, creating AI-controlled virtual agents and adversaries for realistic training scenarios, developing AI-assisted tools to streamline the content creation process, and implementing AI-monitored performance assessment and adaptive tutoring systems. Robust validation and ethical considerations must be embedded to ensure trustworthy decision support in high-stakes situations.

Sixthly, ensuring secure and robust systems integration, networks, and infrastructure is foundational. This requires developing secure and high-bandwidth communication networks capable of supporting low-latency XR applications in challenging environments. Establishing distributed and secured collaborative frameworks, including Live-Virtual-Constructive interoperability protocols, and ensuring numerical continuity through seamless integration with asset management systems and DTs, will create truly integrated operational environments.

Furthermore, integrating human monitoring capabilities, such as biometrics and cognitive load monitoring, is essential for enhancing human performance and ensuring the well-being of operators in high-stress environments, necessitating transparent data governance and ethical frameworks.

Finally, addressing economic and market fragmentation is vital for scaling the adoption of XR in defence. Greater cooperation among member states to harmonise procurement processes and promote coordinated investments will create larger, integrated markets. The development of common standards and certification frameworks will facilitate interoperability, reduce duplication, and enhance the global competitiveness of European industries.

1g Cities and public administration

Scope and introduction

Virtual Worlds (VW) technologies, encompassing Digital Twins (DT), Extended Reality (XR), and immersive simulation environments, are opening new frontiers for city planning, public service delivery, citizen interaction, and administrative transformation. Essentially, these technologies enable urban stakeholders to create a parallel digital realm that mirrors and augments the physical city. Within this realm, planners and officials can model urban scenarios, test policies, and engage with citizens in ways not feasible in the analogue world. For city governments confronting complex challenges, ranging from climate change to rapid urbanisation, VW offer a safe, data-rich "sandbox" to experiment with solutions before deploying them in the physical environment. This chapter surveys how such VW applications are being harnessed to transform urban landscapes and governance, outlines the societal benefits and emerging trends, and identifies major challenges and research needs on the path toward "virtual worlds-enabled" cities.

The scope of applications ranges from city-scale DTs, which are dynamic 3D models of urban environments with real-time data, to immersive platforms for public services and civic participation. Key domains include urban planning and design, such as visualising new developments in Virtual Reality

(VR); infrastructure and environmental management, for instance, simulating traffic or energy scenarios via DTs; public service delivery in virtual environments, such as "virtual city halls" for citizen services; and AI-driven decision support systems that leverage city data platforms. The focus is on how these VW tools can support the goals of sustainable, efficient, and inclusive cities, aligning with objectives like the European Green Deal's climate-neutral targets and the European Union's Digital Decade targets for digital public services. Notably, the European Commission and Member States have launched initiatives such as the CitiVerse European Digital Infrastructure Consortium to drive the development of AI-powered local DTs for cities. Concurrently, global interest is surging, with nearly 700 cities worldwide expected to have deployed some form of VW or DT infrastructure by 2030. This momentum underscores the strategic importance of VW in the future of urban governance and justifies a dedicated agenda to guide research and innovation in this field.

Cities and public administrations are progressively adopting VW technologies across various application areas, driven by their potential to enhance sustainability, efficiency, inclusiveness, and governance. Several key trends have emerged in recent years, including the use of city DTs for urban planning, XR for participatory design and civic engagement, empathic tourism and enhanced citizen interaction through advanced AI agents, immersive public services and the city virtual world, AI-powered decision support systems, and virtual training and operational readiness. The confluence of these trends signals a transformative societal impact, with cities reporting benefits such as improved sustainability outcomes, greater efficiency and cost savings, enhanced inclusiveness, and strengthened governance. A proactive commitment to inclusivity and Universal Design principles in the development of CitiVerse applications will unlock significant societal opportunities, fostering a "CitiVerse Truly for All" and catalysing "Innovation Driven by Diversity". Comprehensive digital and psychocultural literacy programmes can empower citizens, transforming them from passive users to active, critical, and creative participants in the digital fabric of their city, thereby strengthening social cohesion and unlocking new forms of civic engagement and community building.

Use cases

This section outlines key research areas within the cities and public administration domain, detailing their significance, current challenges, and proposed objectives for future innovation.

1g.1 Transforming urban landscapes through virtual planning

High-fidelity 3D and VR DTs allow urban planners and residents to visualise proposed developments at street level, test environmental impacts, and pre-empt costly design errors. This approach moves beyond traditional 2D plans, which are often difficult to interpret and limit citizen input, enabling more evidence-based and preventative planning that can identify and mitigate negative outcomes in advance. It supports the safe experimentation with green urban innovations, aligning with climate policies.

Challenges and opportunities: Currently, only a minority of cities possess comprehensive, continuously updated 3D DTs, and existing data often resides in siloed, non-interoperable formats. While VR tools exist, they remain largely disconnected from statutory planning workflows. A significant gap also lies in the limited use of DTs as participatory platforms for urban design, hindering their transformative impact. Furthermore, there is a lack of longitudinal studies to quantify the real-world benefits of virtual planning, such as reduced errors or improved community satisfaction.

Research and Innovation Objectives: Modelling and simulation tools (2e). Automated 3D mapping, multi-domain simulation engines for holistic planning (2e). Human-computer interaction in urban design, haptic feedback, multi-user VR environments for collaborative co-creation (2c). Planning governance frameworks (3b). Standards for virtual public participation (2d). DT analyses integration into official planning processes.

1g.2 Public service delivery and citizen interaction

A "virtual city hall" in VW can offer 24/7 access to public services, reduce travel burdens, and engage digitally native residents. Immersive forums enhance transparency and participation, complementing physical offices and websites. If designed inclusively, these environments can reduce barriers for individuals with mobility impairments or scheduling constraints, making public administration more citizen-centric and accessible.

Challenges and opportunities: Current virtual civic interaction projects are primarily pilots or isolated use cases, lacking a comprehensive strategy for integrating cities into VW. There is limited evidence on the usability, accessibility, and cost-effectiveness of VR public services, alongside a notable absence of standards for identity, privacy, and moderation in civic VW. The user experience for non-tech-savvy citizens remains a significant gap, limiting widespread adoption, particularly among older or disabled residents.

Research and Innovation Objectives: UX designs for diverse populations (3a). Policy experimentation to explore virtual civic rights and norms, potentially extending principles of public access and transparency to virtual spaces (3a). Integrated platforms where a city's DT, public service portal, and citizen engagement forum converge.

1g.3 Simulation models and Digital Twins: From data to decision

Real-time DTs allow officials to test "what-if" scenarios, such as flood routes or urban development impacts, before implementation, leading to cost savings and potentially saving lives. These platforms enable proactive analysis rather than reactive fixes, optimising traffic flow, reducing energy waste, and improving public service delivery. They also facilitate predictive simulations, such as running thousands of variations of an evacuation plan, contributing to more resilient and efficient urban management.

Challenges and opportunities: A significant challenge lies in integrating multi-domain data from various city systems into a coherent, holistic simulation. Many cities struggle with legacy information technology systems and fragmented data pipelines, hindering real-time data assimilation and continuous model updates. There is also a lack of full-scale deployments of city DTs, with most remaining in pilot phases, and limited institutionalisation as daily decision tools across departments. Furthermore, a human resources gap exists, with a shortage of urban planners and analysts skilled in advanced simulations within the public sector.

Research and Innovation Objectives: AI as an "urban brain" that continuously learns from the DT and suggests optimisations (2f). New business models and partnerships for sustaining city DTs, encouraging co-investment and regional collaborations among municipalities (3c). City DT starter kits adaptable for municipalities of different sizes.

1g.4 Artificial Intelligence (AI) -driven decision support and interoperable data platforms

Cross-domain data combined with AI forecasts can optimise traffic, energy, and safety within cities. Interoperable data platforms break down silos, reduce duplication, and provide the backbone for AI-driven solutions, allowing information to flow freely and securely between departments. This enables holistic AI analysis and supports transparent, accountable decision-making in the public sector, aligning with ethical and legal requirements.

Challenges and opportunities: Many cities still operate with fragmented data in departmental silos, and AI deployments are often one-off pilots rather than part of a coherent strategy. Legacy information technology systems hinder easy data sharing, and common ontologies for data integration are often missing. Algorithmic opacity and bias in AI models, particularly for high-risk public sector uses, pose significant challenges to transparency and accountability. Furthermore, regulatory clarity at the local

level regarding AI Act and Data Governance Act implementation remains a gap, potentially slowing innovation.

Research and Innovation Objectives: Trustworthy AI for the public sector (2f). Ethical and legal frameworks specific to AI use in cities (3a, 3b, 3e). Federated city data infrastructure, including technical blueprints for urban data spaces that can interconnect with national and European data spaces.

Recommendations

To effectively harness the transformative potential of VW technologies for cities and public administration, a strategic and integrated approach is recommended across several key areas.

Firstly, a concerted effort is needed to develop and implement comprehensive city-scale DTs. This involves improving city modelling and simulation tools, including automated 3D mapping and multi-domain simulation engines for holistic planning. Crucially, these DTs must be designed as participatory platforms, integrating human-computer interaction advancements like haptic feedback and multi-user VR environments to facilitate collaborative urban co-creation. Reference implementations and templates for city DTs should be developed to serve as adaptable starter kits for municipalities of varying sizes.

Secondly, the development of public service delivery and citizen interaction platforms within VW must be prioritised. This requires user experience designs tailored for diverse populations, ensuring intuitive interfaces and accessibility for all citizens, including those with limited digital literacy or disabilities. Integrated platforms where a city's DT, public service portal, and citizen engagement forum converge into a single, interoperable system are essential. Furthermore, policy experimentation is needed to explore virtual civic rights and norms, extending principles of public access and transparency to these emerging digital spaces.

Thirdly, the integration of AI for decision support and the establishment of interoperable data platforms are fundamental. This involves developing federated city data infrastructure, including technical blueprints for urban data spaces that can interconnect with national and European data spaces. Advancing trustworthy AI for the public sector through algorithmic techniques that embed explainability and fairness checks is crucial, along with creating sandboxing environments for model testing. Ethical and legal frameworks specific to AI intelligence use in cities, including municipal AI ethics guidelines and legal research on liability in AI-aided decisions, must be established to ensure transparent and accountable governance.

Fourthly, addressing the ethical, legal, and socio-technical challenges of urban VW is paramount. This includes developing ethical frameworks and toolkits for cities, alongside establishing legal sandboxes for urban digital innovation to allow controlled piloting of new virtual services or AI deployments. Creating public engagement and education programmes to improve digital literacy and build trust in government technology is vital to ensure diverse participation and mitigate risks of exclusion.

Finally, sustained investment in hardware for XR systems, coupled with a focus on user interaction and ergonomics, is necessary for widespread adoption. This entails developing cost-effective, user-friendly, and ruggedised XR devices with low-latency displays and high-precision spatial anchoring suitable for diverse urban applications. Research into advanced user interface/UX designs that facilitate rapid cognition and minimise distraction in XR environments, alongside human factors research to ensure ergonomic comfort, will be critical for enhancing human performance and ensuring the well-being of urban professionals.

Chapter 2

TECHNOLOGY

Technical outlook and challenges

2a Visualisation, sensing, devices and immersion

The transformative potential of Virtual Worlds (VW) hinges critically upon significant advancements in Human Machine Interfaces (HMI) to create seamless and effective User Experiences (UX) across the continuously expanding range of professional and consumer Extended Reality (XR) applications. While direct view displays like smartphones have a role, our focus here is on near-to-eye 'virtual view' displays, such as head-mounted displays (HMDs), with future possibilities even extending to 'on-eye' devices or direct neural interfaces. HMDs—including advanced headsets and smart glasses—are essential to offering truly immersive modalities and are repeatedly identified as critical enablers across all use cases. Improving their performance, comfort, and sustainability is a central research and innovation priority to support the transition to VW. Also, multi-sensory applications are in scope. Defining the next generations of these physical interfaces for Virtual, Augmented, and Mixed Realities demands a holistic, transdisciplinary approach, encompassing technological innovation, user-centricity, ethical considerations, and sustainability. This hardware-oriented chapter envisions the research priorities needed to build a European industrial and technological roadmap for immersive technologies, with dual-use capabilities (civil and defence applications). They are categorised into four foundational layers: Visualisation, Sensing, Devices, and Immersion.

Realising the full potential of these immersive experiences faces myriad integrated challenges. Fundamentally, devices must be user-centric, intuitive, and eventually adaptive or assistive, minimising learning curves and maximising accessibility for all users, including those with sensory impairments or disabilities, while rigorously addressing critical safety and health impacts, such as motion sickness and long-term visual health.

Concurrently, accurate sensing of the user's environment and behaviour is paramount for responsive and adaptive immersive systems. This requires sophisticated sensors and advanced AI to capture and interpret both explicit inputs (e.g., voice, gesture, facial expressions) and implicit cues (e.g., attention, intent, emotion), alongside contextual data. Effective data transmission and reception are vital to handle the increasing data volume, ensuring smooth and uninterrupted experiences. Within this data-rich environment, privacy and ethics compliance are fundamental, demanding robust protection of user data, transparency, and adherence to ethical guidelines to build trust and ensure regulatory approval.

From a hardware perspective, devices must be compact, wearable, and untethered to afford users mobility and comfort, requiring lightweight, ergonomic designs capable of autonomous operation. Crucially, energy consumption must be optimised as these wearables become more complex and resource-intensive, extending portable device usability and reducing environmental impact. A growing

imperative is sustainability, focusing on creating recyclable, reparable hardware aligned with circular economy principles, and reducing reliance on critical materials.

Furthermore, AI integration is pivotal, enhancing immersive system capabilities from user interaction to system performance, demanding efficient computing power management for real-time rendering, sensing, and interaction. Multimodal interactions and multiuser utilisation are essential for fostering collaborative and social experiences, requiring sensing systems that can accommodate multiple users simultaneously and provide meaningful shared engagements with effective feedback mechanisms. Finally, achieving truly immersive, closer-to-reality experiences necessitates integrating all human senses, moving beyond visual stimuli to include auditory, haptic, olfactory, and gustatory feedback. This level of immersion, alongside robust interoperability across diverse platforms, devices, and applications, will ensure seamless, low-latency, and high-fidelity experiences vital for user satisfaction.

Addressing these interconnected global challenges is vital for advancing the development and adoption of immersive technologies. By strategically focusing on user-centric design, health and safety, hardware innovation, energy efficiency, sensory integration, interoperability, data management, privacy and ethics, sustainability, AI integration, and multimodal interactions, Europe can pave the way for a new generation of engaging, accessible, and sustainable immersive experiences.

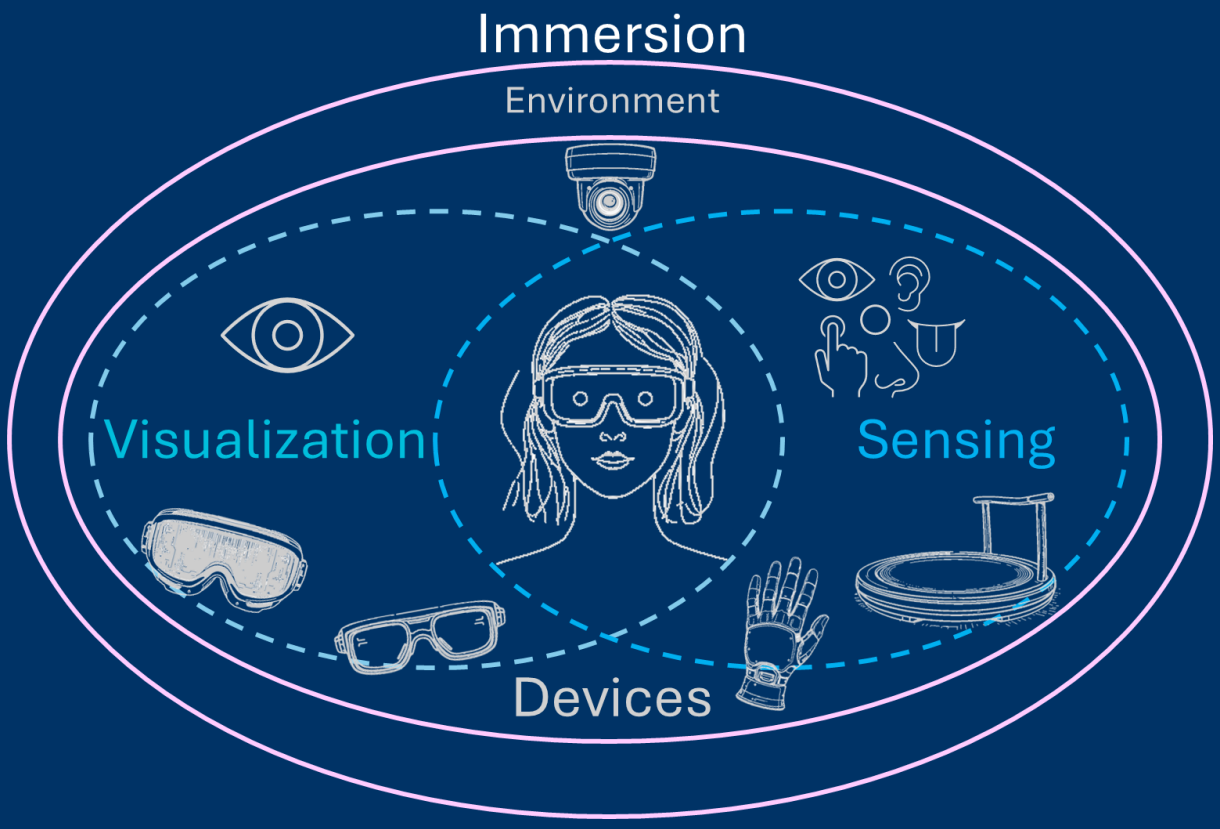

Figure 3. Visualisation, sensing, devices and immersion

Research topics for visualisation, sensing and devices

This section explores the critical technology blocks required to develop immersive visualisation interfaces, advanced multimodal sensors and integrated wearable devices, detailing their significance, current challenges, and proposing strategic research and innovation objectives.

Visualisation: Realism in immersive experiences

Visualisation technologies are the primary interface in virtual, augmented, and mixed reality, fundamentally shaping user engagement and comfort. The core objective is to deliver realistic, perceptually coherent, and comfortable 3D experiences, necessitating advanced display systems. These systems must balance high fidelity, compact form factors, and low energy consumption, especially for wearable devices. Ensuring visual health (topic addressed in 3d Health Aspects Related to VW), safety, and adaptability to individual needs are also crucial. Strategic research in this domain underpins the sustainability and inclusiveness of future VW.

Figure 4. Topology of headsets and glasses for XR

2a.1 High quality, low energy and safe images

Achieving full-colour, high-brightness, and high-resolution images with low energy consumption and a wide field of view is crucial for enhancing realism and ensuring visibility across various lighting conditions, particularly for AR. This aims to improve user immersion and peripheral awareness by minimising geometric aberrations. Additionally, low latency and fast response times are vital for reducing motion blur and simulator sickness, while comprehensive synchronisation mechanisms (e.g., Genlock, Vsync) are necessary to match framerates between diverse devices. Ensuring colour accuracy, uniformity, and dynamic range further supports naturalistic rendering, all while carefully managing brightness and guaranteeing eye safety for end users.

Problem Definition and Research Gap: For wearable devices, achieving these high-fidelity visual metrics is severely constrained by form factor and power budgets. Current Virtual Reality (VR) headsets suffer from insufficient angular resolution and restricted fields of view, especially in the bottom field for near vision, alongside nasal restrictions that hinder comfortable binocular fusion. Large temporal fields of view often introduce optical distortions. In optical see-through architectures, the low transfer efficiency of existing optical combiners necessitates very high-brightness displays. Furthermore, balancing resolution with frame rate in real-time image processing remains a significant challenge. Overall, substantial research efforts are needed to optimise performance and overcome practical design constraints.

Research and Innovation Objectives:

- Develop and optimise display technologies such as Foveated displays, Micro-OLED, OLED-on-silicon, and MicroLEDs to deliver high-quality, full-colour, real-time images with enhanced brightness and resolution, while achieving low energy consumption and compact light engines.
- Address manufacturing challenges for emerging display technologies like MicroLEDs and overcome issues in Laser Beam Scanning (LBS) related to speckle, safety, eye box, and image uniformity, to enable compact and lightweight designs suitable for immersive applications.

- Investigate and implement solutions such as local dimming for optical see-through Augmented Reality (AR) devices to improve contrast and develop transparent micro displays to eliminate the need for external optical combiners and exit pupil expansion, thereby enhancing overall system efficiency and UX.

2a.2 Optical components

Developing versatile and scalable fabrication technologies for novel optical components is crucial for achieving compact optical architectures without compromising visual quality or adding excessive weight to devices. This directly contributes to the miniaturisation of VR, AR and MR headsets, enabling greater ease of personalisation and significantly reducing manufacturing costs for industrial players. These advancements are essential for creating more aesthetically pleasing and comfortable wearable immersive technologies.

Problem Definition and Research Gap: The primary problem lies in the inherent bulkiness of traditional refractive optics, which severely limits the miniaturisation of XR headsets. Existing optical combiners utilising waveguides are often bulky, heavy, and non-aesthetic. Furthermore, folded optics suffer from significant optical inefficiencies, with light transmission frequently below 25%. Diffractive optical elements (DOEs) and holographic optical elements (HOEs) are promising but currently plagued by chromatic aberrations and limited efficiency, particularly in broadband or full-colour applications. While Meta optical elements (MOEs) or Metasurfaces offer potential, achieving broadband, full-colour performance with high efficiency remains a substantial technical challenge. Across DOE, HOE, and MOE technologies, industrial scalability is identified as a major bottleneck.

Research and Innovation Objectives:

- Advance the development of flat optics, metasurfaces, diffractive optical elements, and waveguides, focusing on their maturity for use as optical combiners or integrated optics to enable compact and high-performance immersive devices.
- Research and implement industrial processes for micro- and nanofabrication of DOEs and MOEs, including photolithography, nanoimprint, and 3D printing, to ensure scalability and cost-effective production of these novel optical components.
- Explore and utilise high refractive index materials with industrial processing means, which are essential for manufacturing flat optics or organic optical waveguides that can meet the stringent requirements for miniaturisation and visual quality in next-generation XR hardware.

2a.3 User centric 3D realistic visualisation

Providing realistic 3D visualisation that prioritises user comfort is critical for enhancing perceptual realism and depth cues in immersive experiences. Moreover, visualisation systems must accommodate individual visual needs, such as prescription correction, interpupillary distance (IPD) adjustment, and age or health-related vision changes. This includes also addressing common issues such as the vergence-accommodation conflict (VAC), which impacts cognitive performance, fatigue, and cyber sickness. Enabling a wide range of monocular and motion-based depth cues (e.g., motion parallax, occlusion, shading, focus blur) is essential for a natural experience. Furthermore, developing optical architectures that support aesthetic devices and user privacy (avoiding stray light), alongside facilitating natural and shared spatial understanding in collaborative environments, positions multi-perspective visualisation as a cornerstone for future immersive systems.

Problem Definition and Research Gap: A significant research gap exists across diverse immersive technologies (optical see-through, video see-through, VR, contact lenses, large screens) due to their varied requirements. Most current optical see-through AR devices are monocular with limited fields of

view (20-30°), and existing wearable products poorly manage prescription needs, often relying on add-on lenses. Achieving effective 3D perception and seamless superposition between virtual images and the real environment is crucial but challenging, directly impacting the feeling of immersion. Managing cyber sickness (including VAC) and ensuring user comfort during prolonged wear (e.g., weight, eye strain) remain significant obstacles. While light field and holographic displays offer potential, they are currently prohibitively expensive and bulky for widespread deployment. Furthermore, robust multimodal orchestration is needed for integrating with interaction systems (gestural, vocal, spatial input) across multiple users, and there is a critical absence of a unified protocol or software layer to support cross-device, cross-platform multi-perspective display technologies. Overall, this topic has very low technological maturity.

Research and Innovation Objectives:

- Develop Spatial Light Modulators, Light Field displays, and holographic displays, alongside the use of dynamic optical layers (e.g., Liquid Crystals, metasurfaces) to modulate depth perception and mitigate vergence-accommodation conflict (VAC) based on gaze direction or object depth, requiring new optically active materials.
- Explore and develop novel technologies and paradigms for real-time multipoint-of-view visualisation, including display systems combining directional optics, rear projection, and adaptive rendering for multi-user, headset-free 3D visualisation.
- Implement real-time light field rendering with spatial foveation and neural interpolation for computational efficiency and integrate low latency multiview user tracking to drive dynamic scene recomposition tailored to each observer in collaborative immersive environments.

Sensing: Bridging physical and digital realities

Sensors are fundamental to interaction between the physical and digital worlds in XR, enabling seamless integration and immersion. While current sensing modalities exist, significant advancements are needed for miniaturisation, energy efficiency, and computational efficiency in wearable head-mounted devices. Multimodal sensing, leveraging techniques like sensor fusion, offers increased accuracy and resilience. A deeper understanding of user states—attention, cognition, emotion, and intent—is vital for frictionless, user-tailored interfaces. This necessitates user-specific, privacy-aware multi-modal sensing to realise optimal future XR experiences.

2a.4 Sensing framework for digital environment representations

To effectively augment reality, the physical world must first be accurately sensed and comprehended. It is crucial to minimise the latency between the physical reality and its digital representation, ensuring a real-time understanding of the user's environment. The process of generating this digital representation must also be highly energy-efficient to enable on-device processing close to the sensors, which is vital for the battery life and practicality of wearable devices. This capability is essential for application developers who require reliable and low-latency digital representations of the user's surroundings.

Problem Definition and Research Gap: A significant research gap lies in developing adaptive and resilient sensor fusion frameworks that can dynamically adjust to changing environmental conditions, providing reliable sensing in open-world scenarios and potentially learning from contextual cues to optimise performance. There is a need for energy-efficient, real-time digital representations of the user's surroundings, encompassing not just geometry but also material properties, semantics, and object interrelations. While current solutions for world representation, such as SLAM and spatial computing in devices like Meta Quest 3 and Apple Vision Pro, utilise various sensors (global shutter, 3D, inertial, microphones), further research and development are needed to improve sensor frameworks, data

fusion, and processing for reliable, on-device, and efficient digital representations. Current adoption rates are low due to the high computational load associated with SLAM and world mesh construction. It is acknowledged that this research topic benefits from collaboration with the ADRA partnership and that any double work is to be prevented.

Research and Innovation Objectives:

- Develop adaptive and resilient sensor fusion frameworks leveraging multiple modalities for robust world representation in diverse and changing environments.
- Investigate novel low-power sensor designs, including neuromorphic and event-based sensing, alongside new materials to enhance energy efficiency for on-device operation.
- Research and implement energy-efficient on-device AI processing architectures and algorithms for odometry, SLAM, world mesh generation, semantic segmentation, and object segmentation.

2a.5 User-tailored sensing of the outer physical state of the user

Low-latency, low-power sensing of the user's outer physical state is essential for developing intuitive and frictionless human-machine interfaces for head-mounted devices such as smart glasses. Accurate and real-time tracking of the user's body, head, hands, and gaze is fundamental for enabling natural interaction, achieving realistic avatar representation, and delivering personalised XR experiences that respond seamlessly to user input.

Problem Definition and Research Gap: The primary research gap involves creating adaptive and resilient sensor fusion frameworks specifically focused on generating a digital representation of the user's outer physical state. These frameworks must dynamically adapt to the user and changing environmental conditions, ensuring sensing reliability in open-world scenarios and potentially learning from contextual cues to optimise performance. A key challenge is providing an energy-efficient, real-time digital representation of the user's physical state, including body, head, and eye pose, gaze, hands, gestures, face, and facial expressions. Current solutions often lack the precision (e.g., sub-millimetre for gestures), robustness (e.g., handling occlusion, rapid movements), and energy efficiency necessary for all-day wear and truly natural interaction. While devices like Meta Quest 3 and Apple Vision Pro incorporate sensors for basic pose, hand, and face tracking, further research into advanced sensor frameworks, data fusion, and processing is required to achieve reliable, efficient, and on-device digital representation.

Research and Innovation Objectives:

- Develop adaptive and resilient sensor fusion frameworks leveraging multiple modalities for robust user state sensing in open-world operations, accommodating changing user and environmental conditions.
- Investigate novel low-power sensor designs, including neuromorphic and event-based sensing, along with new materials and energy-efficient on-device AI processing architectures and algorithms tailored for gesture recognition, hand manipulation, micro-gestures, eye and gaze tracking, and head and body pose sensing.
- Research and implement advanced sensing frameworks and power management techniques to achieve higher precision, robustness, and energy efficiency for continuous and natural user interaction in wearable devices.

2a.6 Sensing framework for digital representation of user's inner state

Developing low-power, low-latency sensing and interpretation frameworks for the user's inner state is vital for creating truly frictionless human-machine interfaces. Traditional interfaces, such as buttons or speech prompts, are often unsuitable for head-mounted platforms, as evidenced by current market devices. A deeper understanding of the user's attention, cognitive and emotional states, and intentions is needed to facilitate interaction through implicit communication with AI agents. This capability is key to matching services and interfaces precisely to the user's needs and current state.

Problem Definition and Research Gap: A significant research gap is the lack of unobtrusive, reliable, and validated (bio)sensors suitable for long-term integration into XR wearables. There is a need to develop sensors and biosensors that can be seamlessly integrated into head-mounted displays for improved fit, comfort, and aesthetics. Addressing significant privacy and ethical concerns associated with collecting and interpreting sensitive inner state data is paramount. Challenges remain in robustly interpreting complex bio signals (e.g., EEG, ECG, EDA) to accurately infer cognitive states like attention, workload, or emotional valence, especially outside controlled lab settings. Furthermore, there is a need to develop user-tailored interfaces and data interpretation methods that preserve user privacy, potentially through federated learning approaches that keep user-specific knowledge on the device. User-specific adaptations of interaction and experience based on physiological, physical, and world data also present a significant research area.

Research and Innovation Objectives:

- Develop skin-interfaced biosensors for continuous, unobtrusive physiological monitoring (e.g., EEG, EMG, temperature, hydration) and investigate their integration into smart textiles or accessories associated with the XR experience.
- Research and develop sensors and biosensors (e.g., eye-tracking, SWIR sensing, facial expression sensors, HR sensors) to provide deeper insights into the user's physiological state, including cognitive state, emotional state, biological state, attention, and intent.
- Explore and implement biometric processing directly on sensors or within systems, specifically designing solutions that adhere to stringent privacy constraints to protect sensitive user data.

2a.7 Sensing suite for understanding of real-world semantics and affordances

To enable AR applications that genuinely react to context, a standardised approach is required for understanding real-world semantics and affordances. Current world representations, relying solely on 3D geometry reconstruction (e.g., SLAM), are insufficient for developing contextualised applications that leverage each user's personal environment. A standardised hardware/software solution that provides structured information about objects (semantics) and their potential uses (affordances), directly leveraged by application developers from devices, is crucial for truly context-dependent AR experiences that benefit end users.

Problem Definition and Research Gap: The primary problem definition and research gap is that current world representations, largely based on geometric reconstruction, are insufficient for enabling contextualised applications. There is a need to extend these representations to a higher-level understanding of real-world semantics and affordances. At present, solutions for achieving this high-level understanding are either non-existent or are at a very early stage.

Research and Innovation Objectives:

- Investigate and implement AI solutions, potentially through dedicated AI chips and software, for on-device sensing interpretation to derive high-level semantic information and affordances from real-world input.
- Define and develop standardised data formats and Application Programming Interfaces (APIs) for semantic information to ensure interoperability across various devices and applications, facilitating a shared understanding of the real world for AR applications.

2a.8 Privacy-aware sensing and connectivity in Extended Reality

Privacy-aware sensing and robust connectivity are of paramount importance in XR environments, particularly due to the depth and sensitivity of data collected for world and user understanding. These elements are crucial not only to ensure effective functionality of XR systems but also to align with fundamental EU values such as inclusivity, safety, security, and the protection of personal data. Together, they address the critical need to protect both the user and individuals in their environment from unwanted data exposure, whether during sensing, communication, or storage in the cloud. They support the ethical, responsible, and legally compliant deployment of immersive technologies by safeguarding highly personal AR data throughout its lifecycle.

Problem Definition and Research Gap: Despite the growing ubiquity of AR/VR/XR systems, there is a fundamental lack of established methodologies for ensuring privacy-aware sensing and secure connectivity. Current practices rely heavily on cloud-based infrastructure, often hosted outside the EU, exposing personal data to significant risks during transmission (via Wi-Fi, landline, mobile networks) and while stored remotely. Moreover, sensing mechanisms typically operate without integrated privacy protections, resulting in unnecessary propagation of sensitive data. The Technology Readiness Level (TRL) of existing privacy-preserving techniques in XR remains low, and there is a pressing need for interoperable, edge-centric architectures that minimize third-party exposure and ensure compliance with regulations such as GDPR and the Data Act.

Research and Innovation Objectives:

- Define and develop standardised methodologies for privacy-aware sensing in XR environments that reduce the exposure of sensitive data to third parties, while maintaining sensing effectiveness.
- Investigate and embed privacy-enhancing technologies (PETs) directly into sensing hardware (e.g. through hardware-based watermarking) and software pipelines, operationalising privacy-by-design principles from the ground up.
- Develop local edge computing architectures that reduce the need to propagate personal data to cloud or non-EU infrastructure, thereby keeping processing near the user.
- Implement low-bandwidth and secure communication protocols and develop sovereign wearable OS and connectivity stacks fully aligned with EU privacy standards.
- Investigate and apply confidential computing, hardware/software attestation, and personal data stores, ensuring encryption and security across the entire data lifecycle—including during use of emerging standards such as 6G.

2a.9 Synergies between brain-computer interfaces and Virtual Reality

Exploring the synergies between Brain-Computer Interfaces (BCI) and VR is crucial for transcending the limitations of traditional input devices. This research promises a more natural and direct connection to VW, unlocking novel applications across various sectors for professionals in training and rehabilitation, individuals with motor impairments, and researchers pushing the boundaries of immersive experiences.

Problem Definition and Research Gap: The primary difficulty lies in developing robust, user-friendly, and highly integrated BCI-driven VR solutions that enable seamless communication between neural interfaces and VW. Currently, the technology is at a low TRL (2-3), with early-stage academic research primarily demonstrating proof-of-concept for basic BCI-driven VR interactions and neurofeedback applications. End-user adoption is nascent, largely confined to specialised research labs and niche clinical or high-performance training environments, though some gaming applications are beginning to emerge. This indicates a significant gap in translating foundational research into widely accessible and reliable integrated systems.

Research and Innovation Objectives:

- Integrate advanced neuro-sensing hardware with high-fidelity VR display and haptic feedback systems to create comprehensive BCI-driven VR solutions.
- Leverage AI for real-time neural signal processing and to enable adaptive virtual environments that respond dynamically to brain activity.
- Conduct extensive neuroscientific studies, develop advanced signal processing techniques, and apply machine learning for BCI decoding, alongside human-computer interaction design and iterative UX evaluations to refine integrated BCI-driven VR systems.

Devices: Enabling ubiquitous and sustainable experiences

AR/VR/MR devices serve as interactive terminals, combining visualisation and sensing for immersive experiences. A key challenge is the absence of ubiquitous, all-day wearable XR devices, starting with HMDs, largely due to limitations in ergonomics, battery life, and connectivity. Addressing this requires developing ultra-low power components, high-capacity batteries, and sovereign, privacy-compliant systems. Miniaturisation, energy efficiency, and sustainability are paramount for mass market penetration. Advanced photonic integration and packaging techniques are crucial for achieving cost-effective solutions.

2a.10 Extended Reality wearable device power consumption and battery life

Minimising the overall power consumption of XR wearable devices and maximising their battery life is paramount. This directly enables all-day use without frequent recharging, providing uninterrupted experiences for both consumers and professionals. Overcoming current battery limitations is a key step towards ubiquitous adoption and practical everyday functionality.

Problem Definition and Research Gap: The primary problem definition is that current wearable XR devices are unable to sustain continuous visualisation for longer than eight hours on a single battery charge. This significant limitation hinders the widespread adoption of these devices for all-day use cases. There is a clear research gap in developing technologies and methodologies that drastically reduce power consumption across all device components and enhance battery performance.

Research and Innovation Objectives:

- Develop ultra-low power consumption chip designs and components for XR wearables, alongside high-efficiency optical see-through concepts to reduce power demands.
- Investigate and implement advanced energy-harvesting solutions, high-capacity batteries, and novel battery materials/components, including wireless electric charging concepts.
- Explore methodologies such as offloading computation-intensive tasks from XR wearables to other local devices with higher battery capacity and implementing low-bandwidth data communication within and to/from the device.

2a.11 Minimize the overall form factor of Extended Reality wearables

Minimising the overall form factor of XR wearables is crucial to enable ergonomic, aesthetic, and cost-effective all-day ubiquitous use for both consumers and professionals. This directly addresses current limitations in device comfort and portability, making them suitable for continuous wear and broader societal integration.

Problem Definition and Research Gap: Current XR visualisation wearables are generally too large and heavy for all-day wear and do not meet ergonomic expectations regarding weight, volume, portability, aesthetics, or visual comfort. A significant research gap lies in developing seamless and intuitive input modes for user interaction with visualisation (e.g., voice, unobtrusive gestures, 'thinking') that do not add to the form factor. Furthermore, effectively managing heat dissipation towards the user within a highly miniaturised device remains a key challenge. Current end-user adoption rates are low due to these ergonomic and form factor limitations.

Research and Innovation Objectives:

- Develop monolithic and hetero-integration techniques for various photonic components and advanced packaging solutions, such as chiplets, to achieve significant miniaturisation.
- Research and design seamless and intuitive input modes, including non-invasive brain-computer interfaces, that allow users to interact with the visualisation without requiring bulky external controls.
- Employ user-centric conception methodologies and design for manufacturing and assembly principles to ensure that miniaturisation and ergonomics are inherent to the device's development cycle.

2a.12 Embodied Artificial Intelligence

The integration of Embodied AI into XR devices is essential as these wearables increasingly become carriers for AI agents that interact directly with the end-user and other agents in the environment. This ensures devices are prepared to support such agents from both a computational and connectivity perspective. This is particularly significant given the potential for AR glasses to replace smartphones, with user interfaces becoming agentic (e.g., through natural speech), requiring numerous hardware innovations for scalable and fit-for-purpose deployment.

Problem Definition and Research Gap: The primary problem definition and research gap centres on the demanding computational requirements for running AI algorithms that enable agents to operate effectively, specifically regarding the high number of floating-point operations per second (FLOPS) and, critically, memory. Determining the optimal cloud-edge continuum hardware/software architecture for diverse use-cases is non-trivial, requiring a careful balance of latency, energy expenditure, data privacy, and cost. While NPU's and other hardware systems exist for agentic systems on smartphones, integrating them into AR devices remains challenging due to constraints on area, cost, energy expenditure, FLOPS, and memory. Current solutions often rely on a companion device (e.g., smartphone) for connectivity, indicating a need for on-device autonomy. End-user adoption of agentic AI is currently low, largely in the prototype phase.

Research and Innovation Objectives:

- Introduce edge/embedded AI hardware chips directly into wearable devices to enable real-time processing capabilities for embodied AI.
- Design ultra-low power processors specifically with embedded AI accelerators to meet the stringent energy consumption requirements of wearables.

- Develop techniques and architectures to enable the deployment of local Large Language Models (LLMs) on wearable devices, reducing reliance on continuous cloud connectivity.

2a.13 Agentic Artificial Intelligence compatible Extended Reality devices

Making XR devices compatible with Agentic AI at the hardware level is crucial because these devices are increasingly becoming carriers for AI agents that interact directly with users and other agents in their environments. This ensures that AR devices possess the necessary compute and connectivity capabilities to support such agents, paving the way for AR glasses to potentially substitute smartphones, with user interfaces evolving to become primarily agentic (e.g., using natural speech). This requires significant hardware innovations to achieve scalability and fitness-for-purpose.

Problem Definition and Research Gap: The problem definition and research gap revolve around the substantial computational demands of running algorithms for agent operation, requiring significant FLOPS and, critically, memory. A non-trivial challenge lies in identifying the correct cloud-edge continuum hardware/software architecture for different use-cases, balancing requirements such as latency, energy expenditure, data privacy, and cost. While NPUs and other hardware systems exist for agentic systems on smartphones, integrating them into AR devices remains very difficult due to constraints in area, cost, energy expenditure, FLOPS, and memory. Connectivity is often handled via a companion device (e.g., smartphone), indicating a need for more autonomous device connectivity. Agentic AI is emerging but remains largely in the prototype phase (TRL 6).

Research and Innovation Objectives:

- Develop advanced computing hardware solutions, including chiplets and vertical memory data lanes, potentially leveraging CMOS 2.0 technologies, to meet the high computational demands of agentic AI within compact AR devices.
- Research and implement next-generation wireless connectivity solutions, such as Ultra-Wideband (UWB), Bluetooth 6, and 6G, to ensure seamless and high-bandwidth communication for on-device and distributed agentic AI operations.
- Investigate and design hardware/software architectures that efficiently balance the computational burden between the device and the cloud, optimising for latency, energy consumption, data privacy, and overall system cost for various agentic AI use cases.

Research topics for immersion

This section delves into critical research topics within the technological layer of multimodal immersion, highlighting existing gaps and proposing strategic research and innovation objectives crucial for achieving intuitive, real-time and seamless user interactions.

Immersion: Deepening engagement and presence

Immersion in VW is achieved by blending real and virtual information, significantly enhanced by multisensory feedback. While visual input has been dominant, peripheral devices now offer diverse sensory modalities for interaction. A critical challenge lies in synchronising these various sensory inputs across the user's body and within multi-user environments. This demands sophisticated device design and algorithms for seamless spatial and temporal feedback. Advancing these capabilities is key to deeper, more coherent immersive experiences.

2a.14 Multimodal immersive collaboration

As digital collaboration becomes increasingly spatial, remote, and device-diverse, the inability to coordinate UX across heterogeneous devices hinders fluidity, limits accessibility, and creates friction in co-creation, learning, and decision-making processes. This research directly addresses these

challenges by enabling seamless coordination across a fragmented landscape of devices, transforming individual sensory depth into a shared, coherent experience distributed among diverse interfaces, benefiting designers, engineers, educators, and decision-makers in hybrid environments.

Problem Definition and Research Gap: Currently, no existing framework allows for the seamless orchestration of multimodal experiences across the fragmented landscape of devices, leading to isolated interactions and a lack of coherence in shared digital contexts (e.g., design reviews, hybrid classrooms, collaborative planning). The research gap involves fundamentally redefining immersion to mean a shared, coherent experience distributed among heterogeneous devices, rather than solely individual sensory depth. Current approaches are at TRL 3-5, with partial or vertical solutions that lack generalisability, adaptability, standardisation, and cross-platform integration. End-user adoption is low to moderate due to technical complexity, poor onboarding, and a lack of open, replicable solutions.

Research and Innovation Objectives:

- Explore a distributed, device-agnostic architecture capable of dynamic, role-sensitive, and context-aware rendering of shared content and interactions across XR headsets, mobile devices, and projected environments.
- Develop methodologies combining iterative prototyping, user-centred design, and in-situ experiments within co-creative, educational, or hybrid professional contexts.
- Evaluate the usability, scalability, and user adoption of proposed orchestration layers in practical collaborative settings.

2a.15 Multi-sensory telepresence for remote collaboration

Achieving high-fidelity telepresence using XR, volumetric capture, spatial audio, advanced haptics, and AI is crucial for enabling remote collaboration that genuinely mimics physical presence. This technology promises to reduce travel, facilitate rich and human-centred remote interaction, improve remote team productivity, enhance cross-border collaboration, and ultimately foster greater inclusion across various sectors.

Problem Definition and Research Gap: The primary research gap lies in the absence of any current system that seamlessly integrates real-time holography, multimodal feedback, network optimisation, and a human-centred experience into a single scalable solution. Technologies like holoportation, 3D avatars, and haptic clothing are currently fragmented and immature, typically existing only as lab prototypes (TRL 3-4). Scaling these solutions to a broader audience requires breakthroughs in hardware design, edge computing and 6G communication. End-user adoption is extremely low, limited to research and demonstrations, with no solution currently available for the general public, despite high interest across sectors.

Research and Innovation Objectives:

- Develop technologies for real-time 3D capture and mixed reality display systems, integrated with ultra-low latency streaming for seamless remote interaction.
- Design modular multisensory systems that include advanced haptics and privacy-by-design principles, utilising AI-driven compression and translation for efficient data handling.
- Conduct exploratory system integration, evaluate Quality of Experience (QoE) for multi-sensory devices, implement emotion-aware UX design, and develop open standards for edge/cloud architecture and security audits.

2a.16 Multimodal haptic design

Multimodal programmable haptics is vital for enhancing realism and skill transfer in XR-based training through multisensory feedback. Combining several haptic stimuli improves precision, builds confidence, and reduces cognitive load in complex tasks. This capability is also indispensable for remote operation scenarios in hazardous or inaccessible environments, providing appropriate haptic feedback that simulates real-world interactions. The development of context-aware haptic interfaces integrated into XR systems is crucial for simulating complex haptic interactions in industrial training, robotics, or remote manipulation.

Problem Definition and Research Gap: Current haptic feedback systems are largely limited to basic vibrations or simple force feedback. There is a significant research gap in developing context-sensitive, scalable, and wearable haptic systems capable of simulating complex properties like material textures, nuanced tool interactions, or fine motor gestures. While lab demonstrations exist for technologies such as wearable exoskeletons, ultrasonic haptics, and electro tactile interfaces (TRL 3-5), their real-time integration into XR workflows remains immature. End-user adoption is very low, primarily due to the high cost, bulkiness, or complexity of current haptic devices, although there is strong interest from advanced industrial sectors.

Research and Innovation Objectives:

- Develop modular, wearable, low-latency haptic systems (e.g., gloves, vests, handheld tools) with programmable feedback profiles that can be linked to DT and XR simulations.
- Research and implement real-time coupling between haptic systems and physics engines, alongside AI, to accurately simulate resistance, textures, and event-driven haptic sensations.
- Conduct comprehensive haptic signal modelling and material simulation, focusing on hardware miniaturisation and wearable ergonomics, while performing usability studies and psychophysics validation for applications.

2a.17 Spatial and adaptive sound design

Sound is a critical driver of presence, realism, and cognitive focus within XR environments. It enhances situational awareness, emotional engagement, and action timing, yet its potential is often secondary in XR design. In safety-critical or educational contexts, sophisticated acoustic cues can effectively guide user behaviour, reduce visual overload, and significantly improve learning outcomes. One key challenge is to develop real-time 3D spatial audio systems and adaptive sound perception models that improve immersion, user orientation, and task performance in XR.

Problem Definition and Research Gap: Most XR systems currently rely on simple stereo or non-contextual spatial audio. There is a significant research gap in designing and integrating real-time, personalised, and dynamic soundscapes, as these remain difficult to achieve and are poorly integrated into existing systems. A key limitation is the lack of models associated with appropriate devices that can adapt audio feedback to a user's position, task, and environment, especially in shared XR spaces. Core technologies (e.g., ambisonics, binaural rendering, spatial audio engines) exist at TRL 4-5, but their seamless integration into XR workflows, multi-user setups, and adaptive models is limited. Few tools currently bridge the gap between sound design principles and live XR interactivity. End-user adoption remains low to medium, primarily confined to high-end VR games and simulations, due to complexity and lack of awareness and tools.

Research and Innovation Objectives:

- Integrate interactive sound engines with XR platforms, leveraging head tracking, gesture recognition, scene analysis, and AI to dynamically adjust audio cues in real-time.
- Include auditory icons, voice spatialisation, acoustic AR, and multimodal synchronisation within immersive sound design.
- Develop methodologies encompassing acoustic scene modelling, psychoacoustics, user testing, and sound design prototyping, alongside adaptive feedback loops and cross-modal attention studies.

2a.18 Olfactory interfaces for scent-driven interaction

Developing compact, programmable olfactory systems and scent-based interaction models for XR applications is crucial for enhancing immersion through scent-driven interaction. Smell is profoundly linked to emotion, memory, and realism, yet it is largely absent from current digital experiences. In XR, olfactory cues can significantly deepen presence, aid learning, and enable multisensory storytelling. For specific applications like safety training, food sciences, or cultural heritage, olfaction can recreate essential contextual information, benefiting museums, educators, healthcare professionals, perfumers, and game developers alike.

Problem Definition and Research Gap: Current olfactory systems are generally bulky, offer a limited range of scents, suffer from slow diffusion, and exhibit poor synchronisation with visual and other sensory feedback. There is no standardised interface for olfactory output within XR. Integration with digital scenes and user interaction remains minimal, alongside a critical lack of user studies and frameworks for olfactory UX. These technologies are currently at a low TRL (2-4), with early prototypes existing but no widely usable or standardised platform. End-user adoption is extremely low, confined mostly to niche art installations or experimental labs, hindered by cost, hardware complexity, hygiene concerns, and challenges in content design.

Research and Innovation Objectives:

- Develop wearable or headset-mounted olfactory modules, alongside digital scent libraries and authoring tools, to enable precise triggering, synchronisation, and personalisation of scent delivery.
- Conduct extensive research into odour diffusion modelling, hardware miniaturisation, and user-centred olfactory UX design, coupled with psychophysical studies and cross modal perception research to understand and optimise scent-based interactions.

2b Real-time user interaction

To transform the foundational technologies of immersion, sensing, and visualisation into compelling User Experiences (UX), research must focus on intuitive, real-time user-interaction. This includes the development of real-time simulation technologies that can dynamically respond to user inputs and environmental changes. UX design is another critical area, requiring innovative approaches to create seamless and intuitive interactions within Virtual Worlds (VW). Bridging the gap between technology and UX involves addressing challenges in latency, responsiveness, and the naturalness of interactions. By overcoming these hurdles, we can ensure that users have a fluid and immersive experience in VW.

This chapter addresses the key technological challenges for the design of real-time user interactions. It is divided in two main parts, corresponding to the two main components of the 3D interaction loop: the VW on one side and the users on the other side. Both hardware and software components are needed to provide a seamless 3D interaction between users and extended environments. This chapter handles the key technologies that are needed within the next years for reaching fluid and immersive experiences.

Technologies addressed in this chapter are diverse, spanning from 3D interactions techniques and their associate algorithms to architecture and frameworks of immersive environments, gathering the inputs and outputs required for the user to interact with various types of VW. Within the context of a human-centric approach, UX is fundamental and key components of its design will also be addressed in this chapter.

One of the key challenges for the design of real-time user interaction is related to the interactivity of the technological solutions that must be built. Most of the time, it requires a challenging technological trade-off between realism of the interactions and computational performances. When entering the UX within the loop, several criteria could be introduced to evaluate it, such as presence, immersion or naturalness. These criteria can be assessed through dedicated tools and their associate challenges will also be addressed at the end of this chapter.

Research topics for Virtual Worlds creation and data integration

This paragraph explores the essential technology blocks required to create, manage, and utilize VW, focusing on their applications in various domains and the integration of real-time data. The paragraph is addressing challenges related to the design of interaction models and techniques at the interface between the user and the VW, the design of the VW themselves and finally the data management during interactions of the user with VW.

Design of interaction models and techniques

2b.1 Interaction techniques with whole human body information

The evolution from classic Human-Computer Interaction (HCI) to Human-Computer Context Interaction (HCCI) necessitates developing systems that respond not only to explicit commands from 3D interaction devices but also to implicit cues, such as gaze behaviour, emotional state, and environmental conditions. Current 3D interaction techniques are often task-specific, focusing on elements like object selection or navigation, and lack adaptation to the full spectrum of potential user inputs due to an absence of fusion algorithms for diverse physical and physiological measurements. This research is important as it addresses the need for more natural and intuitive engagement in XR environments.

Problem Definition / Research Gap: The diversity of information available from the whole human body calls for 3D interaction models and techniques that adapt in real-time to the user's context by combining multimodal inputs, such as voice, gestures, and eye-tracking, with contextual intelligence. Such techniques can significantly reduce cognitive load and foster intuitive engagement, particularly in XR environments. Furthermore, they could enhance UX by synchronising different sensory modalities into seamless multi-sensory feedback. This direction supports the EU's ambition for human-centric immersive technologies and opens opportunities for adaptive training, accessible navigation systems, and behaviour-driven interaction flows.

Research and Innovation Objectives:

- Design 3D interaction techniques that effectively utilise information from the whole body via multiple sensors.
- Develop user-adapted sensor fusion algorithms capable of integrating diverse physical and physiological measurements.
- Monitor physiological measures of users and synchronise them with sensor information to adapt 3D interaction models to each user, accounting for different sensory modalities.
- Design behaviour-driven interaction flows between users to enhance natural and intuitive engagement.

2b.2 Runtime interoperability across devices and platforms

Despite the establishment of open standards like OpenXR and WebXR, achieving seamless runtime interoperability across devices and platforms remains a significant challenge. The current state of standards and interoperability hinders citizens from meeting seamlessly across various XR devices, personal computers, or social media spaces. Addressing these issues is crucial to fostering a unified XR ecosystem that provides consistent experiences across devices and platforms, thereby promoting wider adoption.

Problem Definition / Research Gap: XR technologies offer the potential for embodied, intuitive interaction models, but realising this requires careful design of interface architectures. Hand gestures, spatial navigation, and voice commands need to align with natural motor and cognitive processes. Current research focuses on adaptive XR interfaces that reduce friction, guide user attention, and respect perceptual thresholds, such as motion sickness and fatigue. These insights are especially relevant for inclusive XR, where ease of entry and intuitive onboarding are critical for wide adoption. Evaluating interaction fluency across diverse user profiles is essential to support trusted, user-centric XR deployments. There is a lack of interoperability between XR technologies, for both hardware and software components, preventing combined use of interaction devices and frameworks.

Research and Innovation Objectives:

- Facilitate interconnections between various technical build blocks within the XR ecosystem.
- Bridge existing standards into a cohesive stack of interconnected interoperability provisions.
- Design seamless cross-platform solutions for user interactions, encompassing different connected devices, interfaces, and operating systems.

2b.3 Blending of physical and digital components

A fundamental cornerstone for creating truly immersive experiences is the design and development of augmented and mixed reality scenarios that seamlessly blend physical and digital worlds. Spatial computing enables this integration by providing technologies that allow digital systems to perceive, interpret, and interact with the user's spatial environment in real-time. Advanced spatial understanding contributes to more natural and intuitive interactions by contextualising user behaviour within their environment. This means digital content can respond intelligently not only to user inputs but also to the surrounding physical context, such as lighting conditions or proximity to physical objects. Furthermore, accurate object tracking in XR is crucial for realistic occlusion of digital objects, supporting dynamic movement of real-world objects like furniture or people, which maintains the realism of augmented scenarios.

Problem Definition / Research Gap: The rise of hybrid experiences necessitates new models of cross-reality interaction, enabling seamless engagement between users in physical and virtual spaces. This involves real-time coordination between XR users and physical audiences or operators, as seen in hybrid concerts, remote guidance scenarios, or dual-space exhibitions. Such interactions demand tight temporal coupling, responsive feedback loops, and alignment of spatial and social cues. Designing hybrid systems that feel cohesive and intuitive remains a complex challenge, despite the high potential for applications in events, education, and telepresence. It is acknowledged that this research topic benefits from collaboration with the ADRA partnership and that any double work is to be prevented.

Research and Innovation Objectives:

- Integrate capabilities into XR devices such as spatial mapping, object recognition, and object tracking.

- Build a dynamic model of the physical environment, enabling virtual content to be accurately anchored in the real world and manipulated with spatial coherence.
- Develop robust spatial anchoring techniques leveraging e.g. SLAM algorithms, capable of managing lighting variations, moving objects, occlusions and sensor drift or noise.
- Integrate interaction with physical objects through robust object recognition and tracking.
- Design fusion algorithms for integrating user inputs with their physical environment and generating multi-sensory feedback.

Design of interactive virtual worlds

2b.4 Modelling and animation of 3D complex virtual environments

Real-time user interaction necessitates the modelling and animation of various components within VW. While graphics technologies have advanced significantly in geometry processing, animation, simulation, and 3D rendering, achieving interactive framerates often requires trade-offs between realism and computational performance. Therefore, the design of complex and realistic dynamic virtual environments remains a key challenge, directly impacting user immersion. From a design perspective, users can co-design VW, manipulate simulations, or generate procedural content with the aid of generative AI models. These co-creative workflows demand interfaces that enable iterative refinement, explainability, and intuitive control, benefiting VR designers, academic researchers, and application developers.

Problem Definition / Research Gap: Computer graphics methodologies allow the creation of increasingly immersive virtual, augmented, and XR environments. Although several graphics engines have been developed to faithfully simulate physics, manage data formats, and enable novel visualisations like 3D holograms, immersive contexts still lack components with sufficiently complex geometries and behaviours, hindering natural and seamless interactions. Addressing this challenge is crucial for democratising immersive communication, enabling everyday users, educators, creators, and professionals to seamlessly and affordably enter VW. The technical barrier requires immediate research focused on creating solutions leveraging innovations in depth-sensing cameras, AI-based reconstruction algorithms, efficient compression techniques, 3D animation algorithms, physics-based simulations, photorealistic rendering and advanced real-time processing capabilities of consumer-grade hardware.

Research and Innovation Objectives:

- Build 3D geometry processing algorithms (capture and reconstruction, modelling) that exploit the power of graphics cards and engines.
- Manage 3D geometrical models for interactive manipulation within virtual environments.
- Animate VW that encompasses diverse physics-based behaviours through powerful, physics-law-based simulations.
- Explore AI-based models for generating 3D VW, supporting co-creative workflows.
- Visualise virtual environments for multiple users and multiple display devices, rendering photorealistic virtual scenes.

2b.5 Representation of the self: Avatars, sense of embodiment, social presence

VW are emerging as environments where new social fabrics are formed, allowing humans to manifest their personalities and make individual choices about how they present themselves via selected avatars, and to what extent these features represent their real identity. The construction of identities with specific

digital signatures, previews, and integrity can be anonymous or offer connections with the physical person. Potentially, each person can represent their choices or themselves with multiple avatars, leading to multiple identities and personalities. This is important for designers, engineers, neuroscientists, and psychology experts, as it addresses the need for self-expression and social interaction in digital spaces.

Problem Definition / Research Gap: A key aspect of user-centric XR design is the cultivation of social presence – the subjective experience of being with others in a shared virtual space. While advances in avatar realism, synchronised gestures, and spatial audio contribute to this sense of co-presence, current research needs to go beyond technical realism. Empathic interaction is increasingly relevant: immersive environments can evoke emotional resonance by simulating human affect, mirroring user behaviour, or fostering shared rituals and feedback. These features hold particular promise in domains such as remote therapy, collaborative learning, and social storytelling. Designing for social presence requires both technological innovation and a deep understanding of interpersonal dynamics in virtual contexts. There is a high demand for accurate avatar representation, yet limited knowledge on its impact on users.

Research and Innovation Objectives:

- Mirror user states and adapt avatar behaviour through the integration of real-time sensor inputs, such as facial expression capture, physiological monitoring, and gesture recognition.
- Develop cross-platform standards for avatar embodiment, ensuring consistent representation.
- Adapt virtual humans in real-time based on user signals to enable new directions for personalisation, accessibility, and emotional engagement.
- Study the impact of avatar representation on the physical real world, including how virtual socialisation transforms physical socialisation, changes in work, and the significance of virtual identities.
- Explore and enhance social presence within VW.
- Handle the management of new types of data and digital content, including avatar data, emotional data, social data, and spatial and spatio-temporal data.

Data integration

2b.6 Data management

Effective data management is a cornerstone of user-centric and interoperable virtual environments. Video-based point cloud compression (V-PCC) and Geometry-based point cloud compression (G-PCC) are pivotal formats for the efficient transmission of volumetric data. However, their widespread adoption faces challenges due to limited hardware acceleration support. G-PCC, with its continuous development and 3D compression approach, is even less supported by current hardware accelerators as it requires specialised processing not commonly found in existing GPUs. Furthermore, there is a lack of complete frameworks of tools for creating and manipulating point cloud data to support the full workflow from capturing to editing and compression using these standards. This hinders creators and developers from fully adopting the standards. Uncompressed point-clouds, even after reconstruction, can exceed 1 Gb/s; state-of-the-art codecs struggle with quality versus framerate and require new compression pipelines, as raw data at such speeds is currently impossible to send over today's broadband. Without efficient codecs and advanced compression pipelines, XR cannot run over today's broadband or mobile links, which is crucial for VR developers, application designers, and data scientists. Efficient data management encompasses the responsible handling of identity data, robust data governance frameworks, and mechanisms to ensure data portability, particularly the seamless transfer of digital assets like avatars across different virtual platforms. These issues are increasingly pressing as the EU

aims to shape an open and inclusive virtual ecosystem aligned with its core values, benefiting decision-makers, engineers, and application developers.

Problem Definition / Research Gap: One of the key challenges in designing real-time extended worlds is enabling collective experiences that span multiple physical locations. Emerging use cases, such as live concerts with interactive remote audiences or multiplayer XR simulations in connected venues, require ultra-low latency, synchronised data processing, and edge computing capabilities. These scenarios demand robust frameworks for co-presence, real-time responsiveness through data processing, and interaction smoothness across geographically distributed users. Successful implementation will expand what is possible in hybrid entertainment, education, and public participation experiences, supporting Europe's ambition for interconnected virtual ecosystems. Ensuring that the total head-motion-to-photon delay remains below 20 ms, ideally between 7-15 ms, is also crucial to avoid motion sickness and maintain immersion.

Research and Innovation Objectives:

- Efficiently combine different computation paradigms, including high-performance computing, distributed computing, edge computing, and cloud computing.
- Develop high-performance computing and high-speed networks to supply highly demanding functions in real-time, such as visual rendering, data synchronisation, and motion tracking and capturing.
- Minimise latency, data transfer, and processor load through the optimisation and parallelisation of computations over complex and distributed architectures.
- Develop future mobile communication technologies to facilitate ubiquitous services to users, enabling remote and real-time persistent connections between real and VW.
- Create legal and technical frameworks for the portability of avatars and digital assets across VW.

Research topics for User Experience design

This paragraph delves into the needs for creating and managing UX design. A first paragraph describes technological agnostic challenges and focuses on human perception whereas the two next paragraphs address research needs linked to metrics and methodologies for designing and evaluating UX.

Metrics for User Experience

2b.7 Measuring and optimising cognitive load during 3D interaction

Optimising cognitive load is a key factor in ensuring smooth and effective interaction within immersive environments. XR systems must carefully balance the amount and complexity of sensory, informational, and decision-related input presented to users. This is important for VR designers, engineers, and developers of training and learning applications, as it directly impacts user engagement and performance.

Problem Definition / Research Gap: Excessive visual clutter, non-intuitive navigation, or unclear task structures can quickly lead to cognitive overload, reducing engagement and impairing performance. Motion sickness and disengagement from virtual tasks are critical behaviours that prevent the widespread use of virtual applications for a general audience. Adapting XR technologies to each user by personalising inputs and outputs between the user and the VW is fundamental for achieving general adoption of XR applications. This constitutes a significant research gap in ensuring accessible and comfortable immersive experiences.

Research and Innovation Objectives:

- Leverage neuroscientific insights into attention, working memory, and information processing.
- Gain a deeper understanding of the neuroscientific impact of 3D interaction within VW and the various criteria involved in cognitive load.
- Develop adaptive systems that respond to users' mental workload in real-time. Techniques could include progressive information disclosure, contextual highlighting, and multimodal redundancy, for example, combining visual cues with spatial audio.
- Personalise interaction complexity to the user's current state through dynamic adaptation based on biometric signals, such as pupil dilation or gaze fixation, to increase both usability and inclusivity.

2b.8 Longitudinal effects of immersive environments on user well-being

While immersive environments offer compelling short-term engagement, their longitudinal effects on user well-being are still insufficiently understood. Extended XR usage may induce digital fatigue, disrupt spatial orientation, or alter social behaviour. To ensure healthy adoption, XR systems should incorporate features like break reminders, adaptive pacing, and cognitive load monitoring. This research is vital for VR designers, engineers, developers of training and learning applications, and EU regulators to ensure responsible development and deployment of immersive technologies.

Problem Definition / Research Gap: Current studies are beginning to examine the cognitive toll of prolonged immersion, as well as patterns of escapism or dissociation that may emerge from extended engagement with virtual environments. However, a comprehensive understanding of these long-term impacts, particularly on user well-being, remains a significant research gap. Without this understanding, it is challenging to develop guidelines and features that promote healthy and sustainable interaction with immersive technologies.

Research and Innovation Objectives:

- Design longitudinal studies to assess how immersive technologies reshape attention, presence, and social norms over time.
- Design ethical frameworks to regulate the use of immersive environments, ensuring user well-being in the long term.

Methodologies for user studies

2b.9 Frameworks and tools

The evolution of immersive virtual environments necessitates robust methodologies to assess and enhance user interaction, focusing on Quality of Experience (QoE), acceptability, and trustworthiness. QoE encompasses users' holistic perceptions of system performance, integrating technical metrics with subjective experiences. Acceptability pertains to users' willingness to engage with and adopt new technologies, influenced by factors such as usability, perceived value, and cultural relevance. Trustworthiness involves users' confidence in the system's reliability, data security, and ethical standards. This is vital for VR designers, developers, and standard writers to ensure effective and trusted immersive solutions.

Problem Definition / Research Gap: Current methodologies often lack the capacity to capture the complexity of UXs in real-world settings. Living Labs offer a solution by providing user-centric, co-creative environments where innovations are tested and refined in real-life contexts. These settings facilitate iterative feedback loops between developers and users, enhancing the relevance and efficacy of technological solutions. To systematically evaluate QoE, frameworks have been proposed that

integrate objective performance indicators with subjective user feedback, enabling a comprehensive understanding of user satisfaction. Assessing acceptability requires methodologies that consider ethicality, intervention coherence, and opportunity costs, among other factors. Trustworthiness assessments benefit from tools that evaluate transparency, accountability, and data protection measures, ensuring alignment with users' expectations and regulatory standards.

Research and Innovation Objectives:

- Develop integrated frameworks that combine technical performance metrics with user-centric evaluations to comprehensively assess Quality of Experience.
- Create standardised tools and protocols for measuring acceptability across diverse user groups and cultural contexts.
- Implement Living Lab initiatives to facilitate real-world testing and iterative development of immersive technologies.
- Establish benchmarking systems to compare and improve user study methodologies across different applications and sectors.

2b.10 Tools for analysing the User Experience

The advancement of immersive virtual environments necessitates sophisticated analytical tools to assess user interactions, physiological responses, and behavioural patterns. These tools encompass data analytics, physiological monitoring, human behaviour analysis, and both laboratory-based and real-life testing methodologies. This is important for VR designers, developers, and standard writers to gain deep insights into how users interact with and are affected by immersive experiences.

Problem Definition / Research Gap: Data analytics in VW involves the collection and interpretation of vast datasets generated by user interactions within immersive environments. This includes tracking movement patterns, decision-making processes, and engagement levels, providing insights into user behaviour and system performance. Such analytics are crucial for optimising UX and ensuring the effectiveness of virtual applications.

Physiological data monitoring, through wearable sensors and biometric devices, enables the assessment of users' physical responses to virtual stimuli. Metrics such as heart rate, galvanic skin response, and eye movement offer valuable information on user engagement, stress levels, and overall well-being during virtual interactions. This data is instrumental in tailoring virtual experiences to individual needs and ensuring user safety.

Human behaviour analysis within virtual environments allows for the study of social interactions, decision-making, and behavioural responses in controlled yet realistic settings. This facilitates research in psychology, sociology, and human-computer interaction, contributing to the development of more intuitive and user-friendly virtual systems.

Laboratory-based testing using CAVE (Computer Animated Virtual Environment) infrastructure provides immersive, high-resolution simulations for evaluating user interactions and system functionalities. These controlled environments are essential for iterative design processes, usability testing, and the refinement of virtual applications.

Real-life testing and validation involve deploying virtual applications in actual operational settings to assess performance, user acceptance, and practical utility. Such field evaluations are critical for identifying potential issues, ensuring reliability, and facilitating the integration of virtual technologies into everyday contexts. Benchmarking and evaluation tools are essential to ensure the effectiveness and

reliability of immersive technologies, with emphasis on robust testing and experimentation facilities to support innovation and ensure the development of trustworthy digital environments.

Research and Innovation Objectives:

- Develop advanced data analytics platforms specifically tailored for immersive virtual environments.
- Integrate physiological monitoring systems into virtual applications for real-time user assessment.
- Establish standardised protocols for human behaviour analysis within virtual settings.
- Enhance CAVE infrastructure across research institutions for comprehensive laboratory-based testing.
- Implement large-scale real-life testing and validation programs to facilitate the adoption of virtual technologies in various sectors.
- Develop benchmarking and evaluation tools to assess the performance and reliability of immersive technologies.

2b.11 Handling Inclusivity, Diversity, Use Skills

Immersive technologies such as VR, AR, XR, MR offer transformative potential across various sectors. However, to fully realise this potential, it is imperative to address inclusivity and diversity in both the design and utilisation of these technologies. This entails ensuring that immersive experiences are accessible to all individuals, regardless of their abilities, backgrounds, or socio-economic status. This is crucial for designers, engineers, application developers, and EU regulators to ensure broad and equitable access to immersive technologies.

Problem Definition / Research Gap: Recent studies have highlighted significant accessibility barriers in AR/VR technologies, particularly for individuals with disabilities. These barriers include challenges related to physical, cognitive, visual, and auditory impairments, which can hinder full engagement with immersive environments. To overcome these challenges, a user-centred design approach is essential, involving diverse user groups in the development process to ensure that technologies meet a wide range of needs.

Moreover, the adoption of immersive technologies necessitates specific user skills, including digital literacy, spatial awareness, and the ability to navigate complex virtual environments. Research indicates a need for comprehensive training programs to equip users with these skills, thereby promoting equitable access and participation.

Research and Innovation Objectives:

- Develop inclusive design frameworks that prioritise accessibility and user diversity in immersive technology development.
- Implement participatory design methodologies that involve users from diverse backgrounds, including those with disabilities, in the creation of immersive experiences.
- Create standardised training programs to enhance user skills necessary for effective interaction with VR/AR/XR technologies.
- Establish evaluation metrics to assess inclusivity and accessibility in immersive environments, ensuring continuous improvement and accountability.

2b.12 Understanding of Human Perception

A deep understanding of human perception is essential for developing intuitive and natural interactions in immersive environments. Neuroscientific insights into visual attention, multisensory integration, and cognitive load can inform how virtual environments should be designed to align with users' perceptual expectations and limitations. For instance, findings on motion sensitivity and spatial disorientation can help reduce VR-induced fatigue or cybersickness. Research into neuroplasticity and sensory substitution also opens pathways for making immersive systems more inclusive, enabling interaction for individuals with sensory impairments. This knowledge is crucial for VR designers, psychologists, and neuroscientists.

Problem Definition / Research Gap: While devices providing access to VW appear to have a catalytic role in human experiences and interactions, the human brain can easily adapt to current interfaces. Most people can achieve full immersion in a simulated 3D environment, even without specialized equipment, simply through screen-based graphic design. This human ability, however, is still not fully understood. Many factors contribute to the sensation of presence in VW, linked to internal brain processing by our different sensory modalities. This represents a significant research gap in understanding the complex interplay between human cognition and immersive technology.

Research and Innovation Objectives:

- Improve understanding of human perception within VW through neuroscience knowledge and user studies.
- Gain a better understanding of the balance between the sensory modalities.
- Enhance understanding of affective computing, which enables immersive systems to detect and respond to users' emotional states via modalities such as facial expression analysis, voice tone, and physiological data.
- Integrate emotion-aware mechanisms into XR to enhance engagement, support mental health interventions, and personalise training scenarios.
- Explore the role of neural synchrony, the alignment of brain activity between people, in enhancing group coordination and mutual understanding within virtual environments.

2c Authoring and experience design

Authoring and designing Virtual Worlds (VW) experiences are crucial for XR technology and market development. This involves creating and structuring interactive experiences that blend virtual and real worlds. Authors, e.g. independent creators, artists, developers, studios, and companies are vital; without them, there's no innovation, content, or sustainable infrastructure. Authoring acts as a strategic lever, intersecting technological challenges, creative uses, Web4 industrial structuring, and digital economy sustainability, forming a foundational element for all use-cases from Industry to Healthcare.

However, two major barriers impede this: First, authoring VW experiences is highly complex and multidisciplinary, requiring mastery of multiple technologies, making it inaccessible to many. This hinders the democratisation of content creation, which is a significant driver of societal and economic development. Second, Europe's content production relies heavily on non-European authoring tools and content distribution infrastructures. This dependence imposes external standards and commercial constraints on Europe's industry and autonomy.

In the rapidly growing VW market, authoring and design are often overlooked, despite being critical for valuing digital experiences. While XR job growth is projected, authors are often marginalized in terms of

value and resource access. The sector's complexity, fragmentation, and lack of standards hinder professionalisation, though European platforms show promise for collaborative design.

The dominance of non-European platforms creates unprecedented dependency, concentrating authoring tools and distribution. This limits creative diversity and traps communities in closed ecosystems, posing strategic, economic, and cultural risks.

Ultimately, experience design is key for widespread immersive technology adoption. The quality of interaction, relevance of narratives, and perceived usefulness depend on creative excellence and technological performance. Large-scale adoption demands engaging, accessible, and value-generating experiences, which require robust technologies and collaborative co-design platforms.

Authoring must be recognised as a prerequisite for technology adoption and market development, not a secondary output, especially given Europe's opportunity in content-based services. Fostering innovative authoring conditions and tools is key to building a sovereign, sustainable European VW ecosystem.

Foundations for authoring and experience design

Dependence on closed non-EU ecosystems: EU autonomy at risk

Immersive authoring largely depends on non-European tech providers who monopolize tools and distribution, imposing proprietary standards. This systemic dependency undermines Europe's ability to define its own standards, strategic autonomy and to spread its cultural values. Lack of major European players hinders independent technical communities and viable sovereign ecosystems.

Industry and creators are forced to master foreign technologies, making Europe a follower susceptible to non-EU commercial restrictions (e.g., U.S. laws). Talent relocation is often prioritized, limiting transnational openness. Training in closed systems homogenizes practices, reducing diversity. Lack of interoperability impedes content circulation and innovation. This dependency also offshores talent and IP.

Strategic actions:

- Support European leaders in XR authoring tools, content, and distribution to guarantee EU autonomy. Foster strong technical communities to achieve this.
- Develop a strategy to reach critical mass in resources for solutions and creators to drive adoption, ensuring ecosystem growth and independence.

Rebalance market's power dynamics

The immersive market sees power concentrated among a few non-European tech giants, limiting diversity and innovation. The sector is largely techno-centric, prioritizing features over impactful content. This impedes adoption and strains authors with fragmented, complex tools. Studies on authoring methodologies and authoring working conditions are lacking. This concentration fosters predatory practices and precarious conditions for creators.

Tech actors control authoring solutions and communities, making authors dependent on proprietary technologies. These communities operate in closed ecosystems where training and resources are controlled by dominant players. Lack of independent, technology-agnostic communities obstructs a healthy, dynamic market.

Strategic actions:

- Conduct global studies on VW creators' labour conditions to inform policies promoting equitable, sustainable creative ecosystems.

- Conduct strategic research to dynamically map platform ecosystems, their territoriality, and automate key actor monitoring.
- Investigate, support, and design independent, technology-agnostic collectives and communities to foster open, diverse digital ecosystems and reduce proprietary platform dependency, promoting for instance standardisation, openness, and interoperability.

Empower creation capabilities

The immersive experience sector's vitality relies on experimentation, prototyping, and rapid iteration based on user feedback in variable conditions. Three obstacles hinder this: First, insufficient support for experiential research limits exploration and prototyping, hindering innovative formats and risk-taking. Second, the lack of fast, shared analytical tools impedes iterative improvement based on user feedback. This limit understanding of user impacts and expectations, making it harder to guide creators toward successful productions. Third, content creation tools have yet to evolve to fully support the design of complex and collaborative experiences. Significant room remains for innovation to enhance their capabilities, expand creative practices, and enable a wider range of use cases and contributors.

Strategic actions:

- Strengthen R&D capacities in immersive creation for non-commercial projects and increase direct funding for creators.
- Support research programs on new forms of XR content at the intersection of academic, cultural, and industrial sectors, promoting iterative design through experimentation and prototyping.
- Support research on tools that empower content creation tools.
- Investigate the design and development of standardized assessment tools for early integration of user feedback.

Structuring of skills and professions in a multidisciplinary sector

A key challenge for VW design is its extreme multidisciplinary characteristic, driven by the immersive nature of VW. The shift from 2D to 3D/4D transforms design and UX profoundly. Spatial interface design requires diverse skills: 3D modelling, real-time programming (Unity, Unreal), immersive interaction design (spatial UX/UI), interactive storytelling, cognitive psychology, and sensor engineering. A multidisciplinary approach ensures coherent, high-performing, and engaging experiences. This is crucial as sectors adopt immersive technologies, which demand specific skills. This leads to new, transdisciplinary design modes requiring close collaboration.

Lack of structured learning and educational pathways is a major obstacle. Immersive technology training is fragmented, often limited to technical modules. The emerging immersive environment demands new professional roles. This gap contrasts with the sector's need for hybrid profiles. Recruiting high-level curriculum experts is costly, leading to missed opportunities and undermining training quality.

To offer interdisciplinary, project-based training aligned with economic needs, stronger bridges are needed with each sector (health, education, retail). This enables knowledge exchange between sector practices and creators. Mutual understanding and collaboration are essential for authors to gain real-world insights and for sectors to recognize immersive content's creative potential.

Strategic actions:

- Investigate multidisciplinary curricula aligned with industry needs, in collaboration between academic institutions and industry.

- Support capacity building and education to enable universities and training centres to attract top-tier immersive technology experts.
- Foster scalable, accessible, and practice-oriented training models across Europe that respond to rapid evolution of immersive tools and workflows, addressing cost and accessibility barriers.

Research topics for authoring and distribution

2c.1 Development of European authoring and distribution tools

Authoring and distribution platforms are strategically vital in the immersive technology value chain. Developing European solutions and preventing interdependence between authoring and distribution tools is crucial to address the current concentration of solutions in few hands and the dominance of non-European players. This approach is key to achieving industry standards, interoperability, and reclaiming strategic autonomy for Europe.

Problem Definition and Research Gap: The current ecosystem suffers from an unprecedented concentration of creation tools, standards, and distribution channels in the hands of a few dominant non-European players. Authoring platforms, though adapting to VW, are largely established 3D engines not specifically designed for XR, affecting content creators' competitiveness. Similarly, distribution platforms are often evolutions of broader platforms. This structural imbalance binds VW actors to technology providers' restrictive practices, limiting content circulation, diversity, and innovation. There is a strong need for European alternatives that foster open, interoperable solutions, unlike the current closed ecosystems.

Research and Innovation Objectives:

- Investigate tools, approaches, and methodologies to reduce structural interdependence between authoring and distribution, fostering a more modular and competitive immersive industry.
- Support the unification of EU technological bricks towards, open-source authoring and/or distribution solutions as collaborative ecosystems promoting transparency, modularity, and long-term accessibility.
- The ambition is to develop European XR-dedicated authoring and distribution solutions, reduce dependence on non-European ecosystems, enhance market diversity, empower creators, and achieve industry standards and interoperability.

2c.2 Tools and metrics for experience and impact evaluation

Establishing clear, unified metrics, KPIs, and KVIs for evaluating VW experiences is crucial. This helps quantify benefits, limitations, and ROI, addressing the current difficulty in predicting the concrete impacts of VW content. Providing tools to certify experience quality (utility, usability, ergonomics, efficiency, accessibility) is essential for accelerating VW adoption by making impacts predictable and measurable.

Problem Definition and Research Gap: Evaluating the impacts of VW is complex due to a lack of unified metrics, KPIs, and KVIs to quantify benefits, limitations, and ROI precisely. There are no tools to certify that a VW was experienced as designed, and no recognised frameworks to evaluate XR experience quality across various metrics like utility, usability, ergonomics, efficiency, and accessibility. The strong dependence on major technology providers means authoring solutions rely on their often-confidential data regarding experience and economic success. These gaps directly impede VW adoption as it's difficult to predict concrete, on-the-field impacts over short to long terms.

Research and Innovation Objectives:

- Explore subjective and objective metrics and techniques to quantify XR experience quality. Investigate how to make such tools accessible to VW creators to facilitate iterative design.
- Perform short, mid, and long-term studies to validate metrics and better understand concrete impacts of deployed VW on end-user practices.
- Explore how collaborative authoring and/or experiencing environments and integrated platforms can support early-stage evaluation, enabling user feedback and impact assessment directly within design workflows.

Research topics for authoring tools and workflows

2c.3 Versioning and development

Improving the collaborative design process for VW experiences by effectively managing multiple past and concurrent versions. This addresses the limitations of current 3D frameworks that offer poor support for collaborative design, hindering multidisciplinary teams. Facilitating robust versioning, replaying modifications, and re-using components would significantly enhance maintainability, evolution, and efficiency of VW experiences.

Problem Definition and Research Gap: A significant challenge for collaborative design of VW experiences is managing multiple past and concurrent versions. Current major 3D frameworks like Unity offer poor or no direct support for collaborative 3D scene design. Challenges include tracking, documenting, debugging and replaying modifications, easily switching design alternatives, and merging versions with precise control. Git-based versioning is adopted but offers limited support for the multidisciplinary, non-developer profiles needed for VW authoring. Facilitating the re-use of previously designed components remains cumbersome. The diversity of XR hardware and software ecosystems directly impacts version management, as developing and testing experiences on heterogeneous setups (varying immersion, interaction capabilities) is complex and time-consuming. This is amplified by low robustness to OS, hardware, and 3D engine evolutions.

Research and Innovation Objectives:

- Investigate and design expressive, easy-to-use versioning tools for collaborative XR 3D scene editing. Further research is needed for XR scenes to converge towards robust versioning standards and integrated tools.
- Explore tools and methods to perform authoring while experiencing VW on target devices and setups, from mobile (smartphones, tablets, headsets) to immersive spaces.

2c.4 Integrating Artificial Intelligence into design workflows

Leveraging AI to significantly enhance and simplify the authoring of XR experiences. AI promises to support human-AI collaborative 3D scene editing, automate operations, and guide creators. This integration aims to streamline complex workflows, improve content quality, and ultimately make authoring solutions more accessible and powerful for a wider range of creators.

Problem Definition and Research Gap: AI offers great promise for supporting XR authoring but raises challenges concerning content generation and integration into existing solutions. Firstly, there's a lack of professional tools for guiding or specializing generative models, making it difficult to ensure the quality, coherence, and performance of AI-generated content (e.g., UIs, 3D models, code) and to validate assets against XR-specific constraints. Secondly, integrating AI and automatically generated assets into demanding XR pipelines is challenging. Current authoring solutions are already complex and target

specialized developers; adding AI must simplify usage, not add complexity. Clear workflows and user interfaces are needed for seamless human-AI collaboration, allowing creators to steer and personalize AI outputs. Furthermore, rapidly evolving LLM capabilities complicate versioning, and AI model integration must comply with evolving ethical standards, privacy regulations (e.g., GDPR, AI Act), and transparency requirements, including equitable wealth distribution from AI-generated content.

Research and Innovation Objectives:

- Investigate tools and methods to inspect the quality, coherence, and performance of AI-generated content for XR scenes.
- Explore human-AI collaboration approaches and techniques to support co-editing of VW content.
- Facilitate the integration of AI agents and customizable models into authoring solution pipelines.
- Develop standardized evaluation frameworks and best practices for AI-generated assets in XR, covering metrics like rendering efficiency, usability, and inclusivity.
- Design systems for transparent versioning and traceability of AI contributions within collaborative workflows.

2c.5 Accessibility of solutions, no-code approaches and creator empowerment

Empowering a wider range of VW creators, especially non-experts, to contribute effectively to design and development, including for demanding XR experiences in uncontrolled environments. This addresses the high technical complexity and steep learning curves of current authoring solutions. Low-code to no-code approaches aim to democratise VW creation, essential given the diverse digital expertise levels.

Problem Definition and Research Gap: Current authoring solutions are too technically complex and have steep learning curves, preventing non-expert users from efficiently contributing. While approaches like authoring by demonstration, bodystorming with tangibles, and gesture-based 3D terrain editing exist, there are no unified solutions that cover all aspects of 3D virtual scene editing in an expressive yet accessible manner. Existing interaction techniques and tools are often limited to specific tasks and simple operations.

Research and Innovation Objectives:

- Expand existing accessible authoring tools and methods by investigating innovative low-to-no-code approaches for designing VW experiences, including authoring by demonstration and tangibles.
- Investigate AI's potential to simplify workflows, automate operations, and provide guidance to creators, also in complex environments.

2c.6 Real-time collaboration on multiple supports

Facilitating efficient real-time collaboration among diverse users (developers, artists, designers) for designing VW. This addresses the multidisciplinary nature of XR authoring, which demands flexible collaboration across various locations, times, and user groups. Real-time features would significantly shorten lengthy design processes, allowing for easier input, iteration, and faster convergence on refined designs.

Problem Definition and Research Gap: The multidisciplinary nature of XR authoring requires real-time collaboration tools that support diverse situations (co-located, hybrid, remote; asynchronous to synchronous; varying participant numbers, roles, and expertise). Current tools lack features for

effectively tracking interactions, supporting group-awareness, providing fine control over private/public spaces, and facilitating 3D scene versioning. VW experiences also impose unique collaboration constraints due to the wide range of XR displays and devices. Creators use and test experiences on heterogeneous setups (tablets, smartphones, XR headsets, CAVE systems), whose differing capabilities (immersion, bulkiness, interaction modalities) create a significant barrier to fluid cross-device collaboration. While some platforms explore device-agnostic, multi-user environments, achieving truly fluid, cross-device collaboration requires deeper technical interoperability and thoughtful design of collaborative workflows, user interfaces, and interaction metaphors.

Research and Innovation Objectives:

- Investigate tools and methods for real-time collaboration in VW scene design. These should support diverse situations (locations, times, user groups), improve group-awareness, and manage private vs. public versions, leveraging social/cultural differences.
- Explore innovative mechanisms to improve cross-device creator collaboration, including tailoring VW experiences to heterogeneous XR devices for both off-site and in-situ workflows. Cloud-based computing may be a promising direction.
- Focus on solutions that integrate seamlessly into existing design and collaboration environments, enabling iterative, inclusive workflows for teams of varying expertise.

2c.7 Interoperability of experiences and authoring solutions

Enabling seamless interaction and data exchange between different VW experiences and authoring tools. This is crucial for overcoming the current fragmentation of the immersive ecosystem, which leads to lost efficiency, complicates creators' work, and hinders talent mobility. Achieving interoperability is a prerequisite for developing a coherent, sustainable, and collaborative ecosystem, especially for integrating diverse multisource content.

Problem Definition and Research Gap: The current XR authoring landscape is highly fragmented, with multiple creation environments, diverse programming languages, and incompatible proprietary formats (e.g. for 3D, IoT, BIM data). This results in lost collective efficiency, complicated workflows, and limited talent mobility. The low adoption of universal standards like OpenXR and glTF severely restricts interoperability between platforms and tools, hindering collaboration and multisource content integration. The growing diversity of multisource content (e.g., external information systems, real-time streams) to be integrated into experiences, coupled with co-creation by actors with varied expertise and device usage, further complicates interaction and demands unifying authoring approaches. Major technology players often impede interoperability to maintain control over content distribution and quality within their proprietary platforms. Furthermore, the absence of an independent authority to oversee interoperability standards increases the risk of lasting fragmentation.

Research and Innovation Objectives:

- Continue to apply and refine European standardisation strategies for XR to ensure adoption of open formats, guiding future norms towards sustainability, accessibility, and digital autonomy (e.g., Gaia-X project).
- Investigate and design a governance framework for an independent oversight authority responsible for ensuring adherence to interoperability standards by technology stakeholders.

2c.8 Scalability and performance

Ensuring that complex, collaborative, and interactive XR scenes can be rendered efficiently in real-time, regardless of device limitations or user scale. This addresses the challenge of resource-intensive

computations required for high-quality VW, especially on user-worn XR devices with limited capabilities and for multi-user, worldwide VW applications. Optimised performance leads to better UX and enables larger-scale deployments.

Problem Definition and Research Gap: Rendering complex, collaborative, and interactive XR scenes in real-time requires heavy computation, yet many user-worn XR devices have limited technical capabilities. While tethered setups exist, many VW experiences need non-tethered devices for user mobility. Additionally, many XR experiences are multi-user oriented, with VW applications aiming for worldwide scale, involving significant data (heavy 3D models, point clouds, real-time environmental monitoring). These scalability and performance issues necessitate cloud-native and distributed-rendering solutions with appropriate network infrastructures. However, there are few commercially available solutions, and the absence of open-source EU-based authoring or distribution solutions raises concerns about EU autonomy for creating and diffusing large VW experiences. Finally, there's a gap in training professionals on these scalability, performance, and optimisation topics; technology education needs to emphasize computing-cost-saving practices.

Research and Innovation Objectives:

- Design open, cloud-native, and distributed rendering approaches for XR experiences. These should allow high-quality, real-time rendering for multi-user XR scenes across diverse devices and interactions.
- Investigate methods and tools to better ensure the training of VW creators (including non-developers) on performance, scalability, adaptability to various technical constraints and optimisation aspects of XR experiences.

2c.9 Adaptation to end user contexts

Ensuring VW experiences are accessible and inclusive by dynamically adapting to diverse user profiles, environmental conditions, and hardware. This allows creators to tailor experiences for specific populations (e.g., impairments, varying digital skills) and environments, overcoming the current challenges of high project costs and reliance on scarce expert knowledge. Providing adaptable solutions improves UX and broadens XR adoption.

Problem Definition and Research Gap: Adapting VW experiences to target audiences involves tailoring many parameters related to user profiles (e.g., impairment, physical, mental, and digital skills), environmental conditions, and available hardware possibilities and limitations. While crucial for accessibility and inclusivity, these adaptations remain a challenge for professionals due to project costs and the need for specialized knowledge. Providing relevant adaptations often requires expert knowledge that is difficult for developers to acquire and is not adequately reflected in standard usability practices. Therefore, a significant research challenge lies in developing guidelines and solutions to facilitate and/or automate dynamic adaptations of VW interfaces, content, interaction, and modalities.

Research and Innovation Objectives:

- Investigate new guidelines, tools, and methods to dynamically adapt VW experiences, allowing creators to easily perform context-aware adaptations and design accessible applications.
- Explore innovative ways to detect user and environmental conditions while preserving end-users' privacy and confidentiality, respecting EU laws.

2d Standardisation and interoperability

The European Commission's vision for Virtual Worlds (VW) and Web 4.0 underscores a critical need for open standards and global governance. This strategic approach aims to steer the next technological transition towards an open, secure, trustworthy, fair, and inclusive digital environment for all EU citizens, businesses, and public administrations, preventing market dominance by single entities and fostering a more equitable landscape.

Foundations for interoperability

European vision and strategic imperatives

The European Commission's strategy for Web 4.0 and VW is rooted in the ambition to shape a digital future defined by openness and global governance. This involves actively supporting open standards to ensure fair and equitable governance, preventing large organisations from monopolising the burgeoning digital sphere. Fundamentally, this strategy is designed to create a digital environment that is open, secure, trustworthy, fair, and inclusive, benefiting EU citizens, businesses, and public administrations alike.

These strategic objectives directly align with the overarching goals for Europe's digital future. Firstly, ensuring fair and equal governance through open standards and interoperability is paramount to preventing market dominance, fostering a level playing field, and lowering entry barriers for small and medium-sized enterprises (SMEs) and innovators. Secondly, interoperability is a foundational prerequisite for cultivating a digital environment that citizens can trust, ensuring security and privacy by design, promoting fairness in data access and economic participation, and guaranteeing universal inclusivity and accessibility. Finally, by developing robust European standards and interoperable frameworks, the EU aims to enhance its digital autonomy, reducing dependency on non-EU platforms and technologies, thereby empowering European actors and upholding European values.

Foundational challenges for a cohesive ecosystem

Addressing the infrastructural challenges inherent in VW is crucial for fostering a cohesive and interconnected ecosystem. Current research gaps include the urgent need for common data formats and protocols that enable seamless information exchange across diverse systems and platforms. Specifically, Digital Twin (DT) exchange mechanisms must be standardised to ensure broad compatibility and effective integration across various applications. Furthermore, the development of robust API integration is essential to facilitate communication and interaction among diverse systems within these complex virtual environments. Overcoming these fundamental challenges is key to ensuring that different technologies and platforms can collaborate harmoniously, driving the overall progress and accessibility of VW. This document, therefore, establishes a Strategic Research and Innovation Agenda (SRIA) for building interoperable systems within the context of the VW Programme, diligently following the best practices outlined in the European Interoperability Framework (EIF). Standards are recognised as a primary means for achieving interoperable systems, and this agenda elaborates on the characteristics that define a good standard.

Guiding principles for European interoperability

The European Interoperability Framework (EIF), published in 2018, articulates interoperability as the capacity of organisations to interact towards mutually beneficial goals. This interaction involves sharing information and knowledge through their supporting business processes, facilitated by the exchange of data between their Information and Communication Technology (ICT) systems. A significant impediment to progress in the digital single market is precisely this lack of interoperability. By leveraging the EIF to guide European interoperability initiatives, the aim is to foster a coherent European interoperable environment, thereby facilitating the seamless delivery of services that operate effectively, both within

and across organisations or domains. The EIF provides a commonly agreed approach to delivering European public services in an interoperable manner, defining essential interoperability guidelines through common principles, models, and recommendations.

The EIF also introduces the concept that interoperability is inherently layered and interdisciplinary. In 2018, it formalised this by identifying four distinct layers: the legal, organisational, semantic, and technical layers, all of which require integrated governance. Furthermore, the concept of common European dataspaces, exemplified by reference architectures such as the IDS Reference Architecture Model (IDS-RAM), outlines key roles and components for data ecosystems, including data providers, consumers, and brokers. It defines interactions within a sovereign data-sharing ecosystem, strongly aligning its interoperability mechanisms across the semantic, technical, organisational, and legal layers with the principles of the EIF. It is also important to acknowledge the inherent tension between achieving deep semantic richness for specific product functionalities and ensuring broader interoperability through the reuse of existing standard domain models; the value-adding use case must be clearly defined to navigate this balance effectively.

Foundations for interoperable standards

Standards to interoperability

Standards serve as a primary method for achieving interoperable systems, with their development typically reliant on consensus among stakeholders. While standards offer the advantage of broad compatibility, there is an inherent tension between striving for the richest possible semantics for a highly specific product and reusing existing standard domain models for the sake of wider interoperability. Products are often designed with maximum specificity, yet successful interoperability often necessitates a clear definition of the value-adding use case to balance specific semantic richness with broader applicability.

Categorisation of standards

Standards can be broadly categorised into several high-level types. Domain vocabulary terms constitute reusable terminology crucial for semantic interoperability, ensuring that organisations interpret concepts uniformly. Examples of these include the use of UML models, OWL, RDFS, and SKOS. Application profiles (schema), on the other hand, explain how specific functionality is coded against particular properties. They enable data providers to understand precisely what data is required for a certain client to operate effectively. These profiles are consumer-oriented and promote the feature-based reuse of API patterns, with examples such as ActivityPub and Linked Data Event Streams. Finally, an Implementation Model is a document designed to assist consumers in picking components in an orthogonal, complementary manner.

Evolvability and transferability: Cornerstones of resilience

The principles of evolvability and transferability are critical mechanisms for counteracting the fragmentation caused by a multitude of isolated standards, actively driving their convergence to achieve truly comprehensive and lasting interoperability.

Evolvability refers to a standard's capacity to adapt and change over time in response to new technological advancements, evolving user requirements, and emerging use cases, without necessitating complete overhauls or causing widespread breakage. This involves utilising mechanisms for versioning, extension, and modularity, which allow components to evolve independently and thereby ensure the long-term viability and continued relevance of interoperability frameworks.

Transferability, conversely, addresses the ability to apply or adapt standards, knowledge, components, and best practices from one domain, context, or system to another. This includes the complex process of

merging standards from different domains into a cohesive meta-standard. Both evolvability and transferability are indispensable for building a resilient and dynamic VW ecosystem capable of effective growth and integrating diverse contributions efficiently.

Sustainability: Enduring and inclusive interoperability

Sustainability is essential to ensuring that interoperable systems remain viable over time—technically, economically, socially, and environmentally. Standardisation promotes sustainability by reducing duplication, promoting reuse, and enabling more energy-efficient architectures. Efficient-by-design systems minimise waste—not only in computation but also in infrastructure and development cycles—supporting lower carbon footprints and longer-lasting technologies. Economically, sustainable interoperability reduces barriers to entry and long-term maintenance costs. It enables smaller actors and under-resourced regions to participate without relying on expensive, proprietary platforms. However, this requires the emergence of new business models that prioritise shared value, service-based innovation, and long-term collaboration over short-term control or exclusivity. Community-led ecosystems like Linux or Blender demonstrate how open participation, distributed governance, and modular standards can support economic resilience and technological longevity. Their models show how sustainability thrives when economic incentives align with openness, adaptability, and shared stewardship. Therefore, sustainable interoperability must support building ecosystems that are efficient, equitable, and capable of evolving without extracting disproportionate social, environmental, or economic cost.

Research topics for standardisation and interoperability

Core standardisation and semantic foundations

2d.1 Evolvability and cross-domain transferability

This research topic addresses the critical need for standards to adapt gracefully to continuous technological advancements and emerging use cases without causing systemic breakage. It also focuses on enabling the transfer of successful standard features and knowledge across different domains. This is vital for counteracting fragmentation in the VW ecosystem, fostering convergence among disparate systems, and ultimately building resilient, future-proof interoperability that can sustain long-term relevance.

Problem Definition / Research Gaps: There is a notable absence of formal "meta-standards" or established methodologies for designing standards that can evolve gracefully, supporting robust versioning, extension, and deprecation. Current approaches lack systematic methods for transferring features between existing standards or merging them into more comprehensive "meta-standards," thereby hindering reuse and convergence. Furthermore, there is an insufficiency of metrics and frameworks to quantitatively assess standard evolvability, measure the impact of transferability, or guide the design of consumer-oriented, composable standards that can be combined flexibly. For example, a key question is what composability standards (e.g. WebXR extensions) will let disparate studios publish interactive scenes that interoperate in a shared virtual event.

Research and Innovation Objectives:

- Develop formal models and "meta-standards" for specifying standard evolvability, encompassing versioning, defined extension points, and comprehensive lifecycle management protocols.
- Establish methodologies and toolkits for systematic cross-domain standard analysis, semantic mapping for feature transfer, and pathways for convergence towards composable "meta-standards."

- Define robust metrics to quantify evolvability and transferability effectiveness, and promote design patterns for modular, consumer-oriented standards and their flexible composition.

2d.2 Semantic and data interoperability frameworks

This topic is crucial for enabling structured and consistent knowledge representation across diverse VW platforms and their ecosystems. It facilitates real-time reasoning, efficient content discovery, dynamic behavioural consistency, and seamless data exchange, all of which are essential for creating fluid UXs and ensuring the portability of digital assets within and between virtual environments.

Problem Definition / Research Gaps: A significant gap exists due to the lack of universally accepted semantic frameworks, ontologies, and knowledge graphs capable of effectively capturing temporal complexities, evolving world states, and dynamic relationships inherent in virtual environments. Current VW ecosystems are fragmented and isolated, characterised by incompatible data models that hinder cross-platform interoperability and shared understandability. Additionally, there is insufficient standardisation for semantic self-description and context-awareness in DT and VW, making it challenging to interpret data reliably across different systems. One fundamental question is what minimal, extensible ontology or meta-model will let heterogeneous industrial assets register and sync in real-time across multiple platforms.

Research and Innovation Objectives:

- Develop adaptive, linked ontologies and knowledge graph standards that integrate both symbolic and statistical AI elements for robust knowledge representation.
- Foster federated learning and semantic reasoning protocols to enable decentralised knowledge sharing while rigorously preserving data privacy.
- Define semantic data schemas and cross-modal retrieval frameworks to ensure unified access to heterogeneous content across VW.
- Develop a collaboratively constructed, pan-European glossary for the immersive sector, standardizing terminology across disciplines and stakeholders. This fosters semantic coherence and interdisciplinary communication.

2d.3 Standardized interfaces, APIs, and protocols

This research ensures the consistent integration and synchronisation of diverse sensory inputs, including visual, audio, and physiological data, along with AI-driven components and real-time inference pipelines across a variety of devices and platforms. This interoperability is foundational for delivering immersive, low-latency, and scalable extended reality (AR/VR/XR) experiences, making interactions fluid and responsive.

Problem Definition / Research Gaps: Despite advancements, there is an absence of unified multimodal fusion frameworks and standardised synchronisation protocols, leading to fragmentation in how different sensory data streams are combined and coordinated. A significant gap exists in runtime API standards that can orchestrate distributed AI inference effectively across heterogeneous edge-cloud infrastructures and diverse device hardware accelerators. Furthermore, current standards are insufficient for cross-modal adaptation and embedding alignment among foundation AI models, which is crucial for creating cohesive and intelligent virtual environments. A key question here is how to architect latency-compensated interaction protocols that preserve causality ("who touched what when") in synchronised audiovisual performances and collaborative tasks.

Research and Innovation Objectives:

- Create interoperable data formats, synchronisation methods, and standardised API layers specifically designed for multimodal inputs and AI inference in XR systems.
- Develop hybrid AI architectures, such as symbolic-statistical and LSTM-RF hybrids, alongside multimodal adaptation pipelines, supported by open benchmarks for performance evaluation.
- Enable cross-platform and cross-device spatial anchoring techniques, coping with differences in sensor fidelity and calibration and possible inconsistent coordinate systems.
- Integrate edge-cloud orchestration standards that facilitate dynamic task partitioning and efficient model migration across distributed computing resources.

Infrastructure and system runtime interoperability

2d.4 Runtime interoperability and conformance testing for Extended Reality

This research guarantees consistent UXs and ensures the trustworthy and secure operation of VR/XR systems. It achieves this by enforcing standardised runtime environments, codecs, identity models, and interaction models, which are critical for building reliable and scalable immersive ecosystems.

Problem Definition / Research Gaps: Despite the existence of standards like OpenXR and WebXR, fragmentation persists within the XR ecosystem, exacerbated by a lack of comprehensive conformance and certification frameworks. There are no widespread benchmarking tools that effectively combine objective technical performance metrics with subjective user-centric measures. The variability in device implementations significantly impairs seamless interoperability, impacts quality, and erodes user trust in XR experiences.

Research and Innovation Objectives:

- Develop scalable, automated benchmarking and certification suites that cover key performance aspects such as latency, rendering quality, codec performance, identity management, and multimodal interaction.
- Integrate UX (QoE) metrics through methodologies like Living Labs and large-scale field studies to provide holistic performance assessments.
- Promote cooperative initiatives among standard bodies to enforce compliance and drive ecosystem-wide adoption of interoperability standards.

2d.5 Standardisation of network and compute infrastructure

Robust, low-latency, and secure network and compute standards are vital for enabling real-time synchronisation, distributed rendering, and scalable multi-user immersive experiences. This is crucial across heterogeneous infrastructures, including cloud, edge, and on-device computing, ensuring that VW and DTs can operate seamlessly and efficiently.

Problem Definition / Research Gaps: A significant research gap lies in the currently undefined Quality of Service (QoS) and latency requirements specifically tailored for DTs and synchronous XR interactions. There is a fragmentation of cloud-edge compute standards and a lack of effective interoperability layers between these different computing paradigms. Furthermore, insufficient orchestration protocols exist for dynamic allocation of resources in real-time XR workflows, hindering scalable and responsive immersive experiences.

Research and Innovation Objectives:

- Define comprehensive network and compute performance benchmarks specifically tailored to the demanding requirements of immersive use cases.

- Develop interoperable cloud-edge middleware and orchestration standards that facilitate seamless distribution of computation and data.

Create adaptive resource management frameworks capable of ensuring seamless end-to-end performance across distributed VW and DT deployments.

2d.6 Secure, decentralized data sharing and interoperability frameworks

This research is essential for enabling secure, trustworthy, and privacy-preserving data exchange across industrial, healthcare, and virtual ecosystems. It reduces the risks of vendor lock-in and ensures data sovereignty, empowering users and organisations with greater control over their information in interconnected digital environments.

Problem Definition / Research Gaps: Centralised data exchanges currently lack sufficient security, traceability, and interoperability with emerging decentralised frameworks. There are no mature, standardised protocols that effectively integrate blockchain, distributed ledgers, and semantic AI for robust cross-domain interoperability. Significant challenges remain in securely blending heterogeneous data types across organisational boundaries, which is crucial for collaborative and comprehensive data utilisation. A pertinent question here is whether federated learning over multiple industrial DTs preserve data privacy while improving cross-company predictive-maintenance models?

Research and Innovation Objectives:

- Integrate blockchain-enabled provenance and access control standards into data sharing frameworks to ensure data integrity and user control.
- Develop semantic data translation layers and privacy-preserving computation techniques, such as federated learning and edge AI, for secure and efficient data processing.
- Advance Web 4.0 protocols to facilitate the linking of real and VW via open, decentralised architectures, promoting data fluidity and sovereignty.

User content and collaborative experience

2d.7 Cross-platform interoperability of avatars and digital humans

This research is vital for enabling seamless digital identity portability, consistent social presence, and privacy-compliant representation of users through avatars and digital humans across multiple VW and applications. This fosters user agency and a cohesive digital identity experience.

Problem Definition / Research Gaps: A significant research gap is the fragmentation of avatar data formats, behaviour models, and identity schemas, which severely limits portability and unified representation across different platforms. There is a lack of interoperable frameworks for multimodal data fusion, which is essential for integrating motion capture, physiological data, and behavioural patterns into comprehensive human models. Furthermore, insufficient ethical AI frameworks exist to ensure privacy, mitigate bias, and provide transparent management of avatar autonomy. A critical question is which lifecycle-management standards for people-centric twins (avatars, biometrics, behavioural profiles) guarantee portability, consent management and data sovereignty across platforms.

Research and Innovation Objectives:

- Standardise avatar data formats, behaviour control APIs, and interoperable identity management protocols to ensure consistent representation and portability.
- Extend DT standards to incorporate the cognitive and physiological dimensions of digital humans, enabling more holistic digital representations.

- Integrate privacy-preserving frameworks and ethical auditing tools directly within avatar platforms to address ethical concerns proactively.

2d.8 Collaborative authoring and versioning frameworks

This topic addresses the need to support collaborative, multi-user content creation and scene management within VW, significantly enhancing productivity. It also enables the seamless sharing, reuse, and evolution of VW assets across heterogeneous devices and platforms, fostering efficiency and innovation in content development.

Problem Definition / Research Gaps: Existing authoring tools commonly lack integrated, XR-tailored version control systems and real-time collaboration features that function effectively across multi-device environments. Proprietary and incompatible content formats and scripting languages fragment VW ecosystems, severely hindering content portability and reuse. Furthermore, there is limited unified support for scalable authoring workflows that can accommodate diverse levels of expertise through low-code/no-code solutions and AI-augmented tools.

Research and Innovation Objectives:

- Develop expressive versioning systems with XR scene-aware tracking, robust merge and revert functionalities, and integrated privacy controls to support cross-platform collaboration.
- Promote open export/import standards for 3D assets and behavioural scripts, such as glTF and OpenXR, to enhance content portability.
- Build interoperable, modular authoring frameworks that seamlessly integrate AI assistance and facilitate real-time multi-user editing experiences.

2d.9 Interoperability frameworks for collaboration and real-time interaction

This topic focuses on enabling secure, low-latency, and synchronous multi-user experiences, which are vital for social, educational, industrial, and healthcare applications within VW. Standardisation in this area facilitates seamless interactions and ensures scalability across diverse networks and devices, enhancing the overall collaborative potential of virtual environments.

Problem Definition / Research Gaps: The landscape of multi-user communication tools is currently fragmented by proprietary solutions, limiting effective cross-platform collaboration. There are no unified standards for synchronisation, session management, moderation, and the exchange of multi-modal interaction data, leading to inconsistent experiences. Significant challenges persist in ensuring Quality of Service (QoS) and accessibility in heterogeneous and bandwidth-constrained networks, which can degrade real-time multi-user interactions. A key question is how to architect latency-compensated interaction protocols that preserve causality ("who touched what when") in synchronised audiovisual performances and collaborative tasks.

Research and Innovation Objectives:

- Define open, adaptive communication protocols, potentially extending existing standards like WebRTC and MQTT, specifically tailored for immersive multi-user scenarios.
- Develop APIs that support role-based permissions, moderation functionalities, and real-time feedback mechanisms within collaborative virtual environments.
- Establish consistent event schemas and data formats for the synchronised exchange of gestures, voice, avatar states, and shared resources in multi-user settings.

2d.10 Frameworks for AI-generated content and ethical governance

This research ensures the authenticity, trustworthiness, and ethical compliance of AI-generated content and avatars within VW, impacting domains such as culture, media, industry, and healthcare. Establishing these standards is vital for fostering user trust and broad adoption of AI-generated assets.

Problem Definition / Research Gaps: There is a significant lack of standardised frameworks for validation, explainability, provenance tracking, and bias mitigation specifically for AI-generated assets. Fragmented ethical and governance frameworks currently complicate the adoption and trust of AI-generated content. Furthermore, there is insufficient integration of ethical auditing mechanisms directly into content creation and curation tools, making it challenging to ensure compliance throughout the lifecycle of AI-generated assets.

Research and Innovation Objectives:

- Develop comprehensive metadata schemas, blockchain-based provenance frameworks, and human-in-the-loop validation models for AI-generated content.
- Create ethical AI toolkits that promote fairness, transparency, and privacy, integrated seamlessly into both authoring and runtime platforms.
- Foster participatory governance models and implement continuous compliance auditing mechanisms to ensure ongoing ethical adherence for AI-generated content.

2d.11 Accessible and inclusive interoperability standards

This research ensures that VW are accessible to persons with disabilities, older adults, and users from diverse linguistic and cultural backgrounds, thereby significantly reducing digital inequalities. Establishing these standards is crucial for fostering an inclusive XR ecosystem.

Problem Definition / Research Gaps: A key research gap is the lack of interoperability protocols that effectively support assistive technologies and alternative access methods within virtual environments. Current systems often have inadequate multilingual and contextual user guidance, and insufficient avatar representation standards for comprehensive inclusivity. Furthermore, there is a missing framework for standardised assessment and certification of accessibility compliance in immersive content, making it difficult to ensure consistent accessibility across platforms.

Research and Innovation Objectives:

- Develop comprehensive accessibility certification standards and integration protocols, including robust support for features like subtitles and sign language avatars.
- Standardise multi-modal authentication and interaction methods that are fully compatible with a wide range of assistive devices.
- Build authoring toolkits and real-time usability testing frameworks designed to ensure consistent accessibility compliance across diverse XR platforms.

Domain-specific interoperability

2d.12 Interoperability standards for Digital Twins and their ecosystems

The development of open, interoperable DT standards is essential for enabling cross-domain integration, real-time synchronisation, federated system composition, and collaborative workflows. These capabilities are fundamental for the widespread adoption and effectiveness of VW in critical sectors such as industry, healthcare, urban planning, and cultural heritage, fostering efficiency and innovation.

Problem Definition / Research Gaps: A significant research gap is the lack of comprehensive, domain-agnostic DT standards that adequately cover their architecture, semantics, and lifecycle management. Current approaches are characterised by fragmented modelling techniques and limited formal frameworks for validation, verification, and continuous updates, hindering their reliability and long-term utility. Furthermore, there is insufficient interoperability between established data sources like BIM, CAD, IoT, and simulation data with emerging VW platforms. Key questions include how a versioned schema-evolution mechanism can be designed so factories and warehouses can upgrade their DTs without breaking shared simulations, and how to certify and audit the fidelity and privacy compliance of hosted patient twins when they move between care-provider systems or research platforms. Another pertinent question is what minimal, extensible ontology or meta-model can be defined to let heterogeneous enterprise systems (ERP, MES, CRM, BPM engines) register and synchronize real-time digital-twin data and business-process state.

2d.13 Interoperability standards in urban and public administration contexts

The integration and standardisation across city DTs, virtual planning tools, public services, and AI-driven decision support systems are crucial. This enhances sustainable urban management, promotes participatory governance by citizens, and improves the accessibility of public services within virtual environments.

Problem Definition / Research Gaps: Urban data is often fragmented across siloed systems, hindering the creation of interoperable city DTs and effective virtual planning tools. There is a lack of open standards for civic avatars, public service workflows, identity management, and the integration of services across multiple platforms. Furthermore, insufficient explainability, fairness, and privacy guarantees exist in municipal AI and data sharing environments, posing risks to trust and public acceptance. Key questions include which spatio-temporal data standards (CityGML, SensorThings) can harmonise IoT streams, GIS layers and citizen-generated content into a single city-scale DT, and what semantic interoperability layers let urban planners, first responders and public users query and annotate the same city DT. Additionally, how to architect streaming pipelines that keep an urban DT "live" (traffic, utilities, crowd flows) while respecting data-privacy and anonymisation laws, is a critical concern.

Research and Innovation Objectives:

- Develop open, modular data standards combining existing frameworks like CityGML, IFC, and OpenXR with semantic data models specifically for urban DTs.
- Build interoperable identity frameworks aligned with eIDAS, supporting robust avatar authentication and ensuring user privacy within public virtual services.
- Implement privacy-preserving APIs, develop participatory XR citizen platforms, and create explainable AI pipelines with human-in-the-loop feedback mechanisms for municipal applications.

2d.14 Interoperability for cultural and arts applications

This research topic enables the scalable sharing, reuse, and participatory co-creation of cultural heritage content across various platforms. This supports inclusivity, ensures digital preservation of valuable assets, and fosters sustainable innovation within the cultural and arts sectors in virtual environments.

Problem Definition / Research Gaps: A significant research gap is the absence of widely adopted standards for cultural content formats, metadata, avatar behaviour, and interaction models within VW. There is insufficient integration with existing domain-specific standards like BIM, CIDOC CRM, and the European common data space for cultural heritage, leading to isolated cultural content. Furthermore, a

lack of open, modular authoring tools that are interoperable with cultural heritage institutions and their existing systems hinders broader adoption and collaborative content creation.

Research and Innovation Objectives:

- Define shared metadata, interaction, and avatar behaviour standards specifically aligned with established cultural data frameworks to ensure consistency and interoperability.
- Establish open APIs for content migration, collaboration, and multi-device XR experiences tailored for cultural applications.

Promote community-driven consensus-building initiatives that actively engage cultural institutions and XR developers to foster widespread adoption of these standards.

Research and Innovation Objectives:

- Advance the standardisation of Asset Administration Shell (AAS), semantic web technologies, and DT orchestration protocols to create a unified framework.
- Develop model-driven engineering approaches, comprehensive verification pipelines, robust versioning mechanisms, and automated calibration methods for DTs.
- Design middleware and APIs that enable federated, semantic, and spatio-temporal data exchange across diverse DT ecosystems.

Governance, economy and trust

2d.15 Open standards for identity, governance, and portability

Establishing open standards for user control over digital identities, assets, and data across virtual ecosystems is paramount. This enhances trust, promotes inclusivity, ensures data sovereignty, and facilitates compliance with EU regulations such as GDPR and the Data Act. Robust governance frameworks are crucial for responsible data sharing and fostering economic fairness within virtual economies.

Problem Definition / Research Gaps: Current solutions for privacy-preserving, cross-platform identity management and asset portability are limited, creating significant barriers to user agency. Centralised architectural approaches often hinder user control and transparency in governance. Furthermore, there is a lack of interoperable stewardship models that effectively integrate legal and ethical compliance frameworks into VW operations, making robust governance challenging. A crucial question is which lifecycle-management standards for people-centric twins (avatars, biometrics, behavioural profiles) guarantee portability, consent management and data sovereignty across platforms.

Research and Innovation Objectives:

- Research and develop decentralised identity protocols (e.g., blockchain or DID-based) and data governance frameworks to ensure user-centric control over personal data.
- Design standardised APIs for asset and avatar portability that inherently support traceability and consent management across various platforms.
- Develop transparent data stewardship frameworks that align with EU legal requirements and principles of digital sovereignty, fostering trust and compliance.

2d.16 Decentralized and cross-company business collaboration

Open and interoperable standards for decentralised business networks and cross-company collaboration are essential. They enable secure, efficient workflows and cooperative innovation beyond

organisational boundaries, fostering multi-party trust, synchronised processes, and new digital marketplaces in VW. This is crucial for scaling business ecosystems and enabling seamless interactions across enterprises.

Problem Definition / Research Gaps: Existing business networks and collaboration tools are often siloed, proprietary, and fragmented, lacking a universal open protocol for ensuring synchronisation, confidentiality, auditability, and consistent multi-enterprise workflow execution. This significantly limits secure, persistent, multi-organisation interactions and hampers the integration of enterprise data and workflows into virtual environments. A key question is what minimal, extensible ontology or meta-model can be defined to let heterogeneous enterprise systems (ERP, MES, CRM, BPM engines) register and synchronize real-time digital-twin data and business-process state.

Research and Innovation Objectives:

- Advance open standards for multi-party process synchronisation and secure workflow automation across decentralised networks.
- Define interoperable session management protocols, shared virtual environment standards, and cross-domain access control models for business collaboration.
- Standardise interfaces and data schemas for transaction automation, auditability, and real-time business process orchestration compatible with existing enterprise workflow systems.
- Develop interoperable identity and trust frameworks that facilitate cross-company collaboration and support joint asset ownership.
- Investigate standardised economic and incentive models designed to support open decentralised business ecosystems.

2d.17 Digital asset ownership, payment systems, services for interoperability

Consistent and interoperable standards for digital asset ownership, payment mechanisms, and reusable platform services are crucial. They enable commerce, facilitate asset mobility, and reduce friction across VW and platforms, thereby enhancing user trust and supporting royalties and economic interactions. Additionally, these standards reduce redundant development efforts by promoting modular infrastructure.

Problem Definition / Research Gaps: Digital asset standards are currently fragmented, and incompatible protocols limit cross-platform transfer, validation, provenance tracking, and commercial use of virtual goods. Diverse payment mechanisms lack standardised integration with enterprise financial systems, leading to usability issues. Furthermore, the absence of commonly adopted modular platform services results in inconsistent ecosystem experiences, hindering seamless interoperability and the growth of virtual economies.

Research and Innovation Objectives:

- Establish standardised frameworks for digital asset metadata, provenance, ownership tracking, lifecycle management, and commercial interactions.
- Define interoperability protocols that enable secure asset transfer and validation across heterogeneous ledgers and registries.
- Develop standardised APIs and protocols for integrating various digital payment methods with financial and enterprise platforms, including models for cross-border payments that minimise currency conversion risks.

- Create modular, open platform services, such as identity management, digital asset handling, and wallet services, based on open standards with well-defined APIs bridging immersive technologies, web platforms, and enterprise applications.
- Foster cross-industry alignment of device, communication protocols, and governance frameworks to ensure coherent interoperability and ecosystem development.

Sustainability, inclusion and long-term resilience

2d.18 Economically sustainable standardisation and interoperability

Economically sustainable standards lower the cost of compliance, integration, and maintenance, enabling broad participation from SMEs, open-source communities, and public sector actors. This inclusivity fosters innovation, mitigates monopolisation, and supports a fair, profitable ecosystem driven by shared economic value. New business models aligned with open standards are essential for sustaining long-term engagement and ensuring a viable return on investment (ROI) for all contributors.

Problem Definition / Research Gaps: Current standardisation processes are often shaped by large industry players due to high technical complexity, licensing barriers, and the absence of economic incentives for smaller actors. Fragmented cross-sector efforts lead to duplicated investments and inefficiencies. There is a lack of practical guidance on business models that reward participation in open standardisation and demonstrate measurable economic benefit. ROI remains unclear for many stakeholders, particularly those outside of dominant commercial ecosystems.

Research and Innovation Objectives:

- Design modular, low-overhead standards to reduce implementation costs and support incremental adoption.
- Promote open licensing and hybrid public-private funding models to ensure economic inclusivity in standard development and maintenance.
- Develop business model frameworks and toolkits that quantify cost-benefit ratios and long-term economic value of adopting and contributing to open standards.
- Support cross-sector standardisation alignment to reduce redundancy and unlock new economic efficiencies.
- Explore new monetisation strategies (e.g. service-based, data-sharing, reputation-based) tied to open and interoperable ecosystems.

2d.19 Environmentally sustainable standards and interoperability frameworks

Sustainable standards can significantly reduce the environmental impact of digital infrastructure by promoting energy-efficient design, hardware reuse, and responsible data practices. As digital ecosystems grow, environmentally aware interoperability frameworks are essential for minimising carbon footprints, supporting hardware longevity, and aligning with climate goals through green-by-design architectures.

Problem Definition / Research Gaps: Most existing standards neglect environmental performance, leading to energy-intensive systems and computational inefficiencies. There is no shared methodology for assessing or benchmarking environmental impact in digital ecosystems. Green interoperability principles, lightweight data protocols, and hardware-aware design are underrepresented in current efforts. Lifecycle sustainability, especially regarding DTs and virtual assets, lacks standardisation and practical guidance.

Research and Innovation Objectives:

- Embed eco-design principles and carbon impact metrics directly into interoperability and standardisation frameworks.
- Develop lightweight, energy-efficient protocols and data formats suitable for low-power devices and legacy infrastructure.
- Standardise lifecycle-aware practices for digital assets, including reuse, recycling, and end-of-life management.
- Create open benchmarking tools and certification schemes for green compliance in virtual ecosystems and dataspaces.
- Foster sector-specific green standards and best practices across cloud computing, edge infrastructure, and XR systems.

2d.20 Technically and community sustainable standardisation and interoperability

Technically robust and community-supported standards are essential for long-term interoperability. Sustainability here means not only durable, maintainable technical architectures, but also the active involvement of diverse communities (including open-source contributors, academia, and civic organisations) who ensure resilience, innovation, and collective ownership.

Problem Definition / Research Gaps: Many standards become stagnant due to limited community involvement, weak governance, and lack of supporting tooling. Dominance by a few large entities restricts the diversity of contributions and perspectives. Poor onboarding, opaque decision-making, and lack of documentation hinder adoption and adaptation. Technical standards often evolve faster than their ecosystems (e.g. reference implementations, testbeds, and documentation), impeding real-world usage.

Research and Innovation Objectives:

- Establish long-term sustainability guidelines for standard lifecycle management, versioning, and maintenance practices.
- Invest in tooling, open reference implementations, conformance suites, and publicly available testbeds to encourage adoption.
- Promote inclusive governance models that enable meaningful participation from a wide range of stakeholders.
- Draw from proven community models (e.g. Linux Foundation, Blender) to define contributor pathways, decision frameworks, and stewardship roles.
- Support long-term funding strategies, including consortium-based approaches and civic tech grants, to ensure ongoing standard evolution and community health.

2e Digital Twins, assets and people

Virtual Worlds (VW) are populated with Digital Twins (DTs), assets and people. DTs are sophisticated virtual replicas designed to mirror aspects of their real-world counterparts with relevant fidelity. This mirroring capability extends to both physical assets and human beings, as well as non-physical but real processes. Critically, these virtual constructs can be interconnected with their real-world referents, enabling continuous monitoring, analysis, and even precise control over their behaviour. This section

explores the essential technology blocks required to create, manage, and utilize DTs in their various forms.

It is important to distinguish DTs from digital assets and avatars. While DTs are intrinsically linked to a *real-world* entity (an asset or a person) that they represent, digital assets encompass a broader range of virtual objects, from game items to cinematic effects, which can be entirely imaginary or representations of real objects. Similarly, avatars can be representations of real people (e.g., in a social VR space) or entirely fictional characters. A crucial distinction within the human dimension is the concept of avatars for AI co-pilots, which are human-like representations of AI engines serving as human-machine interfaces, distinct from a digital replica of a real or imaginary person.

Research topics for Digital Twins and assets

The foundational technologies for DTs focus on their applications in diverse domains, their representativeness and the integration of real-time data. For digital assets, the emphasis is on the technologies needed to design, create, and manage these virtual objects, highlighting their role in immersive experiences and the importance of secure ownership and interoperability.

This section delves into critical research topics within the broader DT ecosystem, highlighting existing gaps and proposing strategic research and innovation objectives crucial for advancing the field.

Immersion, devices, sensing and visualisation

2e.1 Sensors and data for Digital Twins (for assets and humans)

The efficacy of DTs, whether representing a complex industrial asset or a human physiological system, is intrinsically linked to their ability to accurately reflect real-world conditions. Sensors and advanced data collection methods provide the indispensable link between physical assets or human bodies and their digital counterparts, enabling the capture of real-world data. This foundational capability is vital for accurate monitoring, control, and ultimately, optimizing decision-making and system performance. Furthermore, by fusing sensor data with ab-initio physics-based models, DTs enable augmented or virtual sensors which can provide insights into quantities that are otherwise unmeasurable. They also address the critical challenges of data noise and the overwhelming deluge of information, making multi-source data usable and insightful. High-fidelity (e.g. 3D) models are essential for creating accurate DTs of assets (e.g., a manufacturing plant) and for facilitating immersive VR experiences (e.g., for training operators). For Human Digital Twins, sensing technologies allow for personalized healthcare, activity monitoring, and human-machine interaction. Beyond individual asset or human monitoring, these technologies enable secure cross-company information sharing, pivotal for initiatives like tracing carbon footprints in manufacturing processes or enabling personalized production. They also foster production-as-a-service models and establish unified interfaces for continuous integration within heterogeneous system landscapes. The ability to perform virtual Hardware-in-the-Loop (vHiL) simulations during engineering phases for validation and verification of system requirements and testing is also a direct benefit, as is the development of self-descriptive systems for enhanced automation in dynamic system coupling.

Problem Definition and Research Gap: Despite significant progress, substantial gaps remain in achieving the full potential of sensor and data integration for DTs. Many real-world processes or human physiological states remain under-instrumented or rely on outdated sensing technologies. Sensing some quantities can be intrusive, prohibitively expensive, or, in some cases, currently impossible. A significant challenge lies in integrating diverse sensor types with varying data rates, potential real-time gaps, and inherent measurement noise, which is particularly complex for human data due to privacy and variability. The sheer volume of data necessitates advanced real-time data processing and dimensionality reduction techniques. Critically, there are current limitations in processing large datasets in real-time at

scale. Beyond hardware and processing, the lack of EU-wide standardisation in DT formats and implementations, particularly for data exchange, presents a major interoperability hurdle. Furthermore, inconsistent network connectivity, especially in rural areas, and insufficient interfaces for AI integration further impede seamless data flow and intelligent decision-making.

Research and Innovation Objectives:

- Develop innovative, non-intrusive, and cost-effective augmented sensing technologies for challenging or currently unmeasurable physical quantities (for assets) and physiological/behavioural parameters (for humans), focusing on robust data acquisition in complex and sensitive environments.
- Advance real-time data fusion, synchronisation, and reduction methodologies capable of handling massive, heterogeneous datasets from diverse sensor modalities, integrating seamlessly with AI-driven analytics, while addressing privacy concerns for human data.
- Establish and promote open EU-wide standards and interoperability frameworks for DT data exchange and communication protocols for both assets and humans, ensuring secure, cross-company/cross-domain data sharing and integration with emerging data spaces (e.g., Manufacturing-X, Health Data Spaces).

2e.2 Digital Twin immersion for perception and systems understanding

DTs, regardless of whether they represent an asset or a human, inherently generate vast and intricate datasets that are notoriously difficult for human users to comprehend and act upon in real-time. Immersive tools, such as AR and VR, and spatialized audio (auralisation), provide an intuitive bridge for users to interpret and interact with this complex data. By enabling a more natural and intuitive interpretation, these tools facilitate superior decision-making for managing industrial plants or understanding human health data, foster enhanced collaboration among distributed teams, and enable proactive maintenance strategies or personalized interventions. This shift from passive data consumption to active, intuitive engagement is crucial for leveraging the full value of DTs. This also applies to the interaction with AI co-pilots, where immersive interfaces can make the AI's "understanding" and recommendations more intuitive and accessible.

Problem Definition and Research Gap: A significant research gap exists in the human-centred dimension of DT tools. Current solutions often prioritize data acquisition and analytics, overlooking the critical need for users to intuitively "feel," understand, and navigate data in a natural way. There is a marked lack of integrated solutions that seamlessly combine real-time data visualisation, auralisation, and interactive capabilities within truly immersive environments. While early prototypes for combining DTs and immersive visualisation exist (TRL 4-5), mature, industrially deployable solutions for assets and clinically relevant solutions for Human DTs remain limited. Adoption by end-users is still nascent (Low to Medium), with interest largely confined to pilot projects in specific sectors like aerospace, manufacturing, smart cities, and early medical applications.

Research and Innovation Objectives:

- Develop advanced immersive platforms capable of real-time visualisation and auralisation of complex DT data (for both assets and humans) within VR/AR environments, ensuring intuitive user interaction and multimodal feedback for diverse user roles (e.g., designers, operators, clinicians, policy makers).
- Research and implement novel methods for seamlessly integrating heterogeneous data sources (sensor fusion, 3D models) into immersive DT environments, focusing on cross-device

accessibility and robust integration with existing DT pipelines, including those for Human Digital Twins.

- Co-design with end-users and iterative prototyping and testing in real-world industrial, urban, and healthcare contexts to evaluate the impact of immersive DTs on decision-making efficiency, situational awareness, and collaborative problem-solving.

Intuitive, real-time user interaction

2e.3 Real-time collaboration around Digital Twins

The potential of DTs for collaborative design, operations, and decision-making is often constrained by their typical static or single-user nature. Real-time collaboration capabilities are paramount, enabling multiple stakeholders to synchronously or asynchronously interact with the same digital model. This significantly improves problem-solving, fosters innovation, and accelerates response times in complex projects, particularly in dynamic environments. Crucially, addressing real-time collaboration also involves ensuring data sovereignty for data providers in cross-company data exchange (e.g., on data space platforms like Catena-X for industrial data) and secure sharing of sensitive human data in healthcare data spaces. This also extends to collaborative interfaces with AI co-pilots, where human users can interact with and co-create alongside an AI's digital representation.

Problem Definition and Research Gap: A primary gap lies in the absence of robust multi-user collaboration features within many current DT platforms. This is further compounded by a lack of sophisticated Attribute-based Access Control (ABAC) mechanisms, which are essential for managing varied access rights and ensuring data security and sovereignty in complex, multi-stakeholder environments. While research prototypes and commercial pilots for multi-user DT collaboration exist (TRL 4-5), truly immersive, real-time, and multi-scale collaborative DT platforms are still in early developmental stages. Consequently, widespread integration into operational workflows remains low to medium, with initial adoption concentrated in select industries (e.g., aerospace, automotive, energy) and early pilot projects in healthcare.

Research and Innovation Objectives:

- Design and develop real-time, multi-user DT platforms supporting asymmetric access (e.g., view, comment, edit) and seamless cross-device interaction (e.g., XR headsets, touch displays, mobile devices) for both asset and human DT applications.
- Implement advanced Attribute-based Access Control (ABAC) mechanisms and data sovereignty frameworks to ensure secure and controlled data exchange in multi-stakeholder, cross-company, and cross-domain DT collaboration environments, with particular attention to sensitive human data.
- Integrate sophisticated versioning, annotation, and conflict management systems within collaborative DT platforms, capable of handling complex, multi-scale data from sensors to simulations, and facilitating effective human-AI collaboration via AI co-pilot avatars.

2e.4 Real-time interaction with Digital Twins

Real-time interaction with DTs is fundamental for their utility in dynamic, critical, and safety-sensitive applications. Model Order Reduction (MOR) techniques are critical for allowing complex, high-fidelity models to run at significantly faster speeds, enabling real-time simulation and interactive virtual environments. Natural and effective interaction with digital assets within these environments is essential for usability and immersion in training, design, or collaborative virtual work. This includes sophisticated hand gesture recognition from egocentric device input, which provides natural, controller-free interaction in XR, crucial for intuitive wearable control, and for controlling AI co-pilots. Real-time

rendering and feedback are vital for delivering high-quality, immersive visuals, preventing motion sickness, and enhancing realism. Furthermore, the integration of Explainable AI (XAI), particularly neurosymbolic AI, is paramount for increasing the trustworthiness of involved AI models, essential for trust, debugging, adoption, and regulatory compliance, particularly in safety-critical and regulated fields.

Problem Definition and Research Gap: Despite the acknowledged importance, several challenges persist in real-time interaction with DTs. High-fidelity models are often too slow for real-time use, and there are gaps in reducing model size while retaining accuracy and stability, especially for nonlinear and parameter-varying systems. Current methods for interacting with digital assets frequently lack realism or intuitiveness, necessitating improvements in haptic feedback, precise tracking, and multi-user consistency. Egocentric view hand tracking is significantly limited by occlusion, motion blur, and visual clutter, leading to gaps in accuracy, latency, generalisation, and data efficiency. Achieving a balance between realism and speed for real-time rendering and feedback remains a trade-off, requiring advancements in rendering fidelity and latency. Finally, AI models often function as "black boxes," highlighting significant gaps in interpretability, feature extraction, knowledge integration, and robust trust metrics. While traditional MOR is high TRL, novel ML-driven MOR approaches are still low TRL, and the overall "packaging" for end-user adoption often hides this complexity. So called hybrid MOR approaches combine the best of the two worlds, currently also still at low TRL.

Research and Innovation Objectives:

- Develop advanced Model Order Reduction (MOR) techniques, including ML-driven and hybrid approaches, capable of reducing the complexity of high-fidelity, nonlinear, and parameter-varying models while preserving accuracy and stability for real-time DT applications.
- Research and implement novel real-time interaction paradigms for virtual environments, focusing on egocentric hand gesture recognition with improved accuracy and robustness, haptic feedback integration, and multi-user synchronisation for realistic digital asset manipulation and seamless human-AI co-pilot interaction, including development of advanced deep neural networks, exploring novel approaches for integrating multi-modal sensor inputs on XR devices and development of computational models and optimisation techniques for on-device hand tracking and gesture recognition algorithms.
- Advance research into Explainable AI (XAI) and neurosymbolic AI for DTs, developing methodologies for improved interpretability, transparency, and trustworthiness of AI-driven insights and behaviours in safety-critical and regulated virtual environments, especially for AI co-pilots in industrial or medical settings.

2e.5 Optimisation and Uncertainty Quantification

VW, powered by DTs, provide unparalleled support for scenario-based decision-making by offering real-time insight into multi-attribute performances, based on simulation and data models. As reliance on model outputs (which are inherently approximations and predictions) grows drastically in VW contexts, the critical importance of Uncertainty Quantification (UQ) and optimisation becomes evident, especially for industrial, health and defence use cases. These disciplines contribute significantly to user awareness of the limitations of model predictions and underpin robust decision-making. By quantifying and visualizing uncertainty, users can make more informed choices, mitigating risks associated with relying on potentially imprecise outputs. Optimisation, particularly multi-attribute optimisation, allows for the exploration of solution spaces, "what-if" scenarios, and automated decision-making support within the virtual world, ensuring more robust and reliable outcomes.

Problem Definition and Research Gap: While UQ is a well-established research domain, its application in early VW implementations is often lacking due to complexity and the absence of established

visualisation methods for UQ results. There is a general tendency to neglect uncertainty because it is perceived as "not attractive" or too complex to integrate. The core problem definition is how to effectively convey insights into the uncertainty of predictions at scale within VW applications, making it accessible and actionable for end-users. Although theoretical UQ and optimisation techniques boast high TRL levels (6-9), the practical visualisation and standardisation of these methods for deployment have low TRL levels (2-5). Furthermore, novel approaches like Quantum Inspired algorithms are also in early TRL stages (2-5). Consequently, the current adoption rate by end-users remains low.

Research and Innovation Objectives:

- Develop novel methodologies and tools for the intuitive visualisation and communication of uncertainty levels in DT predictions, focusing on scalable solutions for complex VW applications.
- Advance applied Uncertainty Quantification and multi-attribute optimisation techniques tailored for real-time DT scenarios, including the exploration of Quantum Inspired algorithms for enhanced performance in decision-making support.
- Conduct human-computer interaction research to identify effective strategies for making end-users aware of the inherent uncertainties in suggested solutions and empowering them to make robust, risk-aware decisions.

Authoring and experience design

2e.6 3D Object creation for visual representation

The ability to create accurate and visually rich 3D objects is foundational for bridging the gap between physical and VW. This capability is crucial for DT fidelity. It is also vital for developing compelling immersive experiences across various sectors. Advanced tools in this area aim to reduce development time and costs for 3D content creation, democratize 3D modelling, and enable the creation of both realistic (for DTs) and imaginative objects (for digital assets/avatars). A key aspect is the seamless integration of physical properties (e.g., textures, mass distribution, plasticity) and semantic properties (e.g., function, intended usage, or affordance) into digital representations, allowing VW to blend seamlessly with the physical one. This includes addressing challenges like missing part completion in 3D models and enabling creative generative tools for personalized design, including new designs for assets or unique avatars.

Problem Definition and Research Gap: Significant limitations persist in the integration of physical and semantic properties within current 3D modelling systems, hindering the creation of truly "right-fidelity" DTs. There is a notable gap between high-fidelity modelling and creative, generative approaches, leading to a lack of comprehensive tools that combine accuracy with creative flexibility. The need for better semantic understanding in virtual objects is pressing, as is the current limitation of real-time physical property simulation. Challenges also exist in translating text descriptions into physically plausible objects (for assets) or highly detailed, plausible human representations (for avatars) and in handling complex object relationships and interactions. Furthermore, there is limited ability to transfer learned properties to novel object categories or to create nuanced human representations. The current TRL is approximately 4, with a low end-user adoption rate, indicating an early stage of market readiness.

Research and Innovation Objectives:

- Develop advanced 3D modelling and mesh generation techniques that seamlessly integrate both physical (e.g., material properties, dynamics) and semantic (e.g., function, affordance) properties into digital representations for high-fidelity DTs of assets and accurate, contextually rich avatars for humans or AI co-pilots.

- Research and implement novel AI/ML-driven generative tools (e.g., Text-to-3D, text-to-avatar) for co-creation of 3D assets and scenes, focusing on prompt-based interfaces, physics-aware representations, and the ability to generate physically plausible objects or expressive human/AI representations from high-level descriptions.
- Advance methodologies for automated missing part completion in 3D models and explore techniques for style transfer on 3D models and avatars, enabling rapid and efficient creation of diverse and accurate digital assets and representations.

2e.7 Capturing real world asset and scene information

VW are fundamentally dependent on accurate digital models of the actual world. Therefore, the ability to capture real-world assets (e.g., machinery, infrastructure), environments (e.g., factories, cities), and even people (for Human DT) in 3D is a fundamental prerequisite for the realisation of high-fidelity DTs and immersive VW. This includes addressing the challenge of cost-effectively and accurately capturing large areas or highly detailed scenes. Advanced 3D reconstruction methods, including radiance and splatting techniques, are vital for this process, transforming raw sensor data into usable digital representations for a DT.

Problem Definition and Research Gap: The primary complexity in 3D data capturing lies in the multitude of information sources that need to be merged. This includes both visible (e.g., shapes, colours) and invisible (e.g., textures, structural details, internal components) information, which can be collected through diverse means. For Human DTs, capturing goes beyond static 3D forms to include subtle movements, expressions, and physiological states. The overarching problem definition is how to develop robust, automated data capturing and merging pipelines that can efficiently and accurately realize DTs of real-world assets and complex 3D scenes, including dynamic human environments. Current TRL for these technologies ranges from 3-6, with a low end-user adoption rate, indicating that significant development is still required for widespread practical implementation.

Research and Innovation Objectives:

- Develop advanced sensor fusion and data integration pipelines for seamlessly merging heterogeneous data sources to create comprehensive and accurate 3D DT models of real-world assets, complex scenes, and human beings.
- Research and implement automated segmentation and reconstruction techniques, including AI-based methods and Neural Radiance Fields (NeRF) and Gaussian Splatting, for cost-effective and highly detailed capture of large areas, complex environments, and dynamic human subjects.
- Focus on methodologies that enhance the semantic enrichment of captured 3D data, enabling the automatic extraction and integration of functional and contextual information to create more intelligent and usable DT representations.

2e.8 Physics based modelling

While generative AI models can today produce visually realistic 3D animations, most applications demand traceable, accurate, and explainable physics-based calculations of behaviour. Accurate physics-based (i.e. explainable based on an implementation or discretisation of the laws of physics) models, including foundational models, enable the solution of real-world problems within VW in an explainable and rapid manner. This involves model hybridisation, combining both inductive (data-driven) and deductive (physics-based) models to create robust DTs capable of calculating parameters such as carbon footprint, offering detailed insights into complex systems, and predicting physiological responses in Human Digital Twins.

Problem Definition and Research Gap: The critical research gap lies in developing scalable, physics-informed simulation frameworks that enable accurate and robust modelling of complex, coupled systems for real-time DT applications. The challenge is balancing the computational intensity of high-fidelity physics simulations with the need for real-time performance. This necessitates advanced techniques for reducing computational cost while maintaining predictive accuracy and integrating diverse physics domains within a unified simulation environment. There is a need for robust frameworks that can seamlessly combine data-driven approaches with fundamental physics principles, especially for predictive modelling and optimisation in dynamic systems.

Research and Innovation Objectives:

- Develop scalable, physics-informed simulation frameworks that enable accurate and robust modelling of complex, coupled systems for real-time DT applications across diverse domains, including industrial assets and human physiology, focusing on efficient numerical solvers and parallel computing architectures.
- Research and implement advanced model hybridisation techniques that seamlessly combine inductive (data-driven) and deductive (physics-based) models to create high-fidelity, predictive DTs capable of tasks like carbon footprint calculation, complex system behaviour simulation, and personalized physiological prediction.
- Explore and integrate novel methodologies for optimizing the computational cost of physics-based simulations while maintaining predictive accuracy, enabling their widespread adoption in dynamic and safety-critical DT use cases.

2e.9 Digital Twin engineering, connectivity to real world assets and updates

DTs are inherently complex software systems that demand sophisticated engineering approaches to ensure their efficacy, reliability, and longevity. The development of dedicated tools and methods for DT engineering is crucial for enabling their robust validation, promoting reusability across different applications, facilitating seamless interoperability with other systems, and ensuring their composability into larger, more intricate twin ecosystems. Furthermore, effective engineering practices are essential for managing the continuous evolution and maintenance of DTs throughout their lifecycle, thereby safeguarding their long-term value and relevance. Without proper engineering foundations, the promise of DTs as dynamic, adaptable entities cannot be fully realized.

Problem Definition and Research Gap: The current landscape of DT implementation is largely characterized by ad-hoc approaches, which severely restrict their potential for rigorous validation, widespread reuse, sustainable maintenance, and efficient evolution. This fragmented development also impedes the opportunistic federation of Digital Twins (DTs), limiting their ability to combine and collaborate for more comprehensive insights and capabilities. The critical research gap lies in the urgent need for a comprehensive suite of dedicated tools and methods. This includes the establishment of robust DT software architectures, the definition of standardized DT interfaces to enable seamless communication, and the development of intuitive programming abstractions and interfaces for creating and integrating VW within the DT context. Moreover, there is a pressing need for advanced validation and verification techniques specifically tailored to the unique complexities of DTs to ensure their accuracy and reliability.

Research and Innovation Objectives:

- To develop low-code platforms and advanced modelling concepts and languages that streamline the engineering of DTs, fostering rapid prototyping and deployment.

- To establish comprehensive DevOps actions and pipelines for the continuous integration, validation, deployment, and evolution of DTs, ensuring agility and responsiveness to change.
- To research and define architectural patterns, quality assurance mechanisms, and deployment strategies for DTs, focusing on uncertainty quantification, fidelity assessment, and security considerations.

2e.10 Digital Twin verification and (continuous) validation

The trustworthiness and utility of a DT are intrinsically linked to its accuracy and credibility as a representation of its physical counterpart. DT verification and continuous validation are paramount in ensuring that this alignment is maintained throughout the entire lifespan of the asset. This research area focuses on developing robust methods and tools to validate and verify that the virtual environments within a DT are not only safe and accurate but also consistently reflect the real-world system's state and behaviour. By continuously monitoring and adapting the DT, these efforts ensure that it remains a reliable source of information. Furthermore, automated validation processes reduce manual effort, enhance efficiency, and enable early detection of system changes, which is critical for maintaining the twin's value and preventing erroneous conclusions. The ability of DTs to accurately track spatio-temporal dynamics and quantify fidelity is also crucial for advanced analytics, safety protocols, and the anchoring of AR applications, thereby expanding their utility across various industrial and operational contexts.

Problem Definition and Research Gap: Despite the critical importance of accuracy, current DT development significantly lacks rigorous validation frameworks, making it challenging to confidently rely on their outputs. A major research gap exists in developing comprehensive methodologies for validating DTs that are continuously evolving and increasingly driven by AI, necessitating new approaches for benchmarking and standardisation. The current state of model updating often involves labour-intensive manual processes, highlighting a critical need for research into reliable online identification and model updating techniques to ensure real-time accuracy and adaptability, including enhanced estimation approaches for DT parameters and structures. Furthermore, achieving high-precision indoor localisation and effective spatio-temporal data management remains a significant challenge, requiring advancements in sensor fusion and algorithms. Finally, there is a clear need for robust methods to quantify the fidelity of a DT, providing a clear measure of how closely it replicates reality. It is acknowledged that this research topic benefits from collaboration with the ADRA partnership and that any double work is to be prevented.

Research and Innovation Objectives:

- To develop adaptive system parameter/input/load identification methods, real-time data assimilation techniques, and machine learning models for drift detection and automated, safe updates of DT models.
- To create advanced spatio-temporal localisation algorithms, including SLAM and geospatial databases, coupled with fusion methods for high-precision indoor tracking and trajectory analysis.
- To define robust key performance indicators and develop automated testing frameworks, statistical methods, and machine learning approaches for continuously assessing DT fidelity and uncertainty.

Interoperability and standardisation

2e.11 Open standards for Digital Twins

The proliferation and effective utilisation of DTs across diverse industries are fundamentally dependent on the establishment and widespread adoption of open standards. These standards provide a crucial

common language and a shared set of protocols and specifications, guiding the design and development of DT solutions. By ensuring robust data and model interoperability, integrity, and consistency, open standards overcome the current fragmentation, enabling seamless exchange of information and collaboration. Furthermore, the development of standards that incorporate mechanisms for integrating diverse Digital Twins (DTs), progressing towards a "DT of Digital Twins," and for assessing the quality of a DT solution is vital for fostering a coherent and scalable ecosystem. Standardized domain-specific languages are essential to ensure the semantic meaning of data across exchanges, allowing the VW to contain structured data for direct processing and enabling DTs to provide semantic self-descriptions for dynamic system coupling, thus facilitating the creation of adaptive Systems-of-Systems.

Problem Definition and Research Gap: A significant impediment to the widespread adoption and integration of DTs is the pervasive lack of universally recognized standards related to DT terms and architectures. This deficiency severely hampers the interoperability of data and models among different DTs. The intricate problem of integrating disparate DTs, a challenge that extends far beyond mere model integration, has received insufficient exploration. This complexity is compounded by the interdisciplinary nature of DTs leading to a profound heterogeneity of underlying technologies. While certain standardized technologies like Functional Mock-up Unit / Functional Mock-up Interface (FMU/FMI), OPC Unified Architecture (OPC UA) and the Asset Administration Shell (AAS) serve as foundational enablers for specific components of a DT's architecture, they do not encompass the full spectrum of DT functionality. Moreover, these technologies are often confined to specific fields, whereas the DT concept is inherently domain-agnostic, necessitating broader and more comprehensive standardisation efforts.

Research and Innovation Objectives:

- To advance the international standardisation of the Asset Administration Shell (AAS), FMU/FMI, OPC UA and their associated sub model templates, ensuring comprehensive coverage of DT architectural aspects and promoting industry-wide adoption.
- To research and develop semantic technologies, including ontologies and knowledge graphs, and leverage large language models to enable robust semantic representation, integration, and cross-modal information retrieval for DTs.
- To establish standards for assessing DT quality and fidelity, and to investigate middleware solutions for robust real-virtual synchronisation, facilitating seamless integration and coordination of complex DT systems.

Research topics for digital human representations

The evolution of digital human representations, encompassing human DTs, avatars, and humanistic agents, marks a significant frontier in our digital future. These distinct virtual representations of humans offer profound opportunities, from revolutionizing personalized medicine and product design to enhancing virtual interactions and serving as intuitive interfaces for AI. While their potential is immense, unlocking their full capabilities requires dedicated investment in addressing fundamental research gaps. This section outlines critical areas for research and innovation, emphasizing their importance to both researchers and policymakers, and paving the way for a new era of human-centric digital experiences.

Immersion, devices, sensing and Visualisation

2e.12 Sensing systems for human behaviour

Accurate and comprehensive human behaviour sensing is foundational for creating truly immersive digital humans. Full-body motion tracking enables natural, intuitive interactions in virtual environments, seamlessly bridging the physical and digital for AR/VR experiences. Non-invasive wearable sensors continuously capture physiological and movement data, allowing early detection of subtle health

changes and facilitating personalized wellness feedback. Moreover, virtual sensing, a crucial advancement, infers hidden states (e.g., pain levels, internal forces, fatigue) by fusing physics-based models with sensor inputs, extending human sensing for safer decision-making in virtual environments and enhancing real-world health monitoring.

Problem Definition and Research Gap: Achieving high-fidelity 3D human pose estimation without cumbersome suits or markers remains challenging. Camera-based tracking often suffers from occlusions and environmental dependencies, while current VR solutions lack full-body motion capture. There's a critical gap in reliable, affordable, and minimally intrusive real-time whole-body tracking. Integrating data from diverse sensors (e.g., IMUs, depth cameras) is complex, with noise and calibration issues demanding robust multi-sensor fusion algorithms for precise motion tracking in everyday settings. Non-invasive wearables, while valuable, often provide limited data streams and can be unreliable, necessitating research into expanding gatherable bio-signals and improving derived metric reliability. Critically, interpreting continuous wearable data into meaningful health insights and DT updates is underdeveloped. Finally, collecting sensitive human data via cameras and always-on wearables raises significant privacy concerns, requiring advancements in data security, continuous user consent, and robust governance frameworks for biometric data.

Research and Innovation Objectives:

- Develop advanced deep learning models and hybrid AI frameworks for marker-less motion capture, combining data-driven pose predictions with kinematic models for enhanced stability and accuracy across diverse environments.
- Create lightweight sensor suits and sophisticated sensor fusion algorithms integrating various technologies (e.g., IMUs, electromagnetic trackers, ultrasound) for comprehensive, always-available motion data, with solutions exploring mobile implementations of pose estimation.
- Design and implement virtual sensing technology leveraging non-invasive wearable data with physiological models to estimate unmeasured factors, providing richer health insights and exploring on-device processing and secure enclaves for privacy-preserving data management.

2e.13 Data acquisition for human Digital Twin creation

The utility of a human DT is directly proportional to its data richness and quality. Acquiring diverse data - from genomic information to daily activity logs - creates a comprehensive individual view, paramount for precision medicine. This integrated approach moves beyond "one-size-fits-all" healthcare, enabling personalized models reflecting unique biological and lifestyle characteristics. Multi-source data integration facilitates early health issue detection and timely interventions. Rich data feeds are essential for safe "what-if" simulations, allowing clinicians to virtually test drug responses or therapy reactions without patient risk. Crucially, this data acquisition directly addresses health data silos by creating robust frameworks to link disparate datasets into a coherent, unified representation, enhancing patient care and accelerating biomedical research. Technology development will strongly support activities described in application section 1b.

Problem Definition and Research Gap: A research gap is seamlessly combining disparate data types into a single, coherent human DT model. There's a pressing need for standardized protocols and advanced algorithms to fuse these multimodal data streams in real-time for consistent twin updates. Furthermore, human DTs demand high-quality data, but real-world inputs often have incompleteness, noise, or gaps. Robust methods are needed to handle missing or uncertain data, ensuring twin functionality. Continuous data curation and rigorous validation protocols are also lacking. Aggregating sensitive personal data raises significant privacy and security concerns. Research must create innovative governance frameworks and technical solutions to utilize data while meticulously preserving

privacy, alongside transparent consent mechanisms to build patient trust. Many existing health IT systems aren't designed for continuous data flows, highlighting a gap in creating real-time pipelines from devices/EHRs to the twin. Aligning data of different frequencies and determining optimal update frequencies are significant research questions. Lastly, efficiently generating personalized baseline models from raw data remains an underdeveloped area.

Research and Innovation Objectives:

- Develop integrated platforms and advanced algorithms to ingest and synthesize diverse data streams into scalable infrastructures, ensuring real-time updates through sensor fusion techniques.
- Create automated toolchains for constructing individual-specific models from raw data, encompassing image processing, patient-specific geometry setup, and automated parameter identification to streamline personalisation.
- Establish robust data governance frameworks and technical solutions for privacy preservation, including automated data quality checks, cross-validation mechanisms, and comprehensive twin validation suites to certify trustworthiness and accuracy.

Intuitive, real-time user interaction

2e.14 Behavioural modelling

Importance and Problem Multimodal emotion recognition and stress detection are crucial for building sophisticated, responsive digital humans, significantly enhancing our ability to understand user states and intentions. This leads to more natural, engaging, and effective virtual interactions. By detecting emotional cues and stress levels, digital humans can adapt responses and the virtual environment, improv user satisfaction and build trust. This is vital in applications requiring real-time understanding of user feelings, such as education, healthcare (therapeutic interventions), or disaster management where timely, adaptive interventions are essential. Sensing and responding to emotional states contribute to greater situational awareness and enables personalized, empathetic digital interactions.

Problem Definition and Research Gap: A primary research gap in multimodal emotion recognition and stress detection is the challenge of accurately and swiftly recognizing emotions across diverse cultures and contexts while rigorously preserving user privacy. Integrating multiple modalities (e.g., visual, audio, physiological signals) promises performance improvement but introduces complexities in data collection and input synchronisation. Robust algorithms are needed to interpret subtle emotional cues from various sensory data streams and generalize across different demographics and situations. Furthermore, the sensitive nature of emotional and physiological data necessitates advanced privacy-preserving techniques, ensuring ethical use with appropriate anonymisation or pseudonymisation of training data.

Research and Innovation Objectives:

- Develop advanced models that effectively combine visual (facial expressions, eye tracking), audio, and physiological sensor signals for robust multimodal emotion and stress detection across diverse user populations and contexts.
- Research and implement early and late fusion techniques for integrating multimodal data streams, optimizing synchronisation and leveraging complementary information for improved accuracy in emotion recognition.
- Design and validate privacy-preserving prediction model generation methods, including anonymisation and pseudonymisation of training data, to ensure ethical and secure handling of sensitive user emotional data.

Authoring and experience design

2e.15 Human Digital Twin modelling

Human DTs represent a transformative approach in healthcare, enabling the creation of dynamic, high-fidelity digital replicas of individual patients. These twins integrate multimodal data—ranging from genomics and imaging to real-time physiological signals—to simulate and predict health outcomes, optimize treatment plans, and support surgical planning. By allowing clinicians to test interventions virtually before applying them in real life, human DTs promise to enhance precision medicine, reduce risks, and improve patient outcomes. Their potential spans from personalized drug response prediction to virtual surgery rehearsals, offering a paradigm shift in how care is delivered and optimized.

Problem Definition and Research Gap: Despite their promise, human DTs face critical challenges in achieving the necessary accuracy, adaptability, and clinical trustworthiness. The primary research gap lies in the development of scalable and clinically validated DT frameworks that can accurately reflect the complexity and variability of human physiology. This includes integrating heterogeneous data sources, ensuring model interpretability, and maintaining up-to-date representations of the patient's state. Furthermore, ethical and regulatory frameworks must evolve to address the implications of using such detailed personal models in clinical decision-making. The field requires robust methodologies for validation, personalisation, and secure deployment of human DTs in real-world healthcare environments.

Research and Innovation Objectives:

- Develop integrated frameworks for multimodal data fusion (e.g., imaging, genomics, bio signals) to construct and continuously update high-fidelity Human DTs.
- Advance predictive modelling techniques that enable personalized simulation of treatment outcomes and surgical scenarios, ensuring clinical relevance and interpretability.
- Establish rigorous clinical validation pipelines and regulatory pathways to ensure the safety, efficacy, and ethical deployment of HDTs in healthcare settings.
- Investigate privacy-preserving architectures and ethical governance models to manage consent, data ownership, and the societal implications of HDT use in medicine.

2f Applied Artificial intelligence for Virtual Worlds

AI is a cornerstone technology for the development of Virtual Worlds (VW), in the stage of content creation and in VW operation. Research gaps in this area include the creation and management of digital content, automating processes, improving the quality of virtual experiences, enabling interoperability. Machine learning techniques must be refined to create more realistic and dynamic virtual entities, from non-player characters to virtual assistants. AI can enhance the development of advanced algorithms that can understand and respond to user behaviour in real-time. Additionally, by addressing these research challenges, we can harness the power of AI to create more immersive, interactive, and intelligent VW.

Research topics for AI for Virtual Worlds

AI for perception and sensing

Understanding the environment is crucial for enabling immersive and interactive VR/AR/MR applications. AI plays a significant role in interpreting sensory data, but several challenges remain to achieve truly effective perception and sensing in VW applications. The main envisioned research topics include those discussed in the following sections.

2f.1 Artificial intelligence -based computer vision methods

AI in computer vision empowers virtual environments to understand the physical world. This enables capabilities like object recognition, pose estimation, and spatial mapping, allowing virtual elements to inherit semantics and properties from their physical counterparts. This fosters a more realistic blending of physical and digital worlds, enhancing user interaction and context awareness.

Problem Definition / Research Gap: Current digital-physical interactions are largely limited to graphical overlays. A truly realistic blending demands AI to capture diverse aspects beyond appearance, including object semantics and contextualisation. These properties must be dynamically captured and updated, with changes in one world reciprocally impacting the other, allowing users to perceive and modify virtual elements based on real-world properties.

Research and Innovation Objectives:

- Develop and exploit foundational multimodal models (e.g., vision-language models) for comprehensive scene analysis and information transfer to 3D models.
- Advance vision-based AI for accurate semantic and property association with virtual elements from real-time or acquired 3D data.
- Ensure dynamic property updates and perceptible real-world reflections in the virtual environment.
- Egocentric, energy efficient and mobile perception of the scene and user interactions.

2f.2 AI for Audio analysis

AI-based audio analysis enhances real-time speech recognition, which, integrated with Natural Language Processing (NLP) and Large Language Models (LLMs), facilitates more natural interaction with virtual environments (e.g., smart digital assistants). Voice analysis also detects user emotions. Furthermore, audio analysis improves situation awareness by identifying environmental features crucial for seamlessly blending physical and digital worlds.

Problem Definition / Research Gap: Human hearing is paramount for communication and environmental awareness. To enable natural user interaction in VW, this fundamental capability must be effectively transferred and replicated digitally. This requires sophisticated AI models to accurately interpret diverse real-world audio cues and translate them into actionable information within the virtual environment, bridging a key sensory immersion gap.

Research and Innovation Objectives:

- Develop advanced speech recognition and synthesis technologies, combined with Generative AI and LLMs, to create highly interactive virtual smart digital assistants.
- Enable digital assistants to understand user requests and respond verbally, personalising answers based on language, context, and culture.
- Utilise audio analysis to enhance situation awareness and identify environmental features for improved physical-digital blending.

2f.3 AI for multi-modal Human-Machine Interaction and sensor fusion

Haptic devices and wearable sensors provide users with multi-sensory perceptions in VW, including touch, temperature, smell, and force feedback. These technologies capture detailed user data, allowing machines to interpret human intention and emotional state. Simultaneously, AI-based sensor fusion of diverse inputs, such as cameras, eye trackers, and bio signals, enhances the accuracy, robustness, and

resilience of virtual applications. By leveraging AI to orchestrate and combine sensor data, systems can maintain functionality even if certain inputs fail, making virtual interactions more immersive, adaptive, and reliable.

Problem Definition / Research Gap: Advancing the state of the art of sensor fusion and training such Ai-models poses several challenges: multimodal datasets must be precisely annotated, data sources must be time-synchronised, and strong coordination is required between individual modality analysis and fusion modules to ensure real-time performance and coherence of the virtual experience.

Research and Innovation Objectives:

- Utilise deep machine learning to analyse signals from both haptic and sensing devices.
- Employ AI to modulate actuation signals for realistic, individual- and context-adaptive haptic feedback.
- Leverage AI to reliably interpret raw sensor signals into higher-level concepts, enhancing user intention and emotion understanding.
- Develop and implement machine learning methods, such as hybrid LSTM–Random Forest networks, for effective multi-modal sensor fusion.
- Enhance accuracy and robustness in virtual applications by strategically combining heterogeneous sensor data.

Edge AI and distributed intelligence

Edge AI in VR/XR integrates AI into immersive devices while coordinating with edge nodes and the cloud for optimized performance. This enables real-time, context-aware, and privacy-preserving interactions by distributing tasks across a multi-tiered system. It tackles latency, bandwidth, and security challenges, ensuring smooth and adaptive experiences. Applications span training, simulation, design, healthcare, and entertainment, making Edge AI crucial for next-gen immersive systems.

2f.4 On-device AI for inference in headsets, haptic devices and sensors

On-device AI enables real-time, low-latency, and privacy-preserving interactions in VW without constant cloud connectivity. This is vital for time-sensitive or privacy-critical applications using immersive AR/VR environments. It ensures seamless UX by mitigating delays that could break immersion or cause discomfort, while also reducing energy consumption and data transmission.

Problem Definition / Research Gap: Current AI systems often demand too many resources for edge devices constrained by power, memory, and compute capacity. Many existing solutions rely on cloud connectivity, limiting their use in remote or privacy-sensitive scenarios. A key research gap lies in developing AI models, hardware architectures, and interaction pipelines that can operate fully or partially on-device, enabling distributed intelligence across the VW.

Research and Innovation Objectives:

- Develop and benchmark machine learning models tailored for resource-constrained devices, focusing on lightweight neural network architectures and model optimisation techniques (quantisation, pruning, distillation).
- Explore hardware acceleration, including custom ASICs and microcontroller-based AI execution, alongside methodologies like hardware/software co-design.
- Research edge-based federated learning and continual learning paradigms for local adaptation, ensuring privacy-preserving on-device intelligence.

2f.5 Federated learning for collaborative training without compromising privacy

VW systems increasingly collect sensitive user data, such as gaze, motion, and physiological responses. Federated learning (FL) allows valuable insights from this data to improve immersive experiences—like adaptive interfaces and personalised haptics. This method safeguards user privacy while facilitating collaborative model training across distributed edge devices.

Problem Definition / Research Gap: Most current VW systems rely on centralised AI models, which limits privacy, increases latency, and hinders scalability. Edge devices in these environments are resource-constrained and manage complex, heterogeneous, and dynamic data streams. Existing FL approaches aren't fully equipped for the real-time, multimodal nature of XR workloads. This necessitates lightweight, context-aware, and privacy-preserving FL mechanisms specifically designed for distributed, real-time VW systems.

Research and Innovation Objectives:

- Develop lightweight FL algorithms tailored for streaming, multimodal VW data.
- Integrate FL with edge-based privacy-preserving mechanisms, such as secure aggregation and differential privacy.
- Research cross-device and cross-user learning approaches that maintain temporal continuity and interactivity, including hierarchical or decentralised FL architectures.

2f.6 Distributed intelligence across devices, cloud, and edge networks

VR/XR experiences require ultra-low latency, high throughput, and real-time responsiveness. Distributed intelligence offers a transformative approach by enabling adaptive partitioning of AI tasks across XR devices, edge nodes, and cloud backends. This optimises resource use, ensures high quality of experience (QoE), and provides continuous, context-aware AI support.

Problem Definition / Research Gap: Current XR systems lack intelligent orchestration strategies to dynamically allocate tasks across heterogeneous edge environments and offer limited support for collaborative intelligence between co-located or remote devices. Effective edge-centric frameworks must balance latency, energy consumption, privacy, and accuracy, adapting to rapidly changing conditions.

Research and Innovation Objectives:

- Design distributed inference pipelines split across headsets, controllers, edge nodes, and the cloud, supported by dynamic orchestration and AI model migration based on context.
- Implement edge-native caching and prefetching for predictive rendering and interaction, leveraging 5G/6G for low-latency task offloading and synchronisation.
- Integrate AI accelerators across tiers for seamless collaboration, using methodologies like hierarchical task scheduling and cross-layer optimisation.

AI for content creation

Generative AI extends beyond prediction to creation, generating novel samples that follow training data distributions while remaining distinct. These technologies also hold great potential for design, creation and editing of 3D VW. This includes the generation of assets such as geometry, textures, animations, and entire scenes—enabling faster iteration cycles and lowering barriers for creative professionals and developers alike.

2f.7 Generative AI for virtual content creation and multi-scale 3D asset generation

AI content creation tools accelerate production workflows and reduce the barrier to entry for non-expert creators. Furthermore, multi-scale spatial and temporal data integration empowers the accurate reconstruction and simulation of real-world phenomena in virtual environments. Simultaneously, advances in 3D object generation and novel view synthesis allow for realistic and interactive 3D content creation from limited input, enhancing immersion and streamlining the design process across industries.

Problem Definition / Research Gap: Despite their promise, current diffusion models lack the ability to generate actionable assets in standardized 3D formats required for integration into modern content creation pipelines, limiting their utility in professional environments. Additionally, existing AI models often struggle with integrating heterogeneous datasets across spatial and temporal dimensions, which hinders accurate prediction and simulation of dynamic real-world scenarios. In 3D generation, the need remains for methods that produce high-fidelity, physically plausible objects and views from sparse data while maintaining compatibility with industry-standard graphics workflows—challenges that must be addressed for scalable, real-world deployment.

Research and Innovation Objectives:

- Integrate generative models into existing production pipelines to improve content creation efficiency.
- Design AI systems for multi-scale data fusion using temporal attention and generative reconstruction of missing data.
- Create models capable of spatio-temporal prediction from heterogeneous sources, improving realism and coherence in virtual environments.
- Build 3D object generation frameworks using diffusion and GAN architectures, integrating priors like Neural Radiance Fields and Gaussian splatting.
- Enable advanced features such as scene relighting, material editing, and novel view synthesis while ensuring compatibility with graphics engines.

2f.8 Physics-enabled content generation

Physics-enabled content generation is crucial for creating realistic and interactive virtual environments. For designers, simulation developers, and XR content creators, this ensures physical plausibility and natural behaviour of generated elements, which are essential for achieving deep immersion and high usability within VW.

Problem Definition / Research Gap: A key challenge is that current generative models struggle to produce physically accurate results. There is a notable absence of AI models capable of incorporating fundamental physical laws, such as gravity, fluid dynamics, and object continuity, into the content they generate, limiting the realism and fidelity of virtual environments.

Research and Innovation Objectives:

- Develop generative models, including diffusion models and physics-informed neural networks, that embed physical constraints.
- Implement simulation-guided learning techniques for creating content with inherent physical accuracy.

2f.9 Storytelling and application workflows

Integrating AI into storytelling and application workflows enables the creation of dynamic, personalised narratives within VW. This enhances user engagement, streamlines content creation processes, and allows for the scalable production of interactive experiences, benefiting narrative designers, game developers, and educators.

Problem Definition / Research Gap: Traditional storytelling workflows are often linear and resource-intensive, limiting adaptability and scalability. There is a need for AI-driven systems capable of generating and managing complex narratives in real-time, adapting to user interactions, and significantly reducing manual content creation efforts.

Research and Innovation Objectives:

- Develop AI frameworks combining natural language processing, procedural content generation, and user interaction data for adaptive storytelling.
- Create tools that facilitate real-time narrative generation and seamless integration with existing content pipelines.

2f.10 Multi-modality, sounds, audio, and alignment of modalities

This area enables the generation of synchronised talking avatars or human-like faces directly from audio, drastically reducing the need for video data and manual animation. For VW developers and communication platform engineers, it enhances realism, supports ultra-low-bandwidth applications like synthetic video conferencing, and increases accessibility in storytelling, education, and assistive technologies.

Problem Definition / Research Gap: Current systems struggle to produce realistic and expressive human videos purely from audio, particularly in maintaining consistency in lip sync, facial emotion, and head movement across diverse speakers and acoustic conditions. There is a need for models that not only align modalities accurately but also generate high-fidelity talking avatars or human faces from speech alone with minimal input data.

Research and Innovation Objectives:

- Integrate speech-driven generative models, such as audio-conditioned diffusion models and deformable neural avatars, for realistic rendering from audio signals.
- Focus on real-time performance and deployment on lightweight devices for practical application.

2f.11 AI for inclusion and cultural awareness

Virtual environments must support diverse users across cultures and abilities to ensure immersive, inclusive, and globally relevant experiences. For XR developers and accessibility tool providers, AI enables real-time multilingual communication, cultural sensitivity, and adaptive interfaces, enhancing engagement and broadening participation in VW.

Problem Definition / Research Gap: Current platforms lack for cultural adaptation, and accessibility, leading to exclusion and reduced immersion. There is a need for AI systems that support culturally aware interactions and accommodate diverse user needs through real-time adaptation and barrier-free design principles embedded from the start.

Research and Innovation Objectives:

- Develop AI models for real-time language translation, sentiment analysis, and cultural understanding.

- Enable seamless and respectful communication in virtual spaces through integrated AI solutions.
- Create adaptive interfaces and assistive tools for users with varying abilities.
- Build content creation tools that incorporate accessibility by design to ensure inclusive virtual experiences.

2f.12 Semantic AI and knowledge graphs and knowledge modelling

World models help AI evolve from perception to deep understanding in virtual environments through structured knowledge representation. They tackle semantic interoperability, real-time reasoning, and accessibility challenges, benefiting developers, researchers, and policymakers. This approach also enhances language interaction, content generation, personalized learning, and digital inclusion, creating a smarter and more accessible virtual world.

Problem Definition / Research Gap: VW pose challenges in handling evolving objects and relationships over time. Semantic interoperability is limited by isolated ecosystems and incompatible data models, making data integration and consistency difficult. A key research gap is developing knowledge models that learn from continuous data streams, capture causal relationships, and enable real-time reasoning in dynamic environments.

Research and Innovation Objectives:

- Develop adaptive knowledge graphs that evolve based on observed interactions, enabling robust ontologies and semantic reasoning.
- Advance data-driven knowledge modelling by combining symbolic and statistical methods for learning from VW data streams.
- Improve natural language understanding for intuitive interaction through speech and text, integrating hybrid symbolic-neural approaches and federated learning.

Foundational models for Virtual Worlds

The use of foundation models can be of paramount importance when dealing with and developing solutions for VW. Here are some research topics that might need to be investigated for this

2f.13 Adaptation and specialisation of foundation models

XR experiences demand tailored interactions matching individual cognitive, physical, and contextual user profiles. Current foundation models, trained on generic data, lack the specificity and adaptability required for specialised immersive scenarios like skill training or rehabilitation. For application designers and UX researchers, this research addresses the need for personalised, context-aware interactions in VW.

Problem Definition / Research Gap: Integrating domain-specific knowledge into foundation models is difficult, as expert data is often locked in proprietary multimodal sources. Key challenges include developing efficient multi-modal fine-tuning and Retrieval-Augmented Generation (RAG) methods with limited data. Current models also struggle with personalisation that adapts to user history, behavior, and spatial context with proper semantic grounding.

Research and Innovation Objectives:

- Develop methods for multi-modal fine-tuning of foundation models using limited domain-specific data.

- Create efficient Retrieval-Augmented Generation (RAG) pipelines to integrate structured and unstructured domain knowledge.
- Enable model personalisation that adapts to individual usage history, behaviour, and spatial context, ensuring robust semantic grounding.

2f.14 Foundation models for reasoning, planning, and tool use

XR systems need autonomous agents for user assistance, task planning, and adaptation. While foundation models excel in text, they struggle with contextual planning, memory, and tool use. Integrating structured reasoning with external tools like scene graphs, physics engines, and 3D interfaces is key to enabling real-time intelligent assistance, benefiting developers, immersive learning designers, and DT integrators.

Problem Definition / Research Gap: XR tasks require contextual and sequential reasoning, including memory, long-horizon planning, and 3D grounding. Key gaps include weak task planning in foundation models, limited scene understanding and spatial memory integration, and inadequate frameworks for using external tools like 3D viewers and spatial databases.

Research and Innovation Objectives:

- Combine language reasoning with spatial mapping and planning APIs, such as using Chain of Thought (CoT) prompting with 3D graph search.
- Develop multi-agent architectures for collaborative XR environments using foundation models.
- Integrate external tool APIs, like physics simulators and CAD libraries, into foundation model workflows.
- Design memory-augmented architectures for consistent, history-aware interactions and experiences in XR.

AI for avatars

Creating lifelike, expressive avatars is key to VW but presents major AI challenges. Current methods are slow, costly, and can reinforce biases, limiting inclusion and diverse expression. AI's advanced capabilities also raise concerns about impersonation and realistic fakes, threatening trust and psychological safety in virtual interactions.

2f.15 AI for avatar design and creation

AI for avatar design and creation empowers users to express themselves authentically and creatively in digital spaces. It supports diverse representation and democratises avatar creation across various technical and creative skill levels. This addresses the critical need for inclusive, accessible, and safe digital identities within virtual environments, benefiting end users, designers, developers, and accessibility advocates.

Problem Definition / Research Gap: Current AI avatar tools often lack diversity in representation, may perpetuate algorithmic bias, and can be challenging for non-experts to use. There is a pressing need for AI-driven solutions that ensure inclusivity, prevent the creation of harmful or misleading avatars, and provide accessible, intuitive interfaces for a wide range of users, including those with diverse abilities.

Research and Innovation Objectives:

- Develop generative AI models, such as diffusion and GANs, with explicit controls for diversity in ethnicity, gender, age, body type, and ability.

- Integrate bias detection and mitigation modules, along with safety filters, into avatar creation pipelines.
- Design user-friendly interfaces with features like real-time customisation and accessibility functionalities (e.g., voice-guided creation, templates for low-vision users).

2f.16 AI for avatar control and autonomy

AI enables avatars to shift between user-driven and autonomous control, enhancing immersion, expression, and believability in virtual environments. It supports adaptive, emotionally expressive interactions while improving engagement and accessibility. Intuitive interfaces help users manage avatar autonomy, ensuring comfort and psychological safety, benefiting developers, designers, and end users.

Problem Definition / Research Gap: Current avatar systems lack robust, explainable AI for nuanced behaviour and context adaptation. There is limited support for seamless transitions between user control and autonomy, and absence of intuitive user interfaces for managing it. Existing models frequently fail to provide deep contextual awareness or believable independent action, particularly in complex, multi-agent VW, creating a significant research gap.

Research and Innovation Objectives:

- Develop explainable AI models for behaviour modelling, leveraging reinforcement learning, imitation learning, and cognitive architectures.
- Integrate deep contextual awareness of geometry, objects, and other avatars to enable adaptive behaviour.
- Design intuitive user interfaces for live control and customisation of avatar autonomy, ensuring clear user oversight mechanisms.

2f.17 Conversational AI and autonomous Non-Player Characters

Conversational AI and Large Language Model (LLM)-driven autonomous Non-Player Characters (NPCs) enable the creation of engaging, believable, and interactive NPCs and avatars that can hold natural, contextually relevant conversations. This enhances immersion, player satisfaction, and the overall quality of virtual experiences. This benefits game developers, VW designers, and educators.

Problem Definition / Research Gap: Current NPCs often lack comprehensive contextual awareness, persistent memory, and the ability to conduct coherent, emotionally intelligent dialogues. There is a need for models that can ground conversations in the virtual world, maintain consistent personalities, remember past interactions, and understand complex user intents and emotions.

Research and Innovation Objectives:

- Develop LLM-based conversational agents with multimodal input (text, voice, gesture, facial expression) and robust world grounding.
- Implement persistent memory, personality modelling, and emotion recognition capabilities in these agents.
- Integrate ethical alignment frameworks to ensure safe and inclusive interactions.

2f.18 AI for social avatar behaviour

AI for social interaction, crowd simulation, and emergent dynamics enhances the realism and vibrancy of virtual environments by enabling avatars to engage in believable social interactions and group

behaviours. This significantly improves user immersion and psychological safety, benefiting game developers, VR designers, social scientists, and urban planners.

Problem Definition / Research Gap: Existing models often lack the capability to generate nuanced non-verbal communication, such as gaze, posture, and gestures, and struggle to effectively align multimodal interaction cues. Additionally, simulating emergent crowd behaviours that adhere to social norms and contribute positively to virtual environments remains a complex challenge, limiting the authenticity of virtual social spaces.

Research and Innovation Objectives:

- Develop AI models capable of generating nuanced non-verbal communication and aligning multimodal interaction cues.
- Research and implement methodologies for simulating emergent crowd behaviours that adhere to social norms within virtual environments.
- Explore agent-based modelling, deep reinforcement learning, and Large Language Models for realistic social dynamics.

AI for user interaction and human-AI collaboration

Creating intuitive and adaptive AI interactions in VW is challenging. Real-time user modelling—tracking state, skills, preferences, and cognitive load—is essential but complex. Current systems struggle with predicting behaviour and intentions in dynamic environments where goals shift rapidly. While VW offer accessibility potential, developing AI that seamlessly adapts content in real-time remains a significant task.

2f.19 Human-AI collaboration frameworks and interaction paradigms

Integrating AI into virtual environments can augment human capabilities, address individual limitations, and enhance accessibility. This includes real-time content adaptations, such as colour adjustments for colour-blind users, dynamic text simplification, language translation, and sign language interpretation. Such advancements will benefit VR developers, accessibility advocates, and end-users with diverse needs.

Problem Definition / Research Gap: Current virtual environments often lack systems to adapt to diverse user needs, leading to suboptimal UX. There is a need for frameworks that enable AI to seamlessly collaborate with humans, providing personalised assistance and enhancing interaction intuitiveness, thereby improving the overall human-AI partnership.

Research and Innovation Objectives:

- Develop AI-driven frameworks that augment human strengths and compensate for limitations through real-time content transformation and assistive features.
- Aim to align expectations and build mutual understanding between humans and AI agents via transparent information visualisation.
- Enable natural and intuitive multimodal interactions with AI agents, assisting in complex tasks like data exploration, collaborative design, and guided learning.
- Fusion of modalities for interaction and communication driven by AI models: As LLMs are additionally capable of processing and generating multimodal information such as a combination of visual and verbal information new interaction paradigms are emerging and will

create new opportunities for human-in-the-loop based applications, such as virtual instructors/tutors and cognitive companions in decision support.

2f.20 Intelligent multi-agent systems for dynamic and coherent interactions

Interactivity of virtual environments should be enhanced by enabling agents to collaborate effectively, exhibit emergent intelligent behaviours, and provide a coherent UX. This will help game developers, VR designers, in creating dynamic, responsive, and engaging VW with believable autonomous entities.

Problem Definition / Research Gap: Existing multi-agent systems often lack the ability to coordinate dynamically and coherently in virtual environments, leading to disjointed interactions and reduced immersion. There is a need for decentralised coordination mechanisms, shared understanding among agents, and strategies for managing collective behaviour in complex settings, which is crucial for creating truly immersive VW.

Research and Innovation Objectives:

- Develop decentralised coordination frameworks for multi-agent systems in virtual environments.
- Integrate machine learning for adaptive behaviours and implement communication protocols for shared understanding among agents.
- Design algorithms for emergent collective behaviours to create more dynamic and realistic virtual interactions.

2f.21 Explainable AI for Extended Reality interactions and decision support

Explainable AI (XAI) enhances transparency and trust in AI-driven XR applications by providing users with clear explanations of AI decisions. For XR developers, UX designers, and end-users in immersive environments, this improves user engagement and decision-making, fostering confidence and acceptance of AI assistance.

Problem Definition / Research Gap: Existing XR systems often lack mechanisms to explain AI-driven actions in a user-friendly manner, potentially leading to mistrust and reduced user engagement. There is a need for XAI techniques tailored for XR environments, including real-time, context-aware, and non-intrusive explanations that maintain immersion.

Research and Innovation Objectives:

- Develop frameworks and methodologies that integrate XAI into XR platforms.
- Focus on real-time, context-aware explanations that are non-intrusive and enhance user understanding without disrupting immersion.

2f.22 AI-Enhanced information visualisation and visual analytics

Complex datasets and AI model outputs need to be converted into intuitive, interactive, and spatially grounded visualisations. For data scientists, business analysts, and VW developers, this facilitates insight discovery, supports decision-making and addresses the challenge of making data accessible and actionable in VW, while ensuring inclusivity for users with diverse perceptual abilities.

Problem Definition / Research Gap: Current visualisation and analytics tools are primarily designed for 2D screens and do not fully leverage the unique affordances of immersive 3D environments. There is a lack of AI-driven techniques that can automatically adapt, personalise, and spatially anchor visualisations in VW, especially with built-in accessibility features for diverse user needs, which is a key barrier to widespread adoption.

Research and Innovation Objectives:

- Develop AI models that automatically generate, adapt, and personalise visualisations for 3D environments.
- Integrate spatial analytics, interactive exploration, and multi-sensory data representation (e.g., haptics, audio).
- Emphasise accessibility, including customisable visual encodings and alternative sensory outputs for diverse user requirements.

Chapter 3

SOCIO-ECONOMIC

Socio-economic outlook and challenges

Virtual Worlds (VW) are no longer speculative technologies — they are emerging as powerful platforms for interaction, work, culture, and commerce. Yet their development raises not only technical hurdles, but also profound societal, legal, and economic challenges. These non-technical dimensions are not peripheral: they are core to how VW will function, who they will serve, and whether they will reflect the values Europe aims to uphold.

As socio-technical systems, VW must be designed and governed with principles like inclusiveness, transparency, safety, sustainability, and fairness. Without deliberate attention to these aspects, there is a risk that VW will replicate or even amplify societal inequalities, corporate dominance, and opaque decision-making. Inclusive access, meaningful participation, robust oversight, and ethical design are not just desirable outcomes—they are prerequisites for success, adoption, and legitimacy.

Importantly, these challenges are not only considerations to be "managed" after technological deployment. Many raise urgent research and innovation questions. For example, how can algorithmic transparency and user agency be embedded in immersive systems? What governance models ensure both freedom of expression and effective moderation? How can business models remain competitive yet equitable and sustainable? These are not solved by engineering alone; they demand interdisciplinary inquiry and experimentation across legal, social, economic, and ethical domains.

European and international initiatives increasingly recognize this. Projects such as XR4Human and OPENVERSE, as well as frameworks developed by UNESCO and the Council of Europe, emphasize the need to build human-centric, rights-respecting virtual environments. Their work illustrates that values like accountability and inclusivity can—and must—be designed into VW from the ground up.

This chapter addresses these issues across several thematic sections. Each section outlines key societal or systemic challenges and formulates targeted Strategic Research and Innovation Objectives. These include inclusion, participation and accessibility; fundamental rights and democracy; privacy and agency; transparency and oversight; well-being; safety and consumer protection; economic and environmental sustainability; and governance. Together, they provide a foundation for developing VW that are not only technologically advanced, but also socially resilient and value driven.

3a Human rights, safety, participation and societal values

Foundations for inclusion, participation and accessibility

Virtual Worlds (VW) hold vast potential to reshape how we live, work, learn, and socialise, with forecasts predicting an immersive economy in the hundreds of billions of euros within this decade. Realising these opportunities, however, hinges on making VW inclusive, participatory, and accessible by design.

Inclusion ensures all social groups find a place and representation; participation means users have agency and voice in VW communities and governance; and accessibility guarantees that people of all abilities can create, use, and benefit from immersive technologies. These human-centric values are not merely ethical imperatives but prerequisites for mainstream adoption and success. Diversity, equity, and inclusion are foundational to a positive User Experience (UX) and key to widespread adoption. Conversely, VW lacking inclusivity or permitting abusive behaviour risk alienating large segments of users; a 2022 global survey found that 62% of people perceive a current lack of inclusivity, and 82% believe companies should actively ensure accessibility. Therefore, VW must be built for and by a broad spectrum of society, not just a privileged few.

European policymakers and international organisations increasingly recognise this need. The European Commission's 2023 "Web 4.0 and Virtual Worlds" strategy aims to ensure an open, secure, trustworthy, fair, and inclusive digital environment reflecting European values and rights, making the future immersive internet human centric. UNESCO considers truly inclusive and ethical VW "the challenge" of society's transition to immersive digital environments. Similarly, the ITU's Focus Group on the virtual world stresses inclusion, diversity, and accessibility as core principles, advocating for diverse cultures and languages and upholding UN Sustainable Development Goals on equity. Economically, VW offer a rare opportunity to design a more equitable system from the outset, avoiding the reinforcement of past tech inequalities. The following research topics address key challenges and opportunities for inclusion, participation, and accessibility, guiding a human-centric European approach.

Research topics for inclusion, participation and accessibility

3a.1 Bridging the digital divide

A critical challenge for VW is the digital divide and the high-cost barrier, which currently risk excluding large segments of society. Access to rich virtual environments often necessitates advanced Virtual Reality (VR) and Augmented Reality (AR) hardware, high-speed connectivity, and significant computing power. Addressing these socioeconomic barriers is crucial to prevent VW from becoming homogenous platforms accessible only to a privileged few. Bridging this divide ensures broader participation and democratises access to services and opportunities, such as immersive education, telehealth, and global digital collaboration for remote or underserved populations.

Problem Definition / Research Gap: Currently, 38% of consumers are concerned about the affordability of VW technologies. Furthermore, 2.9 billion people globally still lack meaningful internet connectivity, and new digital frontiers like VW risk exacerbating existing inequalities if access is not broadened. Early adopters of Extended Reality (XR) are disproportionately from wealthier groups and regions, leading to a widening gap between those who can engage in 3D digital experiences and those who cannot. Real-world inequalities, including economic disparities and a lack of digital skills and literacy required to engage with complex XR systems, risk being replicated or amplified in VW without deliberate interventions. This gap highlights the need for proactive measures to make VW participation a widely shared capability rather than a luxury.

Research and Innovation Objectives:

- Develop and deploy solutions to make VW access affordable and available to all, including research and development on low-cost XR hardware and network optimisations for efficient bandwidth use.
- Support initiatives to expand broadband infrastructure, examining subsidies or public-private partnerships to provide VR equipment in public spaces.

- Focus research on accessibility in low-resource settings, such as mobile-based or cloud-rendered virtual experiences, to ensure inclusion of developing regions and prevent the exacerbation of existing inequalities for vulnerable groups.

3a.2 Inclusive design and standards

The technical design of VW significantly impacts their inclusivity. A lack of interoperability and common standards can create siloed platforms, preventing users from seamlessly moving between different VW or transferring their digital assets and identity across platforms. This fragmentation harms overall inclusion by limiting network effects and segmenting communities. Designing for accessibility from the outset, known as native accessibility, is equally vital. Without deliberate inclusive design, XR hardware and software can inadvertently exclude people with disabilities, older adults, or others with special needs, making it difficult for them to engage with immersive experiences. By establishing common standards and applying universal design principles, VW can lower technical barriers and improve access for all, fostering broader participation and empowering people with disabilities.

Problem Definition / Research Gap: Current VW proto platforms are often siloed, hindering seamless user movement and asset portability. This fragmentation creates a significant barrier to broad inclusion and limits the scalability of VW. Furthermore, many existing XR interfaces inherently assume certain user capabilities, such as vision, hearing, fine motor control, and the ability to perceive 3D visuals. This poses considerable obstacles for individuals who are blind, deaf, motion-impaired, or prone to cybersickness. The absence of universal design principles as a foundational element in XR development means that products are not inherently usable by everyone, regardless of ability. This gap, if unchecked, risks entrenching digital divides, creating a two-tier system of compatible versus incompatible platforms and experiences accessible only to the fully able-bodied.

Research and Innovation Objectives:

- Create guidelines, standards, and tools for inclusive XR design, spanning both technical and human factors research.
- Establish interoperability standards, including open protocols for avatars, assets, and identity, to build inclusive, open, and ethically responsible VW with privacy and security by design.
- Conduct research on universal design in XR to make interfaces usable for people with diverse sensory, physical, and cognitive abilities, including developing advanced assistive technologies.
- Establish concrete parameters to secure human interaction, such as an XR Accessibility WCAG equivalent, and design toolkits to enable industry to routinely build inclusive features.
- Develop certification processes or an "inclusivity score" for platforms to measure and benchmark accessibility in VW, encouraging competition on inclusivity.

3a.3 Diverse content and representation

Achieving true inclusivity in VW extends beyond infrastructure to encompass cultural, linguistic, and representational aspects. Users need to see themselves reflected in virtual spaces, which is currently challenging as many platforms cater to a narrow demographic. Addressing this ensures that VW are welcoming and relevant to people from diverse genders, age groups, ethnic, and linguistic backgrounds. Furthermore, VW offer a significant opportunity to celebrate multiculturalism, allowing users to experience cultures and languages beyond their own, and to preserve and foster the vitality of various languages, including those of smaller communities.

Problem Definition / Research Gap: A significant challenge lies in how identities and cultures are represented in virtual spaces, as many platforms currently skew towards a narrow demographic, often young, male, and Western. This can alienate individuals from other genders, age groups, ethnic, or

linguistic backgrounds; for example, avatar design options have historically failed to capture the diversity of human skin tones, body types, clothing, or assistive devices. A survey indicated that 36% of U.S. consumers consider extensive avatar customisation options crucial for inclusive VW. If platforms do not provide broad linguistic and cultural representation, many people will not feel a sense of belonging. A darker side is the replication and amplification of social biases and harms within immersive environments, with mounting evidence of online harassment, discrimination, and hate speech feeling more traumatic in VR/AR due to the brain perceiving virtual threats as real, embodied experiences. Women, minorities, and LGBTQ+ users report intense incidents of sexual harassment and other toxic behaviours, which discourages their participation. Without proper safeguards, VW risk mirroring or magnifying real-world inequities, including racism, sexism, and ableism, and can even facilitate cultural erasure.

Research and Innovation Objectives:

- Promote research and creative innovation in linguistically and culturally diverse and representative content for VW.
- Fund experiments in multilingual, multimodal (spoken and signed languages), and multicultural virtual experiences, including indigenous language VR storytelling, virtual heritage sites, and diverse avatar assets.
- Develop inclusive avatar design frameworks that allow representation of different races, genders, body types, and abilities.
- Explore how representation affects user psychology and engagement to provide evidence that broad representation and customisation improve user retention.
- Conduct social science research, including digital anthropology, to study VW cultural parameters and inform guidelines that avoid cultural biases and respect differences.
- Build libraries of open, diverse digital assets—avatars, environments, and narratives—for communities and educators, ensuring European VW reflect Europe's cultural and linguistic diversity.
- Integrate ethical norms and robust content moderation and safety-by-design features (e.g., quick reporting/blocking tools, personal safety bubbles) to combat harassment and hate speech.
- Explore how immersive experiences can enhance empathy and understanding across cultures and abilities, enabling users to "live experiences beyond their own."

3a.4 Empowerment through governance, education and skills

A crucial objective is building the skills and human capital necessary for inclusive VW. This involves educational programmes and research into pedagogies that broaden the participation of currently under-represented groups in XR creation and leadership. Empowering a wide range of people with the skills to create and critically engage with VW ensures these spaces evolve in line with societal needs and values, rather than being dictated by a tech elite. This is essential for preventing VW from being dominated by corporate interests or authoritarian norms and for ensuring its evolution is guided by the many, not just a few.

Problem Definition / Research Gap: Many people currently lack the digital skills to comfortably engage with complex XR systems, which compounds the existing access gap. This highlights a need for comprehensive training programmes to equip users with necessary skills such as digital literacy, spatial awareness, and the ability to navigate complex virtual environments. Furthermore, there is a challenge in ensuring that decision-making and rule-setting in VW are inclusive and participatory, preventing potential domination by corporate interests or authoritarian norms. The absence of inclusive governance frameworks raises concerns about rule of law, human rights, and the potential for new forms of

inequality among citizens if accessibility issues are not addressed. Decentralised technologies, while offering opportunities for participatory governance, can also concentrate power if not deliberately made equitable, representing a challenge in ensuring genuinely inclusive user empowerment.

Research and Innovation Objectives:

- Invest in educational programs and research into pedagogies to broaden the participation of currently under-represented groups in XR creation and leadership.
- Increase the number of women, minorities, and people with disabilities in XR development, design, art, and research through targeted training programs, scholarships, bootcamps, and mentorship networks.
- Enhance digital literacy for citizens at large, helping the public understand how VW work and how to engage safely.
- Create accessible tutorials, citizen hackathons in VW building, and public deliberation exercises to foster broader public engagement and co-creation.
- Explore multi-stakeholder governance models that involve a diverse array of stakeholders (users, experts, civil society, regulators, industry) in setting rules for VW.
- Develop new tools and approaches for content moderation in immersive 3D spaces, such as avatars of moderators, to uphold community standards without infringing rights.
- Conduct experiments in participatory governance, such as extending citizen engagement into virtual city twin environments for urban planning, to enhance democratic participation.

Foundations for democracy and fundamental rights

Democracy and fundamental rights form the foundational bedrock of the European Union (EU), a principle that must be embedded and strengthened through the realisation of VW. These immersive environments have the capacity to develop a new framework for engaging with digital technology, rooted in human dignity, freedom, equality, solidarity, democracy, and the rule of law. The EU's Charter of Fundamental Rights (CFR) should serve as the guiding platform for the development, design, operation, and impact of VW, having proven a robust source of guidance amidst digital-technological transformation.

Research topics for democracy and fundamental rights

3a.5 Democracy

VW offer significant potential to enhance democratic participation by providing novel formats for people to interact and collaborate, access public services, and foster new forms of community life. These platforms enable untapped means for individuals to voice their ideas, opinions, and concerns, and for stakeholders to immersively respond to these inputs, facilitating new forms of collaborative consultation and interaction. At the same time, VW may create or exacerbate novel risks through the distortion of reality. The dynamic engagement enabled by VW, e.g. via fully immersive environments or AR overlays, will need to be closely scrutinised and moderated where risks are apparent. A democracy-first approach to interaction within VW paves the way for new modes of participation and dynamically integrates regulatory needs into their governance, enhancing accountability, particularly for digitally vulnerable individuals, and boosting digital literacy.

Problem Definition / Research Gap: VW have promising capabilities, which can be improve new forms of democratic engagement. The status of new forms of interaction and collaboration, and their role in shaping Virtual World, needs to be better understood, and legally analysed, to concretise these developments. Therein, unknown risks to political processes and existing forms of democratic

participation need to be adequately addressed, such as via effective content and conduct moderation and enforcement mechanisms. There is a specific research gap concerning the integration of democratic input to ensure accountability, especially where it is voiced by digitally vulnerable and intersectional populations. Further research is therefore necessary to fully understand and implement effective and responsive democratic mechanisms that assess and balance the societal impact of new innovations within VW.

Research and Innovation Objectives:

- Research on democracy, including as a principle of fundamental rights, through VW via new forms of collaboration, interaction, accountability, and participation.
- Research and innovation on collaborative and interactive tools for the purposes of democratic engagement through VW.
- Research and innovation on accountability mechanisms in VW.
- Research on democratic participation for the governance of VW.
- Research on democratic expression by digitally vulnerable and intersectional populations through and in VW.
- Conduct research concerning tools to moderate conduct/content in VW to fight against distortion of reality.

3a.6 Fundamental Rights

The EU Charter of Fundamental Rights enumerates a vast range of rights and freedoms, which can be profoundly affected by and uniquely realised within VW. Personal rights, including the right to physical and mental integrity, respect for family life, home, communications, and the protection of personal data, are particularly pertinent. Civic rights, crucial for democratic participation, can be advanced by innovating on user-centred design principles within VW. Furthermore, these environments can enhance and challenge freedoms of thought, expression, information, assembly, and association, allowing participants to meet and exchange ideas in new collaborative ways. Especially considering new forms of technological manipulation, VW can threaten and distort the formation and dissemination of ideas. Important social and economic rights, including the right to engage in work, freedom to conduct a business, workers' rights to information, and intellectual property (IP) rights, can also be enabled, fostering new economically and socially sustainable approaches in digital environments. A proactive approach to promoting openness, inclusion, and accessibility is paramount for the EU's unique strategy towards VW.

Problem Definition / Research Gap: While VW hold potential for enhancing fundamental rights, their current implementations can also affect these rights, necessitating careful consideration during design and deployment. There is a research gap in ensuring that the design and implementation of new technologies within VW consistently align with the CFR's provisions, particularly concerning the equality of persons. This includes addressing issues of non-discrimination, cultural diversity, gender equality, and the protection and accessibility for children, the elderly, and persons with disabilities. With the CFR serving as a vital source of inspiration, further research and innovation are essential to translate these principles into tangible, equality-centred VW, ensuring that the guiding principles on equality are not merely possible but become a lived reality for all users.

Research and Innovation Objectives:

- Research and innovation concerning the frameworks for translating fundamental rights into the context of VW, including specific personal, civic, political, economic, and social rights.

- Research and innovation concerning the protection and guarantee of physical and mental integrity, respect for private and family life, home and communications in VW.
- Promoting and advancing fundamental personal freedoms, addressing risks and threats to the freedoms of thought, of expression and of information within and through VW.
- Investigate VW' contribution to the guarantee of social and economic rights, including the freedom of assembly, respecting the needs of a socially sustainable digital environment.
- Facilitate innovative models for VW on understanding the interplay of design approaches with fundamental rights guaranteeing the equality of persons, including in regard of non-discrimination, cultural diversity, gender equality, the protection of children, the elderly and persons with disabilities.
- Investigate mechanisms that guarantee and support the effective implementation of fundamental rights concerns in VW.

3a.7 Technical tools supporting democracy and fundamental rights

Developing forward-looking practices for integrating democracy and fundamental rights into the lifecycle of VW, especially practices independent of existing large players, is urgently needed. Specific technical tools can substantially support fundamental rights considerations in digitalisation, and their application to VW is of special relevance. These tools include conformity assessment, human oversight, transparency requirements, and the prohibition of specific technologies. Such tools are crucial for ensuring that VW are developed responsibly, adhere to democratic principles, and uphold fundamental rights, thereby providing accountability and a robust framework for their deployment.

Problem Definition / Research Gap: While existing specific technical tools can support democracy and fundamental rights in digital contexts, their role and relevance require further research and innovation specifically for their application within VW. There is a clear gap in understanding how to best adapt, develop, and integrate these tools into the unique lifecycle and operation of immersive environments. Additionally, novel techniques and tools are necessary to increase the participation and responsiveness of VW to multifaceted inputs, indicating a current deficit in advanced mechanisms for robust democratic engagement and rights protection in these new digital spaces.

Research and Innovation Objective:

- Conduct research concerning specific technical tools supporting democracy and fundamental rights, and how they can be further developed for VW.
- Develop new insights into which VW-specific tools support democracy and fundamental rights

Foundations for identity, autonomy and agency

VW have the potential to revolutionise digital engagement by seamlessly integrating social, economic, and cultural activities within virtual settings, ranging from durable social immersive settings to industrial simulations. However, these platforms simultaneously pose complex questions about identity, personal autonomy, and agency, necessitating careful consideration of how users present themselves, authenticate, protect their persona, and maintain control over their experiences.

Research topics for identity, autonomy and agency

3a.8 Enhanced personal identity management

Identity in VW is a multifaceted concept encompassing how users present themselves (avatars), how they authenticate, and how they protect their persona and reputation. VW offer new freedom for identity expression, allowing users to utilise fluid and multiple identities. User identification is a priority, balancing anonymity and trust. Decentralised identity solutions and the European Digital Identity framework are promising approaches, offering users control over their digital identities across services

through verifiable credentials and selective disclosure. This architecture empowers users to reveal only context-appropriate identity attributes, bridging the gap between privacy and authentication in virtual settings, and promoting self-sovereign identity over centralised models. The goal is to enable accountability without mandating constant real-name usage, fostering trust architectures that respect privacy. Ensuring inclusive and user-centric identity representation, particularly through diverse avatar design options, is also crucial for allowing free and safe expression of personal characteristics.

Problem Definition / Research Gap: While VW offer freedom in identity expression, they raise critical challenges around authenticity, accountability, and inclusion. Reputational identity, now portable across cross-platform ecosystems, becomes vulnerable to profiling and appropriation. Traditional notions of identity must be harmonised with the fluid, self-generated digital persons prevalent in VW, raising societal, legal, and ethical questions regarding the preservation of digital identity, the possibility of a single identity across different VW via technologies like blockchain, and the limits on avatar choice or the creation of autonomous AI-powered avatars. The continuous research and innovation challenge lies in balancing anonymity and accountability, particularly concerning identity fraud, malicious impersonations, identity hacks (like deepfakes), and new forms of abuse, including virtual sexual assault and image-based abuse.

Research and Innovation Objectives:

- Create secure, user-centric identity solutions tailored to VW, including developing decentralised digital identity systems and standards aligned with the European Digital Identity.
- Enable users to verify attributes without exposing their full identity, balancing anonymity and accountability, and include safeguards against impersonation and identity theft.
- Explore an "inclusive design approach" to ensure avatars and identity features accommodate various disabilities, cultures, and preferences.

3a.9 Safeguards for user autonomy and mental well-being

Protecting users from manipulative, harmful, or addictive experiences in VW is paramount to ensuring their autonomy and mental well-being. Immersive technologies can empower users by offering new forms of agency, such as the freedom to build and explore entire virtual societies. However, they also possess the capacity to erode agency through design features that subtly manipulate behaviour. The core problem solved is ensuring that users remain in control of their virtual experiences rather than being controlled by the technology or platform operators. Safeguards are particularly critical for minors, who are at increased risk from the potential negative psychological and physical health effects of immersive environments.

Problem Definition / Research Gap: Influential system design poses a significant risk to user autonomy and agency in VW. Gamified feedback loops, adaptive advertising, algorithmically generated interactions, and AI-powered non-player characters (NPCs) can nudge users toward certain behaviours, often without meaningful awareness, complicating the boundary between consent and manipulation. The realistic simulation of sensory inputs in VR makes it a powerful medium for influence, where users may struggle to distinguish the results of choices from nudged ones manipulated outcomes, potentially undermining critical thinking. In this way, VW risk eroding democratic and fundamental-rights-based values. Social pressures, such as hyper-realistic self-customisation leading to conformity, can also affect user agency, potentially undermining diversity. Addiction and dependency are concerns, as users may feel unable to disengage, preferring virtual life to real life, which impairs broader autonomy. Physical and psychological health effects, like motion sickness or blurred reality boundaries, might reduce rational decision-making. Platform power and user agency also present a governance issue, as extensive

control by VW platforms over rules, content moderation, economic terms, and data usage can undermine users' agency as digital citizens. Ensuring effective transparency and human oversight for high-risk AI systems in these environments remains a challenge.

Research and Innovation Objectives:

- Research and implement measures to protect users from manipulative, harmful, or addictive experiences in VW.
- Develop detection tools for manipulative patterns and create opt-out or "safe mode" settings to limit persuasive content.
- Implement content moderation mechanisms capable of handling impersonation and hate appearances.
- Conduct interdisciplinary studies on the cognitive effects of immersive tech to inform legal and ethics guidelines, defining and prohibiting unacceptable practices.
- Ensure virtual environments enhance human agency through features like informed choice prompts and time reminders to prevent overuse, rather than exploiting vulnerabilities.

3a.10 Real-world Extended Reality usage understanding and its societal impacts

It is crucial to gain an empirical understanding of real-world XR usage and its societal impacts to inform effective ethical, societal, economic, and legal discussions. Currently, many of these discussions are based on anticipated scenarios rather than concrete evidence. By conducting interdisciplinary research, this objective aims to provide the necessary data and insights to ground policy, design, and regulatory responses in actual user experiences across diverse populations. This approach enables the identification and mitigation of tangible problems, fostering the development of VW that genuinely serve societal needs and values.

Problem Definition / Research Gap: The primary research gap is that current ethical, societal, economic, and legal discussions regarding VW are largely based on anticipated scenarios rather than empirical evidence of real-world XR usage. There is a pressing need for empirical research to answer specific questions, such as how different populations—including children, adults, and vulnerable groups—experience identity, privacy, autonomy, agency, and safety in current VR platforms. Furthermore, understanding the kinds of manipulative techniques already observable in VR and the identity-related conflicts (e.g., impersonation, hateful avatar expressions) that communities are encountering is essential. Without this interdisciplinary empirical research, discussions remain theoretical, limiting the ability to develop practical, evidence-based solutions for the challenges posed by immersive technologies.

Research and Innovation Objectives:

- Conduct more interdisciplinary work to understand real-world XR usage and its societal impacts.
- Implement empirical research to answer questions such as how different populations (children, adults, vulnerable groups) experience identity, privacy, autonomy, agency, and safety in current VR platforms.
- Investigate observable manipulative techniques in VR and identity-related conflicts encountered by communities (e.g., impersonation, hateful avatar expressions).

3a.11 Adaptive and future-proof regulation

Continuously studying the emerging risks of VW and feeding these findings into agile policy development is crucial for ensuring that regulatory frameworks can keep pace with rapid technological evolution. This objective supports ongoing horizon-scanning to anticipate new challenges, such as those posed by AI-driven virtual agents on user rights. It promotes the design of adaptive regulatory approaches that can be updated as VW evolve, potentially through regulatory sandboxes for testing new rules. This ensures that legal and educational responses remain effective, allowing for the analysis, evaluation, and implementation of applicable existing and new legislation, thereby balancing regulatory compliance with innovation facilitation, which is essential for Europe's leadership in digital transformation.

Problem Definition / Research Gap: The rapid advancement of VW inherently creates emerging risks that outpace traditional regulatory cycles, necessitating a continuous study of these risks and agile policy development. A significant gap exists in anticipating novel challenges, such as the implications of AI-driven virtual agents on user rights. Current regulatory approaches may not be sufficiently adaptive or future-proof to manage the evolving complexities of immersive technologies. Furthermore, ensuring effective transparency and human oversight for high-risk AI systems embedded in XR platforms remains a challenge. There is also a need for a common taxonomy and metrics for XR harms, as well as further research on evolving rights such as "perceptual autonomy" and "cognitive autonomy," indicating a conceptual and practical gap in fully defining and addressing the scope of rights in advancing immersive tech.

Research and Innovation Objectives:

- Continuously study the emerging risks of VW and feed findings into agile policy development.
- Support ongoing horizon-scanning research to anticipate new challenges, such as AI-driven virtual agents on user rights.
- Promote the design of adaptive regulatory approaches that can be updated as VW evolve, potentially via regulatory sandboxes.
- Analyse, evaluate, and implement applicable existing and new legislation, including GDPR, eIDAS, DMA, DSA, and the AI Act.
- Establish common taxonomy and metrics for XR harms (e.g., privacy breaches, manipulation severity).
- Conduct further research on rights like “perceptual autonomy” and “cognitive autonomy” as immersive tech advances.

Foundations for protection of minors

The immersion enabled by VW and the anticipated seamless integration between the physical world and the VW suggest that future generations may live in a reality where the distinction between online and offline experiences becomes blurred 1 —or at least, no longer important.

VW open new frontiers for children engagement in learning, play, and socialisation. In educational environments, VW can enhance skill-based learning, particularly in foreign language acquisition; significantly expand the range of “hands-on” learning experiences available to children; as well as introduce functionalities and opportunities for learners to engage with knowledge in ways not previously possible.2 They also offer new forms of social interaction and cultural events, and could be used in the treatment of mental health illness.3

However, VW introduce unprecedented risks that go beyond those posed by traditional ICTs. While many of the risks children face mirror those encountered by adults, their developmental stage and heightened vulnerability mean the potential for harm is significantly greater. To ensure they can engage with VW safely and ethically, an interdisciplinary approach—encompassing child psychology, education, law, and human-computer interaction—is essential. Only through such collaboration can we design virtual spaces that prioritize children's best interests from the outset.

Research topics for protection of minors

3a.12 Privacy, data protection, and unfair commercial practices

One of the primary challenges XR technologies pose to personal data protection is the sheer volume and diversity of data they collect as discussed above, which can lead to data breaches; biased or unjust inferences; decisions impacting people's lives and opportunities; as well as manipulation and exploitation (both commercially and politically), as these technologies may ultimately understand users better than they understand themselves. Considering that children are more open to external influence and merit specific protection regarding their personal data, as they may be less aware of the risks, consequences and safeguards concerned and their rights in relation to the processing of personal data (Recital 38 GDPR), age-appropriate measures should be in place. Age-appropriate design means that the default state of a platform actively promotes children's best interests, as match children's evolving capacity. Embracing this approach may ensure children's rights and well-being are prioritized from the ground up, rather than considered as afterthoughts.

Problem Definition / Research Gap: Despite growing recognition of the risks that VW pose to personal data protection, there is a significant gap in aligning the processing of children's data with the principle of the best interests of the child. Technology design often fails to incorporate age-appropriate protections by default, leaving children exposed to data-driven harms such as manipulation, profiling, commercial exploitation, and discrimination. Moreover, engineers and developers frequently lack training tailored to children's specific needs and vulnerabilities, resulting in systems that are not built with children in mind from the outset. There is a need for research that not only advances age-appropriate design in VW but also explores practical mechanisms—such as Privacy-Enhancing Technologies (PETs) and specialized training for XR developers—to ensure children's rights and well-being are embedded into these technologies from the outset.

Research and Innovation Objectives:

- Age-Appropriate PETs for VW: Develop PETs specifically tailored to children's developmental stages and digital behaviours in VW. This includes tools for real-time maximum data minimisation, consent management, age assurance mechanisms and identity protection designed with child-friendly interfaces.
- Embedding the Best Interests of the Child into XR Design Frameworks: Co-create with children and expert design guidelines and technical standards that operationalize the best interests of the child principle in VW. This involves translating legal, educational and psychological standards into actionable design patterns for developers. A rating system could also be prototyped to provide labels for VW that comply with child-safe design practices.
- Child-Centred Training Programs for XR Engineers and Developers: Design and implement interdisciplinary training modules that equip technology developers with knowledge of child development, digital rights, and ethical design practices.

- Assess how existing regulatory frameworks that protect children's data online, such as the GDPR, DSA, AVMSD and AI Act, apply to online worlds and whether additional regulation or guidance is needed to promote a precautionary approach.

3a.13 Children's safety

VW offer rich social interactions, but these can be exploited for grooming, bullying, and access to inappropriate content. The immersive nature of these environments makes all forms of abuse feel more immediate and emotionally impactful than on traditional online platforms, potentially lowering a child's defences much more quickly.4 Additionally, the use of avatars introduces new forms of behavioural cyberbullying, such as identity manipulation or avatar-based harassment. These dynamics highlight the need for behavioural moderation—not just content moderation—to effectively protect children in immersive virtual spaces.5 This is especially important in the gaming area and can be improved by AI flagging tools.6

Problem Definition / Research Gap: VW demand moderation approaches that go beyond traditional content filtering to include behavioural moderation, requiring systems that can detect and address problematic interactions in real-time, often mediated through avatars and spatialized communication. Furthermore, a major gap exists in the adequate implementation of age assurance mechanisms that are effective, privacy-preserving, and grounded in children's developmental needs.7

Research and Innovation Objectives:

- Design virtual world experiences that are age-appropriate, with strong interpersonal privacy protections embedded by design and by default. These environments should prioritize children's developmental needs and safety, ensuring that social interactions occur within clearly defined and controllable boundaries. This avoids unwanted contact and peer pressure.
- Develop advanced behavioural moderation techniques for VW that can detect and mitigate harmful interactions—such as grooming, bullying, and avatar-based harassment—in real-time, enhancing the protection of children beyond traditional content moderation. Crucially, these technologies should not only be privacy-preserving and based on children's rights by design, but also balance and respect other fundamental rights, such as freedom of expression. An important discussion also lies in defining the extent of gatekeeping power that platforms should have regarding users' fundamental rights online.
- Implement effective age assurance mechanisms that prevent children from accessing inappropriate content in VW. Develop and deploy robust, privacy-preserving technologies and protocols to accurately assess the age of users in immersive environments without exposing their identity (zero-knowledge proof technologies)

3a.14 Digital and AI literacy

Children, parents, and educators must be equipped with the knowledge, understanding, and skills to navigate VW safely and confidently. While such efforts cannot replace the need for age-appropriate, ethically designed platforms rooted in children's best interests, targeted digital and AI literacy programs play a crucial complementary role. These programs can empower children to recognize and respond to risks such as grooming, manipulation, unwanted contact, peer pressure, and algorithmic influence. They also help establish healthy digital habits, including setting boundaries around time spent online, managing emotional responses to virtual interactions, and maintaining a clear sense of self. For parents

and educators, these tools offer guidance on how to support children's online experiences, foster open communication, and advocate for safer digital ecosystems.

Problem Definition / Research Gap: Immersive experiences in VW are a novelty for everyone and human beings are certainly not fully prepared to deal with the differences they present to "normal" platforms. They introduce new psychological, social, and cognitive dynamics that users—especially children—are not fully equipped to navigate. Children, parents, and educators often lack the necessary digital and AI literacy, including the critical understanding of how immersive technologies affect attention, emotion, social interaction and decision-making. There is a pressing need for guidance and tools that help develop these competencies, especially within educational environment.

Research and Innovation objectives:

- Design and test VW safety education curricula tailored to different age groups, using interactive scenarios that enable children to practice recognizing and responding to online risks within VW.
- Co-design practical resources and training for parents, caregivers, and educators to support safe, balanced, and age-appropriate use of VW, including safety guides, household rule-setting tools, and supervision strategies that respect children's autonomy. Materials may address both technical controls (e.g. platform settings, safe play spaces) and socio-emotional guidance (e.g. managing dissociation, setting time limits).

Foundations for safety, security and consumer protection

The rapid evolution of the European consumer perspective has brought new policy significance, particularly within discussions on protecting consumers' economic interests. Emerging risks, stemming from growing information and power imbalances between digital service recipients and providers, pose new challenges for ensuring safety and security in this evolving environment, especially for vulnerable individuals like children. The emergence of VW and AI systems necessitates further research and innovation to maximise their potential in setting new standards for safety and fairness.

Research topics for safety, security and consumer protection

3a.15 "Safety and fairness by design" principles

VW present an unprecedented opportunity to create inclusive and safe environments that are "safe and fair by design." Experience with digital technologies shows that VW can profoundly impact vulnerable individuals. Amidst growing societal awareness of risks related to behavioural profiling, attention-grabbing techniques, and interface tricks (dark patterns), consumers are expected to welcome virtual environments that protect and care for them, rather than exploiting individual weaknesses. This offers a significant opportunity for legally informed research and innovation to address emerging vulnerabilities, potentially fostering a "race to the top" among service providers who prioritise consumer trust, safety, and security.

Problem Definition / Research Gap: The policy debate has seen the rise of "digital asymmetry," reflecting a permanent state of weakness for individuals due to knowledge imbalances, lack of control over online choice architectures, and asymmetries in contracting power, particularly in hyper-personalised environments. VW, enabled by worldwide sharing of personal data and behavioural tracking, pose new risks by potentially capitalising on dispositional vulnerabilities. Existing protection paradigms based on disclosure and consent are backsliding. While "fairness by design" could reverse the burden of proof in cases where individuals are affected by this asymmetry (e.g., in hyper-

personalised environments or where nudges exploit temporary vulnerable states of mind), comprehensive implementation strategies and frameworks for VW are still needed.

Research and Innovation Objectives:

- Develop and implement "safety and fairness by design" principles in VW to mitigate new digital vulnerabilities and address digital asymmetry.

3a.16 Frameworks to analyse and regulate new forms of transactions

Recent years have seen an influx of consumer-trader interactions in which money is not exchanged or does not fully cover the counter-performance (e.g., social media platforms where data constitutes the counter-performance). These transactions can also address novel products and services, blurring the line between established understandings of sale, transfer of ownership and provision of services. On the one hand, explicit recognition of these interactions as "transactions" by the Commission Guidance to the Unfair Commercial Practices Directive is groundbreaking, extending consumer law protection to attention and engagement markets. On the other hand, questions remain concerning a unified approach for transacting for novel 'objects' within VW. Developing comprehensive frameworks to analyse and regulate these new forms of transactions is crucial for ensuring consumer protection and fair practices within VW. This will clarify consumer rights and safeguard market dynamics in these evolving environments.

Problem Definition / Research Gap: While interactions where data constitutes the counter-performance have been implicitly recognised as transactions, a comprehensive theoretical underpinning for their full implications under consumer law, particularly in the context of VW, is lacking. The Commission Guidance, although groundbreaking, is non-binding, meaning its full implications for consumer protection in VW require further research. Additionally, a clearer legal understanding of the objects of these transactions is needed. Some virtual objects may provide the impression of being protected as 'property', whereas others are more obvious (new types of) services. There is thus a need to develop robust analytical and regulatory frameworks that account for the unique characteristics and complexities of transactions within immersive online environments, ensuring that consumer rights are clearly defined and upheld, and that fair practices are enforced across all forms of value exchange.

Research and Innovation Objectives:

- Develop comprehensive frameworks to analyse, evaluate and regulate new forms of transactions in VW, ensuring consumer protection and fair practices and preventing abusive practices.
- Based on legal analysis, foster a consistent understanding of the objects of new transactions within VW.
- Explore the full impact of novel transactions on consumer rights and dynamics within VW markets, including in regard of dependencies with adjacent markets.
- Inform consumers on the legal enforceability of new forms of transactions in VW.

3a.17 Fair pricing practices

Prices are a crucial signal to consumers regarding the value of goods or services. Within VW, pricing practices – as well as similar monetisation mechanisms such as virtual currencies – must uphold the high level of consumer protection of the EU. Rigorous research into protecting consumers from behavioural price personalisation is required to create a level playing field. While generally not prohibited, price personalisation based on behavioural data to assess a consumer's "willingness to pay" is a contentious policy topic. Aspects of such practices may also be intentionally concealed to 'gamify'

the consumer experience within VW Addressing this is vital as such techniques, while economically beneficial to traders, are typically detrimental to consumer welfare, carry significant discrimination risks, and can hinder consumers' ability to learn market prices and make informed choices.

Problem Definition / Research Gap: Despite being permissible under the updated Consumer Rights Directive, behavioural price personalisation raises doubts regarding its reconciliation with various consumer protection laws. It can hinder consumers' ability to ascertain market prices, affect informed choices, increase knowledge and power imbalances between consumers and traders, and potentially lead to anti-competitive effects, especially when behavioural data is shared among traders. Although few providers admit to using these techniques, their economic benefits to traders are substantial, while the detriments to consumer welfare are notable, including penalising product dependency. As VW present unique commercial opportunities, research is needed to clarify consumers' rights on digital assets and to better understand and avoid unfair pricing practices within these new environments.

Research and Innovation Objectives:

- Evaluate the role of pricing in the context of novel transactions within VW and critically evaluate potential sources of abusive discrimination.
- Develop and implement fair pricing practices in VW to protect consumers from the risks associated with behavioural price personalisation.

3a.18 Adaptive and future-proof regulation for consumer protection

Continuously studying the emerging risks in VW and feeding findings into agile policy development is essential for adaptive and future-proof regulation. This objective supports ongoing horizon-scanning to anticipate new challenges, enabling the design of regulatory approaches that can evolve with VW, potentially through regulatory sandboxes. Such adaptive regulation ensures that relevant existing and new legislation on consumer protection, including the Consumer Rights Directive, Digital Content Directive, General Product Safety Regulation, Unfair Commercial Practices Directive, and the Digital Services Act, are effectively analysed, evaluated, and implemented, thereby maintaining a high level of consumer safety and protection in dynamic digital environments.

Problem Definition / Research Gap: The rapid evolution of VW introduces new and complex risks that existing consumer protection legislation may not fully address, necessitating continuous research and agile policy development. There is a need for ongoing horizon-scanning to anticipate novel challenges that arise from these immersive environments. A key gap lies in designing regulatory approaches that can effectively adapt as VW evolve, and in implementing mechanisms like regulatory sandboxes to test new rules. Furthermore, ensuring the effective analysis, evaluation, and implementation of applicable existing and new consumer protection legislation within the unique contexts of VW remains a significant challenge.

Research and Innovation Objectives:

- Continuously study the emerging risks of VW and feed findings into agile policy development.
- Support ongoing horizon-scanning research to anticipate new challenges.
- Promote the design of adaptive regulatory approaches that can be updated as VW evolve, potentially via regulatory sandboxes to test new rules.
- Analyse, evaluate, and implement applicable existing and new legislation on consumer protection, including the Consumer Rights Directive, Digital Content Directive, General Product Safety Regulation, Unfair Commercial Practices Directive, and the Digital Services Act.

3a.19 Robust cybersecurity measures

Ensuring robust cybersecurity for the infrastructure enabling VW is an overarching concern for traders, consumers, and various economic operators. Research is vital to closely follow and scrutinise required cybersecurity measures and obligations under the EU's legal cybersecurity framework, including the Cybersecurity Act, Cyber Resilience Act, Cyber Solidarity Act, and the NIS 2 Directive. A research-informed understanding of these acts will assist in operationalising their various requirements, particularly where VW include products with digital elements (e.g., AR applications) or utilise specific information infrastructure. This complements ongoing research in cybersecurity innovation, enhancing the overall security of VW.

Problem Definition / Research Gap: A key problem is ensuring that the cybersecurity measures and obligations incumbent upon actors in VW effectively comply with the EU's legal cybersecurity framework. There is a need for research to provide a comprehensive understanding of how the requirements within the Cybersecurity Act, Cyber Resilience Act, Cyber Solidarity Act, and the NIS 2 Directive translate into operational implementation specifically for VW. This includes contexts where VW incorporate products with digital elements (like AR applications) or utilise specific information infrastructure. The gap lies in connecting these legal requirements with concrete technical implementations, ensuring that the unique cybersecurity challenges posed by immersive environments are adequately addressed and aligned with existing cybersecurity innovation development.

Research and Innovation Objectives:

- Develop and implement robust cybersecurity measures for VW, ensuring compliance with relevant EU Cybersecurity frameworks.
- Promote the uptake of cybersecure products and service in VW through the formulation of guidelines and dissemination of information to relevant stakeholders concerning their advantages.
- Provide regulatory bodies with adequate oversight concerning the cybersecurity risks relating to VW and providing effective enforcement tools to operators of VW implementations.

3b Governance and law enforcement

Foundations for privacy, data protection and data governance

Virtual Worlds (VW) represent a convergence of physical and digital realities into an interconnected and data-driven environment, rapidly expanding the ability to collect, store, and connect vast datasets. User engagement within these environments generates and processes large amounts of personal data, encompassing declared, observed, and inferred information. To ensure that VW in the EU respect the right to privacy and data protection of their users and affected individuals, it is crucial to identify, analyse, and further research the most urgent privacy and data protection challenges. Addressing these challenges is essential for fostering the development of trustworthy and secure VW.

Research topics for privacy, data protection and data governance

3b.1 Privacy and data protection by design

It is crucial to develop and implement innovations in privacy and data protection by design to safeguard user trust in VW. XR devices continuously capture highly sensitive personal data, blurring the lines between biometric and behavioural information and allowing for the inference of an unprecedented range of intimate details about users. This enables deep profiling, raising concerns about invasive user models that could be used for ad targeting, manipulation, or surveillance. Adopting principles of 'privacy

and data protection by design' is paramount for ensuring VW adhere to regulations like GDPR and the e-Privacy Directive, fostering trustworthiness and security.

Problem Definition / Research Gap: The complexity of data collection in VW, where highly sensitive personal data such as emotional states, cognitive reactions, and subconscious preferences are inferred, requires thorough evaluation. Challenges include obtaining informed, free, and meaningful consent, as immersive services often rely on implicit, continuous data collection, and users frequently lack understanding of the scope and use of their data. Issues persist in ensuring adequate data control, data minimisation, purpose limitation, transparency, and the effective exercise of data subjects' rights, as well as maintaining data security and portability. Loss of anonymity is a serious concern, as biometric patterns can uniquely identify users, leading to continuous surveillance. Inferences from XR data may qualify as sensitive data requiring robust safeguards, and the possibility of discrimination or dignity harm from misuse of such data is significant. Bystander privacy presents an emerging challenge, as devices collect data on non-users without consent. Furthermore, new data legislation poses challenges for innovation, and significant gaps remain in understanding the implications of these regulations within immersive environments. Fragmented data governance could also inadvertently hamper innovation and collaborative research.

Research and Innovation Objectives:

- Develop, incentivise, and enable the uptake of innovations in privacy and data protection by design for VW to safeguard user trust.
- Address main challenges such as robust user consent/control and transparency, handling new data types and protecting vulnerable users, ensuring interoperability and portability, mitigating data security risks, and enabling the exercise of data subject's rights.
- Tackle challenges related to identity and anonymity, abusive profiling and surveillance, and the evolving normative expectations regarding privacy that make it difficult for users to understand how their data will be used.
- Stimulate a shift from static consent mechanisms towards real-time transparency and adaptive governance for inferred and synthetic data.

3b.2 Evaluation of data governance frameworks in practice

Comprehensive, interdisciplinary normative analysis of legal dimensions is paramount for Europe to fully harness the economic, societal, research, and innovation potential of VW. The EU's data governance model, based on fundamental rights and values, aims to empower all actors in the data economy. This includes enabling companies to pool relevant data for more realistic VW environments while preserving commercial confidentiality, often through trusted data intermediaries. Evaluating these frameworks in practice is essential to understand their effects on technology deployment, innovation speed, UX, and cross-sector interoperability.

Problem Definition / Research Gap: Significant gaps persist in understanding the implications of current data law within specific immersive, interactive environments. Research efforts need to focus on data governance to promote the effective implementation of recent EU legal instruments, such as the Data Act and Data Governance Act, in the context of VW, ensuring parties are adequately protected without creating unjustified and disproportionate obstacles to the goals pursued by these legal frameworks. These include a promotion of competition and innovation, including by reducing barriers to data sharing, and the strengthening of the EU's open strategic autonomy. Governance frameworks must specifically address the complex real-time data flows, user interactions, and interoperability requirements inherent in VW to enable EU competitiveness in agile global markets.

Research and Innovation Objectives:

- Evaluate data governance frameworks in practice, particularly their effects on technology deployment, innovation speed, UX, and cross-sector interoperability.
- Inform policy refinement by balancing regulatory compliance with innovation facilitation, essential for fostering Europe's leadership in digital transformation.
- Fund multi-disciplinary collaborations involving academia, technologists, policymakers, and industry stakeholders to achieve these goals.
- Investigate data governance frameworks and their enforcement in VW, including via novel techno-regulatory approaches, while maintaining a high standard of human oversight.

Foundations for governance

Governance in VW encompasses the legal, institutional, participatory, and ethical frameworks that regulate how immersive digital environments function. These mechanisms are critical for ensuring virtual spaces align with societal norms, support democratic values, and protect fundamental rights. Unlike traditional online platforms, VW blend persistent 3D environments with avatars, biometric data, and real-time interaction, raising novel governance challenges that outpace existing laws and institutions.

The European Commission's 2023 strategy on Web 4.0 and VW recognises governance as a cornerstone of its vision: open, interoperable, inclusive, and ethically sound virtual spaces that support innovation without compromising user rights. However, current systems are fragmented, overly reliant on corporate discretion, and often lack effective mechanisms for public oversight or user participation. This chapter explores four key governance challenges and proposes strategic Research Topics to ensure that future virtual environments serve European public interests.

Institutional gaps and legal fragmentation

One of the foremost challenges in VW is the absence of a cohesive legal and institutional framework. Jurisdictional ambiguity undermines the enforcement of laws in borderless environments. For instance, when a user in one country experiences harm from another user in a different jurisdiction on a platform hosted elsewhere, it is unclear which legal system applies or how redress is pursued. Such gaps are especially problematic for issues like virtual harassment, fraud, and the regulation of digital assets.

The Council of Europe's 2023 recommendation on democratic governance in virtual environments was a milestone in identifying these institutional blind spots, but implementation remains at an early stage. Fragmentation among Member States, and between the EU and global actors, risks a patchwork of laws that invite regulatory arbitrage by dominant platforms. To address this, coordinated legal frameworks must be explored, including potential adaptations of the Digital Services Act (DSA), Digital Markets Act (DMA), and the AI Act to immersive contexts. Research must focus on legal models that accommodate immersive experiences, digital property rights, and identity sovereignty while supporting cross-border cooperation. There is also a growing case for an EU-level governance sandbox to test how existing rules can be applied—or where they must be extended—to effectively regulate the VW.

Limits of platform self-regulation

Currently, most governance in VW is dominated by platform operators, who enforce their own terms of service and community standards. While self-regulation allows for flexible, fast-moving rule-setting, it frequently lacks transparency, consistency, and accountability. Platforms act as lawmakers and enforcers without independent oversight, leading to arbitrary enforcement, unclear redress mechanisms, and potential suppression of user rights.

Moreover, content moderation in immersive environments is significantly more complex than on 2D platforms. Moderators may be unable to review three-dimensional, time-sensitive interactions without advanced tooling, and AI systems lack the nuance to address complex social behaviour in VR. Despite this, platforms are rarely held accountable for governance failures, and many users are unaware of how decisions are made or appealed. To overcome these shortcomings, hybrid models of co-regulation must be explored. These could include enforceable industry codes of conduct developed in collaboration with civil society and regulators, accompanied by independent audits or certifications. The XRSI Privacy and Safety Framework (2020) and Meta's Oversight Board are examples of emerging accountability mechanisms, but broader and more inclusive frameworks are needed. Research should investigate scalable governance architectures that embed transparency and allow for third-party review and user input.

Fragmented standards and governance models

The development of common standards for interoperability, safety, accessibility, and ethical design is essential for governing VW. Yet the current standards landscape is fragmented. Multiple actors—including the IEEE, Metaverse Standards Forum, ISO, and ITU—are developing overlapping or divergent protocols, creating confusion and inefficiencies. While technical interoperability (e.g., avatar or asset portability) is a necessary foundation, socio-technical standards that embed human rights, child safety, and privacy into design are equally crucial.

EU-funded projects such as OPENVERSE and XR4Human are attempting to address this by integrating ethical principles into the development of European VW. These initiatives demonstrate the importance of standards not just for functionality, but for upholding shared values and ensuring compliance with EU legal norms. However, uptake remains voluntary, and without alignment to regulatory frameworks or incentives such as funding conditionality or procurement criteria, many platforms may not adopt them. The EU should therefore lead in promoting European-led standards that are open, human-centric, and globally compatible. Research should identify ways to harmonise these efforts, evaluate impact, and ensure broad adoption, particularly among smaller developers.

Civic and multi-stakeholder participation

Ensuring democratic legitimacy in VW governance requires mechanisms for stakeholder and citizen participation. These include public consultations, citizen panels, advisory councils, and even direct democratic tools like virtual assemblies or decentralised autonomous organisations (DAOs). The European Citizens' Panel on Virtual Worlds (2023) provided a successful example of participatory foresight, generating citizen-driven recommendations on fairness, safety, and inclusion.

Yet these mechanisms are not yet embedded into virtual platforms. Most users remain passive consumers, with little say in the rules that govern them. Even in decentralised platforms that use voting systems, participation often skews toward wealthy or tech-savvy users, risking new forms of exclusion. Civic governance models must therefore be carefully designed to ensure accessibility, diversity, and accountability. Future research should focus on building participatory governance tools that are inclusive, scalable, and legitimate. This includes exploring how civic tech methods such as digital sortition, participatory budgeting, or co-design workshops can be translated into VR environments. These innovations can support trust, increase rule compliance, and make VW more responsive to societal needs.

Research topics for governance

3b.3 Develop harmonised legal frameworks for immersive environments

The inherent borderless nature and real-time interactivity of VW create significant legal uncertainties regarding jurisdiction, liability for AI-driven actions, and digital rights. Developing harmonised legal

frameworks is crucial for establishing clear rules, ensuring consistent enforcement of civil, criminal, consumer, and fundamental rights, and providing effective redress for online harms. This will reduce legal fragmentation, prevent regulatory arbitrage, and provide legal certainty for users and operators, fostering a trustworthy and legally sound environment for innovation and growth.

Problem Definition / Research Gap: One of the foremost challenges in VW is the absence of a cohesive legal and institutional framework, leading to jurisdictional ambiguity and undermining law enforcement. When harm occurs across borders or involves AI-driven actions, it is unclear which legal system applies, or how redress is pursued. Current legal frameworks, including the DSA, DMA, and AI Act, may require adaptations to effectively regulate immersive contexts. There is a need for research on legal models that accommodate unique aspects like immersive experiences, digital property rights, and identity sovereignty while supporting cross-border cooperation. Additionally, a gap exists in using EU-level governance sandboxes to test existing rules and identify where extensions are needed for effective VW regulation.

Research and Innovation Objectives:

- Investigate how existing laws (covering civil, criminal, consumer, and fundamental rights) can be adapted to the immersive, interactive, and cross-border nature of VW.
- Define jurisdiction in cases of online harm, liability for AI-driven actions, and enforceable rights over digital identity and assets.
- Utilise comparative legal studies, regulatory sandboxes, and co-design workshops with legal scholars, regulators, and platform operators to help shape practical policy blueprints for the EU and Member States.

3b.4 Design scalable co-regulation models for platform governance

Current governance in VW is largely dominated by platform operators, leading to a lack of transparency, consistency, and accountability in rule enforcement. This often results in arbitrary decisions, unclear redress mechanisms, and potential suppression of user rights. Content moderation in immersive environments is also more complex than on 2D platforms, requiring advanced tooling and nuanced AI systems. Designing scalable co-regulation models that augment platform self-regulation with independent oversight and legal safeguards is essential for embedding transparency, accountability, and user rights into VW governance. This will enhance legitimacy and ensure users have meaningful recourse.

Problem Definition / Research Gap: Most governance in VW is currently dominated by platform operators, leading to a lack of transparency, consistency, and accountability. These platforms act as lawmakers and enforcers without independent oversight, resulting in arbitrary enforcement and unclear redress mechanisms, potentially suppressing user rights. Content moderation in immersive environments is significantly more complex than on 2D platforms, requiring advanced tooling and nuanced AI systems, yet platforms are rarely held accountable for governance failures. There is a notable lack of research on how to design hybrid models of co-regulation that combine voluntary industry codes of conduct with enforceable obligations for transparency reporting, external auditing, and meaningful redress mechanisms. A key gap is investigating how such systems can be effectively scaled across platforms of different sizes, including SMEs, to ensure broad adoption and equitable application of governance principles.

Research and Innovation Objectives:

- Design and test co-regulatory frameworks that combine voluntary codes of conduct (e.g., on content moderation, biometric data use, algorithmic fairness) with obligations for transparency reporting, external auditing, and meaningful redress mechanisms for users.
- Give special attention to how such systems can be scaled across platforms of different sizes, including SMEs.

3b.5 Advance standards for ethics and interoperability

The current standards landscape for interoperability, safety, accessibility, and ethical design in VW is fragmented, leading to confusion and inefficiencies. While technical interoperability is foundational, socio-technical standards that embed human rights, child safety, and privacy into design are equally crucial for upholding shared values and ensuring compliance with EU legal norms. Advancing European-led standards that are open, human-centric, and globally compatible is essential for fostering a cohesive and values-driven VW ecosystem, attracting broader adoption, especially among smaller developers, and integrating ethical principles into technological development.

Problem Definition / Research Gap: The development of common standards for interoperability, safety, accessibility, and ethical design is essential for governing VW, yet the current standards landscape is fragmented, with multiple actors developing overlapping or divergent protocols. While EU-funded projects are integrating ethical principles, their uptake remains voluntary. There is a need to identify ways to harmonise these efforts, evaluate their impact, and ensure broad adoption, particularly among smaller developers, especially without direct alignment to regulatory frameworks or strong incentives. A key gap lies in fostering robust EU participation in global standard-setting efforts while simultaneously funding technical and socio-technical work to create new standards that explicitly embed accessibility, safety-by-design, privacy-enhancing technologies, and sustainability requirements, and validating their adoption through pilot implementations across sectors.

Research and Innovation Objectives:

- Align interoperability standards (covering avatars, virtual assets, data portability, and communication protocols) with ethical principles and user rights.
- Support EU participation in global standard-setting efforts (e.g., IEEE, ISO, Metaverse Standards Forum).
- Fund technical and socio-technical work to create new standards embedding accessibility, safety-by-design, privacy-enhancing technologies, and sustainability requirements.
- Utilise pilot implementations to validate adoption across sectors.

3b.6 Pilot multi-stakeholder governance bodies at the EU Level

To ensure democratic legitimacy and balanced rulemaking in VW, mechanisms for stakeholder and citizen participation are crucial. Currently, such mechanisms are not yet deeply embedded into virtual platforms, leaving most users as passive consumers with limited say in the rules governing them. Piloting multi-stakeholder governance bodies at the EU level, involving regulators, civil society, industry, and academia, will foster legitimacy and accountability. These bodies can co-develop policy recommendations, provide platform accountability metrics, and ensure VW are more responsive to societal needs and diverse user input.

Problem Definition / Research Gap: Despite the success of participatory foresight mechanisms like the European Citizens' Panel on VW, such mechanisms are not yet embedded into virtual platforms, leaving most users as passive consumers with little say in the rules that govern them. Even in decentralised

platforms, participation often skews toward wealthy or tech-savvy users, risking new forms of exclusion. There is a research gap in designing and piloting multi-stakeholder governance bodies at the EU level that are inclusive, scalable, and legitimate. This includes exploring different compositions (e.g., rotating councils, "governance observatories," permanent advisory boards) and governance models, and assessing their impact on platform behaviour and public trust to ensure effective and balanced rulemaking in VW.

Research and Innovation Objectives:

- Fund testbeds that bring together regulators, civil society, industry, and academia in advisory or oversight roles for VW.
- Explore different compositions and governance models (e.g., rotating councils, “governance observatories,” or permanent advisory boards) and assess their impact on platform behaviour and public trust.

3b.7 Participatory governance tools and civic technology

To ensure democratic legitimacy and enhance trust in VW governance, users need structured ways to participate in decision-making processes. Currently, most users remain passive, and existing decentralised governance models can still lead to exclusion. Developing inclusive, scalable, and legitimate participatory governance tools and civic tech specifically for VR environments will empower users, increase their understanding of rules, and foster a stronger sense of ownership and social cohesion within virtual spaces. This will make VW more responsive to societal needs and increase rule compliance.

Problem Definition / Research Gap: Currently, users of VW often lack structured ways to participate in decision-making processes, from community guidelines to governance reforms, remaining largely passive consumers. Even in decentralised platforms using voting systems, participation can be skewed, risking new forms of exclusion. There is a research gap in developing virtual democratic mechanisms that are inclusive, scalable, and legitimate for immersive environments. This includes exploring how civic tech methods such as digital sortition, participatory budgeting, and co-design workshops can be effectively translated into VR environments, and assessing their usability, inclusiveness, and representativeness to ensure that governance is truly responsive to societal needs.

Research and Innovation Objectives:

- Develop virtual democratic mechanisms (e.g., avatar-based deliberation spaces, voting tools, participatory budgeting systems, VR-based citizen juries).
- Assess the usability, inclusiveness, and representativeness of these tools.
- Adapt and extend methods from digital democracy and civic tech into immersive environments.

3b.8 Establish indicators and benchmarks to evaluate governance practices

Effective governance requires objective measurement to assess its quality and impact. Currently, there is a lack of defined and operationalised indicators for governance quality in Virtual Environments, making it difficult to evaluate transparency, fairness, accessibility, responsiveness, and inclusivity. Establishing robust indicators and benchmarks will provide crucial metrics for certification schemes or benchmarking tools, empowering users to make informed choices and incentivising platforms to continuously improve their governance practices. This objective will enhance accountability and build public trust in VW operations.

Problem Definition / Research Gap: Effective governance in VW currently lacks robust measurement. There is a significant research gap in defining and operationalising indicators for governance quality in virtual environments, such as transparency, fairness, accessibility, responsiveness to user complaints, and inclusivity. These metrics are essential for establishing certification schemes or benchmarking tools that could empower users and incentivise platforms to improve governance practices. Furthermore, research is needed to explore how to effectively collect and validate these data in the complex, real-time settings of immersive environments, ensuring that the evaluation frameworks are accurate and reliable.

Research and Innovation Objectives:

- Define and operationalise indicators for governance quality in virtual environments, such as transparency, fairness, accessibility, responsiveness to user complaints, and inclusivity.
- Form the basis for certification schemes or benchmarking tools that empower users and incentivise platforms to improve governance practices.
- Explore how to collect and validate these data in immersive, real-time settings.

3b.9 Strengthen global coordination on governance frameworks

VW are inherently global, meaning a fragmented approach to governance risks regulatory arbitrage and hinders broad adoption. Europe must play a proactive role in aligning governance frameworks internationally by participating in key fora like the ITU's metaverse working groups, UNESCO's digital ethics programs, and WSIS+20. Strengthening global coordination will support the development of shared principles, interoperability agreements, and mutual recognition mechanisms across jurisdictions, ensuring that VW develop as consistent, fair, and trustworthy global spaces, aligning with European values on an international stage.

Problem Definition / Research Gap: VW are inherently global, and the lack of coordinated governance frameworks internationally invites regulatory arbitrage and hinders broad adoption of shared principles. There is a need for Europe to play a proactive role in aligning governance frameworks internationally, but this requires supporting research that maps the positions of key global actors and develops effective diplomatic and policy instruments for cross-border cooperation. A specific research gap lies in identifying the most effective mechanisms for developing shared principles, interoperability agreements, and mutual recognition across diverse jurisdictions to ensure a globally consistent and ethically sound VW ecosystem.

Research and Innovation Objectives:

- Support the development of shared principles, interoperability agreements, and mutual recognition mechanisms across jurisdictions.
- Map the positions of key global actors and develop diplomatic and policy instruments for cross-border cooperation.

3b.10 Civic literacy and capacity-building for user governance

For governance mechanisms in VW to be truly effective and inclusive, users must possess a foundational understanding of their rights and roles. Currently, many users lack this civic and digital literacy, limiting their ability to engage meaningfully with governance processes. Supporting civic literacy and capacity-building programmes will empower citizens to actively participate, enhance accountability, and strengthen social cohesion within virtual spaces, ensuring that VW evolve as truly democratic and user-centric environments rather than opaque private fiefdoms.

Problem Definition / Research Gap: For governance mechanisms in VW to be effective and inclusive, a significant research gap exists in creating tools and programmes that build civic and digital literacy among users. Currently, many users lack a comprehensive understanding of their rights and roles within these new digital environments, which hinders their capacity to engage effectively in governance. There is a need to develop accessible educational campaigns, explainer materials, and capacity-building initiatives tailored for marginalized communities and civil society groups. Without such efforts, even well-designed governance tools risk being underutilised or misunderstood, thus limiting their impact on accountability and social cohesion in virtual spaces.

Research and Innovation Objectives:

- Create tools and programs that build civic and digital literacy in the context of VW.
- Include in-world education campaigns, accessible explainer materials, capacity-building for marginalized communities, and toolkits for civil society groups.

Foundations for law enforcement

VW are immersive and complex environments that pose novel risks for misconduct and crime. As these spaces become sites of real psychological, social, and economic harm, ranging from cyber harassment to fraud, traditional law enforcement must evolve to address these emerging threats. The real-time, embodied nature of virtual interactions enables illicit acts to result in immediate psychological and economic harm. However, the global, complex and dynamic nature of virtual spaces challenges current legal frameworks and traditional law enforcement. Conventional legal and forensic tools often fall short. As a result, law enforcement must adopt new methods and digital tools tailored to virtual settings. This digital transformation not only extends the reach of policing but also reshapes its daily practice. Nonetheless, such new practices demand a reevaluation of rights and safeguards in the virtual context. As VW evolve, a proactive, research-driven approach is needed to develop law enforcement models that are effective, fundamental rights-preserving, and adapted to these novel environments. Ensuring accountability while protecting fundamental rights requires innovative, rights-preserving enforcement strategies. As a result, this section identifies key research areas for enabling effective and rights-preserving law enforcement in VW. Main challenges include regulating new crime types such as cyberbullying and cyberstalking, cross-border jurisdiction, crime prediction and its limits in VW the design of digital evidence standards for virtual spaces and deep fake detection.

Research topics for law enforcement

3b.11 Investigation Methods in Virtual Worlds

Real-time interventions are critical in VW, where harassment or abuse can escalate quickly. Existing intervention approaches, which often depend on delayed victim reports, fail to provide the responsiveness required to maintain safety and trust. Therefore, new investigative methods are essential to effectively detect, prevent, and respond to misconduct in these dynamic environments.

Problem Definition / Research Gap: The main challenge for law enforcement is developing investigative tools that are technically robust, operationally responsive, and normatively grounded. AI tools designed to detect and forecast crime are often unreliable in real-time, high-variability environments, leading to hallucinations, false positives, or discriminatory outcomes. Moreover, the legal and ethical foundations for using such tools remain underdeveloped: due process, transparency, and proportionality are difficult to guarantee in systems that rely on opaque algorithms and pseudonymous interactions. There is a pressing need to design new methods that enhance the effectiveness of digital policing while embedding

technical safeguards to prevent misuse, minimise algorithmic bias, and ensure full compliance with legal and ethical standards.

Research and Innovation Objectives:

- Develop real-time avatar-based policing systems, involving verified human or AI agents capable of providing visible intervention and immediate support in virtual spaces.
- Advance predictive analytics and AI-based crime detection techniques tailored to immersive interactions, while embedding safeguards to minimise hallucinations, bias, and wrongful attribution.
- Integrate privacy-by-design and accountability measures into all new investigative technologies, ensuring that tools are transparent, explainable, and aligned with constitutional rights.
- Establish legal frameworks for regulating immersive investigative powers, clarifying conditions for evidence collection, real-time surveillance, and lawful intervention.

3b.12 Jurisdictional complexity of immersive crimes

Immersive crimes occurring in VW frequently transcend national borders, creating complex jurisdictional dilemmas. In many cases, the victim may reside in one country, the perpetrator in another, and the platform hosting the interaction in yet a third jurisdiction. In the absence of clear legal frameworks governing such transnational digital spaces, perpetrators may exploit legal ambiguities to evade accountability. Establishing coherent jurisdictional rules is therefore essential to ensure that criminal acts committed do not go unaddressed. Legal clarity in this domain enhances users' trust, facilitates enforcement, and promotes consistency in the application of justice across digital environments.

Problem Definition / Research Gap: Traditional legal systems are based on geographically defined jurisdictions, where physical territory typically determines legal authority. However, VW lack a stable spatial anchoring, complicating the assignment of jurisdiction for offences that occur within them. Existing legal systems do not offer adequate criteria for determining which state has the authority to investigate and prosecute immersive crimes, especially when elements of the offence span multiple national boundaries. Divergent national legal standards further exacerbate the problem, often resulting in jurisdictional paralysis or contradictory rulings. Without targeted reform, immersive crimes risk falling into enforcement gaps, thereby weakening the rule of law in digital contexts.

Research and Innovation Objectives

- Analyse cross-border VR crime scenarios to expose legal conflicts and enforcement voids.
- Develop new legal doctrines and models for establishing jurisdiction in VW (e.g. by harm location or asset use).
- Support the reform and harmonisation of national legal systems to explicitly extend jurisdiction to immersive misconduct.

3b.13 Capturing and analysing spatial digital evidence

Investigating crimes in VW requires capturing not just messages, but movement, proximity, and embodied interaction. Establishing reliable methods to log and reconstruct 3D events ensures that immersive crimes can be proven in court. This creates accountability, deters misconduct, and ensures digital environments are not evidence-free zones.

Problem Definition / Research Gap: Existing forensic tools are not designed to handle the complexity of VW, where interactions occur across multiple sensory and spatial modalities. There is no standardisation for logging immersive behaviour and for formats of storing and reconstructing events. Furthermore, there is a need for a common legal framework for treating such data as admissible evidence. Moreover, privacy rules may limit what can be collected or shared. Without interoperable formats, legal standards, or tools to interpret immersive data, investigations remain piecemeal and inconclusive.

Research and Innovation Objectives

- Develop forensic capture tools to log avatar movement, voice, and object states securely.
- Create analytic software to reconstruct VR incidents from multi-source spatial data.
- Define standards and legal protocols for the admissibility of immersive evidence.
- Establishment of secure data storage, chain-of-custody mechanisms, and audit trails.
- Harmonisation of forensic standards across different jurisdictions to ensure interoperability.

3b.14 Safeguarding rights during immersive investigations

The application of law enforcement in VW raises critical questions about privacy, data protection, due process, and freedom of expression. Without embedded rights protections, immersive policing risks undermining trust in law enforcement and violating fundamental rights. Ensuring transparency and legal compliance prevents abuse, protects civil liberties, and legitimises VR policing in democratic societies.

Problem Definition / Research Gap: There is a need for clear rules on how law enforcement can operate in immersive environments while respecting fundamental rights. Practices such as digital search and seizure, behavioural monitoring, and the use of biometric data lack safeguards and legal grounding. Current models risk over-collection, accidental surveillance of bystanders, or a lack of legal basis. The balance between proactive safety and user rights remains unresolved, leaving enforcement either overreaching or paralysed by legal uncertainty.

Research and Innovation Objectives

- Embed privacy-by-design into all VR investigation tools and protocols.
- Define virtual search and seizure procedures aligned with constitutional rights.
- Create oversight systems to audit and review immersive policing activities.

3b.15 Traceability in pseudonymous worlds

In VW, users frequently operate under pseudonymous or anonymous identities. Selective traceability mechanisms may allow the lawful identification of individuals engaged in criminal behaviour, without resorting to indiscriminate surveillance or compromising the privacy of regular users. By enabling targeted enforcement actions within a rights-respecting framework, selective traceability can facilitate accountability and uphold the rule of law in immersive digital environments.

Problem Definition / Research Gap: Avatars are often not directly linked to verifiable real-world identities. Practices such as identity spoofing, the creation of multiple accounts for malicious purposes, and the exploitation of cross-platform anonymity significantly impede law enforcement investigations. While biometric and behavioural identification techniques offer potential solutions, they introduce

substantial privacy and ethical concerns. Moreover, legal procedures for accessing identity-related data held by platforms remain fragmented, inconsistent, and often slow. The lack of scalable, privacy-preserving traceability mechanisms not only hampers enforcement capabilities but also fosters a climate of impunity in immersive environments.

Research and Innovation Objectives

- Design and validate AI tools for behavioural pattern attribution that can reliably detect repeat offenders across platforms, with built-in safeguards to prevent misuse or profiling.
- Establish clear legal and technical protocols for cooperation between VW platforms and law enforcement agencies to enable identity unmasking in compliance with due process and data protection standards.

3b.16 Cross-Border Legal Frameworks for Immersive Misconduct

Criminals exploit legal fragmentation across jurisdictions. An international framework for VR crime would close enforcement gaps, streamline cooperation, and ensure that immersive misconduct is addressed consistently. Harmonised laws improve justice delivery and platform accountability globally.

Problem Definition / Research Gap: Existing treaties (e.g. Budapest Convention) tackle cyber-crimes yet still lack certain rules to regulate immersive contexts. It does not per se allow common legal definitions or procedures for all VR-specific offences. Despite international efforts, legal cooperation proves to remain slow and inconsistent. Hence, without more comprehensive international collaborations, virtual crimes may remain unprosecuted or lead to conflicting legal outcomes.

Research and Innovation Objectives

- Define common legal terms for immersive offenses (e.g. “virtual assault”, ’cyberstalking’’).
- Propose protocols for enhancing VR crime cooperation.
- Design further standards for cross-border evidence sharing, aligned with privacy law.

3c Economics and innovation

Foundations of economic sustainability

Market trends analysis

The Virtual Worlds (VW) and Web 4.0 markets remain a sector with strong economic potential. Annual funding estimated between 8 and 10 billion dollars for virtual worlds-related technologies is at a level comparable to that observed during the early days of AI, reflecting a growing market and a real innovation momentum (Joint Research Centre, 2023). In 2024, the size of the AR/VR market was 16.32 billion USD and is projected to reach 123.06 billion USD by 2032 (Fortune Business Insights, 2025). This trend also verifies with the other markets involved in VW. The year 2022 was also exceptional for funding startups on the Internet of Things with an average funding amount of 15.9 million dollars worldwide per round, and even 16.7 million in Europe (IOT business news, 2023). The year 2024 was marked by a historic record of funding in the edge computing sector, with over 6 billion dollars invested, highlighting the strategic importance of this technology for the performance of VW and immersive services (STL Partners, 2024).

Actor type	Category	Estimated Market Share (%) of Total Ecosystem	Proportion of European companies

Infrastructure / Cloud / Connectivity	Service	17%	~15%
Hardware	Product	27%	~8%
Software	Product	38%	~25%
Content creators, artists and developers	Service	12%	~30%
Venues and events	Service	4%	~20%
Hardware rental	Service	2%	~20%

Source: Fortune Business Insights 2025, Grand View Research 2025, IDC (International Data Corporation) 2025, IMARC Group. 2025, MarketsandMarkets. 2025, Precedence Research 2025, Research and Markets 2024, The Business Research Company 2025

The substantial recent investments reflect the confidence of financial players in these technologies' ability to generate real added value while market revenues over the last five years show these new markets have evolved towards maturity.

Actor type	Category	Realized Revenue (2019–2024)	Key Insights
Infrastructure / Cloud / Connectivity	Service	USD 41.98B (2019) to USD 61.8B (2023)	Backbone for immersive experiences through cloud and 5G technologies. Growth driven by consumer and enterprise demand for AR/VR devices.
Hardware	Product	USD 15.9B (2024)	
Software	Product	USD 15.9B (2024)	Expansion of development platforms and enterprise applications. Dominance of individual creators and subscription-based content models. Rise in location-based entertainment and immersive physical experiences. Emerging demand for cost-effective access to AR/VR equipment.
Content creators, artists and developers	Service	USD 33.37B (2023) to USD 35.99B (2024)	
Venues and events	Service	USD 10.1B (2024)	
Hardware rental	Service	Data limited	

Sources: Business Wire, 2023, MarketsandMarkets 2024, Research and Markets, 2023, SkyQuest Technology Group, 2023[5]

Revenue analysis faces several obstacles. As of today, there is no standardized reporting system comparable to those in the financial or energy sectors that can aggregate and certify economic data from these emerging industries, especially given the highly fragmented nature of the market. Companies operating in these domains rarely publish disaggregated data by segment. Moreover, data on actual realized revenues is often reserved for clients of economic analysis firms or embedded in paid proprietary reports. This issue calls for the development of common methodological and statistical frameworks at the European level to support the growth of the immersive economy.

Despite this, the economy of VW continues the well-known dynamics of the digital economy, where a few platforms concentrate most users, creators, data, and economic value. Large platforms develop closed ecosystems where they impose access rules, control the data and content generated, and favour their own services. These dominant players expand into new markets by leveraging their existing user base and offering bundled services, thus blocking competition (Next Generation Virtual Worlds: Societal, Technological, Economic and Policy Challenges for the EU, 2023).

Moreover, to build a truly competitive market around VW, affordability to immersive experiences and devices is a prerequisite, to foster an inclusive, equitable, and sustainable market.

[5] Note: The market share percentages and the estimated proportion of European companies within each category, as presented in our previous table, are a synthesis and estimation derived from cross-referencing information found across the types of reports and analyses provided by these organisations. No single publicly accessible source provides the exact consolidated breakdown as shown in the table. Access to the full, detailed reports from these firms typically requires purchase or subscription

To go further on a responsible and resilient economy, these technologies offer performative tools to improve green finance (see next section) or to bring ESG criteria to life in dynamic and intelligible ways can help reinforce methodological rigor, break down internal silos, meet growing demands for accountability, and support the development of more robust and impactful CSR strategies. This leverage is a strategic tool to enhance the credibility and attractiveness of economic actors in the sustainable transition

The wealth generated by the VW' economy remains largely concentrated in services. It is therefore essential to develop a strategic vision that values authors, creators, and innovators, supports the emergence of independent creation and distribution solutions, and invests in sovereign hardware. This multi-pronged strategy is a key lever for building fairer, more ethical, and more resilient economic ecosystems. Such a dynamic would strengthen the attractiveness of the European market, boost research and innovation, and help attract and retain talent on a global scale.

Economic models and future perspectives

VW are seeing the emergence of several economic models at varying stages of maturity.

The most developed model currently is service provision, involving the production of IP or experiences billed to clients, often with IP rights transferred to the client. While effective, this model relies heavily on commissioned work, limiting recurring revenue streams.

Another driver is the sale or exchange of digital goods, often purchased with platform-specific virtual currencies or blockchain-based tokens. This model, drawing from Web3 principles and the digital scarcity economy, shows growth in immersive social environments. However, interoperability of digital currencies remains limited, and the ability to convert them back into fiat money is often uncertain, posing challenges for liquidity and real economic value extraction.

The monetisation of IP represents a significant transformation of the creative economy, driven by new hybrid economic models such as subscriptions, licensing schemes, pay-per-use, video on demand, or marketplaces for 3D assets. Revenues from digital licensing are projected to exceed USD 80 billion by 2026. While more sustainable and enabling passive income, this model tends to favour strong distribution actors and often excludes authors of experiential content. Implementing programmable royalty mechanisms could rebalance the value chain, ensuring continuous and automated compensation for original creators. This requires cultural transformation and tailored training for creators to adopt new tools and scalable business models.

The monetisation of data generated through interactions in VW is a major strategic asset. This data is more granular, contextual, and behaviourally rich than traditional web data. With its strict regulatory framework, particularly GDPR, Europe is uniquely positioned to offer a distinctive and ethical alternative. The EU could lead a new economic paradigm by promoting revenue redistribution models based on royalties or data dividends, for instance, by making data used to train generative AI models traceable and compensating original content creators proportionally. Considering that the VW sector already comprises 3,700 actors in Europe, and the personal data economy is projected to exceed USD 1 trillion globally by 2030, such reallocation mechanisms hold significant potential. A model where users are compensated for their data could fundamentally disrupt current competitive dynamics, positioning Europe as a pioneer of a more ethical, equitable, and autonomous immersive web.

Affordability: A key issue for competitiveness

To build a truly competitive market around VW, accessibility to immersive experiences is a prerequisite. This requires lowering entry barriers at two levels: hardware (access to XR devices) and software (optimised, resource-efficient, and cross-platform applications). Content must run on a wide range of

devices, including low-power ones, with cloud computing offering a sustainable path. Widespread adoption of applications and services depends on their integration into daily life and democratised access, especially for populations with limited digital access. Affordability is therefore a strategic lever to ensure the economic viability of creative businesses and to foster an inclusive, equitable, and sustainable market.

Research topics for economic sustainability

3c.1 Innovative frameworks for data monetisation

The monetisation of data generated through interactions in VW represents a major strategic asset in the evolving digital economy, offering data that is more granular, contextual, and behaviourally rich than that from traditional web platforms. Exploring the exploitation of such data could possibly enable European companies of all size to be able to compete with leading non-European players that are using the wealth generated by user data. Be able to offer low price points on the use of their solutions.
Europe, with its robust regulatory framework like GDPR, is uniquely positioned to establish a distinctive and ethical economic paradigm by promoting revenue redistribution models, such as royalties or data dividend compensating users for their data use could fundamentally disrupt current competitive dynamics, positioning Europe as a pioneer of a more ethical, equitable, and autonomous immersive web.

Problem Definition / Research Gap: Despite the strategic value of data monetisation in VW, there is a significant gap in developing and implementing innovative frameworks, methods, and tools specifically adapted to these immersive and AI-driven environments. Current economic models primarily focus on service provision or digital goods sales, which have limitations. While the potential for revenue redistribution (e.g., traceable data for AI training leading to compensation for creators) is recognised, practical mechanisms for implementing such models at scale, ensuring fairness, proportionality, and adherence to European values, are not yet fully defined or widely adopted. Research is needed to bridge this gap, translating ethical aspirations into viable economic models.

Research and Innovation Objectives:

- Investigate innovative frameworks, methods, and tools for designing data monetisation models, particularly those adapted to virtual and immersive and AI environments.
- Investigate, support, and design the introduction of a "fair trade" label for VW to promote towards fairer and more equitable trade standards

3c.2 Affordable and accessible immersive technologies

To build a truly competitive and inclusive market around VW, affordability and accessibility of immersive experiences are prerequisites. This requires lowering entry barriers on both hardware (access to XR devices) and software (optimised, resource-efficient, and cross-platform applications) levels. Ensuring content can run on a wide range of devices, including low-power ones, and leveraging cloud computing, is crucial for democratising access. When access is democratised, especially for populations with limited digital access, applications and services can achieve widespread adoption and become part of people's daily lives, thereby ensuring the economic viability of creative businesses and fostering an inclusive, equitable, and sustainable market.

Problem Definition / Research Gap: A key barrier to the widespread adoption and economic viability of VW is the lack of affordability and accessibility of immersive technologies. This creates a digital divide, limiting equitable access across different socio-economic and geographic populations. Currently, there is a research gap in innovating design and distribution methods that can effectively lower the entry barriers for XR devices and ensure that software is optimised, resource-efficient, and cross-platform

compatible. The challenge lies in developing solutions that enable content to run efficiently on a wide range of devices, including low-power ones, and in fully leveraging cloud computing as a sustainable means to achieve broad accessibility, ensuring that VW do not become exclusive to a technologically privileged segment of the population.

Research and Innovation Objectives:

- Innovate in the design and distribution of affordable and accessible immersive technologies to reduce the digital divide, ensuring equitable access to VW across different socio-economic and geographic populations.

Foundations for innovation, Intellectual Property and creativity

VW represent a pivotal technological frontier where digital and physical realities converge, enabling transformative processes across diverse sectors. While these immersive digital environments offer substantial benefits, legal uncertainties, particularly in IP rights (IPRs), present challenges for innovation, human creative labour, and public and private investments. Comprehensive, interdisciplinary normative analysis of these legal dimensions is paramount for Europe to fully harness the economic, societal, research, and innovation potential of VW.

Research topics for innovation, Intellectual Property and creativity

3c.3 Legal insights and frameworks

VW are inherently content-intensive ecosystems, heavily reliant on digital assets commonly protected by copyright and other IPRs. In an era where intangible assets constitute up to 90 percent of companies' market value, transparency and fairness in terms of IPR ownership and exploitation are a policy priority. By developing novel legal insights and frameworks, Europe can establish global standards, moving beyond merely conforming to international developments. This will empower European companies, researchers, and policymakers to confidently and sustainably drive innovation forward, ensuring Europe's competitive advantage in VW.

Problem Definition / Research Gap: Pressing questions arise as to the application of existing rules on IP validity, ownership, and exploitation to (co-)creation ecosystems in VW, where platform terms and conditions play a significant role against the backdrop of existing legal frameworks. The creative process within VW must be scrutinised from a legal perspective. VW also constitute a potential platform for new types of IPR infringement, such as unauthorised use of trademarks, requiring in-depth research on the application of various infringement grounds. The global nature of VW leads to vital questions of public and private enforcement, including applicable law, jurisdiction, burden of proof, and appropriate cross-border sanctions. Moreover, traditional IPR frameworks and infrastructures are increasingly proving inadequate for managing digital innovation, particularly given the proliferation of generative AI. Fundamental questions about access, transparency, infringement, liability, governance, and remuneration for AI-generated content remain unresolved, undermining creators' incentives, researchers' access, and industry adoption. Furthermore, the effectiveness and scope of Trade Secrets (TS) protections within VW remain poorly understood, especially given the necessity for interoperability, transparency, and standards development. Without clear legal guidelines balancing secrecy with necessary openness, Europe risks fragmenting its technological base, reducing collaboration, and undermining innovation potential.

Research and Innovation Objectives:

- Focus funding priorities and action on exploring in an interdisciplinary manner the theoretical and practical legal and policy implications relevant to the unique challenges posed by VW.

- Enable advanced research and training within Europe's academic and research institutions, creating a skilled workforce capable of managing the intricate legal and governance challenges inherent in VW.
- Resolve IP complexities and streamline data governance frameworks through targeted research programs designed to address these legal uncertainties.

3d Sustainability, health and environment

Foundations for environmental sustainability

The development and growing adoption of Virtual Worlds (VW) technologies raise both major environmental challenges (carbon footprint, biodiversity loss, energy consumption, etc.) and unprecedented opportunities to advance sustainability. When strategically aligned with our environmental goals, these technologies can become powerful levers to support the ecological transition by fostering ecological awareness, optimising resource use, and enabling efficient planning. This ambivalence calls for proactive governance and ethical innovation, highlighting the need for integrated research and innovation efforts to assess, regulate, and harness the environmental potential of Web 4.0, ensuring that technological progress actively contributes to climate and biodiversity objectives. It would also be strategic to develop innovative financial tools and methodologies tailored to the specificities of immersive technologies, linked to their environmental performance, to strengthen investor and stakeholder confidence in funded projects by maximising sustainable financing effectiveness and steering investments toward more responsible solutions.

Research topics for environmental sustainability technology

3d.1 Hardware-related environmental sustainability

The widespread adoption of VW technologies, characterised by immersion, simultaneity, persistence, and virtualisation, represents a major carbon footprint challenge. Proactive measures for digital sobriety, eco-design, and infrastructure decarbonisation are crucial to mitigate the increasing carbon footprint of the digital sector by 2030. Investigating new components and circular economy frameworks for hardware design is essential to ensure that the growth of immersive technologies aligns with sustainability goals, reducing their environmental impact and fostering more responsible technological development.

Problem Definition / Research Gap: Forward-looking analyses indicate that the development of immersive technologies will be a factor in the increasing carbon footprint of the digital sector by 2030, potentially emitting up to 4 gigatons of CO_2 equivalent per year, representing approximately 7% of total global emissions, unless significant measures are implemented. This expansion also drives a growing demand for digital devices and infrastructure, intensifying the extraction of rare earth elements (projected to increase by 400-600% in coming decades), which significantly impacts biodiversity and ecosystem preservation. Furthermore, global electronic waste is forecast to reach approximately 74 million tonnes by 2030, with only about 17.4% formally collected and recycled, leading to improper management that aggravates pollution of soil, water, and air, harming ecosystem health and biodiversity.

Research and Innovation Objectives:

- Investigate new components on the design and innovation of core materials and conductors for computing systems, including hardware components, to improve sustainability, efficiency, and performance.

- Investigate new circular economy frameworks tailored to the lifecycle management of specific digital hardware integrated into Web 4.0 devices, such as VR headsets, AR glasses, and other emerging technologies.

3d.2 Software-related environmental sustainability

The expansion of cloud services and the complexity of immersive technologies could lead to a significant increase in energy consumption. Software eco-conception offers a dual strategic benefit: it ensures a responsible and sustainable consumption of VW applications and enables developers to create experiences with the highest level of performance. Optimised software, based on rigorous access rights management and efficient code design, is a key lever for reducing computational costs and energy consumption, particularly in the emerging context of spatial computing which mobilises a wide range of hardware and software resources.

Problem Definition / Research Gap: The expansion of cloud services in Europe, driven by the widespread adoption of immersive technologies, could increase energy consumption by a factor of 5 to 10 due to the complexity and intensity of 3D computations, real-time video streaming, and continuous infrastructure operation. A crucial issue lies in the fine governance of software conception and its direct impact on energy consumption. Software permissions, which determine access to hardware and software resources, significantly influence energy consumption. Broad permissions make it complex to control resource consumption and predict energy impact precisely. There is a need to develop a methodological foundation for sustainable software design that incorporates principles like DRY (Don't Repeat Yourself), micro-coding, data compression/decompression techniques, and procedural generation for resource efficiency. Furthermore, there is a gap in standardised and binding mechanisms to control digital sobriety practices aimed at reducing computational costs, such as automated control tools integrated into creation and distribution platforms. The difficulty of conducting a systemic analysis of environmental impacts also lies in assessing indirect and rebound effects, where efficiency gains paradoxically lead to an overall increase in consumption.

Research and Innovation Objectives:

- Investigate and design a methodological foundation for sustainable software design, focused on DRY principles (Don't Repeat Yourself), micro-coding with lightweight, purpose-specific routines, data compression/decompression techniques to optimise storage and bandwidth, and procedural generation for dynamic, resource-efficient instantiation of digital content.
- Explore tool and methodology standardised and binding mechanisms to control digital sobriety practices aimed at reducing computational costs. These mechanisms could be automated control tools integrated into creation and distribution platforms and tools, acting as a pre-export filter, validating compliance with commitments regarding responsible coding, resource optimisation, and limitation of the computational cost of applications.

3d.3 Software and hardware interplay for environmental sustainability

Understanding the combined environmental impact of both software and hardware in Web4 digital infrastructures is crucial for a comprehensive approach to sustainability. Developing measurement tools capable of real-time monitoring of ecological and energy footprints allows for evidence-based decision-making. Comparative studies of different adoption scenarios, like cloud versus native computing, are vital for improving the understanding of direct, indirect, and rebound effects, enabling more accurate assessments and informed strategies to mitigate environmental consequences of digital technology.

Problem Definition / Research Gap: The difficulty of conducting a systemic analysis of the environmental impacts of digital technology lies in the ability to assess indirect effects (environmental

consequences not directly resulting from use but induced by adoption) and rebound effects (where efficiency gains paradoxically lead to an overall increase in consumption). This complexity means there are currently insufficient robust measurement tools to accurately monitor the sustainability of Web4 digital infrastructures, encompassing both hardware and software, in real-time. There is a need for studies and prospective analyses that can compare different adoption scenarios to comprehensively understand these complex interactions and their true ecological and energy footprints.

Research and Innovation Objectives:

- Innovate and develop measurement tools for the sustainability of Web4 digital infrastructures, both hardware and software, capable of enabling real-time monitoring of the ecological and energy footprint associated with new practices and usages.
- Investigate studies and prospective analyses comparing different scenarios adoption (like cloud computing versus native computing) with the aim of improving understanding of direct, indirect effects and rebound effects.

Research topics for environmental sustainability applications

3d.4 Immersive environments for environmental awareness

The interactive nature of VW significantly enhances learning, awareness, and ecological engagement by providing a **deep understanding of environmental issues** through AR/VR experiences. Studies have demonstrated that immersive visualisations (e.g., of melting glaciers) can significantly impact climate change awareness, surpassing traditional formats, and influence behaviour change related to sustainable consumption. Investigating immersive environments tailored to raise public awareness is crucial for fostering a more environmentally conscious society and driving engagement with critical ecological challenges.

Problem Definition / Research Gap: While there is promising evidence that immersive environments can significantly enhance environmental awareness and even influence behaviour, there is still a need for further dedicated investigation into their design and effectiveness. Specifically, research is needed to systematically explore how different immersive experiences (AR/VR) can be best designed to communicate complex environmental issues, foster ecological understanding, and encourage tangible behavioural changes across diverse demographics. The challenge lies in developing scalable and impactful immersive applications that go beyond anecdotal success to provide robust, measurable outcomes in public environmental literacy and engagement.

Research and Innovation Objectives:

- Investigate immersive environments aimed at raising public awareness and understanding of critical environmental issues.

3d.5 Immersive tools for resource and logistic efficiency

Immersive technologies provide powerful levers to make distribution chains more efficient and sustainable. Pioneering applications in industry and e-commerce demonstrate strong potential to reduce logistical costs and carbon footprint, including waste, transportation, product returns, and physical storage. The use of digital prototypes in the design process can significantly reduce the carbon footprint of fashion brands by limiting textile waste and associated energy consumption. By investigating advanced tools and methods for VW applications in key sectors like retail supply chains, it's possible to support production reduction, enhance resource and logistic efficiency, and promote circular economy principles.

Problem Definition / Research Gap: While there is promising potential for immersive technologies to enhance efficiency and sustainability in distribution chains, quantitative data remain limited. There is a need for further investigation into advanced tools and methods for VW applications specifically tailored to key sectors such as the retail supply chain. This research should focus on how immersive technologies can effectively support production reduction, enhance resource and logistic efficiency, and promote circular economy principles across the entire supply chain. Bridging this gap will involve developing and testing practical applications that demonstrate measurable reductions in logistical costs, waste, and carbon footprint.

Research and Innovation Objectives:

- Investigate tools and methods advanced for VW applications across key sectors such as the retail supply chain to explore how immersive technologies can support production reduction, resource and logistic efficiency, and circular economy principles.

3d.6 Immersive E-commerce solutions for waste reduction

Integrating immersive and AR solutions into e-commerce platforms offers a significant opportunity to improve inventory and production management, enhance forecasting accuracy, and refine consumer behaviour modelling. This can lead to substantial reductions in overproduction, waste, and product returns, contributing to a more sustainable retail sector. By enabling consumers to make more informed choices through immersive experiences, such as virtual fitting rooms and immersive configurators, these technologies enhance efficiency and minimise environmental impact.

Problem Definition / Research Gap: Despite the promising potential, there is a need for comprehensive investigation into tools, applications, and methodologies for effectively integrating immersive and AR solutions into e-commerce platforms. While the distribution sector is a major area of investment in AR/VR technologies, specific research is needed to determine the optimal ways these technologies can improve inventory and production management, enhance forecasting accuracy, and refine consumer behaviour modelling to directly reduce overproduction, waste, and product returns. Collaborating with industry stakeholders is crucial to develop and validate practical solutions that translate these technological capabilities into tangible environmental benefits.

Research and Innovation Objectives:

- Investigate tools, application and methodologies for integrating immersive and AR solutions into e-commerce platforms.
- Collaborate with industry stakeholders to improve inventory and production management, enhance forecasting accuracy, and refine consumer behavior modelling, thereby reducing overproduction, waste, and product returns.

3d.7 Impact-based funding matrix for immersive technology companies

DTs and VW enable the creation of detailed and interactive virtual representations of funded projects, which improves the quality, reliability, and granularity of data used for ESG reporting. This facilitates a more transparent and rigorous assessment of environmental and social impacts, providing access to up-to-date information on environmental performance. By investigating and developing an Impact-Based Funding Matrix, it's possible to link access to public or private funding with the environmental performance of companies developing or using immersive technologies. This will strategically leverage green finance to enhance the management of complex data related to environmental, social, and governance (ESG) criteria, directing investments towards more responsible solutions and strengthening investor and stakeholder confidence in sustainable financing.

Problem Definition / Research Gap: While Web4 technologies are leveraging green finance to manage ESG data, there is a specific need to investigate and develop a multi-criteria evaluation framework—an "Impact-Based Funding Matrix"—that directly links access to public or private funding with the environmental performance of companies involved in immersive technologies. The current gap lies in the absence of a standardised methodology to comprehensively assess and quantify the environmental performance of immersive technology companies to inform funding decisions. This framework needs to be robust enough to reflect the complex environmental impacts (both positive and negative) of their hardware and software, ensuring that financial incentives genuinely promote more sustainable practices within the sector.

Research and Innovation Objectives:

- Investigate tools, application and methodologies for an Impact-Based Funding Matrix for Immersive Technology Companies, like a multi-criteria evaluation framework linking access to public or private funding with the environmental performance of companies developing or using immersive technologies.

Foundations for health and well-being

As VW become increasingly embedded in work, education, and leisure, their potential health impacts must be addressed through proactive and interdisciplinary research. Immersive technologies pose unique risks compared to traditional media: they alter sensory input, affect users' perception of agency, and introduce novel physiological and psychological stressors. This section identifies research priorities to ensure VW promote health, respect user autonomy, and avoid long-term harm. The focus is on physical, sensory, cognitive, and occupational health impacts across all user demographics, excluding children unless unique concerns arise not already addressed in the section on Protection of Minors.

Research topics on health and well-being

3d.8 Physical and visual health in immersive environments

VW require head-worn displays and embodied interaction, introducing ergonomic strain and visual health risks. As users spend longer durations in immersive environments – whether for work, training, or entertainment – the risk of discomfort, injury, or lasting physiological impacts grows. Prolonged use can contribute to neck and shoulder pain, reduced blinking, dry eyes, visual fatigue, and postural stress. Preventing such risks is vital for the long-term adoption of VW across age groups and settings, particularly for professionals using VR/AR daily. Ensuring physical and visual well-being will also promote equitable access, enabling older adults, people with disabilities, and vulnerable users to participate safely.

Problem Definition / Research Gap: Current immersive hardware often lacks ergonomic optimisation, placing stress on the neck, arms, and eyes. Factors like device weight, headset fit, motion intensity, interpupillary distance (IPD), brightness, and environmental lighting affect user comfort. Visual discomfort is particularly complex: vergence-accommodation conflict, low frame rates, and reduced blink rate all contribute to strain, but their long-term effects, particularly on children and adolescents, remain understudied. There is a need to define acceptable exposure limits, especially for repetitive professional use. Today's safety standards for visual exposure and physical strain in VW are fragmented and rarely tested in real-world settings. Research must therefore bridge human–computer interaction, optometry, ergonomics, and occupational health.

Research and Innovation Objectives:

- Develop ergonomic, lightweight XR hardware and controller designs based on musculoskeletal data to reduce postural fatigue across diverse user groups.
- Implement adaptive brightness and contrast control based on ambient lighting and real-time fatigue detection to reduce visual strain.
- Conduct clinical trials using eye biomarkers (e.g. pupillometry, ocular surface health) to assess visual health impacts across age groups, with special attention to children and adolescents.
- Create spatial awareness systems and interaction frameworks that prevent injuries from real-world collisions during full-body movement.
- Establish usage recommendations and safe exposure guidelines for immersive work and leisure contexts, including dynamic break schedules and positioning advice.

3d.9 Sensory overload and cybersickness

Cybersickness is one of the most reported barriers to XR adoption, causing nausea, dizziness, disorientation, and fatigue. These symptoms arise when visual motion cues do not match the user's bodily sensations, often during navigation or high-speed experiences. Immersive environments also present intense visual and auditory stimuli, which can result in cognitive overload and hinder task performance. Mitigating these effects is essential to ensure that VW can be used comfortably across sessions and user types, especially in education and professional settings where prolonged use is expected.

Problem Definition / Research Gap: While short-term cybersickness is well documented, long-term exposure studies are scarce. We lack predictive models of individual susceptibility, especially for older adults and neurodiverse users. Furthermore, immersive systems rarely adapt to user discomfort in real-time. Real-world applications often fail to integrate proactive safeguards, such as real-time motion smoothing or adaptive field-of-view controls. Additional concerns include post-experience disorientation and lag in spatial perception, which may interfere with daily functioning or increase accident risk. There is a need for advanced detection methods and personalised adaptation strategies to reduce sensory strain.

Research and Innovation Objectives:

- Design adaptive systems that monitor biometric indicators (e.g. heart rate variability, head motion) to detect discomfort and dynamically adjust motion, perspective, or environment stimuli.
- Investigate visual-vestibular mismatch mechanisms in immersive contexts to develop predictive tools for cybersickness susceptibility and mitigation strategies.
- Establish user-specific comfort profiles and labelling systems to rate experiences based on sensory load and suitability across demographics.
- Study sensory recalibration and recovery patterns to inform best practices for session duration, exit protocols, and gradual re-entry into the physical world.
- Integrate AI-driven comfort modes in XR applications to limit strain during prolonged or intense experiences.

3d.10 Mental health and psychological agency

VW can empower users through creativity, exploration, and social interaction. However, the same design features can erode mental well-being and autonomy if they exploit user attention or emotional vulnerabilities. Issues such as overexposure, compulsive use, and identity confusion emerge in immersive settings that blur the lines between reality and simulation. Ensuring that users retain a sense of control and informed consent in their experiences is essential to prevent manipulation, support mental health, and preserve digital agency – particularly in the face of persuasive design patterns and algorithmically steered interactions. This challenge becomes even more complex when it comes to children and adolescents, who are in a formative stage of cognitive, emotional, and social development. VW can negatively interfere with the processes of identity formation, emotional regulation, and boundary-setting. This can lead to confusion, as well increased vulnerability to external validation loops and manipulation. Moreover, constant connectivity and the pressure to maintain a virtual presence can contribute to anxiety, sleep disturbances, and reduced real-world social engagement.

Problem Definition / Research Gap: Immersive environments can introduce addictive mechanics, social pressure, and behavioural nudging through adaptive feedback loops, AI-powered NPCs, and persistent engagement rewards. These systems may influence user decision-making subconsciously, especially when sensory realism amplifies perceived consequences. Current regulation frameworks do not address these risks in immersive contexts, where embodiment and emotional presence intensify impact. There is limited research into how such design patterns affect users' sense of self, autonomy, or critical reasoning. Furthermore, withdrawal effects after intensive use, such as derealisation or post-VR sadness, are poorly understood but reported anecdotally. Tools for identifying and preventing manipulative experiences are still lacking.

Research and Innovation Objectives:

- Create detection tools for manipulative or addictive design patterns and develop opt-out mechanisms or "safe modes" that promote informed choice and usage transparency.
- Study the psychological effects of avatar embodiment, social conformity, and virtual identity dynamics on self-esteem, critical thinking, and autonomy.
- Define legal and ethical thresholds for influence, particularly for vulnerable users, and develop guidelines to prohibit unacceptable persuasive practices.
- Integrate time-awareness features and digital well-being prompts in immersive systems to support self-regulation and reduce compulsive use.
- Explore immersive withdrawal phenomena and develop re-entry practices to ease cognitive transition and emotional recovery after deep engagement.
- Investigate the long-term effects of VW environments on children's identity formation through longitudinal studies, informing age-appropriate design and ethical development practices

3d.11 Occupational health and extended immersion

VW are entering the workplace for training, remote collaboration, and simulation. While promising, this shift introduces new occupational health risks. Extended immersion can cause eye strain, postural discomfort, mental fatigue, and technostress. Productivity may decline if environments are not designed ergonomically or cognitively aligned with task requirements. Ensuring XR systems support worker health will help organisations adopt these tools responsibly and sustainably.

Problem Definition / Research Gap: Most workplace XR systems are not designed with occupational ergonomics in mind. Employees may spend long periods in environments that strain their vision or posture, with limited guidance on safe usage patterns. There is little empirical data on optimal session lengths, cognitive workload, or multi-tasking capacity in VR/AR contexts. Additionally, few tools exist to support worker well-being in real-time, such as in-headset assistants or health-aware user interfaces. Inclusive design for neurodiverse or physically impaired employees remains underdeveloped. There is a clear need for workplace-focused XR research that translates into practical, evidence-based policy.

Research and Innovation Objectives:

- Conduct field studies comparing immersive and non-immersive work to evaluate impacts on productivity, fatigue, and musculoskeletal load across roles.
- Develop in-XR ergonomic assistants and posture monitoring tools to guide users toward safe usage habits and suggest breaks or adjustments.
- Produce standardised occupational health protocols for immersive work environments, covering hygiene, exposure limits, and accessibility.
- Co-create interface designs tailored for cognitive efficiency in professional tasks, including adaptive interface density and distraction reduction.
- Explore organisational integration of XR tools with employee wellness strategies and existing occupational health monitoring systems.

3e Trust and human oversight

Foundations for transparency, explainability and human oversight

The emergence of immersive Virtual Worlds (VW) presents unprecedented opportunities but also heightens concerns regarding transparency, explainability, and human oversight. These environments integrate AI-driven algorithms, pervasive data collection, and complex socio-technical systems that profoundly shape user experiences. Algorithmic opacity and a lack of accountability in immersive spaces can erode user trust, undermine privacy and autonomy, and potentially threaten democratic values. Transparency and responsibility are recognised as dominant principles for addressing XR's ethical challenges, and international bodies emphasise transparency and human control as prerequisites for protecting human rights in AI-infused virtual environments. This chapter examines key challenges of algorithmic opacity, content moderation governance, and data practices in VW, linking each to specific research gaps and innovation requirements, with an emphasis on societal and governance dimensions alongside technical advances in explainability.

Research topics for transparency, explainability and human oversight

3e.1 Design for human oversight of Extended Reality

VW platforms increasingly rely on algorithms and AI agents to mediate user experiences, from content recommendations to non-playable character behaviours and adaptive learning scenarios. However, these algorithmic operations often function as "black boxes," making their decisions uninterpretable and unpredictable. In immersive settings, AI-driven agents or recommendation engines can subtly shape users' perceptions and actions without their awareness, leading to an asymmetry of information that can be exploited. This opacity undermines user trust and complicates accountability, as it becomes unclear who or what is responsible for automated decisions. Ensuring human oversight is critical for safeguarding fundamental rights and promoting user empowerment in these environments.

Problem Definition / Research Gap: A significant problem is the "black box" nature of algorithmic operations and AI agents in VW, making their decisions opaque to users and even developers. This lack of transparency leads to trust erosion and accountability issues, as users are rarely informed about automated tasks or algorithmic decision-making processes. There is a notable absence of research on Explainable AI (XAI) techniques specifically tailored to immersive XR contexts, as traditional explainability tools do not translate well to 3D/AR interfaces. Open questions remain on how to convey algorithmic workings in real-time within an embodied experience without disrupting immersion, and few studies examine user comprehension of AI explanations in VR. From a policy perspective, regulatory mandates for transparency, such as the EU AI Act, lack defined enforcement mechanisms and standards for "appropriate transparency" in XR. There is insufficient research on audit frameworks for complex, proprietary XR algorithms, and a need for multi-disciplinary research to link technical transparency solutions with ethical design, avoiding information overload and aligning explanations with human values.

Research and Innovation Objectives:

- Create new techniques for explainable AI in immersive environments, enabling VW systems (recommender engines, AI agents, moderation bots) to provide clear, contextually relevant explanations to users in real-time.
- Research visualisation and interaction methods for conveying algorithmic logic within VR/AR settings, as well as methods to change these settings.

3e.2 Establish auditing frameworks

Establishing robust auditing frameworks for VW is essential for increasing transparency and accountability in their operations. When algorithmic operations and content moderation are opaque, user trust is eroded, and it becomes difficult to hold platforms accountable for potentially biased or arbitrary decisions. Implementing transparent logging mechanisms and independent audit tools allows regulators and third parties to inspect and verify platform behaviour. This provides a necessary mechanism for scrutiny, ensuring that VW meet explainability and risk management criteria, thereby fostering a culture of algorithmic accountability within the XR industry.

Problem Definition / Research Gap: A significant gap exists in establishing standardised frameworks for auditing XR platforms. There is a lack of defined processes for independent auditors or oversight bodies to technically inspect proprietary XR algorithms for bias or risks, given their complexity. Current regulations, such as the EU AI Act, may mandate certain transparency, but enforcement mechanisms and standards for "appropriate transparency" in XR are still undefined. Additionally, while the EU plans centres for algorithmic transparency for very large online platforms, extending such oversight to VW platforms requires further definition and implementation. This absence of clear, verifiable audit procedures hinders accountability and limits the ability of external bodies to ensure algorithms meet necessary explainability and risk management criteria.

Research and Innovation Objectives:

- Design and pilot standardised frameworks for auditing XR platforms, including transparent logging mechanisms, independent audit tools, and procedures for regulators or third parties to verify platform behaviour.
- Make VW operations inspectable and verifiable, laying the groundwork for accountability.

3e.3 Implement AI content labelling and moderation explainability

Developing robust systems to label AI-generated or manipulated content and ensuring explainable content moderation decisions are critical for maintaining user trust and protecting fundamental rights in VW. The immersive, real-time nature of these environments amplifies challenges around content moderation, where harassment, hate speech, and abusive behaviours can take novel forms demanding swift intervention. However, current internal moderation processes often lack transparency, leading to user distrust and perceptions of bias or arbitrariness. By providing clear explanations and appeals processes for moderation decisions, and by effectively labelling AI-generated content, platforms can enhance legitimacy, uphold free expression, and ensure due process rights for users.

Problem Definition / Research Gap: A key problem is the lack of transparent and accountable content moderation processes in VW, where platforms often handle moderation internally with little disclosure to users or outsiders. Users frequently do not understand why decisions were made, leading to distrust and assumptions of bias. There are minimal avenues for appeal or external oversight, raising concerns about due process rights and the ability of regulators and civil society to scrutinise platform practices effectively. Furthermore, content moderation in XR is a nascent field with significant gaps in developing tools suited to 3D/VR environments, particularly for automated detection of visual or behavioural violations and the interpretation of complex spatial behaviour or voice chat. There is also a gap in understanding user expectations and optimal ways to convey moderation processes. While regulations like the EU Digital Services Act (DSA) mandate transparency, their extension and enforcement mechanisms for immersive platforms require further development.

Research and Innovation Objectives:

- Develop robust systems to label AI-generated or manipulated content in VW (avatars, objects, media) so users can distinguish synthetic from real.
- Ensure content moderation decisions—whether by human or AI—are accompanied by meaningful explanations and appeals processes in XR, building on DSA's transparency requirements.
- Bring existing and new mechanisms for combating disinformation to XR environments.

3e.4 Develop standards and codes for transparent and ethical design

Collaborating across industry, academia, and civil society to produce European standards or codes of conduct for transparent and ethical XR system design is crucial. Such standards define best practices for transparency, explainability, and user oversight, ensuring that VW are developed with human values and rights at their core. These guidelines are essential for avoiding dark patterns, requiring algorithmic fairness assessments, and ensuring human-in-the-loop control for high-risk applications, thereby bolstering user trust and accountability. This collaborative approach helps define norms in a rapidly evolving technological landscape, informing future regulation and voluntary certification schemes.

Problem Definition / Research Gap: A significant gap exists in establishing widely adopted standards and codes of conduct specifically tailored to transparency and ethical design in XR systems. While there are emerging efforts, there is no comprehensive set of European-level guidelines that define best practices for explainability and user oversight. This includes a lack of clear guidance on how to avoid dark patterns, establish requirements for algorithmic fairness assessments in VW, and implement provisions for human-in-the-loop control for high-risk applications effectively. The absence of such unified standards means that transparency and ethical considerations are often implemented inconsistently or insufficiently across different XR platforms, leaving users vulnerable and impeding the development of a trusted ecosystem.

Research and Innovation Objectives:

- Collaborate across industry, academia, and civil society to produce European standards or codes of conduct that define best practices for transparency, explainability, and user oversight in XR system design.
- Include guidelines on avoiding dark patterns, requirements for algorithmic fairness assessments in VW, and provisions for human-in-the-loop control for high-risk applications.
- Inform both future regulation and voluntary certification schemes for XR platforms.

3e.5 Monitor and mitigate algorithmic harms

Continuously monitoring the societal impact of VW algorithms and developing intervention strategies to mitigate harms is crucial for safeguarding fundamental rights and societal trust. This approach ensures that transparency and oversight are living commitments, allowing for the collection of evidence and the iterative, evidence-based adaptation of governance. By identifying early warning indicators for issues like algorithmic bias, addictive design, or harmful manipulation in VR, this objective enables proactive measures to ensure VW flourish as environments for creativity, connection, and commerce, grounded in respect for digital rights and EU laws and values.

Problem Definition / Research Gap: A significant research gap exists in the continuous monitoring of the societal impact of VW algorithms, particularly their effects on mental health, equality, or democratic discourse. There is a need to develop robust early warning indicators for emerging issues such as algorithmic bias, addictive design patterns, or harmful manipulation within VR environments. Furthermore, research is required to innovate effective intervention strategies, such as configurable user settings or regulatory "circuit breakers," that can mitigate these identified harms. This signifies a challenge in establishing an iterative, evidence-based approach to governance that can adapt as new algorithmic harms manifest in immersive technologies.

Research and Innovation Objectives:

- Launch research initiatives to continuously monitor the societal impact of VW algorithms, studying effects on mental health, equality, or democratic discourse.
- Develop early warning indicators for issues like algorithmic bias, addictive design, or harmful manipulation in VR.
- Innovate intervention strategies to mitigate these harms, such as configurable user settings or regulatory "circuit breakers" for certain features.
- Treat transparency and oversight as living commitments by collecting evidence and adapting governance in an iterative, evidence-based manner.

Chapter 4

EUROPEAN RESEARCH AND INNOVATION CONTEXT

European research and innovation context

The Virtual Worlds (VW) partnership acknowledges the importance of collaboration with other research domains. Concretely, VW strongly build on data governance, data analytics and data processing capabilities. Also, advancements in infrastructure, networks and compute power are prerequisites for the realisation of VW applications. Moreover, optics and photonics technologies are crucial for realizing visualisation and sensing devices supporting these applications. As these topics are addressed in other EU initiatives, they are referred to in this SRIA.

4a Data governance, analytics and processing

The emergence of VW as persistent, intelligent, and interconnected digital ecosystems necessitates a radical rethinking of how data is governed, processed, and analysed. Unlike traditional internet platforms, VW are immersive, dynamic, and designed for multiple users, incorporating real-time AI-driven interactions, biometric feedback, decentralised content generation, and cross-domain services.

In such environments, data governance should be considered as a foundational design principle that ensures trust, inclusivity, security, compliance, and ethical alignment. This necessitates robust frameworks for interoperability, access control, consent management, and auditable data flows, consistent with European regulatory frameworks such as the General Data Protection Regulation (GDPR), the AI Act, the Data Act, the Data Governance Act, and forthcoming Digital Identity regulations.

Equally important are advanced data analytics and novel data architectures to support capabilities such as context-aware behaviour modelling, content personalisation, moderation, and economic system simulation.

Finally, the strict demands of VW, particularly in terms of real-time responsiveness, adaptiveness and scale-up, require seamless integration of data processing pipelines with diverse computing infrastructures, including edge, cloud and HPC. These systems must operate in real-time and across geographies, while maintaining end-to-end low latency, data security, and energy efficiency.

Key research topics for data governance, analytics and processing

To build future-ready and ethically grounded VW, several research themes must be addressed:

4a.1 Data formats and interoperability

- End-to-end data interoperability across VW components, ensuring technical interoperability in all VW elements, and semantic interoperability in those intended to interpret and use the data

- Seamless deployment of data pipelines over heterogeneous infrastructures, including adaptive orchestration across edge, cloud, fog, and HPC environments, ensuring low latency, resilience, and energy efficiency.

4a.2 Data governance and compliance

- Point-to-point data governance, including traceability, privacy, data quality, consent management, identity assurance, and security
- Ethical and legal compliance by design, embedding compliance, fairness, explainability, and inclusiveness into data practices from the design phase, aligned with evolving European regulations.

4a.3 Data processing

- Secure, scalable, and federated data processing architectures, specifically conceived to address VW requirements, including privacy preserving computation (federated learning) and architectures to handle sensitive, distributed, and high-volume data securely.
- Domain-specific data preparation and representation, including techniques to pre-process, clean, annotate, enrich, … data for its specific use in VW related applications, such as DTs, AI agents, content generation, behavioural simulation, …
- Integration and analysis of multimodal and real-time data, to support context-aware AI, personalisation, and adaptive experiences.

Relevant EU programs and initiatives contributing to the realisation

The European Data strategy, published in 2020 paved the way to fully unlock the value of data in Europe, through the European Common Data Spaces. The implementation of these data spaces, funding under the Digital Europe Programme, initially targeted eight relevant domains in the EU, including media (Trusted European data Space for Media / TEMS). Additionally, the Horizon Europe Programme is funding research and innovation actions to advance the state of the art in topics like compliance, privacy preservation, green and responsible data operations, data management, data trading, monetizing, exchange and interoperability, architectures and standards for complex data cycles, or AI-driven data operations and compliance technologies. This strategy will be reinforced with the upcoming European Data Union strategy, that will rely on three pillars: facilitate or increase the access to data (specially for AI), regulatory simplification and international data sharing

In July 2024, the European Commission's AI Innovation Package introduced AI Factories, funded by the EuroHPC JU. These open ecosystems, built around EU supercomputers, are designed to develop and train large AI models, offering AI and data services and accessing vast amounts of high-quality industrial data. Complementing this, the AI Continent Action Plan proposes Data Labs to ensure AI developers have access to sector-specific, high-quality data.

Lastly, significant standardisation efforts, like CEN-CENELEC's JTC25 "Data, dataspaces, cloud and edge", aim to establish harmonized standards supporting interoperability, trust, and scalability in European data ecosystems, in line with the Data Act.

From the private side, BDVA has been supported the development of the EU data economy, first as the private counterpart of the EC for the BDV PPP, then as part of ADRA for the ADR-PPP. BDVA joined forces with IDSA, FIWARE and Gaia-X to form the Data Spaces Business Alliance. BDVA is a private member of the EuroHPC JU and of the Computing Continuum Initiative.

4b Infrastructure, networks, and compute

Intelligent connectivity is key for the implementation and deployment of edge intelligent immersive technologies combining Augmented, Virtual and Extended Reality (AR/VR/XR) with concepts like VW, multiverses, next-generation spatial web, Web 4.0 as part of future VW. This requires advancements in infrastructure, networks and compute.

Future VW applications will place entirely new demands on the network in terms of uplink, downlink, latency, and jitter requirements depending on the deployment scenario. For example, while near-term 5G conversational AR applications may require somewhere up to 20 Mbps downlink, 10 Mbps uplink and 10 milliseconds latency (including RAN and Core), it is expected that future massive multi-sensory XR could require anything up to 1 Gbps downlink, 100 Mbps uplink and 5 milliseconds latency – with a need for high edge cloud compute offload. Some extremely demanding holographic communication use cases featuring very high fidelity could even place demands of up to 10 Gbps downlink, 5 Gbps uplink and as low as one millisecond latency on the network.

AI-native architectures, API-enabled network platforms, and new compute fabrics such as energy-efficient neuromorphic computing, will also carry significant weight in terms of service enablement and acceleration, and must also be addressed in the coming years.

The interplay between multimodal sensing, ubiquitous connectivity, and 6G positioning technologies, together with DT and cloud-based spatial mapping technologies, will form a cornerstone of future programmable VW providing a new playing field for truly immersive communication.

High-quality VW experiences will also be dependent on the advancement of video compression technologies. For instance, Versatile Video Coding (VVC) will free up networks to not only handle traffic from cutting edge technologies like mixed reality – AR and VR applications that have the potential to transform everything from city planning, to education, to gaming – but also to deal with the increased amount of video conferencing and remote collaborative tools.

6G will revolutionise XR by addressing current limitations (latency, bandwidth, mobility) and providing communication and computing integrated network to enable new use cases:

Key research topics for data governance, analytics and processing

4b.1 Ultra-low latency for real-time interaction

- To cover all VW use cases, the optimal latency should be around 10 ms. For motion to photon latency 10ms is expected (most VR headsets render at 90fps, meaning 11ms). Latency is highly depending on what kind of computation is done remotely: visual rendering (around 10ms), haptics feedback computation (around 20ms), relocalisation (no strong needs for high latency)
- Holographic Communication: 6G's sub-millisecond latency will support real-time holograms for telepresence, remote collaboration, and social XR.
- Tactile Internet: Enables haptic feedback in VR/AR, crucial for remote surgery, industrial training, and gaming.
- Immersive triplets and DT

4b.2 Massive bandwidth for high-fidelity Extended Reality

- 8K/16K 360° Streaming: 6G's terabit-level speeds will support ultra-high-resolution XR content without compression artifacts.
- Multi-Sensory XR: Supports smell, touch, and taste simulations in virtual environments.

4b.3 AI-integrated edge computing

- Distributed AI Processing: 6G networks will use AI-driven edge computing to offload XR rendering tasks, reducing device dependency.
- Context-Aware XR: AI in 6G will enable adaptive XR experiences based on user behaviour, environment, and network conditions.

4b.4 Ubiquitous connectivity with terahertz (THz) and satellite integration

- THz Frequencies (100 GHz – 10 THz): Enable ultra-high-speed short-range XR data transfers (e.g., wireless AR glasses).
- Non-Terrestrial Networks (NTN): 6G will integrate satellites and drones for global XR coverage, enabling outdoor AR navigation and disaster response.

4b.5 6G for wearable extended reality devices

- 6G's energy-efficient protocols will extend battery life for lightweight AR glasses and VR headsets.
- An opportunity for European Industry to take the lead on XR devices (Smart glasses, Head Mounted Displays, Interaction controllers, haptic devices, holographic display, ...).
- The border between network and devices is getting ever fuzzier, some of those should become part of the future networks. This is addressed in multiple chapters in this SRIA.

4b.6 Centimetre (cm) accurate positioning systems

- Integration of new radio and computer-vision based localisation positioning systems will enable large-scale AR experiences indoor and outdoor

Relevant EU programs and initiatives contributing to the realisation

The Smart Network and Services Join Undertaking (SNS JU), The New European Media Initiative (NEM), and the Alliance for AI, IoT and Edge Continuum Innovation (AIOTI) are addressing research in several activities and projects supported by the European Commission that can contribute to the VW partnership on this specific domain. Network infrastructures including edge computing, IoT and devices are key enablers contributing to the adoption of VW in various verticals such as manufacturing, transport and logistics, healthcare, media and entertainment, cultural heritage, automotive, education, public safety and disaster response (PPDR), smart cities, and others. Several SNS JU projects are already addressing such use cases that could contribute to the definition of the VW partnership

4c Optics and Photonics

The realisation of VW hinges on the advancement of optics and photonics technologies. As an enabler of fast data transmission, high-resolution display systems, and advanced sensing capabilities, photonics plays an important role in shaping the performance, scalability, and user experience of VW.

Photonics underpins the optical communication infrastructure that supports the large bandwidth and ultra-low latency requirements of VW applications. This includes the deployment of high-capacity fibre-optic networks, integrated photonic circuits, and optical interconnects to facilitate data exchange between edge, cloud, and high-performance computing (HPC) environments. These technologies enable real-time responsiveness, synchronisation, and scalability. In addition, optics and photonics serve next-generation display and imaging systems for immersive experiences. Innovations in micro-LEDs, holographic displays, and light field technologies are required for visual interfaces, while optical sensors and LiDAR systems enhance spatial awareness, gesture recognition, and environmental interaction

within VW. Photonics also contributes to energy efficiency and sustainability by reducing power consumption of data centres and communication networks through optical switching and signal processing. This aligns with broader goals of environmental responsibility and long-term viability of digital infrastructures.

While photonics is out of scope of this SRIA, its strategic importance as an enabling technology necessitates close coordination with the Photonics21 Association and Photonics partnership, as stated in the position paper, jointly published by Photonics21 and the VR/AR Industrial Coalition in January 2024: "*Optics and Photonics Technologies Serving Virtual Worlds*".

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