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List of acronyms

Abbreviation /acronym	Description
AI	Artificial Intelligence
API	Application Programming Interface
AR	Augmented Reality
AVC	Advanced Video Coding
CP	Consortium Partners
CTU	Coding Tree Unit
DiffServ	Differentiated Services
EIA	Environmental Impact Assessment
EP	Epic
FoV	Field of Views
FVV	Free-Viewpoint Video
GraphQL	Open source Query Language for APIs
HEVC	High-Efficiency Video Coding
HMD	Head-Mounted Display
HRTF	Head-Related Transfer Functions
IntServ	Integrated Services
IP	Internet Protocol
ISOBMFF	ISO Base Media File Format
ITU	International Telecommunication Union
LDT	Local Digital Twin
MIM	Minimal Interoperability Mechanisms
MIV	Metadata for Immersive Video
MMT	MPEG MediaTransport
MR	Mixed Reality
MSF	Metaverse Standards Forum
NGSI-LD	NGSI-LD is an API and information model for sharing context information standardized by ETSI
OMAF	Omnidirectional Media Format
OpenXR	OpenXR is an open, royalty-free standard developed by the Khronos Group to unify the development of VR and AR applications

OTT	Over-The-Top
OUP	Open Urban Platform
PSNR	Peak-Signal-to-Noise-Ratio
RESTful	Representational State Transfer APIs
RSVP	Resource Reservation Protocol
RTP	Real-time Transport Protocol
RTSP	Real-time Streaming Protocol
SAREF	Smart Applications Reference
SDK	Software Development Kit
SLAM	Simultaneous Localization and Mapping
SSIM	Structure Similarity
QoE	Quality of Experience
QoS	Quality of Service
TCP	Transmission Control Protocol
TML	Traffic simulation
UI	User Interface
US	User Story
UX	User Experience
VR	Virtual Reality
VVC	Versatile Video Coding
WCAG	Web Content Accessibility Guidelines
WebXR	WebXR is an emerging technology standard designed to make XR experiences accessible through the web
XR	Extended Reality
3D	Three Dimensional

Executive summary

This report presents a comprehensive study on use case development for the x-CITE project, with the primary goal of creating demonstrators that integrate Extended Reality (XR), Local Digital Twin (LDT) platforms, and participatory digital innovation in European cities. The document lays out the guiding principles, technical frameworks, and collaborative methods that are essential for building modular, user-centric, and scalable digital solutions for urban environments.

At the outset, the report introduces the core aims and structure of x-CITE. It outlines how the project harnesses joint development, integration, and iterative testing within real-world pilot cities. The introductory chapters describe how the project brings together diverse partners and stakeholders to co-develop the CitiVerse environment, relying on the LDT Toolbox as the central technical and methodological resource. The reader gains an understanding of how collaborative development cycles, feedback loops, and reuse of EU-wide assets support responsible and future-proof digital urban transformation.

The section on conceptual design and technical foundations explains the step-by-step process of transforming user needs and project targets into practical solutions. Here, the report details the methods for user system analysis, stakeholder engagement, and the translation of requirements into conceptual designs and demonstrator architectures. This chapter offers the reader clear insight into how software, hardware, and data integration planning ensure that each demonstrator not only addresses local city needs but also aligns with open standards and modularity for broader scalability.

A dedicated chapter on UI and UX design emphasises the importance of building accessible, intuitive, and inclusive interfaces for all user groups. The knowledge captured here guides use case developers through the process of designing immersive, multi-device XR experiences that promote participation, agency, and trust. The report also covers accessibility best practices and highlights the connection between thoughtful design and successful user adoption.

The chapters on technical and governance requirements provide a foundation for developers and planners seeking to ensure interoperability, security, and privacy across all components of the CitiVerse environment. This part of the report maps out the main architectural building blocks, integration points, and emerging standards that must be observed for robust LDT-XR solutions. The content is valuable for those who need to understand how to align pilot use cases with both the technical and ethical expectations of the broader EU digital ecosystem.

In the detailed use case sections, the report reviews the experience and knowledge gained from pilots in Tampere, Rotterdam, and Flanders. Each chapter presents a full description of the local context, objectives, and implementation strategies, showing how the use case teams have leveraged XR and LDT technologies to address cultural, educational, participatory, or environmental challenges. The reader can learn from the practical methods for stakeholder engagement, the iterative refinement of user

interfaces, and the integration of data streams and simulation models. The knowledge contained in these chapters is especially valuable for anyone working on similar urban transformation projects or seeking to replicate successful approaches in other cities.

Importantly, this report matters because it not only documents the technical and organisational progress of the x-CITE project but also provides a clear demonstration of how innovation in the digital urban domain can be responsibly and inclusively achieved. By bringing together practical experience and theoretical insights, the report shows what is possible when cities, technology providers, and citizens collaborate within a shared framework. It achieves a significant milestone by mapping the journey from abstract concepts to working demonstrators in real environments, revealing how robust methodologies, open standards, and stakeholder involvement can yield scalable and adaptable solutions for urban challenges. The lessons learned throughout the project, including the value of cross-sectoral collaboration, the need for flexible technical architectures, and the critical importance of accessibility and inclusivity, offer guidance for future initiatives both within and beyond the x-CITE network.

These findings imply that the next steps for x-CITE should focus on deepening the integration of demonstrators into urban systems, expanding the range of use cases, and strengthening the mechanisms for feedback and knowledge sharing across European cities. The report highlights the necessity of ongoing alignment with EU frameworks and the importance of leveraging the LDT Toolbox to ensure that future projects benefit from established best practices and technical resources. For the wider EU context, the report demonstrates a replicable model for responsible digital transformation, emphasising openness, ethical governance, and user empowerment. As such, it serves as both a benchmark and an inspiration, encouraging stakeholders across Europe to pursue innovative urban solutions that are not only technically advanced but also socially responsive and sustainable.

Finally, the report concludes by reflecting on the lessons learned and the ongoing alignment with the EU LDT Toolbox. The summary highlights how the principles, technical frameworks, and practical experience documented here offer a roadmap for cities and innovators aiming to realise responsible, open, and inclusive digital urban environments. Each chapter of the report contributes essential knowledge for the design, implementation, and scale-up of CitiVerse demonstrators, making this study a cornerstone for future development within the x-CITE project and beyond.

This report stands as both a detailed guide and a practical reference for use case development within x-CITE. It provides the information and tools needed to turn innovative ideas into tested demonstrators, ensuring that digital urban transformation is achievable, sustainable, and beneficial to all stakeholders involved.

x-CITE use cases and leaders

Use Case ID	Name	Leader	Emails
1	Digital public art map	Sanni Leimio	sanni.leimio@tampere.fi
2	Art biennial	Johanna Kangas	johanna.t.kangas@tampere.fi
3	Cathedral 1918 - Civil war storytelling	Antti Hannunen	antti.hannunen@tampere.fi
4	Culture & children (Art Arc)	Liisa Aholainen	liisa.aholainen@tampere.fi
5	Nokia Arena	Jukka Saarinen	jukka.saarinen@nokia.com
6	Neighbourhood engagement	Brenda van Breemen-Olij	b.vanbreemenolij@rotterdam.nl
7	Students' engagement	Beauty and Design Lab	b.vanbreemenolij@rotterdam.nl
8	Insightful spatial implementation plan	Tom Callens	tom.callens@vlaanderen.be
9	Co-design traffic mitigation measures	Tom Callens	tom.callens@vlaanderen.be
10	Enhance quality of traffic debate	Tom Callens	tom.callens@vlaanderen.be
11	Simulate EIA procedure	Karen Bosmans	karen.bosmans@vlaanderen.be
12	Roadmap for EIA LDT	Karen Bosmans	karen.bosmans@vlaanderen.be

Use case exploration and demonstrator development in the x-CITE project

Introduction

The x-CITE project, or Expanding the Experience of Citizens through Extended Reality, is a large-scale European initiative focused on integrating Extended Reality (XR) technologies including Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) with Local Digital Twin (LDT) platforms in urban contexts. Its over-arching goal is to enable immersive, interactive, and user-centric experiences in smart cities and urban planning, while fostering citizen participation and ensuring cross-domain interoperability.

At the heart of the x-CITE project are well-defined principles for use case development, which ensure that new solutions are not isolated efforts but part of a modular, reusable, and federate ecosystem that can grow and adapt alongside Europe's cities. This summary presents a systematic synthesis of those principles, organized into core themes and subchapters, and details how these are operationalized within the x-CITE framework to set new standards for responsible digital urban transformation.

Joint development, integration, and testing of the CitiVerse environment in x-CITE use cases

Within the x-CITE project, the exploration of use cases in Tampere, Rotterdam, and Flanders is anchored in a methodology of joint development, rigorous integration, and continuous testing. The pilot cities are not merely sites for isolated experiments but living laboratories that bring together diverse technical expertise, local knowledge, and the lived experiences of end-users and city stakeholders.

The process is inherently collaborative, requiring developers, designers, and users to work side by side with city officials and local partners. This synergy ensures that every facet of the CitiVerse environment is shaped by both technological innovation and the realities of urban life.

At the core of this approach lies the commitment to leverage the assets and standards provided by the LDT Toolbox, which serves as both a technical resource and a compass for design decisions throughout the project. The LDT Toolbox, developed from extensive EU-funded research, offers modular solutions, integration frameworks, and a suite of reusable best practices.

Use case teams are encouraged to incorporate these tools at every phase, beginning with the adoption of digital twin building blocks, data management templates, security protocols, and interoperability mechanisms. This deliberate reuse not only fosters efficiency and compatibility but also ensures that the pilot solutions remain aligned with EU-wide ambitions for open, interoperable and sustainable digital urban transformation.

The joint development process is cyclical and iterative. Early activities draw upon the LDT Toolbox for baseline architectures and proven frameworks, which are then adapted to local contexts through intensive collaboration. Integration is far from a purely technical exercise; it involves aligning regulatory compliance, ethical standards, and user expectations with the technical capabilities of each pilot.

Project teams conduct regular workshops, participatory design sessions, and simulated deployments, refining the CitiVerse environment through real-world feedback and incremental improvements. These activities are mapped against the LDT Toolbox to help ensure compatibility and to highlight areas where new solutions may be needed.

Testing is an essential driver of innovation and reliability in the x-CITE project. Use cases undergo phased validation, starting with controlled, simulated environments and gradually expanding into real-world urban contexts. Technical assessments such as interoperability trials, scalability tests, and performance evaluations are conducted in parallel with stakeholder and user feedback sessions. Every test is an opportunity to compare the project's outputs against the assets and standards of the LDT Toolbox, ensuring that solutions are not only robust but also transferable across different urban scenarios.

The targets set out in the original project plan are intrinsically linked to broader EU ambitions for smart, sustainable, and inclusive cities. By embedding the principles of interoperability, reusability, and stakeholder participation into every pilot, the x-CITE project contributes to the European objective of creating digital environments where citizens, policymakers, and industry partners can collaborate, innovate, and engage meaningfully.

The use cases are intended as proof of concept for CitiVerse functionalities, generating insights and data that inform user acceptance and feed into the development of scalable, market-ready solutions. These outcomes support the EU's commitment to leveraging digital technologies for urban transformation, and the iterative, collaborative process ensures that solutions developed in one city or use case can be scaled and adapted throughout the European landscape.

Role and scope of use case development

Use case development within the x-CITE project is guided by a set of objectives anchored in the integration of XR with LDTs. The primary aim is to create an enabling environment where use cases are both user-friendly and interoperable, leveraging open standards and modular architectures. These use cases are intended to be adaptable for a wide range of city platforms and XR devices, ensuring that every solution delivers value not only in its original context but as a component that can be replicated and scaled to other European cities.

To achieve these objectives, x-CITE begins each use case process with a comprehensive user system analysis. This foundational analysis identifies the needs, preferences, and accessibility requirements of diverse user groups including citizens, policymakers,

cultural practitioners, educators, students, and software developers. By focusing on inclusivity and adaptability from the outset, the project ensures that XR interfaces can be accessed and meaningfully used by all stakeholders, across a spectrum of devices and platforms.

The development of conceptual designs for use case solutions within the x-CITE project marks a critical juncture where visionary ambition is transmuted into practical implementation. This phase involves a comprehensive process that spans from the articulation of core features and functionalities to the detailed planning of software architectures, hardware deployments, and strategies for seamless data integration. The conceptual design is not a mere preliminary step but the foundation upon which each demonstrator will be built, ensuring solutions are both innovative and robustly compatible with the overarching CitiVerse environment.

Each team begins with an in-depth needs assessment, engaging interdisciplinary experts and local stakeholders to define the essential elements for their specific urban context. The LDT Toolbox remains a central resource at this stage, providing a rich repository of technical templates, architectural guidelines, and integration standards. By referencing the Toolbox, teams can accelerate development, avoid duplication of effort, and ensure their solutions are grounded in best practices for digital twin architectures, data exchange, and system interoperability.

Software development plans are drafted with an emphasis on modularity, scalability, and maintainability. Teams select programming environments and integration layers guided by the LDT Toolbox's recommendations. This ensures compatibility with existing urban infrastructures, facilitates upgradability, and supports long-term sustainability. The software architecture must be flexible enough to accommodate future changes in user needs, regulatory requirements, or technological advances, while also robust enough to deliver reliable performance from the outset.

Hardware setup is equally vital, especially given the diversity of urban environments and technical requirements across the pilot cities. Deployments range from environmental sensors and immersive XR devices to complex data aggregation hardware and high-density IoT networks. Detailed deployment plans are developed using standardized integration points and reference architectures provided by the LDT Toolbox. The aim is to create hardware infrastructures that are secure, resilient, and capable of supporting efficient data flows across urban systems.

Data integration represents a central challenge and opportunity. Urban environments generate vast and varied data streams, from IoT sensor networks to user-generated content and legacy datasets. The LDT Toolbox offers standardized data models, metadata schemas, and interoperability protocols that enable teams to aggregate, transform, and visualize heterogeneous data sources. Security, reliability, and regulatory compliance are paramount, with the Toolbox guiding teams in the deployment of privacy-preserving data operations and robust access controls.

Designing user interfaces and experiences forms another pivotal aspect of conceptual development. While backend architectures determine system capabilities, the front-end must translate these features into intuitive, accessible, and engaging experiences for users. Teams set clear targets for usability, accessibility, and inclusivity based on LDT Toolbox guidelines, ensuring that solutions are not only technically advanced but also user-centric. Iterative feedback from target users is solicited from the earliest design phases, shaping the UI/UX to meet real-world needs.

Scalability and future-proofing remain constant priorities. Choices about technologies, platforms, and integration standards must anticipate the challenges of moving from pilot demonstration to large-scale deployment. The LDT Toolbox serves as a strategic guide, pointing teams toward solutions that are both locally effective and easily replicable across other cities and regions. The conceptual design thus becomes a blueprint for ongoing transformation, embedding flexibility, adaptability, and common design principles into every technical layer.

Throughout this chapter, the original project plan's targets and EU-level objectives are foregrounded. The goal is not only to deliver isolated technical solutions but to contribute to a federated, interoperable, and sustainable CitiVerse that advances European ambitions for digital transformation. By emphasizing collaboration, modularity, and compliance with shared standards, the x-CITE project aims to ensure that use case designs are both visionary and actionable, capable of evolving alongside the needs of European cities and societies.

User interface and user experience design for use case solutions

A defining hallmark of successful digital transformation within the x-CITE project is the creation of user interfaces and experiences that are as intuitive as they are powerful. The design and development of UI and UX are recognized as foundational elements, essential for both user engagement and the overall efficacy of CitiVerse deployments. From the earliest design stages, project teams are tasked with articulating clear targets: interfaces must welcome engagement, facilitate meaningful interaction, and make complex digital twin or XR functions comprehensible for non-expert users.

The design process is iterative and deeply user-oriented. Each team begins by identifying the primary user groups (citizens, policymakers, industry partners) and mapping their journeys through the system. These user scenarios inform the initial wireframes, which are continually refined through cycles of prototyping, usability testing, and feedback analysis. In cases where production-ready or existing products are already in place, developing wireframes may not be necessary or applicable. Engaging real users early ensures that interfaces evolve in response to actual needs, fostering higher rates of adoption and satisfaction.

Central to UI and UX development is adherence to the LDT Toolbox's principles and standards. The Toolbox provides more than technical assets; it offers comprehensive

guidelines for inclusivity, accessibility, and consistency across platforms and devices. Every interface, whether a dashboard for city planners, a mobile app for citizens, or an immersive XR experience, is grounded in shared best practices. Accessibility is prioritized throughout, with adaptive layouts, clear navigation, and support for assistive technologies embedded from the outset. These considerations foster a cohesive digital ecosystem in which users can move seamlessly between different applications, minimizing friction and maximizing engagement.

Translating complex functionalities such as digital twin visualizations, simulation results, and interactive scenarios into interfaces that are both visually engaging and cognitively manageable is a central challenge. Teams deploy advanced visualization tools, contextual help features, and progressive disclosure techniques to guide users through intricate tasks, making sophisticated features accessible without overwhelming them. LDT Toolbox resources such as reusable design patterns and visualization templates accelerate development while securing a high standard of usability and aesthetic quality.

Inclusion and agency are recurrent themes. Every interface is designed to empower users, granting them clear feedback, transparent options, and genuine opportunities for participation. Particularly in participatory urban planning or cultural engagement scenarios, UI/UX is evaluated not only for technical performance but also for its capacity to foster belonging and active contribution among all communities.

Security and privacy are deeply embedded within the design process. Informed by the LDT Toolbox and the project's ethical commitments, interfaces support robust consent mechanisms, transparent data operations, and user sovereignty over personal information. These features build trust and ensure that digital innovations remain aligned with European values on data protection and responsible technology.

The targets outlined in the original project plan and at the EU level are reflected throughout: the aim is to deliver interfaces that support responsible, inclusive, and sustainable digital urban transformation. By embedding LDT Toolbox principles and emphasizing user-driven design, the x-CITE project ensures that every interface not only meets immediate project goals but also sets new benchmarks for future developments across the CitiVerse landscape.

Principles of inclusive UI and UX for XR tools

The guiding principles for inclusive design within x-CITE are detailed and far-reaching. Interfaces are engineered to be not only visually accessible but also to support multiple modes of interaction as like gesture, gaze, voice, and conventional controllers. This multi-modal approach ensures usability across different devices, skill levels, and cultural contexts. Accessibility standards such as the Web Content Accessibility Guidelines (WCAG) are observed, and alternative input methods are supported to cater to users with diverse abilities.

The design philosophy emphasizes intuitive interaction and responsive feedback, minimizing learning curves while enabling role-based adaptations. Consistency is

maintained across XR modalities (VR, AR, MR), ensuring that users can transition smoothly between different environments and devices. Real-time performance is prioritized, leveraging advanced connectivity solutions to deliver low-latency experiences with high visual fidelity.

Governance and participation features are embedded directly into the interface, giving users transparent control over consent, data visibility, and decision-making. Iterative prototyping and testing in pilot environments ensure that user experience remains coherent, trustworthy, and accessible as technical and social expectations evolve.

Spatial organization and visual hierarchy

Designing for XR requires a reimagining of traditional user interface paradigms. Elements such as menus, notifications, and tool palettes are spatially organized in three dimensions, often dynamically adapting to the user's perspective and context. To prevent cognitive overload, non-essential elements can fade or retreat to the periphery until summoned, while essential controls remain within easy reach.

Visual hierarchy is established through the use of contrasting colors, size variations, and depth cues, drawing the user's attention to critical actions or information. Animations and transitions reinforce spatial relationships, while lighting and shadow enhance the tactile quality of controls. Accessibility is further supported by options to reposition or resize UI elements, allowing each user to optimize their workspace for comfort and visibility.

Multi-modal input and interaction

XR interfaces in x-CITE are designed to accommodate a full spectrum of input methods, including hand tracking, gaze, voice commands, and standard controllers. Each mode of interaction is matched with visual cues and feedback to ensure intuitive use. For example, gaze-based selection will highlight UI elements as the user focuses, while confirmation gestures are used to avoid accidental activation. Context-aware systems seamlessly adapt available input modes to user preferences, device constraints, and activity context.

Haptic feedback, spatial audio, and visual highlights collectively provide immediate and multi-sensory responses, reinforcing the user's sense of agency and trust. The interface is adaptive, supporting easy transitions between input modalities and accommodating user-specific needs or abilities, including those with limited mobility or sensory impairments.

Consistency and familiarity

Building user confidence in XR requires a consistent application of interaction logic, iconography, colour schemes, and spatial metaphors. XR interfaces within x-CITE maintain familiar behaviours and standard gestures across different applications, reducing cognitive friction and helping users anticipate outcomes. Elements from traditional interfaces are thoughtfully translated into 3D space, with predictable

behaviours and feedback mechanisms that reinforce mental models and support muscle memory.

Sound cues, haptic responses, and uniform terminology further assist users in navigating complex or unfamiliar environments, fostering a sense of control and mastery over the system.

Accessibility and adaptability

Interfaces are sized and spaced to support comfortable and precise interaction in 3D space, considering different physical abilities and ranges of motion. Adjustable contrast, scalable text, and customizable gestures are key features, while voice navigation and alternative input methods are available to support users with limited mobility or vision.

Adaptability extends to the dynamic repositioning of UI panels, ergonomic workspace customization, and comprehensive onboarding tutorials in multiple languages. Regular testing with diverse user groups helps to identify barriers and drive continuous improvement, ensuring that the benefits of XR are accessible to all.

Feedback and responsiveness

Immediate, multi-sensory feedback mechanisms are a hallmark of x-CITE's UI/UX philosophy. Visual highlights, haptic pulses, and spatial audio combine to confirm user actions, maintain orientation, and build trust. Responsiveness is tightly coupled with system latency; every effort is made to minimize delays and synchronize feedback with user input, thus preserving immersion and reducing frustration or motion sickness.

Adaptive feedback mechanisms are also integrated, adjusting the type and intensity of responses based on user preferences or accessibility needs. Contextual cues, such as tooltips or adaptive panels, ensure that the interface remains uncluttered and focused, guiding users efficiently through complex interactions.

Functional and technical foundations

The architecture and technical foundation of x-CITE are deeply intertwined with its design philosophy. Use case development is supported by a rigorous set of technical requirements that aim to support interoperability, modularity, scalability, and security. These requirements are informed by both the EU Local Digital Twin Toolbox and a comprehensive analysis of existing XR platforms, engines, and toolkits. See more details in D3.1, D3.2 and D3.4 deliverables.

Modularity, reusability and standards

A defining feature of the x-CITE approach is modularity. Use cases are constructed from reusable components, many of which are derived from leading XR development engines such as Unity, Unreal Engine, Godot, ARKit, ARCore, OpenXR, WebXR, Blender, Maya, and Omniverse. These tools are carefully evaluated for their capability to meet the demands of federated, scalable, and standards-based digital twin environments.

The use of open APIs, adherence to semantic data models, and strict compliance with international standards ensure that solutions can be shared, adapted, and scaled across multiple cities and use cases. Each use case is designed not as a standalone application, but as a building block within a federated ecosystem that is capable of evolving alongside technological advances and urban needs.

Integration with Local Digital Twins

At the technical core of x-CITE is the integration of XR tools with Local Digital Twins (LDTs). Digital twins are real-time digital copies of physical entities (cities, neighbourhoods, infrastructure) created through the aggregation of multiple data streams, including maps, sensors, and citizen input. The x-CITE architecture is built on a layered model, composed of a data layer (aggregation and management), an application layer (logic, simulation, personalization), and an interface layer (user interaction).

Seamless synchronization is targeted via lightweight, event-driven communication protocols such as WebSockets and MQTT, supporting low-latency, real-time collaboration. Middleware bridges the gap between data management and immersive rendering, enforcing governance (authentication, privacy, access control) and ensuring that interface experiences remain consistent and responsive in the face of dynamic urban data.

Security, privacy and governance

Security and privacy are foundational to every stage of use case development. The architecture incorporates robust role-based access controls, GDPR compliance, and data encryption. User identities represented often as avatars in XR environments are managed through secure authentication, consent mechanisms, and differentiated access rights. All personal data exchanged within the XR-LDT ecosystem is subject to consent management and offers options for users to anonymize out of data collection.

Governance layers define roles, responsibilities, and processes for managing the digital twin ecosystem, ensuring that data stakeholder engagement are not afterthoughts but integral to the architecture. Every data exchange, visualization, and user action is governed by policies that safeguard both ethical and regulatory requirements.

Scalability and cross-platform compatibility

The x-CITE project is designed with scalability and adaptability at its core. The architecture supports multi-user scenarios, dynamic content synchronization, and performance optimization across a range of devices, from high-end headsets to mobile AR viewers and web-based interfaces. Cross-platform compatibility is assured through support for OpenXR, WebXR, ARKit, ARCore, and a host of SDKs that abstract device-specific constraints.

The layered architecture allows for independent modules to be deployed or upgraded, supporting both local customization and federation across the CitiVerse ecosystem. This

approach ensures that solutions can grow alongside user bases and datasets, accommodating new challenges and opportunities as they arise.

Alignment with EU LDT toolbox

An important unifying theme is the ongoing alignment between x-CITE's technical architecture and the EU Local Digital Twin Toolbox. The LDT Toolbox is a modular, open framework designed to accelerate the deployment of interoperable, standards-compliant digital twins.

By leveraging the Toolbox's building blocks including those for data integration, visualization, scenario management, governance, and analytics, x-CITE ensures that each use case benefits from proven assets and shared best practices, while remaining sufficiently flexible to adapt to local requirements.

The architecture is federated and scalable, supporting both experimental and advanced intelligent twins. It incorporates open standards and minimal interoperability mechanisms (MIMs), ensuring that cities retain digital sovereignty and can collaborate across municipal and national borders.

Interoperability: architectural components and building blocks

The interoperability of XR with LDTs in x-CITE is supported by a suite of architectural building blocks, each with specific roles and requirements. Key components include XR services (AR/VR/MR), data services (real-time and historical access, semantic tagging), governance layers (access control, licensing), spatial mapping engines (SLAM, spatial anchoring), synchronization modules (bidirectional updates), and integration interfaces supporting OpenXR/WebXR.

These components are orchestrated in a way that data is semantically described, stored, and accessed via standardized APIs, then transformed as needed for use within immersive scenes. Visualization and XR applications consume these data streams, often mediated by integrated environments and supported by robust identity and access management. Citizen feedback loops are captured and reintegrated into the system, ensuring that use case development remains grounded in real-world needs and iterative improvement.

Technical and governance requirements

Technical requirements for integration include support for standardized APIs (RESTful, GraphQL), semantic interoperability through shared ontologies (NGSI-LD, SAREF), low-latency data streams, robust security and access control, and cross-platform abstraction. Governance requirements focus on transparent data ownership, licensing, stakeholder engagement, and compliance with ITU and ISO standards.

Integration with XR tools is largely ensured through SDKs and modular architecture, though identified gaps remain in governance enforcement, semantic interoperability, and

real-time data ingestion. Middleware solutions are proposed to bridge these gaps, including semantic translation, governance enforcement, and the development of real-time data pipelines.

User types and interaction scenarios

The x-CITE framework is tested and refined in real-world pilot sites, including Flanders, Rotterdam, and Tampere, each illustrating a distinct set of user types and interaction scenarios. These pilots demonstrate the ability of XR-LDT solutions to support participatory urban planning, cultural engagement, tourism, education, and operational city services.

Citizens and community members access immersive cultural or community services, participate in consultations, and contribute to co-design processes. Policymakers and urban planners use XR-LDT platforms to simulate scenarios, visualize impacts, and gather feedback. Cultural institutions and tourism operators extend their reach through virtual exhibitions and interactive tours, while educators and researchers use these platforms as experimental learning environments. SMEs and developers contribute by building applications, plugins, and services that extend the ecosystem.

These scenarios underscore the need for responsive, inclusive, and adaptable XR systems that can address varying user needs across different urban domains. Feedback from these pilots informs ongoing refinement, driving the evolution of both technical solutions and engagement strategies.

Continuous feedback and iterative development

A core principle of x-CITE is the commitment to continuous improvement through feedback and iteration. Responsive feedback mechanisms, such as progress indicators, achievement badges, and real-time correction, help users understand the outcomes of their actions and encourage exploration. Analytics tools embedded within XR platforms monitor usage patterns, identify pain points, and drive further refinement of interface elements and instructional content.

In collaborative settings, feedback cycles are particularly vital, enabling teams to reflect, co-create, and innovate together. Built-in voting tools, annotation sharing, and post-session surveys facilitate collective improvement, while adaptive assessments and transparent communication about updates motivate users to remain engaged and invested in the evolution of the ecosystem.

Target summary of use case development

The x-CITE project sets a new benchmark for responsible, inclusive, and sustainable digital urban transformation. By embedding joint development, robust conceptual and technical design, and inclusive UI/UX development at the core of every pilot, x-CITE tests the viability of CitiVerse concepts while laying the groundwork for their widespread adoption. The synthesis of principles into actionable frameworks ensures that use case

developers can deliver not only innovative technical solutions but also practical, adaptable frameworks for future growth.

With a foundation in modularity, interoperability, accessibility, security, and scalability, x-CITE paves the way for urban digital ecosystems that are truly citizen-centric. The lasting legacy of the project lies in its ability to bridge technical ambition with ethical and participatory values, fostering a European CitiVerse that is as inclusive as it is innovative. Through iterative development, cross-domain collaboration, and ongoing alignment with EU standards, x-CITE offers a roadmap for cities and stakeholders seeking to harness immersive technologies for the benefit of their communities today and in the digitally empowered future.

In summary, the exploration of use cases and demonstrators within the x-CITE project is embedded in a systematic approach that unites joint development, robust conceptual and technical design, and user-centred UI/UX development. The chapters above have traced a coherent pathway for use case developers, beginning with collaborative integration and validation of the CitiVerse environment, through the meticulous crafting of conceptual designs, and culminating in the creation of interfaces that are both accessible and powerful.

Throughout every stage, the LDT Toolbox stands as both a technical resource and a guiding principle, offering assets and standards that underpin interoperability, reusability, and long-term sustainability. Solutions developed in Tampere, Rotterdam, and Flanders are conceived not as isolated experiments but as building blocks within a federated, interoperable CitiVerse that is capable of evolving in response to changing urban needs and technological advances.

Functional and technical analysis is the core area of effective use case design. At every phase, teams must ground their solutions in common design principles, drawing upon the shared resources of the LDT Toolbox and the collective experience of the x-CITE community. This commitment ensures that each use case delivers not only innovative technical solutions but also practical, adaptable frameworks for future growth. Scalability, modularity, and user-centricity are embedded in every layer, preparing the ground for solutions that can extend across Europe.

The lasting legacy of the x-CITE project is the synthesis of these principles into an actionable framework for use case developers. By embedding joint development, robust conceptual and technical design, and inclusive UI/UX development at the core of every pilot, x-CITE tests the viability of CitiVerse concepts while laying the groundwork for their widespread adoption. In doing so, the project advances a new paradigm for urban digital innovation. One is responsible, inclusive, and deeply responsive to the needs and ambitions of Europe's cities and citizens.

The preceding summary has outlined how the x-CITE project establishes a robust foundation for responsible, citizen-centred digital urban transformation, ensuring that every pilot and demonstrator is grounded in principles of inclusivity, modularity, and technical excellence. As the discussion transitions from these overarching frameworks

and guiding philosophies, the narrative now shifts towards the concrete real-world application of these ideas, specifically through the lens of the pilot sites such as Tampere, Rotterdam, and Flanders. The reader is thus prepared to move from a high-level understanding of the project's conceptual and technical vision to a closer examination of how these principles are translated into practice within diverse urban contexts.

What follows are detailed explorations of individual use cases and demonstrators, starting with the innovative work being carried out in Tampere. Here, the reader will encounter tangible examples of the CitiVerse in action where digital twins, XR technologies, and participatory frameworks converge to create new forms of cultural engagement, learning, and public service. The next chapters will delve into the specifics of these pilots, illustrating how functional and technical analysis, stakeholder collaboration, and iterative feedback mechanisms are put to the test. By examining the challenges faced, solutions developed, and lessons learned within these environments, the reader gains insight into the practical realities of implementing digital urban solutions.

This transition marks a pivotal point in the document: moving from the theory and architectural underpinnings of the x-CITE approach, the reader is now invited to witness the practical manifestation of these ideas as they come alive in real urban settings. The following sections will not only showcase the technological and organisational achievements of each pilot but also highlight the human stories and user experiences that bring depth and meaning to digital transformation. As such, the reader is encouraged to consider how the groundwork laid by the x-CITE framework enables the creative and sustainable evolution of urban life, setting the stage for a future where cities and communities are empowered by immersive, inclusive, and adaptable digital ecosystems.

Tampere use cases

The Tampere CitiVerse use cases focus on digital cultural experiences. CitiVerse solutions will be piloted in two locations in Tampere city centre: The western city centre, the area rich with cultural institutions, heritage and resources, and together with Nokia Technologies, in the new Nokia Arena environment, in a next-generation event experience centre designed for major events.

The pilot builds on the digital twins of the Tampere western city centre and Nokia Arena and develops a platform for physical artworks with a XR layer and explores the digital twin of live arena experience in XR. The pilot (including a major art event in the final phase of the pilot) tests and showcases the potential of combining physical art and event experiences with XR technologies in public spaces and in Nokia Arena.

The pilot tests and showcases the potential of combining physical art and event experiences with XR technologies in public spaces and in Nokia Arena and aims to reach new audiences and expand the cultural spaces using immersive technologies.

In the western city centre, the objective is to allow new forms of interaction with the urban spaces and new opportunities of artistic expression for citizens, artists and cultural institutions by realizing an innovative XR infrastructure and implementing a digital cultural pilot activity. The pilot extends the work of cultural actors and venues beyond their walls and into the streets, parks, and digital environments in the Tampere western city centre. In the use case, a platform will be created for uploading and sharing of digital art, and its localization in specifically chosen sites that would ensure visibility, accessibility, suitability to context and thematic narratives and complementarity to the cultural heritage.

In the Nokia Arena part of the pilot, trials about the concept of digital twin arena in XR environments are presented. The digital twin of the live arena experience in virtual reality requires a replication of the audience, lights, effects and sounds of the arena as they are at the arena. Nokia helps to find solutions for participation in cultural or other events even when people are unable to attend live events because of the distance or medical and physical limitations. City of Tampere will use the knowledge and knowhow of Nokia Technologies demo implementations in Nokia Arena to build its cultural demo trials for large audiences, and in the longer term, supporting the development of digital cultural services, digital tourism innovations and provision of cultural experiences to distant audiences and disadvantaged groups.

In the final phase of the Tampere pilot, the XR platform will be tested and implemented in connection with a larger scale thematic XR art exhibition in public spaces. The activity will involve collaboration with Tampere Art Museum and Tampere Historical Museum in connection with a major exhibition/art festival in 2026. It will involve the creation of physical artworks with a digital XR layer and will be accompanied by a web platform for online viewing and interaction. The focused citizen target group of the Tampere use case is children and youth. As part of Cultural Education Programme Taidekaari,

schoolchildren (all 7th grade classes of Tampere schools) will visit the art event and experiment with CitiVerse/XR art experiences.

Use case 1: Digital public art map

Short description

Citizens and visitors can unlock the history of iconic public artwork and have an interactive experience through a mobile application or website. Tampere City's public art collection will be made accessible through a user-friendly online platform. The Art Museum of Tampere will, therefore, compile, digitize, collect, and preserve information and cultural heritage related to public art in Tampere through a database. The Art Museum of Tampere will also develop a coordination model defining public art processes in Tampere ("Tampereen-malli").

Public Art on the Map is a project led by Tampere Art Museum, aiming to improve digital accessibility and citizen engagement with public art in the urban environment of Tampere city. The project focuses on producing public art related materials, involving digitizing existing materials related to public art, and producing new, engaging digital art related content to establish a new digital channel for exploring public art of Tampere. The collected and produced data will be presented on a new digital platform in a map format. In addition, the project incorporates inherent examination and a strategic review of public art processes, and therefore a new coordination model for public art projects will be designed to strengthen planning and implementation of public art processes, but also to recognize new potential areas for public participation in our common public art projects.

Pilot city

Tampere

Domain

Culture and tourism

Project coordinator

Sanni Leimio

Project leader

Tampere Art Museum

Success factors

- Functioning, user-friendly digital platform established
- New, creative, engaging, digital content created for the platform
- Information acquired and provided through public participation
- New areas of public participation recognized

- Precise and relevant coordination model for public art projects established and communicated

Stakeholders

City of Tampere

- Tampere Culture Service Group
- Tampere Art Museum
- Urban Environment and Infrastructure Services of Tampere
- Community and Development Services of Tampere
- Visual Artists
- The museum field in Finland
- Tampere citizens and other public audiences
- Tampere Jury of citizens (Tampereen raati)
- Tampere Residents' Evenings (incl. organizing team)

Full description

The public art collection of the City of Tampere, administered by the Tampere Art Museum, consists of over 130 pieces of public art, including sculpture, murals and public memorials. Public art plays a vital role in shaping the collective visual experience of citizens and communities. It contributes to cultural and local identity, offers aesthetic and emotional experiences, and fosters reflection and learning in everyday environments. In addition, it enhances the visual character of our common urban environments and serves as landmarks that connect people to places.

Ensuring access to public arts is a matter of cultural equity. By improving the accessibility of public art through digital means, the Public Art on the Map -project aims to enhance inclusive participation in public art and promote the right to meaningful cultural experiences for all.

The project aims to collect, produce and publish information and digital content related to public art, making it accessible to audiences through a new map-based online platform. The platform will showcase public art collection of the City of Tampere, and provide detailed information about each artwork, accessible via users' smart devices. The core objective of the project is to provide information by developing an engaging digital way to approach and explore public art.

The project consists of three main phases, as follows:

Data collection and digitization

While previously Tampere city's public artworks have been made accessible through a website and the Finna service, there is a need for new platform that is easily accessible via smart devices and allows sharing of diverse materials and information in various

formats. Also, the intangible cultural heritage associated with these works of art such as citizen experiences and oral histories remains largely undocumented and unpublished. Moreover, the intangible cultural heritage and citizen experiences related to public art represent a continuously evolving, living heritage and a shared cultural experience.

The project involves digitizing existing but undigitized public art related information and archival materials, as well as collecting and producing new digital content. The project collects and digitizes diverse public art materials such as texts, images, videos, maps, interviews, and conservation records while also exploring the personal and communal significance of public art through participatory methods. In addition, selected public artworks are planned to be accompanied by XR content to expand the experience and enable immersive exploration of the artworks in new ways. All materials will be digitized and published on the online platform.

Establishing an online platform

During this phase of the project an online platform in map format will be created. The online map will geographically display all public art pieces across the city. The user will be able to zoom in/out to explore various neighbourhoods and their public pieces of art. Materials provided via platform will vary according to different pieces of art.

The platform encourages audiences to explore public artworks in the physical urban space but also allows one to explore public artwork from a distance. The project aims to create accessible, user-friendly, and engaging platform solution that meets the needs of a broad and diverse audience.

Developing a coordination model

The third objective of the project is to develop and define a coordination model for public art processes in Tampere. The model will gather and define principles of the production of public art. The model will be informed by audience insights gathered during the project, and it seeks to build a transparent and equitable foundation for future public art initiatives. It further aims to enhance citizens' opportunities to participate in public art processes and establish channels for sharing experiences related to public art.

Augmented Reality as a gateway to public art

In the Public Art on the Map -project Augmented Reality is a possibility to open a new gateway to experiencing public art, bringing playfulness, immersion, and accessibility into the mix. With AR technology, art is no longer confined to physical space or time – it can live digitally, enhance existing pieces of art, or even resurrect destroyed artworks. By integrating AR technologies and 3D-scanning, the project aims to enrich public artworks and ways they are experienced, through for example digital overlays, interactive elements, and playful, gamified elements.

During the data collection phase of the project, we are planning to produce AR content for selected artworks depending on available resources. Actual implementation of AR content is yet to be determined.

The project is currently in the data collection and digitization phase. Initial planning for the online platform and its user interface has commenced. Content production, participatory data collection, and the planning of AR experiences are currently being initiated.

Core XR features

- Online platform (application or website) for exploring digital public art
- Online tool for adding and editing content (for administrators)
- Optional (depending on available resources): AR content for selected public artworks
- Support for multiple languages and rapid content updates.

User interfaces and functionalities

- Intuitive UI/UX: Simple navigation and accessible menus tailored for a broad demographic.
- Multilingual support: Core content and navigation available in Finnish and English to serve both local and international audiences.

Technologies, platforms and tools

- Location tracking of end users (optional)
- 3D modeling & photogrammetry (optional): Utilization of high-resolution 3D scans by Tampere Infra and LDT assets from Kelluu.
- AR/XR tools (optional): ARKit/ARCore for mobile AR experiences. The consideration of Unity or Unreal-based AR pipelines for cross-platform compatibility.

Compatibility with CitiVerse environment

- Where feasible, aligned with CitiVerse standards for security, GDPR compliance, and user consent policies.

Interoperability with EU LDT toolbox

- Where feasible, compliant with EU LDT Toolbox guidelines.

Use case 2: Art biennial

Short description

Hämeenlinna Art Museum and Tampere Art Museum have joined forces with the Lahti Museum of Visual Arts Malva to launch Art Realm, a brand-new series of biennial exhibitions, which will rotate between venues in the areas of Kanta-Häme, Pirkanmaa and Päijät-Häme. The Art Realm forms part of the regional activities undertaken by

Hämeenlinna Art Museum (Kanta-Häme region), Lahti Museum of Visual Arts Malva (Päijät-Häme region) and Tampere Art Museum (Pirkanmaa region), together constituting the historically relevant area of Greater Tavastland.

The Art Realm is envisaged as a continually evolving exploratory process grounded in a biannual exhibition cycle. Each biennial event will constitute its own experimental laboratory that will drive the ongoing development of new collaborative models and structures. We want to make space for new possibilities, for learning and for incompleteness. It is intended that each biennial will generate new forward momentum for the Art Realm as it strives to create greater equality and inclusion within the Finnish art scene.

The Art Realm is a framework through which art is given a central role. Consideration is being given to the implications of art taking a leading position while society responds. Within this context, artistic freedom is acknowledged as a space for broad exploration. Art is not viewed in isolation but is understood to interact continuously with its environment and broader societal structures.

Collaborative relationships with professionals from various fields are being pursued to support this approach. Attention is being directed toward identifying existing power structures and areas of limited visibility within the art sector. Power dynamics and their operation in the art world are being examined. Through this process, efforts are being made to reassess and potentially redefine how power is distributed, in cooperation with artists, researchers, other professionals, and institutional partners.

The Art Realm is structured as an exploratory process anchored in a biennial exhibition program. Traditionally, artists apply and are selected by curators. In this initiative, steps are being taken to redistribute decision-making authority typically held by museums and curators. A new model is being developed that incorporates learning and research, involving artists, museums, subject-matter experts, collaborators, and partners through workshops conducted between exhibition periods.

These workshops are intended to facilitate the exchange of diverse perspectives, including conflicting ones. They are designed to support meaningful dialogue and interaction among participants. The aim is to create an environment where discussion, listening, inquiry, and mutual influence are encouraged. The Art Realm seeks to support the imagining of alternative futures through open and inclusive processes.

Pilot city

Tampere

Domain

Culture & tourism

Project coordinator

Taidevaltakunta (The Art Realm)

Project leader

Tampere Art Museum, Johanna Kangas

Success factors

The goals of Art Realm are multifaceted. Primarily, we aim to discover new ways of collaborating – not only among the regional museums responsible for the initiative and other regional partners, but also with artists, independent cultural actors, and audiences. One of the central objectives is to dismantle expert authority and explore how power – particularly institutional or expert power – can be shared both in the work of artists and in the operations of museums.

It is also essential to examine and reflect on the role of audiences in the processes of artmaking and exhibition development within art museums. We ask: How can artworks and exhibitions engage and include municipal residents, different target groups, and communities? The Art Realm process also investigates the role of regional museums in preserving regional visual art and promoting its accessibility.

Public spaces, urban environments, and digital platforms are important venues for presenting art – especially alongside traditional, often ticketed, museum and gallery spaces. These alternative spaces help make art more accessible to audiences who, for various reasons, may not be able to visit museum facilities.

For this X-Cite project, we have selected one work of art from among the pieces chosen for the Art Realm '26 biennial. Through this work, we explore how the above-mentioned goals are realized. The selected art project is by visual artist Jussi Lahtinen. The artwork is titled Urban AI Art / Tampere Urban Culture, and the artist is developing the piece in collaboration with students. Through this artwork, we also aim to generate insights into what an accessible artistic and digital urban experience could be. A project is described in more detail in the text below.

Stakeholders

- Hämeenlinna Art Museum
- Malva – Lahti Museum of Visual Arts
- City of Tampere, Public Cultural Services Urban
- Finlayson Art Area / Gallery Himmelblau
- Visual artists, especially Jussi Lahtinen
- Visual artists associations / Tampere Artists' Association, Ars-Häme, The Artists' Association of Lahti
- Municipal residents / local citizens

Full description

Art Realm is a multi-year collaboration and network formed by three regional art museums. Its most visible manifestation is the biennial Art Realm exhibition, which showcases regional visual art. The responsibility for producing the exhibition rotates between the partner museums.

In 2025–2026, the production responsibility lies with the Tampere Art Museum, which will organize the exhibition across two venues in Tampere: the exhibition spaces in the Finlayson factory area and Haihara Manor, located in one of Tampere’s suburbs. In addition, selected works will be presented in public urban spaces and online.

The theme of the 2026 Art Realm exhibition is encapsulated in the word ‘Together’. This theme emphasizes the collective nature of visual art, participation, and community in various ways. The selected works highlight artists who challenge the traditional, individualistic notion of the visual artist by reaching out to audiences through the way their works are realized and/or by collaborating with other artists in pairs or collectives.

The selection of works also aims to dismantle the expert authority often associated with art institutions. The jury consisted of 15 members, primarily staff from the three responsible museums, but also included independent artists, partners, and municipal residents from outside the art field who applied to participate in the process. From the applications, the 100 most-voted works were shortlisted, after which the final selections were made through in-person jury discussions.

Urban AI Art by Jussi Lahtinen

UrbanAI Art is a visual artwork powered by artificial intelligence that generates a continuous stream of unique cityscapes. Each image appears only once before being replaced, creating a fleeting experience that invites viewers to reflect on the nature of art and authorship in the age of AI.

Created by Tampere-based visual artist Jussi Lahtinen, the piece builds on his Metropolis series (2015–), inspired by Fritz Lang’s Metropolis (1927). The AI engine behind the work was developed specifically for this project in collaboration with game designers from Moido Games, particularly Henri Sarasvirta.

Launched in spring 2023, UrbanAI Art has been featured at major events across Europe. It is intended to be presented on a large screen in a public space, where viewers can access their own unique image stream via QR code or by visiting urbanai.fi. The artwork is silent and can be experienced anytime, anywhere.

Through this artwork, the potential of artistic and digital urban experiences is being explored. UrbanAI Art challenges traditional institutional structures and seeks new ways of sharing power within the art field by bringing together artists, experts, audiences, and partners in a collaborative process.

XR Features and functionalities

Immersive cityscape visualization

- Dynamic, AI-generated urban landscapes projected via large public screens and personal devices.
- Real-time rendering of unique cityscapes, each visible only once, reinforcing the ephemeral nature of digital art.

- Integration of location-based triggers for enhanced engagement in urban environments.

Participatory art experience

- Audience interaction via personal QR codes, granting access to individualized image streams.
- Collaborative creation features, allowing users and artists to contribute to the evolving digital artwork.

Accessibility and inclusivity

- Public installation and online access, ensuring broad participation regardless of physical location.

User interfaces and experience design

Public display modules

- Large-scale digital screens in urban locations, optimized for high visibility and crowd interaction.
- Intuitive interface for on-site navigation, enabling users to access streams and information via touch or mobile.

Mobile and web platforms

- Responsive web application supporting both desktop and mobile devices.
- Seamless integration with social media sharing options.

Technologies, platforms and tools

Core technologies

- AI-driven image generation engines (custom-built).

Scalability and compatibility

Scalability strategies

- Modular system architecture supporting incremental feature expansion and easy onboarding of new cities and partners.
- Distributed content delivery through CDN integration, allowing efficient access for geographically dispersed audiences.
- Robust user management and analytics to support large-scale participation and continuous improvement.

Compatibility with CitiVerse environment

- Where feasible, aligned with CitiVerse standards for security, ensured GDPR compliance, and user consent policies.

Interoperability with EU LDT toolbox

- Where feasible, compliant with EU LDT Toolbox guidelines.

Use Case 3: Cathedral 1918 - Civil war storytelling

Short Description

Extends 1918 civil war storytelling with role of Tampere Cathedral. During the Finnish Civil War of 1918, the Tampere Cathedral was used as a refuge for civilians during the Battle of Tampere. Visitors of the Cathedral and of the Civil War Museum receive an immersive museum experience about refugees during the Battle of Tampere and the role of the Cathedral by using gamification and technologies not previously used in the museum field, through the website of the Civil War Museum www.tampere1918.fi/en and hopefully also on site at the Tampere Cathedral (AR app).

Pilot City

Tampere

Domain

Culture & tourism

Project coordinator

Museum Centre Vapriikki

Project leader

Antti Hannunen

Success factors

A functioning immersive virtual exhibition ready to be launched with no technical issues and with good UI/UX will be considered a success.

Other success factors before the main success factor above include: a finished and well-made script for the exhibition, excellent game engine design.

New information gathered and skills learned for making virtual museum exhibitions.

Establishing Vapriikki as a benchmark for other museums in the field of immersive virtual exhibitions.

Stakeholders

- City of Tampere
- Museum Centre Vapriikki
- Tampere Cathedral parish
- Younite AI
- History department of Tampere University
- History reenactors
- Tampere Historical Society
- School children from nearby schools

Full description

The Finnish Civil War was part of World War I. In 1917, the world war led to the collapse of the Russian Empire and eventually to a civil war in the country. Finland declared its independence on December 6, 1917, but for various reasons, after armed clashes, it also descended into civil war.

The Finnish Civil War was fought between the forces led by the Finnish Senate and the Finnish People's Delegation from January to May 1918. The Senate's armed forces were the White forces and the People's Delegation's forces were the Finnish Red Guard, or Reds.

The deciding battle of the Finnish civil war was fought in Tampere in late March to early April 1918. Tampere, as a major industrial city, was a main stronghold of the Reds. It was also a crucial logistical hub for the Reds frontline. The Whites won the battle and conquered Tampere, which led to the eventual collapse of the Reds' forces during April and May 1918.

Vapriikki's new Tampere Cathedral 1918 XR-exhibition will focus on the experiences and stories of civilians and refugees during the Battle of Tampere. The Cathedral served as a refuge for local people as well as for refugees from nearby rural areas. About 2000 people sought safety within the stone Cathedral during the bombing of Tampere and the fighting on the streets of the city. New XR technologies will bring the stories of the refugees to life in a never-before-seen way.

The Tampere Cathedral and the surrounding areas will be 3D modelled, and scenes depicting the stories of the refugees will be filmed with live action actors. The scenes will be placed in the virtual 3D Cathedral for the user to experience. Vapriikki has already done several virtual exhibitions on the Civil War theme, and they are published on our Tampere 1918 Civil War virtual museum webpage www.tampere1918.fi/en. The Tampere Cathedral 1918 exhibition will also be published as a browser-based experience on the museum's site. All virtual content can be accessed also with mobile devices. As part of the x-CITE pilot some form of XR version of the exhibition is being planned, however the final technological aspects of the XR version are under the final planning phase.

Unreal Engine 5 will most likely be the main developing tool. Also, photogrammetry will probably be used to create 3D models of museum objects that are used in the exhibition. Vapriikki has good experiences with using these techniques from previous projects. Gamification aspects will be used to enliven the experience of the exhibition. The user will not only be a spectator, but they can also be an active part of the exhibition. However, we are not developing a game, so gamification elements will only serve as a tool to increase the interest factor of the exhibition especially for audiences that normally are not interested in museum content.

The project is still in the script writing stage, so there are no clear technical details to report yet. We have talked about trying out AI as a storytelling tool but that would need us to develop or train our own curated AI. All the data that the AI would use needs to be

approved by Vapriikki's experts so that we can verify that the AI would use academically correct source material. Available resources might become a problem.

For the 3D modelling we have as an available resource a 3D scan of the cathedral done by Tampere Infra, both in and out. Also, a digital twin of Tampere made by Kelluu this summer can be used as a resource for our 3D model. Vapriikki has done additional developing work in co-operation with the City of Tampere on the 3D model already. The technology and modelling will be done by Younite AI company.

Relevant details from Younite's plan for the exhibition:

- Browser based 3D model online experience
- Generative AI guide feature can be added later
- Easy to use UI/UX (no logins, free to use)
- A segment on the architecture and other facts about the cathedral (optional)

Core XR Features

- Immersive 3D environments: Faithful recreation of Tampere Cathedral and surrounding urban spaces using a LDT of the surrounding area, photogrammetry and 3D scanning technologies.
- Live-Action storytelling: Integration of filmed scenes with actors portraying refugees, layered within the virtual environment.
- Interactive narratives: Branching storylines where users can choose different perspectives (e.g., civilians, clergy, Red or White Guard) to experience multifaceted viewpoints of the 1918 events.
- Gamification elements: Embedded challenges, historical quests, and object discovery to increase engagement, without transforming the experience into a conventional game. These are just some examples of possibilities.
- AI-Powered storytelling assistance: Optional generative AI guide to answer visitor questions or provide contextual historical facts, drawing from curated academic sources. (lacks resources at this point)
- Augmented Reality (AR) extensions (optional, depends on available resources): On-site or mobile AR overlays, enabling users to superimpose historical scenes onto present-day locations in and around the Cathedral.

User Interfaces and Functionalities

- Browser-based access: No login required, ensuring frictionless entry for all audiences via desktops, tablets, and smartphones.
- Intuitive UI/UX: Simple navigation, on-screen prompts, and accessible menus tailored for a broad demographic, including school groups and museum visitors.
- Accessibility features: Compatibility with screen readers, closed captioning for all audio content, and adjustable text sizes for inclusivity.
- Multilingual support: Core content and navigation available in Finnish, English, and potentially Swedish, to serve both local and international audiences.
- Personalized experience paths (optional): Allow users to bookmark stories, save progress, and revisit experiences across devices.

- Real-Time feedback mechanisms (optional): Quick surveys or feedback buttons to support iterative content and feature improvements.

Technologies, Platforms, and Tools Selection

- Development platform: Unreal Engine 5 for advanced rendering, realism, and support of both VR and browser-based XR experiences.
- 3D modelling & photogrammetry: Utilization of high-resolution 3D scans by Tampere Infra and LDT assets from Kelluu.
- Web technologies: WebXR and WebGL for seamless browser delivery; JavaScript frameworks (e.g., React) for UI components.
- AI integration (optional): Custom-trained generative AI models, with all datasets reviewed by museum experts for accuracy and safety.
- AR/XR tools (optional): ARKit/ARCore for mobile AR experiences. The consideration of Unity or Unreal-based AR pipelines for cross-platform compatibility.
- Content management: Integration with headless CMS for versioning, translation management, and rapid content updates.

Scalability and Performance

- Distributed content delivery: Deployment via CDN infrastructure to ensure low-latency 3D and multimedia streaming for geographically dispersed users.
- Modular architecture: Separating core engine, content, and interface layers to facilitate iterative upgrades and maintenance.
- Cloud backend: Leveraging scalable cloud services for AI, analytics, and user data where necessary, ensuring reliable operation during peak loads (e.g., school visits).
- Performance optimization: Level-of-detail rendering and adaptive streaming to offer smooth experiences across a wide range of devices, from low-end tablets to VR headsets.

Compatibility with CitiVerse Environment

- Conformance to CitiVerse reference architectures: aiming to align modules, APIs, and content formats with CitiVerse standards for security, GDPR compliance, and user consent policies.
- Theming and branding: Customizable visual layers to reflect local identity while maintaining the overarching CitiVerse visual language.
- API interoperability: Open APIs supporting integration with mobility, tourism, and education platforms within CitiVerse.
- User management: Robust authentication and analytics tied into CitiVerse's centralized user systems, supporting large-scale and persistent participation.

Alignment with EU LDT Toolbox Development

- Standards compliance: Where feasible, digital assets structured for discoverability, reusability, and interoperability according to EU LDT Toolbox guidelines.

- Marketplace participation: Content packaged for contribution to the shared LDT Toolbox marketplace, promoting cross-city exchange and collaborative cultural development.
- Open source contribution: Documentation and code (where feasible) openly shared to support evolving LDT guidelines and community best practices.
- Metadata/tagging: Precise tagging and documentation of all assets to ensure seamless integration and future-proofing within the LDT ecosystem.

Use Case 4: Culture and children (Art Arc)

Short description

Art Arc (Taidekaari) is a cultural education programme for the basic education and early childhood education of the city of Tampere. In X-CITE, Art Arc will reinforce other Tampere use cases by providing young visitors as well as test and develop pedagogical methods that utilize virtual and AR-content. The pilots of Museum Centre Vapriikki and/or Tampere Art Museum will be a part of Art Arc programme of school year 2026-2027. Approximately 600 seventh graders in 30 school groups will explore the created content while attending Art Arc in the autumn of 2026.

Pilot city

Tampere

Domain

Culture & tourism

Project coordinator

Tampere Public Cultural Services

Project leader

Liisa Aholainen

Success factors

Including new content to cultural education programme. Finding new ways to let children and youth learn about Tampere, its history and culture.

Developing pedagogical methods to combine a real-life guided tour that encourages interaction and group work with an immersive virtual exhibition.

Co-operation with the Tampere pilots. Including school children already in the planning and testing phase of the content where possible.

Stakeholders

- City of Tampere
- Museum Centre Vapriikki
- Tampere Art Museum

- Art educators and artists of Art Arc

Full description

Art Arc (Taidekaari) is a cultural education programme tied to the curriculum of basic education and early childhood education of the city of Tampere. Art Arc celebrates its 20th anniversary in 2026, being one of the most established and extensive cultural education programmes in Finland. The programme introduces and engages children from 3 years of age to youth in the 9th grade of upper comprehensive school, in the art and culture of their hometown. Every year all the age groups attend a visit and a workshop according to a fixed scheme, which ensures that every child gets to visit all the main cultural venues of Tampere at least once during their school years. Programme is also built to introduce a rich variety of art forms to try, from poetry and circus to street art and music.

Young visitors for Tampere pilots

Seventh graders' Art Arc includes an interactive workshop tour in an exhibition, which can be in a historical museum or an art museum. Usually, these workshop tours are led by a guide and an artist (drama, music, poetry or other) creating a multidisciplinary experience. Three different workshop tours are created every year to host all the 7th grade groups (approximately 100 groups) of Tampere City.

In the autumn of 2026, one of these workshop entities will be built around the x-CITE pilot of Museum Centre Vapriikki and/or Tampere Art Museum. One third of the seventh graders of Tampere, at the fewest 600 children, will attend these tours. Art Arc will thus reinforce other Tampere use cases by bringing in young visitors.

How to use virtual content in cultural education for school groups

The cultural education programme Art Arc will also develop practical pedagogical methods to plan and execute educational content that utilizes virtual and AR-exhibitions. Often virtual exhibitions are designed with individual visitors or families in mind. Application for school groups may need adjustments. Aim is to find a balance between immersive content and working in a group, to include both virtual and real-life creating and sharing on the tours. To achieve these goals Art Arc co-operates with the Tampere pilots, schoolteachers and freelance art educators who work with children in Art Arc.

Documenting and feedback

During the Art Arc tours in Tampere pilots, Art Arc will document activities, which means organizing in advance permissions from parents to film and photograph schoolchildren. During and after workshop tours Art Arc collects feedback from children, teachers and art educators to evaluate the success of created content. The questions of the feedback survey will be compiled together with the pilots, offering them a possibility to measure success in their main targets.

Core XR features, user interfaces and functionalities

XR Features

- N/A (not a technical solution; related to use cases 1-3.)

User interfaces

- N/A (not a technical solution; related to use cases 1-3.)

Functionalities

- N/A (not a technical solution; related to use cases 1-3.)

Technologies, platforms and tools

- N/A (not a technical solution; related to use cases 1-3.)

Scalability considerations

- N/A (not a technical solution; related to use cases 1-3.)

Compatibility with CitiVerse environment

- N/A (not a technical solution; related to use cases 1-3.)

Alignment with EU LDT toolbox development

- N/A (not a technical solution; related to use cases 1-3.)

Use case 5: Nokia Arena

Short description

360 video/sound and VR experience for visitors and local citizens in Nokia Arena and remote (concerts, live events). As main sponsor of the hockey and concert arena of Tampere. Nokia wants to offer a world-class arena experience to its visitors and viewers at home. Nokia will install six 360° tv cameras in the arena and create an immersive experience for visitors in the arena and at home to enjoy hockey games and concerts through smart phones, XR, 5G and 3D spatial audio technologies. The users will be able to control their video perspective and enjoy close action and front-row seat views.

Pilot city

Tampere

Domain

Culture, sport and tourism

Project coordinator

Nokia

Project leader

Jukka Saarinen

Success factors

- Successful trials and demonstrators in Nokia Arena.
- Understanding of end user needs in real-time environment.
- Understanding of user interfaces in real-time environment.

- Understanding of standardization needs based on trial results.

Stakeholders

- Nokia
- Nokia Arena

Full description

Nokia Arena is in Tampere, Finland. It opened on December 3rd, 2021. The owners of Nokia Arena are Finnish companies LähiTapiola, OP, Ilmarinen, SRV and the City of Tampere. Nokia Arena includes Lapland hotel arena, versatile event spaces and many different restaurants.

Nokia Arena is a next-generation experience center which opens a new era in event experiences. The arena is 50 000 square meters large, and it can fit up to 15 000 event spectators. It is designed for sport events (mainly ice-hockey games), concerts, musicals, and theatre. It has 140 annual events and 1 million visitors a year.

Nokia Arena has ISO 20121 certificate, which means that their operations are sustainable, and they take environmental and social responsibility into account. Gold level of international LEED environmental certificate was set as a design goal in the construction phase. LEED does not focus on just one aspect but looks at the whole, so important elements work together to achieve the best result.

We would like to present our ideas about the concept of digital twin arena in VR testing environments in X-Cite project. The digital twin of the live arena experience in virtual reality requires a replication of the audience, lights, effects and sounds of the arena as they are at the arena. The main benefit for the client company is the fact that the concept can be very widely expandable. The idea is to bring the realistic VR concert alive, but this technique is possible to use in a variety of sports games, musicals, theatre, and other large arena events as well.

The general target is to find a solution to participate in events even when consumers are unable to attend live events, because of distance from the location or medical and physical limitations. Even in a possible new pandemic situation there would be the possibility to still attend and keep the event going, because it is all virtual. It would also help to increase the number of viewers, because even if the arena's capacity is full, there is a possibility of attending the concert virtually.

The organizers could even record the events and sell them afterwards, so consumers can experience the event later. The basic idea is to bring the arena event experience to the customer at home, via virtual reality by creating the whole experience as realistically as possible in the next two years.

The event can also be sold out in just a few seconds after the ticket sales opened, which is a very common issue especially with popular artists. The concept will provide a solution to all these problems and can open many opportunities to raise the ticket sales.

This obviously will benefit the artists as well when they have the chance to sell VR tickets in addition to their live concert tickets.

This concept opens many technical and implementation challenges for Nokia's 360 video modelling research purposes. We identify several key fundamental topics: real-time video delivery with audio experience as well as 360 video modelling of Arena activities. In the first phase we will concentrate on the delivery experience for end customers. At the second phase we can consider simple interaction models. This current ecosystem will give excellent backbone ecosystem for the trials planned in this research use case proposal inside X-Cite project.

Example of practical target setting for demos: Event experience in Nokia Arena – remote audience takes part in concert or sport event at Nokia Arena through 5G network and VR

The event at Nokia Arena in Tampere can be VR concert or sport event where the audience is able to participate live in 360-degree VR over the 5G network. The highly capable 5G network constructed by Elisa and Nokia at the venue can open new possibilities for people to take part in events at the arena regardless of their physical location.

The virtual event experience can be produced with the help of 360 cameras installed in Nokia Arena, the 5G network, and VR headsets located in Tampere, some kilometres away. The audience will be able to move around different parts of the arena in VR and follow the concert thanks to the 360 cameras.

The high-quality 8K video from the 360 cameras and stereo audio can be transmitted almost in real time over Elisa's 5G network. The cameras that are in Nokia Arena utilise a highly capable 5G mmWave network enabled by Nokia's network technologies, which permits the latest gigabit data uplink and downlink speeds as well as an extremely high-capacity network to be used during events at the arena. The transfer of data between Nokia Arena and the audience in Tampere test place can take place over Elisa's public 5G network.

Now that technology is making it possible for the audience to experience concerts and other events regardless of location, the imagination is the only limit to what will be possible at the arena events of the future. Not all artists' tours reach Finland, and VR could offer a solution to this.

Elisa has been a pioneer in bringing 5G to consumers and corporations in Finland, and it is great to see the kinds of innovation that can arise thanks to this highly capable mobile network. Now, the 5G network offers the possibility to attend arena-scale live events from anywhere. Nokia Arena is a great place for arranging world-class events, as digitality has been built into the experience right from the start.

The Nokia Arena is a state-of-the-art, programmable 5G-enabled digital stadium like no other. Through the combined strengths of Nokia's equipment portfolio and Elisa's

network the producer can deliver low latency, high-capacity and ultra-high data speeds via 5G mmWave that enhance the experience of every person attending events like this. Through VR headsets it is possible to experience live performances in 360° even when not physically there. This can be one potential example of the ground-breaking and game-changing partnership between tele-operator Elisa and Nokia.

Nokia Arena use cases for entertainment

Currently, Virtual Reality (VR) has achieved great significance due to the advancements of computing and display technologies. Filmmakers have already started to think creatively about VR technologies because it is not just a gaming trend that is going to get wider. The healthcare industry, immersive telepresence, telehealth, sports, education, etc. are being rapidly commercialized to meet the demands of the market and consumer expectations, etc. According to recent industry forecasts, the global VR market revenue is projected to reach approximately 184.6 billion USD by 2026, reflecting significant growth driven by increased adoption in entertainment, education, and enterprise sectors [1,40].

As one of the essential VR applications, 360-degree video facilitates the user with an interactive experience that was never thought of before. Many commercial broadcasters and video-sharing platforms are showing considerable interest in this domain. Microsoft has released its Windows Mixed [2]. Another platform called ARTE360 VR by ARTE [3] enables the sharing and accessing of various omnidirectional videos through mobile applications.

The Nokia Arena's use case redefines how we can watch concerts, sports matches and other events. When multiple 360° video cameras are placed around a venue, viewers have the power to zoom in on the action from the perspective of their choice. The experience can be enjoyed on either a TV display or an HMD headset. Whether the viewer is watching the action from home or from a pitch-side VIP box, this use case opens new revenue opportunities for event organizers. The solution also brings surveillance capabilities that enhance venue security.

We can identify two main entertainment use cases in detail below:

- Onsite immersive experience
- Experiential remote viewing

Onsite immersive experience

VIP guests can get even closer to the action with 360° video and 3D audio. This creates memorable experiences for customers and opens new entertainment opportunities for onsite hospitality areas as shown in Figure 1.

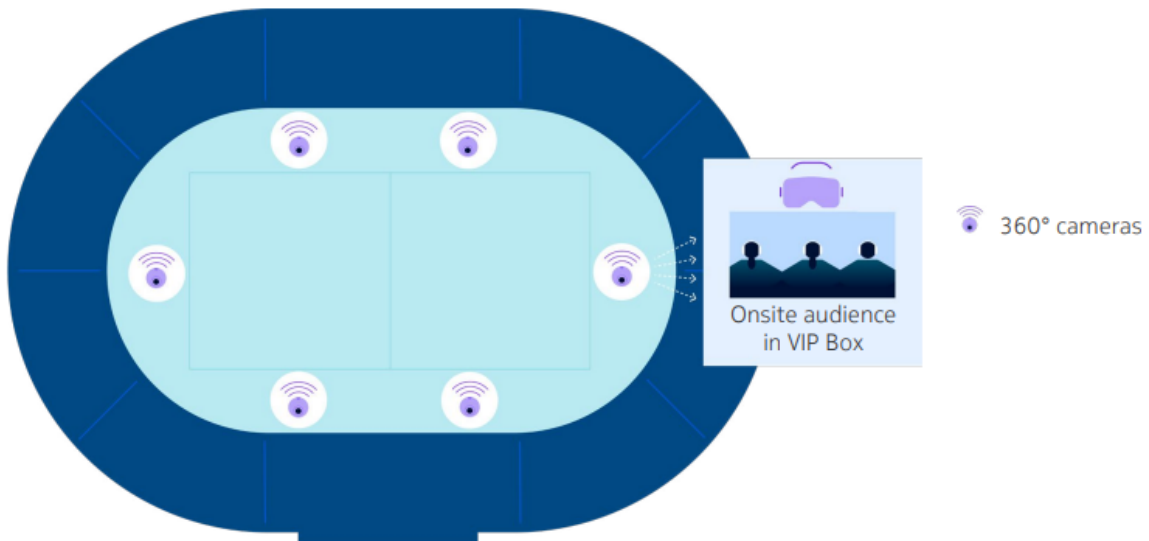


Figure 1 Set up for onsite immersive experience.

The onsite immersive experience has the following features:

- **Multimedia capture:** The stadium or event site has a range of fixed cameras positioned around the arena to get the best view for every second of the action. Six 360° cameras are in different sections of the arena. Each camera can produce independent streams for onsite audience in VIP Box get to the heart of the action.
- **Multimedia consumption:** The multicamera setup provides unparalleled pitch-side views to ensure you do not miss a thing. Viewers can zoom in using either HMD goggles or from a large TV screen in the comfort of the VIP section. A user interface with one, four or nine views. Viewers can zoom in on their selected camera view.

Experiential remote viewing

Remote viewers can now enjoy a front-row seat from the comfort of their homes. Leveraging an array of 360° cameras and 3D spatial audio, offers unparalleled immersion that surpasses current offerings and opens new opportunities for revenue streams. The set up for experiential remote viewing is shown in Figure 2.

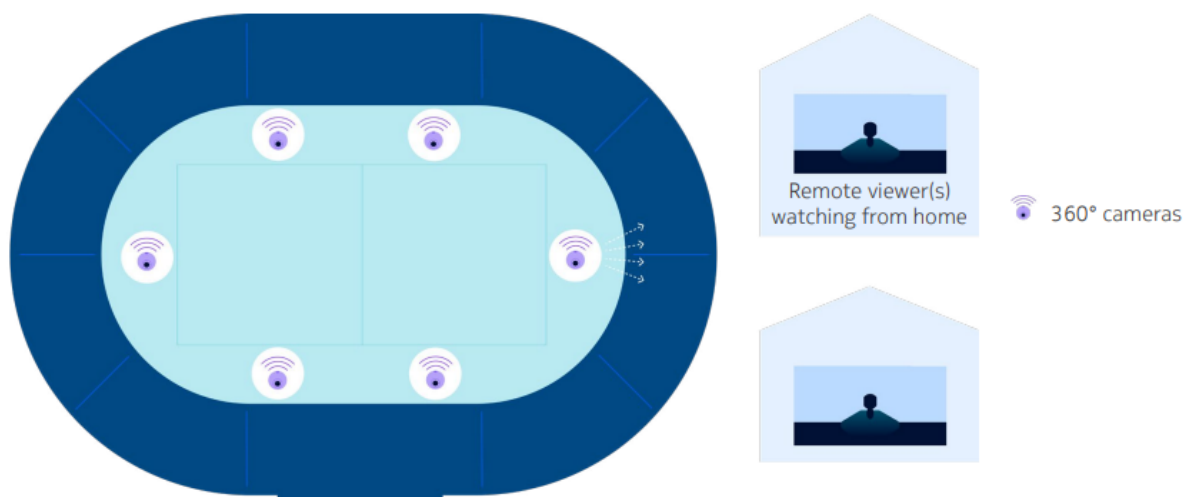


Figure 2 Set up for experiential remote viewing.

The remote immersive experience can own the following features:

- **Multimedia capture:** The stadium or event site has a range of fixed cameras that give viewers pitch-side views like no other. Mobile and fixed 360° cameras with four feeds per camera. Six cameras around the arena. Example: 24 pre-defined feeds a front-row seat, wherever you are.
- **Multimedia consumption:** Viewers can enjoy front-row seats from the comfort of their living room by selecting a range of 360° views via their TV screen. Viewers can zoom in on the respective camera view. The viewport cannot be changed by remote users. User interface can be adjusted depending on the need: one, four or nine views. One possible set up of the remote viewing is presented in Figure 3.



Figure 3 TV screen set up for experiential remote viewing.

System description for Nokia Arena's use case

This chapter includes core features, user interfaces and functionalities in the Nokia Arena use case. The appropriate technologies, platforms and tools for case use are described at a high level. Factors like scalability and compatibility with the CitiVerse

environment will be considered as much as possible. Based on this conceptual design, implementing the technical solutions including software development, hardware setup and data integration are presented.

In Figure 4 we present the software architecture solution for Nokia Arena use case that enables real-time streaming with 360° video and spatial audio. The architecture should be a bandwidth-efficient, low-latency solution for setting the extended reality ecosystem.

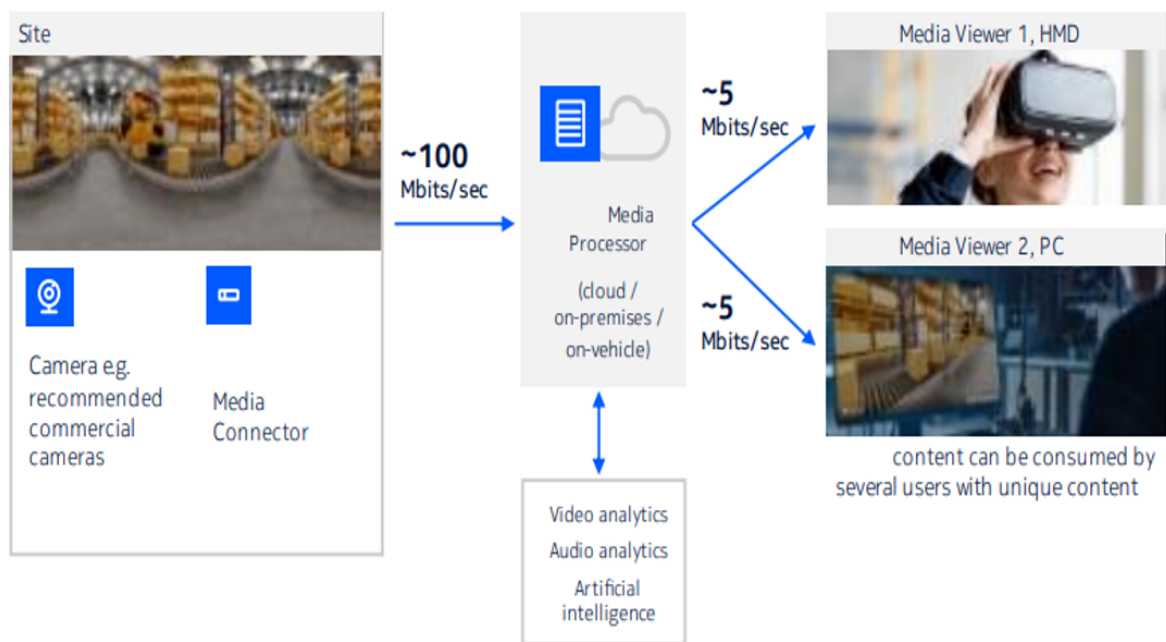


Figure 4 A simple architecture of Nokia Arena use case.

The system architecture should operate anywhere that benefits from 360° multimedia streaming and spatial audio. With extensible interfaces, system integrators can integrate it easily into existing workflows, such as analytics, business, and extended reality media. It should be possible to deploy it locally on your own premises or on a private or public cloud platform. Running on a private wireless network, the system should maximize the level of privacy and reduce operational costs. The system should operate in flexible ways with distributed installations.

With the planned system, the following basic targets and requirements can be set:

- Low latency streaming on secured private wired or wireless networks.
- Spatial audio powered by vibrant and accurate audio technologies.
- Bandwidth-efficient media streaming: the system should stream the part of the 360° video the viewer is watching and thus reduces bandwidth requirements by up to 50-90%.

Basic functions, requirements and technical features for system design and tooling

Real-time 360° viewport-dependent video streaming

One of the system's key technologies is to process and stream view port-dependent 360° content from one or several 360° cameras without blind spots and in real time. The system should offer a flexible video and audio streaming service for different 360° camera vendors and support the streaming standards and standard-compliant viewers of multiple platforms.

The end-user should receive the video stream on all standard desktop and mobile browsers, as well as compatible head mounted displays, such as the Pico 4 virtual reality headset. You should embed the multimedia stream on a web page without any specific development efforts.

With the viewport-dependent streaming technology, the system only streams the part of the content that a viewer is actively watching. This saves bandwidth, reduces network traffic, and results in low-latency delivery. Several viewers can watch the stream simultaneously on different devices, including PCs, mobile phones, tablets, and compatible virtual reality headsets. Each viewer can control independently what to watch in the stream and start and stop their individual streams whenever they want.

Basic elements for system architecture

The planned system's software components consist of:

- Media connector (one or several)
- Media processor (one or several)
- System manager
- System viewers for web browsers and virtual reality headsets

Media connector

The media connector is a standalone module that runs as the client for registering or unregistering a media device to the media processor via the system manager, and for parsing streaming requests from the system manager. It also provides support for various media sources, such as cameras, using wired and wireless protocols, like USB and RTSP. It should provide an abstraction layer as the generic media source to the media processor with a unified interface and streaming format, regardless of the media source hardware. It should also enable multicasting to scale up the system: one media source can be multicast to several media processors.

Media processor

The media processor is the engine of the whole system. It processes the media sources coming from the media connector and generates new content for viewers. It decodes and encodes the incoming streams for the viewers using various codec formats. To lower the

required bandwidth for 360° media types, the media processor uses viewport dependent technology to stream the 360° content to the viewers. Other bandwidth saving and streaming modes are also available, such as Region of Interest based streaming for 360° and non-360° media content. The media processor's main features also include rendering and streaming spatial audio.

Manager

The system manager is the management core of the RXRM system. It manages the media connectors, the media processors, and the viewers. It is lightweight, as it only handles commands and does not process any media. It offers public web interfaces (APIs) for integration by 3rd parties to control the services programmatically.

Viewers

In this Nokia Arena use case, there should be two types of viewers:

- Web XR viewer: The web viewer does not require any installation and can be used directly on most web and mobile browsers. The end-user can also easily integrate the web viewer into 3rd -party web pages as an HTML element. The web viewer JS library offers APIs for custom data overlays to be rendered on top of the streaming content. The web viewer supports both regular audio and spatial audio.
- Native XR viewer: The native XR viewer will work on the Pico 4 and other compatible virtual reality headsets. It contains all the features of the web viewer. The integration is not as easy as the web viewer's case, but you can apply deep integration and full customisation on top of the native XR viewer. Both viewers can specify the streaming parameters, such as expected bit rates and the size of the field of view. One should customize the video resolution streamed from the system based on the condition of the real situation. Also, one should also configure advanced streaming options, such as adaptive bit rate streaming, RTX (re-transmission), and forward error correction.

Data storage

The planned system will use an internal database for storing configurations. For storing multimedia recordings, the system utilizes the S3 Bucket storage. The system has internal S3 storage (implemented via a MinIO database) and the ability to connect to external S3 cloud storage. Storing video data from 360° streaming devices usually requires plenty of disk space, since the output bit rate for this type of device is around 100-150 Mbps. For example, storing a 1–2-minute 360° video clip commonly takes 1-2 GB of disk space from the storage.

The system will store raw data in several small files known as *chunks*. This allows for easier use of recorded data later. For instance, the oldest chunks can be deleted, and a specific part of the full stream can be exported flexibly. The system supports data

exporting as a file. This file (usually in MP4 format) is created on demand by combining file chunks. For playing back stored media streams, the system creates an internal stream from the previously stored file chunks.

Spatial audio technology

System's spatial audio, powered by Nokia's audio technologies, enables you to capture sound and stream it spatially. Spatial audio creates a 360° audio experience for the listener, as it uses geographical and acoustic positioning to render the real direction of sounds and replicate them as experienced in real life.

360° camera management and remote-control interface

The system's camera management and control interface manages the 360° camera hardware and can control cameras remotely over a standard camera API. For example, the system can send commands to a camera to start video streams and to stop them. The camera control API can be easily extended to cover other cameras and camera types.

Standard web viewer

End-users should view multimedia streams on a web browser that supports the standard WebRTC technology. One can also use simple configuration parameters to embed the multimedia stream to any system with full authentication and authorisation capabilities. The web UI has been designed with mobile devices in mind, so it can also be used with smaller touch screen devices.

HMD viewer application for multiple platforms

End-users should use the native viewer on multiple platforms and operating systems, and on compatible head mounted displays.

Recording and playback

The system should support the recording of all video streams. If one uses a 360° camera, the full 360° stream is recorded. End-users should manage and view the recordings in the system. Also, one should be able to export the recordings as multimedia files, download them with a browser, and use them in 3rd party multimedia players and applications.

Collaging

Multiple limited fields of view camera streams can be combined into the one output stream through collaging. With collaging, bandwidth need can be optimized by lowering the resolution of selected streams, in use cases where high resolution of each camera is

not needed. The system includes an API to select pre-created collage layouts. Multiple profiles can be used for different use cases.

External APIs

The system provides external interfaces for communicating with external and 3rd party services, such as video analytics to enable them to use the media content from the system. Once integrated and adapted to your system, the system can also process analytic results and other third-party provided information, such as process values from external services and present them to viewers in real time.

Stream publishing

For broadcasting purposes, the system can be used as a streaming source. This means that admins can set up a set of fixed viewports from selected devices and offer streaming URLs for every viewport. Third party systems, such as media broadcasting can then use these streaming URLs for distributing the same media content for masses.

Flexible user management

The planned system supports local and self-hosted user and user group management. The user interface allows users with admin rights to add, edit, remove, and view users and user groups, and change their access rights and passwords. Users with admin rights can also grant user groups access to device groups.

Dynamic device management

The user interface allows users with admin rights to create, edit and delete devices in the system, and organize the devices by grouping them under sites and device groups.

Conceptual design, functionalities, requirements and the State of the Art

In the following chapters the general video streaming system, different streaming approaches, the immersive standardization efforts, the latest scientific results, and the possible challenges and implications are discussed from Nokia Arena point of view. The most important references in the background research will be highlighted with the scientific findings. The State-of-the-Art analysis is based on the current review articles and publications about the 360-degree video technologies and applications [4, 5, 6, 7, 8].

The main conceptual design topics can be gathered into the following:

- The key functionalities of Nokia Arena case address the architecture of 360-degree video streaming. The purpose is to stay as close as possible to 360-degree video principles by considering both low and high-level implementation perspectives. The content pre-processing stages, e.g., content acquisition, stitching, projection, and encoding are discussed. The transmission and consumption of the 360-degree video are over-viewed.
- The sophisticated streaming technologies for 360-degree video, including viewport-based solutions, are presented and discussed in detail.
- The audio-related technologies that support immersive experience are illustrated.
- The technological efforts to enable the technologies for an extended degree of freedom in immersive multimedia consumption are explained.
- Different technical and design-related challenges and implications are presented for the sake of an interactive, immersive, and engaging experience with 360-degree video in Nokia Arena case.

360-degree video streaming framework

Lately, there is a definite market move towards different forms of immersive video, including omnidirectional or 360-degree video. Cameras with high-resolution are available for close to and professional creation of 360-degree movies. The increased efficiency of stitching software allows for better content preparation than ever. Networks deliver high bitrate content to remote end-users' devices. Devices themselves (e.g., HMDs, mobile phones, tablets, etc.) are equipped with robust sensors, processing, and display components that enable them to receive, process, and display rich media content. However, supporting real-life streaming of 360-degree videos is still very challenging because they are associated with vast amounts of data, and its handling is highly time-sensitive. Figure 5 illustrates the major stages in 360-degree video streaming.



Figure 5 End-to-End 360-degree video streaming framework.

Capturing and stitching

A multidimensional camera is used to capture the 360-degree scene of an environment. Several companies, including GoPro8, Insta3609, Ricoh Theta10, Samsung Gear11, etc., have started manufacturing portable 360-degree cameras. To generate a full 360-degree view of the environment, there is a need for multiple inputs from different cameras (e.g.,

frame rate and aspect ratio). The aspect ratio is recommended to be 4:3 to capture the maximum possible spatial area. Modern applications are used to attach different views to get a full 360-degree view. The captured 360-degree view is then represented as a three-dimensional (3D) sphere.

Projection schemes

After capturing and stitching steps, the 360-degree sphere representation is transformed into a planer format. Two main projection techniques are employed: (i) viewport-independent projection and (ii) viewport-dependent projection.

Encoding of 360-degree video content

The compression efficiency has improved significantly following the development of next-generation coding solutions. Currently, traditional and 360-degree videos use the same encoders, including Advanced Video Coding (AVC)/H.264, High-Efficiency Video Coding (HEVC)/H.265, VP9, VP10, AV1, etc. The current generation 4K 360-degree video requires 10-50 Mbps bitrate, while next-generation and 6DoF 360-degree videos require 50-200 Mbps and 200-1000 Mbps bitrates, respectively [9]. Therefore, the efficient compression of 360-degree video is essential to be able to deliver it over the best-effort networks.

AVC/H.264 standard uses a 16x16 macroblock structure for frame encoding. The size of encoded data is reduced through the motion prediction feature of the encoder. On the other hand, HEVC/H.265 saves nearly 50% video bitrate compared to the AVC/H.264 with the same subjective quality. HEVC/H.265 supports the tiling feature for efficient video streaming [10,11], where a 64x64 Coding Tree Unit (CTU) structure is used to encode each tile and achieves a higher compression ratio than AVC/H.264. The video tiles are physically separated and concatenated in a regular stream to decode them by a single decoder. The next-generation, Versatile Video Coding (VVC) standard [12] is expected to increase compression efficiency by up to 30% compared to HEVC/H.265.

Packaging and transmission

The latest broad access to capturing and storage devices has shifted the production of rich media from studios to the large public. Regular users are not only consuming videos on smart devices, but they are also involved in creating and distributing the content. DASH is a modern standard to facilitate such over-the-top (OTT) services because of its compatibility and simplicity in the context of current network infrastructure. In this context, a client requires a high-quality subset of tiles according to the viewport position and available bandwidth. The quality at which the client requests the tiles is dependent on network delivery.

360-degree videos are bandwidth-hungry streaming applications, demanding low response and buffering time. This is not always feasible, especially when there are far-located data service points. Recently, several new solutions, i.e., micro data centers, fog

computing, and mobile edge computing, have emerged, intending to minimize the distance and number of network components between users and far located large processing centres (i.e., cloud). These technologies augment and extend the storage and computational resources from the current cloud model to the edges of the networks with objectives of low latency, efficient mobility, and real-time interactive support. Thus, the network transmission performance improves the user immersive experience and is considered an essential step towards achieving an experience-centric 360-degree video delivery.

360-degree video rendering and displaying

360-degree video rendering and displaying are computationally expensive due to the considerable processing power requirements. The client-based rendering solution is the most used option in web-based players like YouTube and Facebook, where the viewport is constructed from decoded frames and then presented to the end-user. A major problem is the wastage of computational resources at the client-side to process a big part of the 360-degree video content, which does not belong to the FoV of the user. Another 360-degree video rendering option is cloud-based rendering [13]. The cloud-based rendering minimizes client-side processing. The video data is on the cloud, and only the requested Field of Views (FoVs) are streamed to the end-users with no additional requirements of bandwidth or hardware resources.

360-degree video has become an integral part of multimedia applications. The consumer is always interested in the interactive and immersive streaming experience. The term "streaming" refers to the continuous delivery of audio-visual content to the user. Several standard organizations and industry forums are contributing many helpful insights for the future of 360-degree videos. In general, the architecture of the 360-degree video is still under progress. Security goals are nearly the same for both traditional and 360-degree content. These goals are targeted to protect unauthorized distribution, modification, resolution rights, and output control.

360-degree video streaming system

The concept of streaming media has gained significant attention because of its advancements in video compression technologies. Industry and academia are trying to produce multimedia streaming solutions. However, supporting 360-degree video streaming in real life remains challenging. Such real-time demands are the key differentiators between multimedia and other data network traffic that need special attention.

Overview of video streaming

Academic and industrial research growth has made a great deal of effort by concentrating on producing solutions to stream multimedia. Real-time requirements are important changes, which need special attention, between multimedia and other data

network traffic. A lot of standardization organizations and protocols were obtained to enable multimedia streaming, and Quality-of-Service (QoS)-based streaming.

Some early protocols built on top of the Internet Protocol (IP) were Integrated Services (IntServ) [14] and Differentiated Services (DiffServ) [15] that will ensure QoS-aware streaming and multimedia streaming. Resources are specifically stored by executing a signalling protocol [16] called Resource Reservation Protocol (RSVP) to satisfy the application specifications. This protocol is used by IntServ that defines the QoS requirements for an application's traffic.

Real-time Transport Protocol (RTP) [17] enables end-to-end multimedia streaming in real time by proposing a standardized packet format. Application-layer framing and integrated layer processing are two main concepts that are used to design RTP. A client-server-based connection is established by Real-time Streaming Protocol (RTSP) [18] by controlling the multimedia servers before downloading the required video content.

Some studies have shown that Transmission Control Protocol (TCP) is beneficial for transmitting delay-tolerant-based videos [19]. In return for its reliability, it permits efficient data transmission but must suffer from unpredictable delays. HTTP's design over TCP ensures progressive downloading to download a video file of constant quality as quickly as TCP enables it. A major downside is that clients receive the same video content under different network conditions, which can lead to unnecessary stalls or rebuffering.

This situation has led researchers to turn to the development of HTTP adaptive streams. 360-degree video streaming is different from traditional video streaming. The next subsections present short overviews of existing 360-degree video streaming solutions with pros and cons features.

Viewport-Based streaming

Viewport-based adaptive streaming has gained attention in both industrial and academic communities. The end-users' corresponding viewport can be identified in viewport-dependent streaming based on the user's head movement. Therefore, such solutions are adaptive during the streaming of 360-degree videos, as they dynamically select regions and adjust the quality to minimize the transmitted bitrate. It provides several adaptation sets at the server-side because it is a viable option to smooth the viewport during abrupt head movements. Each adaptation set contains the associated video area with a given viewing orientation.

Viewport-independent streaming is the straightforward way that streams the content of 360-degree video since the entire frame is transmitted in the same quality as conventional videos. Simplicity implementation has been an appealing gateway to viewport-independent streaming. Though, the coding efficiency is 30% lower than viewport-dependent streaming [20]. Additionally, invisible areas require a lot of bandwidth and decoding resources. This form of streaming [21,22] mainly applies to content streaming.

Quality of Experience enabled streaming in 360-degree video

Multimedia streaming has gained considerable popularity among users everywhere, as there are many performance problems while delivering multimedia over different loaded networks. Even more so as the processing and transmission of 360-degree format brings along new challenges (i.e., bandwidth, distortions, etc.). To lower the bandwidth requirements, video material must be compressed to lower qualities, causing compression artifacts that may negatively affect the user's quality of experience (QoE).

QoE refers to the measure of customer satisfaction and experience from a service such as TV broadcasts, phone calls, and web browsing. As with traditional 2D videos, quality assessment of 360-degree videos can be done through both subjective and objective tests, which have their advantages and disadvantages.

Subjective quality assessment

Many subjective video quality assessment methods have been found for 2D videos in the past two decades. Many subjective methodologies have been proposed by the international telecommunication union (ITU). Two metrics are widely used in subjective assessment quality, such as MOS [23], and another metric is DMOS [24]. Currently, different types of subjective assessment methods are identified for omnidirectional videos.

There is still a lack of standardized methodologies for subjective studies and metrics for 360-degree video. The debate on how to develop these is ongoing; consensus has not yet been reached within the research community. Nevertheless, some studies on the subjective experience of omnidirectional content have been performed adapting methodologies from classical video quality assessment.

However, this adaptation is not trivial as viewing through an HMD is substantially different from a regular display that presents different experiences. The viewer is more immersed in the content, and challenges regarding strain and cybersickness arise. Cybersickness is a potential barrier to achieving higher QoE levels and can cause discomfort.

Objective quality assessment

Currently, objective quality in 360-degree video is measured in the planar projection through structure similarity (SSIM) and standard peak-signal-to noise ratio (PSNR). However, they give similar importance to all parts of the spherical image, even though different parts have different viewing probabilities and thus different importance. Additionally, they still do not give a good representation of subjective quality. Viewport-based PSNR or SSIM metrics could be a solution closer to what the users perceive. However, all objective metrics still fail to consider perceptual artifacts such as, for example, visible seams [25].

In short summary, QoE research is important for the development of video streaming technology to most efficiently handle the trade-off between providing good quality and limiting network burden. Additionally, the 360-degree video offers a substantially different experience compared to regular 2D.

Audio technologies for 360-degree video

360-degree and panoramic videos can be broken or made by an audio effect. Spatial audio [26,27] is known as a full-sphere surround sound approach that employs multiple audio channels to mimic the audio representation that we have in real life. The 360-degree video becomes more reliable due to the spatial audio because of the channelling properties of sound that enable it to pass through time and space.

The Google VR Software Development Kit (SDK) [28] optimizes the audio rendering engine for mobile VR. The significance of the 360-degree video display system cannot be overstated in producing the spatial audio soundtrack.

The Facebook spatial Workstation [29] has templates and numerous plugins that are used to support synchronized audio playback for 360-degree video with the help of HMDs. The other audio production environment will be integrated with this type of video monitoring.

Two categories have been described for the reproduction techniques of spatial audio named physical reconstruction and perceptual reconstruction. The physical reconstruction technique is used to synthesize the whole sound field as close as possible to the desired signal. In contrast, psychoacoustic techniques are used in perceptual reconstruction to produce a perception for the spatial sound characteristics [30]. The stereo configuration uses the two speakers in the most popular methods of sound reproduction to facilitate the more spatial information (that includes distance, direction sense, ambiance, and sound stage ensemble). While multichannel reproduction methods [31] are used in the acoustic environment and become popular in consumer devices.

Ambisonics [32], also known as 3D audio, is used to record, mix, and play the 360-degree audio around a centre point. Recently, it has been adopted in the VR industry and 360-degree applications but was investigated in the 1970s and never used before. Ambisonics audio is not like traditional surround technologies. The principle behind the two-channel stereo and traditional sound technologies is the same because all are used to create an audio by sending an audio signal to specific speakers. This is the reason Ambisonics has become standard in the VR industry and 360-degree video. Ambisonics is not pre-limited to any specific speaker as it creates a smooth sound sphere even when the sound field rotates. Still, traditional surround formats provide excellent imaging only in the case of audio scene static. Moreover, Ambisonics also delivers a full sphere to spread the sound evenly throughout the sphere.

Binaural recording [33] that is an extended form of stereo recording, provides a 3D sound experience. Binaural recordings replicate the human ears as closely as possible by using the two 360-degree microphones, the same as regular stereo recordings that capture the sound with directional microphones. 360-degree microphones to the dummy head [33] are used to serve as proxies for the human ears because it provides the precise geometry of ears. The dummy head also produces the sound waves that interact with the human head contours. A spatial stereo image is captured more precisely as compared to any other recording method with the help of 360-degree microphones.

Head-Related Transfer Functions (HRTFs) [34] are used in real-time techniques of binaural audio to reproduce the complex cues that help us to localize the sounds by filtering an audio signal. Multiple factors such as ears, head, and listening environment) can affect the cues because we reorient ourselves to localize the sounds. Hence, it is essential for soundscape researchers to choose the proper sound recording/reproducing technique to enable the playback sounds to be the same as the natural listening scenarios.

Standards

Standardization is a key issue for proper technical interoperability. The overall goal of standardization efforts is to specify the minimum essential to enable creative and competitive technologies and services. Currently, immersive media has gained enormous significance in exploring its technological and scientific challenges. Significant activities are being undertaken by academic and research institutions to facilitate immersive media standardization, and a multi-phase scheme is being pursued to complete this set of standards. MPEG is currently releasing ISO/IEC 23090 MPEG-I to support immersive media coding. MPEG-I consists of the following parts: (1) Technical Report on Immersive Media, (2) Omnidirectional Media Format (OMAF), (3) Versatile Video Coding (VVC), (4) Immersive Audio Coding, (5) Point Cloud Compression, (6) Metrics, (7) Metadata, (8) Network-Based Media Processing, (9) Geometry-based Point Cloud Compression, (10) Carriage of Point Cloud Data, (11) Implementation Guidelines for Network-based Media Processing, and (12) Immersive Video.

OMAF standard defines the storage and delivery formats for omnidirectional media applications, concentrating on images, audio, and synchronized text of 360 degrees videos. Its first edition ensures storage based on ISO Base Media File Format (ISO/BMFF) and MPEG MediaTransport (MMT). OMAF includes several additions such as interactivity, temporal navigation, and natural viewing experience by supporting head motion parallax.

MPEG has divided the standardization associated with VR into the following categories: monoscopic 360-degree video, binocular 3D 360-degree video, stereoscopic 360-degree video, and free-viewpoint video (FVV) [35]. A set of 4 to 6 cameras take 360-degree video shots and then stitches those cameras' images into a single spherical view. In the monoscopic 360-degree video, the data is represented as 2D images but with pixels coordinates interpreted as values. While viewing a 360-degree video on HMD, the movement of users can be explained with three directions (i.e., yaw, pitch, and roll). Therefore, 360-video is also called 3DoF (degree of freedom) because both the user's

eyes see the same panorama, and there is no depth impression. At the end of 2017, the first phase of OMAF enabled the streaming of 3DoF 360-degree video with existing comparison technologies. In 3DoF, the user is static, but the head can change orientation to look around the 360-degree video.

MPEG has carried out explorations on technologies that enable 6DoF to allow the user not only to change the viewer should be considered when compressing the test content. The range of supported possible viewer position is constrained and known. Three different anchors are used; the first one includes MIV (Metadata for Immersive Video) anchor based on HEVC+TMIV. The second one includes the MIV view anchor is also HEVC + TMIV-based but directly encodes a subset of the source views. The third anchor, the MV-HEVC anchor is based on MV-HEVC and VVS. Stereoscopic 360-degree video is a 3D extension of a 360-degree video, where two panoramas of a scene are used and represented with a circular projection.

Nokia is one of the most active contributors and drivers of key metaverse and XR features in 5G standardization organizations. In the context metaverse applications for digital industries and consumers Nokia would drive innovations for years to come. Nokia is a member of the Metaverse Standards Forum (MSF) with the ambition to take an active role in related innovations and interoperability standards. Nokia's world-class standardization experts are internationally renowned in their field. Nokia holds more than 100 board members, chairs and other official positions across all key standardization and industry groups. Nokia is active in 300 standardization and industry organizations globally. This current position creates a solid and credible basis to build the leadership for the technology standardization on the areas that are essential for the metaverse and CitiVerse type of applications.

The MPEG-I standard family keeps on evolving. For example, the Immersive Audio standard project has recently entered its collaborative standardization phase where Nokia will once again play a leading role. We continue our extensive research, technology development and standardization efforts on immersive media to help create a more sustainable, more efficient and a more enjoyable world. The summary of Nokia's research and standardization activities, illustrating its contributions to immersive video, XR features, and CitiVerse interoperability standards is presented in Figure 6.

Research & Standards

Key XR Research Areas

- 5G/6G System support incl. mobility
- Edge cloud (split processing)
- Energy-efficiency
- Multimedia technologies, e.g., video/audio coding
- Positioning and mapping incl. sensor fusion
- Real-time digital twinning
- Device SW research

XR Ecosystem

- Partner with Universities
- Participation in EU/National research projects, Next G Alliance, NSF/RINGS
- Partner with companies, e.g., Tactile

3GPP – 5G-Advanced


- RAN2: R18 XR [enh.](#) for NR: Nokia Rapporteur
- SA2: R18 XR and media services
- SA4 R17 ITT4RT work item (Nokia Rapporteur), and commitment to contribute to the Media Capability, WebRTC-based new work items.

MPEG: Nokia is editor and contributor of:


- Network Based Media Processing (NBMP)
- Visual Volumetric Video-based Coding (V3C) including Video-Point Cloud Compression (V-PCC) and MPEG Immersive Video (MIV)
- Omnidirectional Media Format (OMAF)
- Scene Description
- Immersive Audio

Multi-Access Edge Computing (MEC)

- RNIS information for industries



Volumetric video coding



Vision-based positioning and mapping

Figure 6 Summary view of Nokia’s different research and standardization activities.

Potential for immersive video content

The potential of immersive video content concerning different use cases and projects is an interesting topic. The universal applicability of 360-degree VR video has extended to many commercial sectors. Consumer adoption of the technology remains still in its early stages but is proving well popular in almost every field.

The immense popularity of 360-degree videos is due to the immersive user experience. 360-degree videos have different requirements related to frame rate, resolution, image quality, and user viewing behavior in comparison to regular videos. Further, there are increasing demands in terms of ultra-high network capacity and ultra-low response delay to support a high-quality streaming experience on existing, highly dynamic networks. This opens novel avenues that have attracted the attention of many researchers.

An uninterrupted 360-degree video should be displayed to the user to maintain high perception levels. Therefore, a proper QoE framework that focuses on all features of omnidirectional content is required because the existing 2D video models may suffer from critical limitations for 360-degree video. The perceived quality, spatial presence, as well as the technical parameters and viewer preferences, should be considered for the improved on-demand as well as 360-degree live video streaming. Additionally, the growing potential of immersive rich media content in diverse application domains, which include sports, entertainment, medicine, infotainment, and education applications.

The development of new applications for diverse domains is natural; however, of concern is the need for handling other issues related to immersive media content delivery, including support for long-term accurate viewport prediction, QoE assessment, and QoE-oriented delivery solutions. In conclusion, despite the amount of research done on 360-degree video streaming, several research challenges still exist and provide opportunities for further investigations to reach the goal of having a viable real-life implementation which provides users with the best experience.

Sports applications

360-degree video is viral in worldwide sports (football, ice-hockey). 360-degree video adds numerous advantages to almost every sport. The omnidirectional capturing around an athlete or sports ground brings the most beneficial experiences by providing the users with new viewing-angles. Gänsluckner et al. [36] presented blended learning based 360 degree climbing course to provide the participants with an interactive learning experience. The authors showed that for learning climbing techniques, 360-degree videos are much better than regular videos. Hebbel-Seeger [37] considered the use of 360-degree videos for education and training processes in sports. The authors determined that 360-degree video has high potential in the athletic training process, and there is a need to adopt modern storytelling means to attract user attention.

Content production and broadcasters

360-degree video, also called cinematic VR, is a format with an increasing presence in the news production due to its low-cost production [38]. Many public service media organizations have already seen the potential of this format, evidenced by the creation of applications or simply by the rate of consumption of 360-degree videos. 360-degree news production has evolved from its initial experimental phase to become a more critical part of several news organizations [39]. At the same time, the availability of capable cameras and their use in the fast-paced news environment has lightened the 360-degree news production, so it is natural to note that it is increasingly employed in Europe, America, and Asia.

Many digital broadcasters are focusing on creating and publishing 360-degree VR content on different platforms. The basic aim of this prospective process for almost all companies is to identify the available techniques and learn about their potential. A major UK based broadcaster Sky24 has shown much interest in this field. Yle25 from Finland is actively testing next-generation media experiences. In this regard, Yle has a future media incubator called Yle Beta, which lacks hardware but provides different ways of storytelling, such as iteration and pivoting. However, the progress of these ongoing efforts towards success needs to be further investigated.

Challenges and implications

360-degree videos provide an immersive experience that is difficult to find in traditional 2D videos. A significant number of production possibilities emerge because different events have been captured as 360-degree video. The rapid production in various fields has introduced the 360-degree video to wider audiences through social media platforms. A traditional virtual environment allows the user to navigate in complex theory geometries that reconstruct real areas attempting to stimulate and create real spaces.

The 360-degree video introduces several challenges that need to be explored for a viable implementation of the streaming system. The major challenge experienced by the user

in the virtual environment is a sense of presence. Such an understanding can be enhanced via the creation of close to the real environment while avoiding the visual cues. Many technical and design challenges and implications are explained here for the sake of an interactive, immersive, and engaging experience within 360-degree videos.

- 360-degree video introduces several distortions from acquisition to display. To overcome the distortion issue in 360-degree video streaming, there should be a focus on adding new stitching, projection, and packaging formats that may introduce less noise.
- The 3D objects are being included in the environment besides capturing and use of 360-degree video to represent the real world and actual interacting content. The incorporation of 3D objects is challenging for a realistic view.
- There is a need for a concentrated effort towards designing quality assessment methods and metrics for 360-degree video. This is a complex and challenging problem because of the unknown network fluctuations and traditional video QoE models that do not consider the 360-degree content.
- Special sound effects used in the 360-degree video require strong research intention before using it in the context of attracting attention.
- A fundamental challenge to 360-degree video streaming is viewport prediction. Despite the abundant research history of saliency detection, the existing approaches may provide inaccurate viewport estimation.

Potential research directions in Nokia Arena use case

A detailed literature review shows that despite the recency of the topic, many research efforts have already focused on 360-degree videos to provide smooth playback when delivered over bandwidth-limited highly dynamic networks. Even though the improvements introduced by the research and development community, high-quality 360-degree content creation, distribution, and streaming remain a major issue.

For all innovative immersive multimedia, an important challenge remains the projection/mapping of an increased amount of content. In this context, the direct employment of the existing projection schemes helps as they are supported by the existing graphics hardware. However, oversampling/undersampling may cause information loss in extracted viewports and degrades the performance of a VR system. A possible direction is developing techniques that enhance the projection processing functions and bandwidth utilization by natively allocating more pixels to the viewport.

In a receiver-centric architecture, multiple users are expected to watch different parts of the same content. It is necessary to upgrade the resolutions without further increasing the system latency. For low latency interactivity, adequate compression of 360° data units are required. Many issues related to encoding are open for further research. Certainly, new video coding techniques must be developed to attain higher compression efficiency and fast representation switching to offer lower latency and computational cost.

Most of the existing literature on edge-assisted 360-degree video streaming ignores mobility and scalability in their fundamental design. A possible direction is to ensure scalability in design decisions. In addition, the support for high-speed users will impact on the overall service provisioning, task offloading, scheduling, and resource allocation needs further investigations. Edge nodes placed near users are more vulnerable to security attacks than cloud data centres. One can design secure edge node sites, strong access-control policies, and privacy aware offloading and load balancing schemes to support secure VR communication. Similarly, designing energy-aware computation offloading schemes is also a promising direction.

The high fidelity 8K, 12K, or 16K media services with a high degree of freedom support add pressure to the overall capacity of existing networks. It is the next-generation mmWave wireless technology with several-Gbps communication capabilities that are expected to offer ultra-high capacity, ultra-high transmission reliability, ultra-low latency, ultra-high mobility, and massive communication support for rich media immersive applications over short or long ranges. In the future, transmission of the uncompressed part (viewport only) to multiple mobile users with different viewing patterns and preferences over 5G links can improve the performance of QoS-sensitive applications. Studies of adaptive computing offloading using mmWave communication can support synchronized 360° streaming in both indoor and outdoor environments.

Live broadcasting raises numerous concerns such as handling user interactivity, transcoding decisions, estimation of the bandwidth, achieving fairness, and smooth quality streaming, which are especially critical in an immersive multimedia context. Detailed studies for live VR streaming should be performed focusing on diverse aspects such as inter-stream fairness, user scheduling, taming latency, network traffic balancing, user's feedback, and QoS consideration in a mobile environment.

Summary for Nokia Arena XR use case

Core XR features

- Immersive 360° video and audio: Real-time streaming of high-resolution 360° video with spatial audio, delivering an authentic arena atmosphere to both onsite and remote participants.
- Viewport-dependent streaming: Advanced content delivery that streams only the segment of video each viewer is watching, optimizing bandwidth and providing smooth, low-latency experiences.
- Real-time interactivity: Users control their camera perspective, select viewpoints, and navigate the virtual environment, whether attending live concerts or sporting events.
- Cross-platform accessibility: Compatibility with desktop browsers, mobile devices, and head-mounted displays (HMDs).
- Recording and playback: All event streams are recorded in manageable chunks, supporting flexible playback and export for post-event experiences.

- Spatial audio implementation: Utilization of technologies such as Ambisonics and binaural rendering to deliver full-sphere surround sound adapted to user movement and device capabilities.

User interfaces and functionalities

- Web-based viewer: An intuitive, no-installation-required interface for desktop and mobile browsers, with options to embed streams into third-party platforms. Integrated APIs allow for custom overlays and interactions.
- Native XR viewer: Deep integration with HMDs, including advanced customization and adaptive streaming parameters based on device capability, network conditions, and user preferences.
- Camera management: Remote access and control over 360° camera hardware, allowing operators to adjust streams and layouts.
- User and device management: Centralized interface for administrators to manage users, groups, device permissions, and arena layouts, with robust authentication and access controls.
- Recording and collaging tools: Tools for recording streams, exporting segments, and optimizing bandwidth via collaged or multi-view streams tailored to different use cases.

Technologies, platforms and tools

- 5G mmWave network: High-capacity, low-latency wireless infrastructure (in partnership with Elisa and Nokia) enabling real-time, high-bitrate video and audio streaming.
- Media processing pipeline: Modular architecture leveraging media connectors and processors supporting standard codecs (HEVC/H.265, AVC/H.264, AV1) for efficient, adaptive streaming.
- Storage solutions: Use of S3-compatible object storage (MinIO or cloud), supporting large-scale, chunked video archiving and on-demand export.
- WebRTC and HTTP adaptive streaming: Ensures browser compatibility and efficient content delivery with support for viewport-adaptive tiles and multi-bitrate streaming.
- Spatial audio frameworks: Integration of ambisonics, binaural rendering, and HRTF-based audio solutions for synchronized 3D soundscapes.
- API ecosystem (optional): Extensible APIs for analytics, device control, and integration with external platforms for security, identity, and additional services.

Scalability considerations

- Modular system design: Distributed deployment options for local, private, or cloud-based infrastructure, enabling flexible scaling to accommodate event size, viewer numbers, and geographic spread.
- Bandwidth optimization: Viewport-dependent streaming and collaging can reduce network load, helping to support more concurrent users with minimal impact on experience quality.
- User and device management: Support for large-scale user and device groups, with robust authentication, authorization, and logging for operational oversight.

- Edge computing readiness: Architecture accommodates integration with edge nodes for ultra-low latency and efficient regional delivery as user base grows.

Compatibility with CitiVerse environment

- Reference architecture alignment: Adheres to CitiVerse standards for security, GDPR compliance, and user consent management.
- API interoperability: Seamless integration with CitiVerse's platforms via standardized APIs and data formats should be possible.
- Centralized analytics (optional): User and event data feeds into CitiVerse's analytics and management dashboards for unified insight and governance.
- Content structuring (optional): All assets, APIs, and data formats should be compliant with CitiVerse's requirements for discoverability, reusability, and interoperability targets.

Integration with EU LDT toolbox development

- Toolbox alignment: Modules, APIs, and content formats are structured in accordance with the EU LDT Toolbox's standards for digital asset discoverability and interoperability as much as possible.
- Comprehensive metadata (optional): Rigorous tagging and metadata practices enable integration and searchability across the LDT ecosystem.

Rotterdam use cases

In the past years, Rotterdam focussed on the digital-physical aspects of what the CitiVerse could be. Now it is time to understand what the CitiVerse will mean on a social level for citizens and other stakeholders. In a digital-physical-social world, the city will form a digital Urban Community(ties).

Therefore, Rotterdam will focus on community building and citizen participation. This initiative is an example of how the digital ecosystem could be used to strengthen social networks. This increases the visibility of a robust social neighbourhood.

There are two types of community experiences: a community where citizens can participate in social events and a community where students can follow education and meet professionals and other interested participants in the field. The immersive version of existing neighbourhoods will be able to translate the knowledge gained into an environment that is more like the physical neighbourhood and offers opportunities to experiment with augmented reality.

Rotterdam seeks to develop an open digital ecosystem where stakeholders can connect in a social setting and participate in decision-making processes. The objective with this open digital ecosystem is to bring the CitiVerse industry, including SMEs, together in developing the different layers and technical components of virtual worlds useful for local authorities and citizens. This open digital ecosystem offers the opportunity to various parties to use an interoperable technology that combines the physical, social, and digital worlds, which offers a unique opportunity for citizen participation.

Use Case 6: Neighbourhood engagement

Short description

The City of Rotterdam develops an immersive 3D environment together with partners where people can connect, interact and participate in decision-making processes through avatars. Community experience for citizens participating in social events

Pilot city

Rotterdam

Domain

Citizen participation

Project coordinator

Rotterdam

Project leader

Brenda van Breemen-Olij

Success factors

Safe environment, Collaboration, Participation, OUP, Learning, Iterative working, Trustworthiness, Zone recognition, Digital physical social

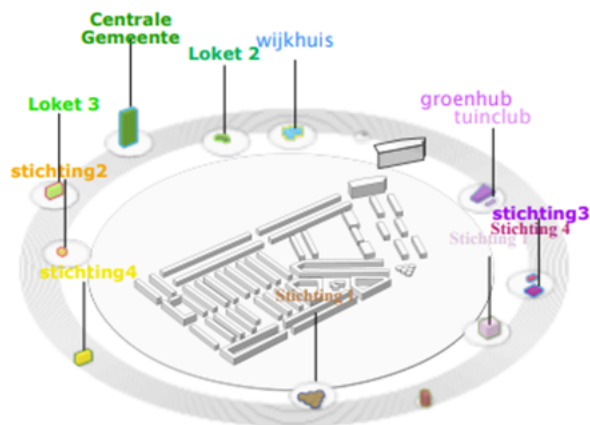
Stakeholders

- **Society:** Residents, Local community foundations, Local community organisations,
- Local news (overmathenesse.nl), Local politicians, Wijkwijs-local citizens engage in research by universities
- **Education:** Students, Zadkine (vocational education), Erasmus university, Primary schools
- **Business:** (Local) companies, Entrepreneurs, Local shops, Immersive tech network and entrepreneurd (e.g. SHINE network, regional hub), Krill Architecture, Open Urban Platform support team (FI)
- **Government:** Municipality, City cleaners, City planner/city maintenance, Veldacademie, IT / CIO, Stadsmarinier, Open Urban Platform support team (CIO), Wijk aan Zet / mijn.rotterdam (local democracy and engagement in neighbourhood), Wijkteam (neighb.team)

Full description

The City of Rotterdam develops an immersive and interactive 3D environment together with Krill-o.r.c.a, Future Insight B.V, Zadkine B&D Lab among others. This enables a public realm which in turn helps to engage citizens in visualizing urban projects, provide feedback, and access services. This ensures transparent and inclusive decision-making for a more citizen-driven city.

For the people in Oud-Mathenesse, in all their roles and identities, we aim to create a digital public realm that reflects the physical public realm. People can connect, interact, and participate in it through avatars. User engagement and agency in four privacy zones (private, collective, parochial, and public). The digital immersive environment of the neighbourhood acts as a landing space for events, services, products and content made for and by various users. In that way, all people can participate in Oud-Mathenesse in ways that suit them. This innovation for the social, physical and digital environment of Oud-Mathenesse will be aligned with the governance and values of an open inclusive democratic society.



Living *Mathenesse* Magazine a community environment for an existing neighborhood

A key feature of XR (Extended Reality) is the seamless integration of the real and virtual worlds. In this pilot, digital content is blended with the physical environment, enabling new ways to visualize and interact with urban data. This is made possible by the Open Urban Platform (OUP), which serves as a catalogue for 3D and 2D data services. Users can register their own tiles in the OUP, which can then be used to build a digital twin. For example, the tile sets that form the 3D city model of Rotterdam are available in the OUP. Additionally, the OUP allows users to share their digital twins via APIs, supporting integration with other systems. More information and documentation can be found on the OUP platform under “Digital Ecosystem | Connect.” A demonstration of these capabilities is shown in the video “Digital Twin in Unreal Engine.”

The 3D environment of Oud-Mathenesse is based on the digital twin of Rotterdam and is connected to the Open Urban Platform. The three-dimensional volumes are derived from 3D Rotterdam. This environment provides space for news and information in the form of announcements, exhibitions, and personal messages from community members. It also offers users the opportunity to create and share their own content.

User interfaces and functionalities

The user interfaces and functionalities listed in this document represent our ambitions and direction for development. We expect that not all of these requirements can be realized within the scope of the current project. However, they serve as guiding principles, and we are committed to working towards them.

Type	Action to be taken	Benefit to be realised
EP	I want to get (free) access to a DTwin environment .	So I gain planning, historical, and artistic insights.
US	I want to access (my account) using my phone, tablet, and laptop .	So I can consult the Digital Twin when, where and how I want.
US	I want to get easy access to the connecting Citiverse DTwin.	So I gain access to the additional information from the Citiverse.
US	I want to connect to other x-CITE tools (when relevant).	So I do not have to change accounts or close and start new tools.
EP	I want to explore content in the DTwin .	So I am informed and get new insights .
US	I want to filter the available content.	So I keep a clear overview.
	I want to gain access to the XR components when applicable.	So I increase my UX to be better informed.
US	I want to gain access to additional background information .	So I am better informed.
EP	I want to monitor user behaviour and keep the DTwin up to date.	So I can fine-tune my communication plan and info is always up-to-date
US	I want to add, modify and delete content .	So the information remains up-to-date.
US	I want to add or update locations (of highlights).	So the information remains up-to-date.
US	I want to modify overarching model settings .	So the model accuracy improves.
US	I want to access user statistics .	So I can adapt my communication plan based on user behaviour.
EP	I want to use models to feed the DTwin.	So I can simulate the project's effects at different levels.
US	I want to model air quality in a DTwin.	So I can simulate the effects on air quality.
US	I want to model noise in a DTwin.	So I can simulate the effects of noise.
EP	I want to use XR on-site with my phone/tablet.	So I can get local information in a DTwin environment.
US	I want to scan a QR code on-site .	So I gain access to the XR-environment and related DTwin content.
US	I want to digitally meet an avatar that informs me.	So I have a better UX with a more comfortable feeling in a familiar setting.
US	I want to have a connection with available (non-XR) DTwin content/GIS layers .	So I get a holistic overview.
	I want to get access to the Citiverse when arriving at the neighbourhood or a school/university.	So I get extra information that is in my interest.
US	I want to get neighbourhood-specific information .	So I am well-informed about the neighbourhood.
US	I want to get university-specific information in the neighbourhood of the university.	So I am well informed, and I can get access to the CitiVerse
EP	I want to use XR remotely (f.i. at home) with my phone, tablet, or laptop.	So I can consult local information in a DTwin environment.
US	I want to log in	So I get access to private content.
US	I can filter the content.	So I received an offer for customised content.
US	I want to use VR technology.	So I can experience sports events, concerts and the Citiverse even better.
US	I want to interact with other citizens, students, and teacher avatars in the XR-environment.	So I can exchange ideas, get in touch or create new contacts.
US	I want to use the Citiverse .	So I can use public or private rooms to promote and expose my artwork.
EP	I want to experience maximal accessibility .	So I can access and absorb information at my own level and pace.
US	I want to have an accessible user interface (UI) for all x-CITE solutions.	So I can clearly understand the case.
US	I want to understand the written x-CITE content correctly without being highly educated.	So I get easily informed at my level.
US	I want to be able to use the UI intuitively and logically , avoiding complexity.	So I get easily informed at my level.

US	I want to get interoperable x-CITE solutions.	So I can reuse the solutions or continue working on them after completing the x-CITE project.
EP	I want to participate and co-create with citizens.	To get feedback and to concretise/tweak suggested solutions.
US	I can provide qualitative feedback (through a survey) to the city officials.	So the city officials are aware of the public sentiment.
US	I want to give in-tool feedback while using it.	So I do not experience obstacles to an immediate response.
EP	I want to communicate with and disseminate information to citizens.	They are therefore aware of the most recent project information.
US	I would like to know when new highlights become available in the city.	So I can visit them.
US	I want to stay up-to-date in the Citiverse .	So I know almost all the recent information in the neighbourhood.
US	I want to communicate with all my stakeholders .	To inform them about updates and news.

Technologies, platforms, and tools

The digital infrastructure of the Open Urban Platform (OUP) will allow Rotterdam to develop these functionalities. The OUP acts as a catalogue for 3D (and 2D) data services. Users can register their own tiles within the platform, which can then be used to assemble a digital twin. For example, the tile sets that make up the 3D city model of Rotterdam are available in the OUP.

We also use various tools and technologies like unreal engine, mobile application framework, web technology, cloud infrastructure and interoperability standards.

Scalability considerations

When implementing the Open Urban Platform (OUP), scalability is a key consideration. The platform is designed to support a growing number of 3D and 2D data services, digital twins, and user-generated content. By starting with two distinct use cases—such as the 3D environment of Oud-Mathenesse (based on the digital twin of Rotterdam) and the fictional B&D Lab environment—the platform can be tested and optimized for different types of spatial data, user interactions, and content management.

These initial pilots allow the OUP to demonstrate its flexibility and robustness in handling both real-world and fictional environments. As more users register tiles and create digital twins, the platform’s architecture ensures that new datasets and functionalities can be integrated without compromising performance. The use of APIs for sharing digital twins also supports future expansion and interoperability with other systems.

Importantly, scalability is not only about expanding the digital infrastructure of the OUP itself, but also about transferring the core concepts and functionalities of these two use cases to similar environments, as well as to entirely new contexts. In this way, the Oud-Mathenesse and B&D Lab pilots serve as inspiration for other communities and organizations, showing how the platform can be adapted and extended to meet diverse needs and ambitions.

By starting with a limited number of use cases, the OUP can be scaled up gradually, allowing for continuous improvement based on user feedback and technical requirements. This approach ensures that the platform remains reliable and efficient as it grows to support more complex urban and community-driven XR applications.

Compatibility with CitiVerse environment

The Open Urban Platform (OUP) is well-aligned with the principles and ambitions of the CitiVerse environment. Both initiatives focus on creating interoperable, people-centered digital spaces where real and virtual worlds merge, enabling smarter urban planning, enhanced public services, and stronger community engagement.

The OUP's architecture on open data, digital twins, and API-driven integration matches the CitiVerse's emphasis on data interoperability and the use of digital twins as a foundation for immersive, collaborative urban environments. By supporting the registration and sharing of 3D and 2D data services, the OUP enables cities to build digital twins that can be integrated into broader CitiVerse ecosystems, facilitating cross-city collaboration and knowledge exchange.

The two initial use cases Oud-Mathenesse (based on Rotterdam's digital twin) and the fictional B&D Lab demonstrate how the OUP can support both real-world and imaginative environments. These pilots are fully compatible with CitiVerse ambitions, as they showcase the ability to create, manage, and share interactive 3D environments for a variety of purposes, from community engagement to urban innovation.

Moreover, the OUP's open and scalable infrastructure ensures that these use cases can serve as templates or inspiration for similar environments in other cities, as well as for entirely new applications within the CitiVerse framework. This compatibility supports the CitiVerse vision of a connected, inclusive, and innovative digital ecosystem for European cities.

Integration with EU LDT toolbox development

The Open Urban Platform (OUP) is well positioned to integrate with the EU Local Digital Twin (LDT) Toolbox, a flagship initiative of the European Commission designed to empower cities with modular, standards-based digital twin tools for smarter, data-driven urban planning. The LDT Toolbox focuses on interoperability, openness, and scalability, enabling local administrations to simulate, analyse, and plan urban environments more effectively.

By aligning the OUP's architecture with the principles and technical standards promoted by the EU LDT Toolbox, we aim to make sure our digital twins - such as those developed for Oud-Mathenesse and B&D LAB - can be easily connected, shared, and reused across different European contexts. This integration supports evidence-based decision-making, policy testing, and sustainable development strategies, while also facilitating collaboration with other cities and communities participating in the LDT ecosystem.

Furthermore, the OUP's support for open APIs and data services enables seamless data exchange and interoperability with the LDT Toolbox modules. This approach not only accelerates the digital transition of our own use cases but also contributes to the broader

goal of creating a pan-European ecosystem of connected digital twins, as envisioned by the EU's digital strategy.

Use Case 7: Students engagement

Short description

The City of Rotterdam develops an immersive 3D environment together with partners where people can connect, interact and participate in decision-making processes through avatars. Community experience for all those that want to be engaged with the crafts of beauty and design, with specific attention for safety and security of the participating students.

Pilot city

Rotterdam

Domain

Education & skills

Project coordinator

Rotterdam

Project leader

Brenda van Breemen-Olij

Success factors

Safe environment, Collaboration, Participation, OUP, Learning, Iterative working, Trustworthiness, Zone recognition, Digital physical social (see excel for more input)

Stakeholders

- **Education:** Zadkine, OCW, MBOraad, Hogeschool Rotterdam (university of applied science)
- **Business:** small businesses and creators, Textile industry, Fashion industry, Maker Spaces, banlieuhouse a shop educating students, Related shops, festival organisers: special events in digital realm, SHINE hub for immersive technologies south Holland, maker spaces, zilvermuseum, museums
- **Society:** hobbyists/enthusiasts: create and share People with an interest in fashion, jewelry hairstyles, (Future) customers/consumers, people that are well-known for inspiration
- **Government:** Municipality, dept of Culture, Wijk aan zet, Politicians / Vice mayor, veldacademie

Full description

The City of Rotterdam develops an immersive 3D environment together with Krill-o.r.c.a, Future Insight B.V, Zadkine B&D Lab among others where people can connect, interact,

and participate in decision-making processes through avatars. Community experience for all those that want to be engaged with the crafts of beauty and design, with specific focus for safety and security of the participating students. The B&D Lab is a fictive immersive 3D neighbourhood. For the participants in the lab, in all their roles and identities, we aim to create a digital public realm that reflects the physical public realm. User engagement and agency in four privacy zones (private, collective, parochial, and public). In the neighbourhood hub we create a landing space for events, services, products and content made for and by various users. In that way all can participate in crafts of beauty and design.

Core XR Features

The 3D environment of B&D Lab is based on a fictional spatial setting, designed to offer a varied and dynamic space for presentations, lectures, and archives. It provides room for news and information in the form of announcements, exhibitions, and personal messages from community members. Users are also encouraged to create and share their own content within this environment.

All of this is enabled by the digital infrastructure of the Open Urban Platform (OUP). The OUP serves as a catalogue for 3D and 2D data services, allowing users to register their own tiles, which can then be used to assemble a digital twin. For example, the tile sets that make up the 3D city model of Rotterdam are available in the OUP. The platform goes even further by enabling users to share their digital twins via APIs, supporting integration with other systems. More information and documentation can be found on the OUP platform under “Digital Ecosystem | Connect.” A demonstration of these capabilities is shown in the video “Digital Twin in Unreal Engine.



Living *B&D-Lab* Magazine
an learning environment for a community of crafts in
beauty & design

User Interfaces and Functionalities

The user interfaces and functionalities listed in this document represent our ambitions and direction for development. We expect that not all of these requirements can be realized within the scope of the current project. However, they serve as guiding principles and we are committed to working towards them.

Type	Action to be taken	Benefit to be realised
EP	I want to get (free) access to a DTwin environment .	So I gain planning, historical, and artistic insights.
US	I want to access (my account) using my phone, tablet, and laptop .	So I can consult the Digital Twin when, where and how I want.
US	I want to get easy access to the connecting Citiverse DTwin.	So I gain access to the additional information from the Citiverse.
US	I want to connect to other x-CITE tools (when relevant).	So I do not have to change accounts or close and start new tools.
EP	I want to explore content in the DTwin .	So I am informed and get new insights .
US	I want to filter the available content.	So I keep a clear overview.
	I want to gain access to the XR components when applicable.	So I increase my UX to be better informed.
US	I want to gain access to additional background information .	So I am better informed.
EP	I want to monitor user behaviour and keep the DTwin up to date.	So I can fine-tune my communication plan and info is always up-to-date
US	I want to add, modify and delete content .	So the information remains up-to-date.
US	I want to add or update locations (of highlights f.i.).	So the information remains up-to-date.
US	I want to modify overarching model settings .	So the model accuracy improves.
US	I want to access user statistics .	So I can adapt my communication plan based on user behaviour.
EP	I want to use models to feed the DTwin.	So I can simulate the project's effects at different levels.
US	I want to model air quality in a DTwin.	So I can simulate the effects on air quality.
US	I want to model noise in a DTwin.	So I can simulate the effects of noise.
EP	I want to use XR on-site with my phone/tablet.	So I can get local information in a DTwin environment.
US	I want to scan a QR code on-site .	So I gain access to the XR-environment and related DTwin content.
US	I want to digitally meet an avatar that informs me.	So I have a better UX with a more comfortable feeling in a familiar setting.
US	I want to have a connection with available (non-XR) DTwin content/GIS layers .	So I get a holistic overview.
	I want to get access to the Citiverse when arriving at the neighbourhood or a school/university.	So I get extra information that is in my interest.
US	I want to get neighbourhood-specific information .	So I am well-informed about the neighbourhood.
US	I want to get university-specific information in the neighbourhood of the university.	So I am well informed, and I can get access to the CitiVerse
EP	I want to use XR remotely (f.i. at home) with my phone, tablet, or laptop.	So I can consult local information in a DTwin environment.
US	I want to log in	So I get access to private content.
US	I can filter the content.	So I received an offer for customised content.
US	I want to use VR technology.	So I can experience sports events, concerts and the Citiverse even better.

US	I want to interact with other citizens, students, and teacher avatars in the XR-environment.	So I can exchange ideas, get in touch or create new contacts.
US	I want to use the Citiverse .	So I can use public or private rooms to promote and expose my artwork.
EP	I want to experience maximal accessibility .	So I can access and absorb information at my own level and pace.
US	I want to have an accessible user interface (UI) for all x-CITE solutions.	So I can clearly understand the case.
US	I want to understand the written x-CITE content correctly without being highly educated.	So I get easily informed at my level.
US	I want to be able to use the UI intuitively and logically , avoiding complexity.	So I get easily informed at my level.
US	I want to get interoperable x-CITE solutions.	So I can reuse the solutions or continue working on them after completing the x-CITE project.
EP	I want to participate and co-create with citizens.	To get feedback and to concretise/tweak suggested solutions.
US	I can provide qualitative feedback (through a survey) to the city officials.	So the city officials are aware of the public sentiment.
US	I want to give in-tool feedback while using it.	So I do not experience obstacles to an immediate response.
EP	I want to communicate with and disseminate information to citizens.	They are therefore aware of the most recent project information.
US	I would like to know when new highlights become available in the city.	So I can visit them.
US	I want to stay up-to-date in the Citiverse .	So I know almost all the recent information in the neighbourhood.
US	I want to communicate with all my stakeholders .	To inform them about updates and news.

Technologies, platforms, and tools

The digital infrastructure of the Open Urban Platform (OUP) will allow Rotterdam to develop these functionalities. The OUP acts as a catalogue for 3D (and 2D) data services. Users can register their own tiles within the platform, which can then be used to assemble a digital twin. For example, the tile sets that make up the 3D city model of Rotterdam are available in the OUP.

We also use various tools and technologies like Unreal engine, mobile application Framework, web technology, cloud infrastructure, interoperability standards.

Scalability considerations

When implementing the Open Urban Platform (OUP), scalability is a key consideration. The platform is designed to support a growing number of 3D and 2D data services, digital twins, and user-generated content. By starting with two distinct use cases - such as the 3D environment of Oud-Mathenesse (based on the digital twin of Rotterdam) and the B&D Lab environment - the platform can be tested and optimized for different types of spatial data, user interactions, and content management.

These initial pilots allow the OUP to demonstrate its flexibility and robustness in handling both real-world and fictional environments. As more users register tiles and create digital twins, the platform's architecture ensures that new datasets and functionalities can be integrated without compromising performance. The use of APIs for sharing digital twins also supports future expansion and interoperability with other systems.

Importantly, scalability is not only about expanding the digital infrastructure of the OUP itself, but also about transferring the core concepts and functionalities of these two use cases to similar environments, as well as to entirely new contexts. In this way, the Oud-Mathenesse and B&D Lab pilots serve as inspiration for other communities and organizations, showing how the platform can be adapted and extended to meet diverse needs and ambitions.

By starting with a limited number of use cases, the OUP can be scaled up gradually, allowing for continuous improvement based on user feedback and technical requirements. This approach ensures that the platform remains reliable and efficient as it grows to support more complex urban and community-driven XR applications.

Compatibility with CitiVerse environment

The Open Urban Platform (OUP) is well-aligned with the principles and ambitions of the CitiVerse environment. Both initiatives focus on creating interoperable, people-centred digital spaces where real and virtual worlds merge, enabling smarter urban planning, enhanced public services, and stronger community engagement.

The OUP's architecture centred around open data, digital twins, and API-driven integration matches the CitiVerse's emphasis on data interoperability and the use of digital twins as a foundation for immersive, collaborative urban environments. By supporting the registration and sharing of 3D and 2D data services, the OUP enables cities to build digital twins that can be integrated into broader CitiVerse ecosystems, facilitating cross-city collaboration and knowledge exchange.

The two initial use cases Oud-Mathenesse (based on Rotterdam's digital twin) and the B&D Lab demonstrate how the OUP can support both real-world and imaginative environments. These pilots are fully compatible with CitiVerse ambitions, as they showcase the ability to create, manage, and share interactive 3D environments for a variety of purposes, from community engagement to urban innovation.

Moreover, the OUP's open and scalable infrastructure ensures that these use cases can serve as templates or inspiration for similar environments in other cities, as well as for entirely new applications within the CitiVerse framework. This compatibility supports the CitiVerse vision of a connected, inclusive, and innovative digital ecosystem for European cities

Integration with EU LDT toolbox development

The Open Urban Platform (OUP) is well positioned to integrate with the EU Local Digital Twin (LDT) Toolbox, a flagship initiative of the European Commission designed to empower cities with modular, standards-based digital twin tools for smarter, data-driven urban planning. The LDT Toolbox focuses on interoperability, openness, and scalability, enabling local administrations to simulate, analyse, and plan urban environments more effectively.

By aligning the OUP's architecture with the principles and technical standards promoted by the EU LDT Toolbox, we aim to make our digital twins such as those developed for Oud-Mathenesse and B&D Lab can be connected, shared, and reused across different European contexts. This integration supports evidence-based decision-making, policy testing, and sustainable development strategies, while also facilitating collaboration with other cities and communities participating in the LDT ecosystem.

Furthermore, the OUP's support for open APIs and data services enables seamless data exchange and interoperability with the LDT Toolbox modules. This approach not only accelerates the digital transition of our own use cases but also contributes to the broader goal of creating a pan-European ecosystem of connected digital twins, as envisioned by the EU's digital strategy.

Flanders use cases

The Flemish government will apply CitiVerse technology in the context of the realisation of an immersive LDT solution to support the Environmental Impact Assessment (EIA) and the public participation processes provided for therein. The EIA CitiVerse approach will be tested at two locations and in two common EIA case types. The first pilot concerns the redevelopment of an industrial site near the city centre of Kortrijk creating a mix of dwellings, businesses and common green spaces, impacting one or more neighbourhoods. The second pilot involves a similar redevelopment around the main train station of the City of Mechelen. The use of immersive technology during the official EIA participation process will focus on the potential improvements in understandability (literacy), public involvement and quality of the EIA in terms of process improvements and quality of the outcomes.

Flanders will enable new methods for engaging government, experts, and citizens within the existing framework, utilising extended digital twins and virtual world technologies. Traffic intensity, noise impact, air quality and visual aspects will be combined to allow citizens to visualise the alternatives and gain a better understanding of why a specific decision was made. This case builds trust by allowing experts to review the algorithms and data alternatives applied.

For the pilot of Kortrijk, the use cases match a specific challenge that requires a specific solution.

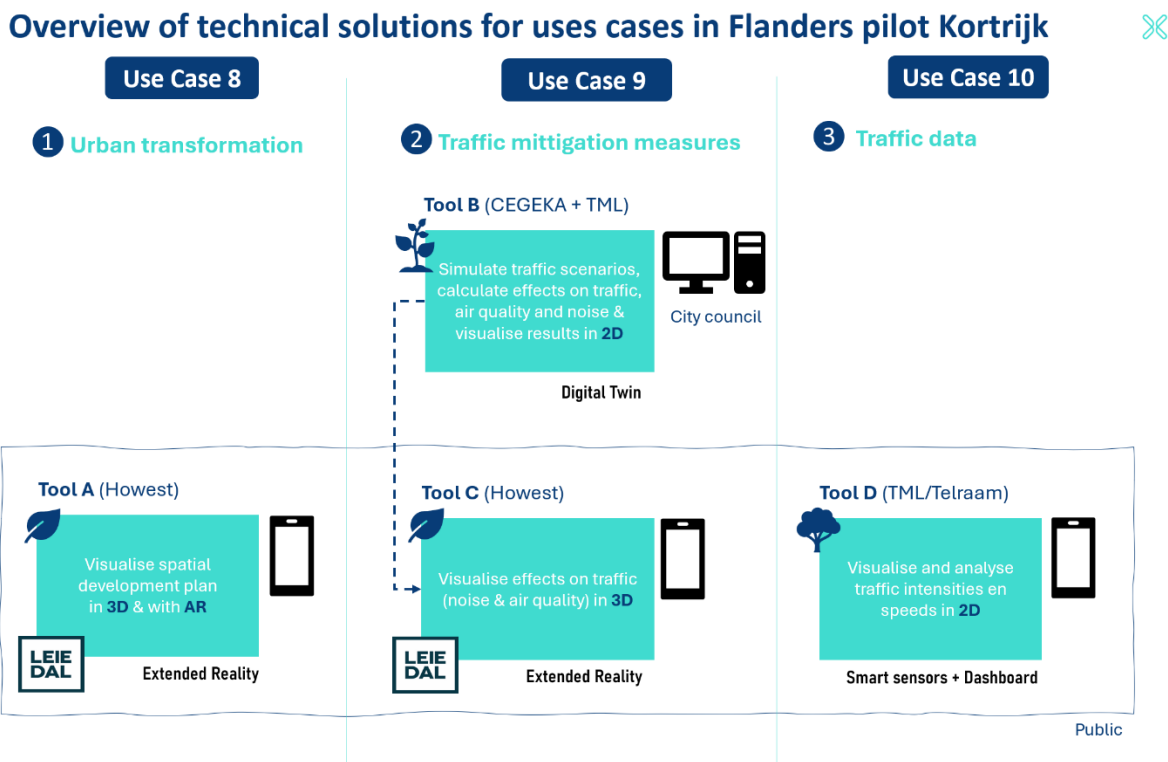


Figure 7 Overview of tools (to be developed) for Use Cases in Flanders pilot Kortrijk

Tool mock-ups for Use Cases of Flanders pilot Kortrijk

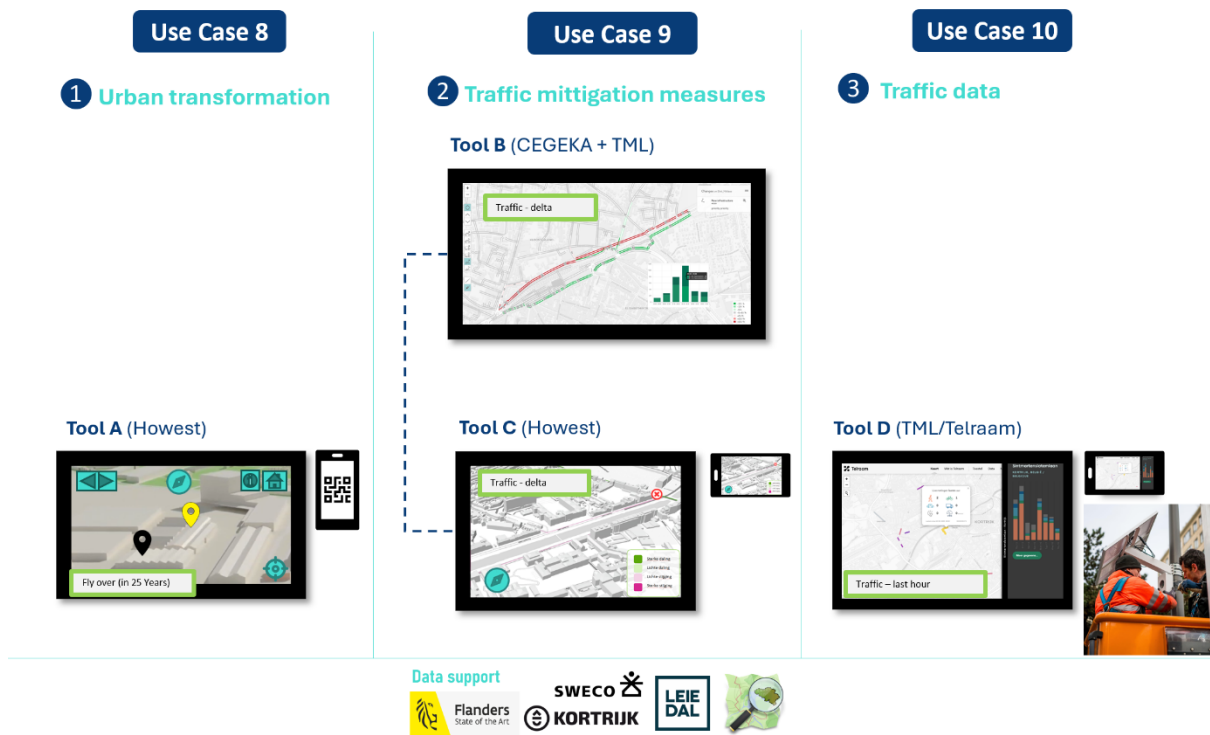


Figure 8 Tool mock-up screens for Use Cases of Flanders pilot Kortrijk

Use Case 8: Insightful spatial implementation plan

Short description

Interactive 3D and XR visualisations help citizens better understand the phased implementation of spatial development plans.

Pilot City

Flanders-Kortrijk

Domain

Environmental policy

Project coordinator

VLO

Project leader

Tom Callens

Success factors

- Citizens reporting improved understanding of planned urban development

Stakeholders

- City council of Kortrijk (departments Urban planning, Mobility, Communication & Participation, Data & ICT) [government]
- Intercommunal organisation Leiedal [government]
- Neighbourhood residents [civil society]
- Neighbourhood committees [civil society]
- Van Marcke NV (owner of the site) [industry]
- Engineering company SWECO (provider of the EIA report) [industry]
- Companies on site [industry]
- Other Companies in project area [industry]
- Parenting organisations [civil society]
- Schools Athena (Ter Bruyninge/Pottelberg/Zoom Freinet) [civil society]
- School BuSO Ter Bruyninge [civil society]
- School De Kleine Kunstgalerij [civil society]
- School O.L.V. van Vlaanderen [civil society]
- School Provinciaal Technisch Instituut [civil society]
- Residential care center (WCZ De Pottelberg) [civil society]
- Howest students (students in city of Kortrijk who follow course of Smart Cities) [academia]
- Smart Flanders (Steering group of Flanders Smart Region network) [government]
- Flemish Environment Agency [government]
- Flemish Department of Mobility & Public Works [government]
- Flemish Agency for Road Management & Traffic [government]
- Vereniging van Vlaamse Steden en Gemeenten (association of Flemish cities and Municipalities) [government]
- Kenniscentrum Vlaamse steden (association of 13 big Flemish cities) [government]
- V-ICT-OR (Flemish association of local ICT providers & users) [industry/government]
- FLAGIS (Flemish association of professional spatial data users) [industry/government/academia]
- Agoria (Belgian employers' organization for technology companies) [industry]

Full description

Together with the City of Kortrijk and intermunicipal organisation Leiedal, we will investigate whether citizens of Kortrijk can better understand and accept a spatial

implementation plan through the interactive use of XR technology and 3D digital twin technology.



Figure 9 Simulation mock-up screen: potential new building versus actual situation

Core features

- Accessibility: Citizens can use their phone to see what is happening.
- Interest: Shows the changes and gives information about the new buildings.

User Interfaces and functionalities

The required functionalities correspond with Epics (EPs) and User Stories (US) that have been identified during functional workshops with the main stakeholders.

Table 1 Epics and User Stories of use case 8.

EP	As a citizen/student	I want to explore content in the Digital Twin .	So I am informed and get new insights .
US	As a citizen/student	I want to obtain local information on spatial planning.	So I get a immersive experience.
US	As a citizen/student	I want to have an interactive, animated UX (utilising animations, videos, sound, etc.).	So I have a better UX informing me better.
US	As a citizen/student	I want to gain access to the XR components when applicable.	So I increase my UX to be better informed.
US	As a citizen	I aim to understand the mobility changes that occur at each stage of the planning process.	So I can help with co-designing solutions for the city.

EP	As a citizen/student	I want to explore content in the Digital Twin .	So I am informed and get new insights .
US	As a citizen	I want to have access to pre-created or customisable flyover movies .	So I get an optimal experience of the 'to be' situation.
US	As a citizen	I want to gain access to additional background information .	So I am better informed.

EP	As a citizen/student/teacher	I want to use XR on-site with my phone/tablet.	So I can get local information in a DTwin environment.
US	As a citizen	I want to scan a QR code on-site .	So I gain access to the XR environment and related DTwin content.
US	As a citizen	I want to explore and review the plans on-site with AR.	So I can better understand how the plans fit into the neighbourhood.
US	As a citizen	I want to select multiple future time points with updated AR visuals.	So I can see the planning, timeline and evolution/progress/phasing of the project.
US	As a citizen	I want to distinguish between different spatial zoning/destinations (legend, filtering).	So I get a deeper understanding of the planned zoning in the area.
US	As a citizen	I want to filter the views.	So I maintain an overview by hiding items that fall beyond my field of interest.
US	As a citizen/student/teacher	I want to have a connection with available (non-XR) Digital Twin content/GIS layers .	So I get a holistic overview.

EP	As an admin	I want to monitor user behaviour and keep the DTwin up to date.	So I can fine-tune my communication plan and info is always up-to-date
US	As an admin	I want to access user statistics .	So I can adapt my communication plan based on user behaviour.

EP	As a citizen/student/teacher	I want to experience maximal accessibility .	So I can access and absorb information at my own level and pace.
US	As a disabled citizen	I want to have an accessible user interface (UI) for all x-CITE solutions.	So I can clearly understand the case.
US	As a moderate citizen with whatever background and age	I want to understand the written x-CITE content correctly without being highly educated.	So I get easily informed at my level.
US	As a moderate citizen with whatever background and age	I want to be able to use the UI intuitively and logically , avoiding complexity.	So I get easily informed at my level.
US	As a city official	I want to get interoperable x-CITE solutions.	So I can reuse the solutions or continue working on them after completing the x-CITE project.

Technologies, platforms, and tools

WebGL, Unity, webbar-foundation (AR), QR

Scalability considerations

- Adjustable: Most pieces are replaceable and adjustable given some time to adjust rotation and/or placement compared to the real-life counterpart.
- User management: No personal data collection is foreseen; if limited telemetry becomes necessary, it will be documented and consent-based.
- Level of detail: Distance rendering between high to lower detailed objects and textures to ensure a more optimized view without losing too many details.
- Cross compatibility: Decision to keep it for web makes it easier to adapt for Android/IOS users

Compatibility with CitiVerse environment

- Performance: Adjusted for usage of smaller hardware.
- Reference Architecture Alignment: Link between models to ensure correct alignments of the real-life counterpart.
- Customizable Placement and Information: Based on the location of the models, it can have additional information placed close to the buildings (or around the area).
- Citizens Participation: Let the user play on location to experience it in person as goal to have a closer connection between citizen and city projects.

Integration with EU LDT Toolbox development project

- BB.07: Extended Reality
- BB.09: Integrated Environment
- BB.10: Interactions
- BB.38: Innovation Planning

Use Case 9: Co-design traffic mitigation measures

Short description

Policymakers and citizens in Kortrijk co-design mitigation measures for traffic by comparing their environmental impact (in 2D & 3D/XR) within Mobilize (Cegeka), which serves as the scenario engine and user interface of the local Digital Twin. The solution (Tool B) aligns with the EU Local Digital Twin (LDT) Toolbox and the CitiVerse (EDIC) initiative to ensure interoperability, reuse, and participatory decision-making across EU

cities. The results of tool B are displayed in a public environment, utilising 3D technology (Tool C).

Pilot city

Kortrijk

Domain

Environmental policy

Project coordinator

VLO

Project leader

Tom Callens

Success factors

- Mobility experts and urban planners experience a valuable user journey with a Digital Twin that supports EIA type analysis and policy testing.
- Citizens feel empowered by meaningful participation and clear visualisation of options and impacts.
- Actionable lessons feed into a roadmap for operationalisation and reuse across cities through the LDT Toolbox and CitiVerse network.

Stakeholders

- City council of Kortrijk (departments Urban planning, Mobility, Communication & Participation, Data & ICT) [government]
- Intercommunal organisation Leiedal [government]
- Neighbourhood residents [civil society]
- Neighbourhood committees [civil society]
- Van Marcke NV (owner of the site) [industry]
- Engineering company SWECO (provider of the EIA report) [industry]
- Companies on site [industry]
- Other Companies in project area [industry]
- Parenting organisations [civil society]
- Schools Athena (Ter Bruyninge/Pottelberg/Zoom Freinet) [civil society]
- School BuSO Ter Bruyninge [civil society]
- School De Kleine Kunstgalerij [civil society]
- School O.L.V. van Vlaanderen [civil society]
- School Provinciaal Technisch Instituut [civil society]
- Residential care center (WCZ De Pottelberg) [civil society]

- Howest students (students in city of Kortrijk who follow course of Smart Cities) [academia]
- Smart Flanders (Steering group of Flanders Smart Region network) [government]
- Flemish Environment Agency [government]
- Flemish Department of Mobility & Public Works [government]
- Flemish Agency for Road Management & Traffic [government]
- Vereniging van Vlaamse Steden en Gemeenten (association of Flemish cities and Municipalities) [government]
- Kenniscentrum Vlaamse steden (association of 13 big Flemish cities) [government]
- V-ICT-OR (Flemish association of local ICT providers & users) [industry/government]
- FLAGIS (Flemish association of professional spatial data users) [industry/government/academia]
- Agoria (Belgian employers' organization for technology companies) [industry]

Full description

Policymakers and citizens in Kortrijk co-design mitigation measures on traffic by comparing their environmental impact (in 2D & 3D). The measures are calculated and visualised through a digital twin.

In the Flanders pilot (Kortrijk), these functionalities are implemented using the Mobilize platform developed by Cegeka, which integrates XR visualisation, expert-level 2D data visualisation, and simulation creation, orchestration and management. Mobilize supports XR connectivity and acts as the core scenario engine within the Local Digital Twin (LDT) architecture. To ensure clarity and alignment with the actual implementation, it is important to make Mobilize's role explicit in the attached diagram, which currently presents a generic view of an ideal digital twin ecosystem. Mobilize covers the following components from the LDT diagram:

- Geospatial Visualisation (B3.1)
- Analytical Visualisation (B3.2)
- Extended Reality (B3.3)
- Case & Scenario Management (B4.1)
- Integrated Environment (B4.2) including:
 - Data Workflow and Component Orchestration
 - Interactions
 - Message Brokering
 - Event-Based Data Publishing
 - Data Platform (B5) including:

- Data Replication Client (B5.1)
- Data Query Service (B5.2)
- Data Storage
- Identity & User Management (EU LDT Identity Management)
- AI Development (B8) including:
 - Algorithms & Models
 - Model Catalogue
 - Model Abstraction

This mapping ensures common understanding and agreement across stakeholders and reinforces the interoperability and reuse principles of the EU LDT Toolbox and CitiVerse initiatives.

Note: The referenced diagram illustrating the ideal digital twin architecture and its building blocks is included in Deliverable D3.4 (Figure 1: LDT Toolbox from EU Project LDT Toolbox). Mobilize’s coverage of these components is mapped accordingly.

Mobilize enables Kortrijk’s policymakers and residents to simulate and compare traffic mitigation measures (e.g., circulation plans, LTNs, timed access, school streets) and to visualise their effects on traffic, air quality, and noise in 2D/3D/XR. The approach follows the EU LDT Toolbox principle of planning/simulation (not real-time ops) and open, interoperable building blocks so results and methods can be shared or replicated across cities within the CitiVerse ecosystem.

Core features

- Integration with simulation models: integrates with traffic simulation (TML), air quality modelling, and noise modelling systems. This allows for comprehensive analysis and comparison of different traffic mitigation measures.
- Centralised Data Processing and Management: a central hub for data processing and management, ensuring that all relevant data is collected, processed, and utilised effectively.
- Output and visualisation capabilities: output and visualisation capabilities through a 2D Web GIS Viewer and a 3D/XR Viewer. This enables users to visualise the impact of different traffic measures in both 2D and immersive 3D/XR environments.
- Cloud-Native Backend Infrastructure: supports a cloud-native backend infrastructure, which ensures scalability, performance, and reliability.

User interfaces and functionalities

The required functionalities correspond with Epics (EPs) and User Stories (US) that have been identified during functional workshops with the main stakeholders.

Table 2 Epics and User Stories of use case 9.

EP	As a citizen/student	I want to explore content in the Digital Twin .	So, I am informed and get new insights .
US	As a citizen	I aim to understand the mobility changes that occur at each stage of the planning process.	So, I can help with co-designing solutions for the city.
US	As a citizen	I want to gain access to additional background information .	So, I am better informed.

EP	As an admin	I want to monitor user behaviour and keep the DTwin up to date.	So, I can fine-tune my communication plan and info is always up-to-date
US	As an admin	I want to add, modify and delete content .	So, the information remains up-to-date.
US	As an admin	I want to add or update locations (such as highlights).	So, the information remains up-to-date.
US	As an admin	I want to modify overarching model settings .	So, the model accuracy improves.
US	As an admin	I want to access user statistics .	So, I can adapt my communication plan based on user behaviour.

EP	As a city official	I want to use models to feed the digital twin.	So, I can simulate the project's effects at different levels.
US	As a city official	I want access to a protected Digital Twin area where I can do modelling.	So, the environment can only be accessed by experts.
US	As a city official	I want to model mobility in a Digital twin.	So, I can monitor potential traffic changes.
US	As a city official	I want to set model parameters interactively using a dashboard.	So, I can simulate the effect of traffic changes by creating different scenarios (e.g., closing streets, changing speed regimes, filtering traffic, etc.).
US	As a city official	I want to be able to add local static traffic data .	So, I can train the traffic model, which will result in better air quality and noise modelling.
US	As a city official	I want to be able to add local dynamic traffic (sensor) data .	So, I can train the traffic model, which will result in better air quality and noise modelling.
US	As a city official	I want to be able to add local air quality sensor data .	So, I can train the air quality model, which will result in better air quality and noise modelling.
US	As a city official	I want to model air quality (NO2, PM2.5, PM10) in a Digital Twin.	So, I can simulate the effects on air quality.
US	As a city official	I want to model noise in a Digital Twin.	So, I can simulate the effects of noise.

EP	As a city official	I want to use models to feed the digital twin.	So, I can simulate the project's effects at different levels.
US	As a city official	I aim to clearly and understandably explore the model results within the Digital Twin.	So, this enables immediate estimation of the current state (“as-is”) and the projected state (“to-be”).
US	As a city official	I want to see the apparent differences (deltas) before and after the local use case implementations.	So, I can see the effects of the project at different stages.
US	As a city official	I want to download the raw model data results.	So, I can compare data with calculations made by third parties.
US	As a city official	I want to be able to export visuals .	So, I can use them for communication purposes.
US	As a city official	I want models to give output in a reasonable amount of time (≤15 minutes for baseline scenarios).	So, simulations can be completed efficiently within the available timeframe.
US	As a citizen	I want to use simplified modelling with free access.	So, I see the effects of, for example, a school street on traffic, air quality and noise.

EP	As a citizen/student/teacher	I want to experience maximal accessibility .	So, I can access and absorb information at my own level and pace.
US	As a disabled citizen	I want to have an accessible user interface (UI) for all x-CITE solutions.	So, I can clearly understand the case.
US	As a moderate citizen with whatever background and age	I want to understand the written x-CITE content correctly without being highly educated.	So, I get easily informed at my level.
US	As a moderate citizen with whatever background and age	I want to be able to use the UI intuitively and logically , avoiding complexity.	So, I get easily informed at my level.
US	As a city official	I want to get interoperable x-CITE solutions.	So, I can reuse the solutions or continue working on them after completing the x-CITE project.

Tool B

Technologies, Platforms, and Tools

- A. Data Ingestion & Governance
 - Data sources: traffic counts/FCD, roadworks, environmental stations (AQ/noise).
 - Interoperability: adopt MIMs Plus (context APIs, standard data models).
- B. Digital Twin & Simulation
 - Mobilize Core (Cegeka): scenario authoring, comparisons

- Traffic simulation (TML): calibrated runs
- Air quality: integrate with VITO Quark style modelling for emissions/NO₂/PM deltas.
- Noise: ingest and visualize from EIA/noise models; compute comparative deltas per scenario (Noise data source TBD either product API if available, or datasets from a noise expert).
- C. Visualization & Co-Design UX
 - 2D Web GIS: baselines, measures, and delta layers; side-by-side or swipe comparisons.
- 3D/XR: immersive scenes aligned with CitiVerse's participatory AR/VR vision; launchable from city portals.
- 3D/XR: visualisation delivered by Tool C (Howest); Mobilize (Tool B) provides the scenario outputs and layers consumed by Tool C.
- Engagement tools: simple toggles/sliders, guided narratives, and feedback capture.
- D. Analytics
 - Predictive hotspot detection, emission exposure estimation
 - Compliance with public-sector transparency goals highlighted for LDT/CitiVerse
- E. Security, Identity, and Access
 - SSO, role-based access, consent and audit trails to support cross-jurisdiction collaboration.
- F. Engineering & Ops
 - Cloud-native containers for simulation workers, analytics, and viewers;
 - Job queues for scenario batches; observability (metrics/traces);
 - Optional HPC/GPU burst for big scenario sets

Scalability considerations

- Modular architecture: each component (simulation, visualisation, analytics) scales independently.
- Multi-city readiness: Mobilize workspace in Kortrijk is exportable to other cities via MIMs Plus profiles.
- Performance: pre-computation and caching for large scenario sets.
- Cloud-native deployment: supports elastic scaling and distributed processing.

Compatibility with CitiVerse environment

- Mobilize aligns with CitiVerse reference architecture and governance principles.
- Supports GDPR compliance, user consent, and federated identity.
- Uses standardised APIs and data models for integration with mobility, tourism, and education platforms.
- Mobilize produces XR-ready outputs interoperable with CitiVerse modules and the XR viewer (Tool C).

Integration with EU LDT Toolbox development project

Mobilize maps directly to LDT Toolbox building blocks:

- BB.02 Case & Scenario Management
- BB.04 Data Query Service
- BB.06 Workflow Engine
- BB.07 Extended Reality
- BB.10 Interactions
- BB.11 Message Broker
- BB.13 Model Catalogue
- BB.15 Algorithms & Models
- BB.18 Data Storage
- BB.19 Access Control
- BB.20 Analytical Visualisation
- BB.30 Geospatial Visualisation
- BB.31 Identity Management
- BB.35 User Management

Mobilize's implementation in Kortrijk demonstrates how a single platform can fulfil multiple LDT Toolbox capabilities, ensuring reuse and alignment with EU standards.

Note: The architecture schema illustrating these components is aligned with the LDT Toolbox diagram presented in Deliverable D3.4 (Figure 1). Mobilize's coverage of the building blocks is mapped accordingly.

Technical steps

- MIMs Plus conformance for Mobilize APIs/data models (roads, measures, indicators).
- Scenario API: export/import scenario definitions and results as Toolbox-recognised packages.
- Metadata : indicators (flows, NO₂/PM deltas, dB(A) deltas).

Simple architecture diagram

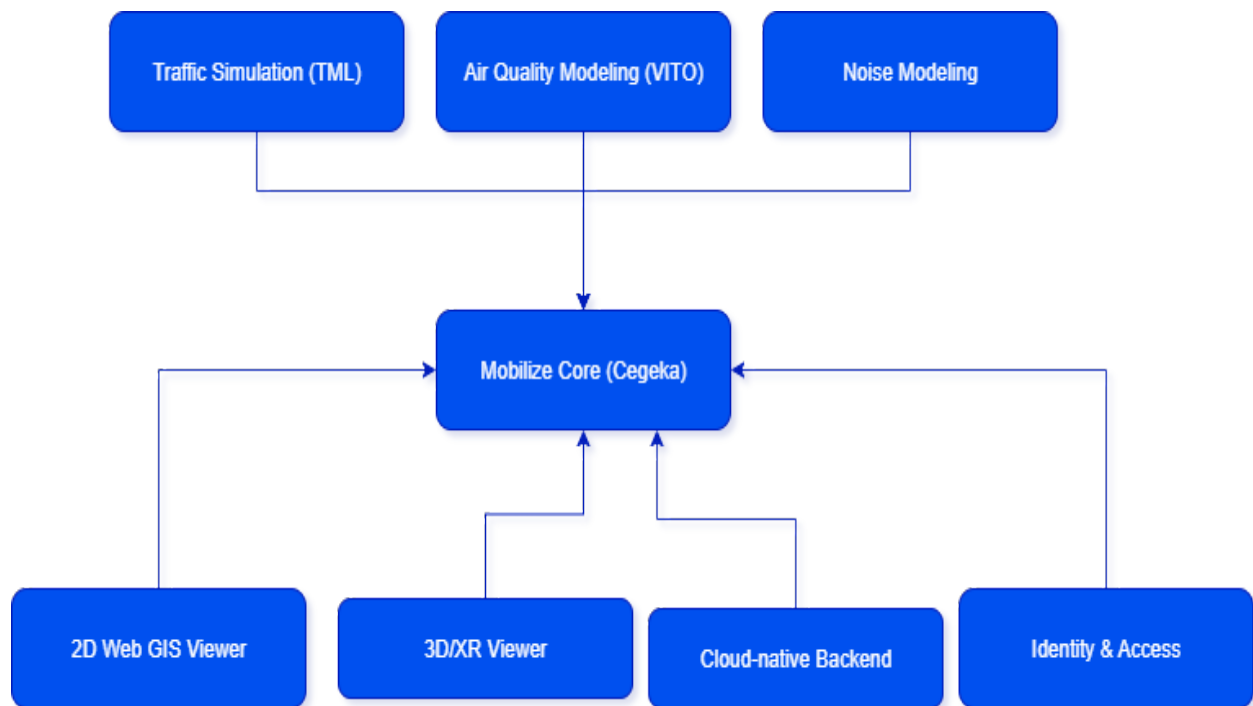


Figure 10 Architecture diagram of tool B

Risks & mitigations

- Data quality/calibration → early baseline checks; iterative calibration rounds with experts (TML/VITO inputs).
- Privacy & ethics → aggregated indicators; consented feedback; transparent explainability.
- Digital divide → inclusive UX; low-bandwidth 2D fallback

Tool C

Technologies, platforms and tools

- WebGL, Unity

Scalability considerations

- Web optimisations: For simulations and 3D visualisation.
- Model and texture streaming: Considerations in the form of performance versus visual quality.
- Cross compatibility: Decision to keep it for web makes it easier to adapt for Android/IOS users.
- Level of detail: Using distance to make the change of high to low detailed objects and textures to ensure a more optimised view without losing too many details.

Compatibility with CitiVerse environment

- Performance: Adjusted for the usage of smaller hardware.
- Reference Architecture Alignment: Link between models and simulation to ensure it works on the terrain.
- Customizable data for simulation.
- Citizens Participation: Let the user play with the simulation and let them be informed about the traffic of the location.

Integration with EU LDT toolbox development project

- BB.02: Case & Scenario Management
- BB.07: Extended Reality
- BB.09: Integrated Environment
- BB.10: Interactions
- BB.15: Algorithms & Models
- BB.20: Analytical Visualization
- BB.30: Geospatial Visualization

Use Case 10: Enhance the quality of the traffic debate

Short description

Citizens are empowered to participate in local traffic debates.

Pilot city

Flanders-Kortrijk

Domain

Environmental policy

Project coordinator

VLO

Project leader

Tom Callens

Success factors

- Citizens/companies/organisations have a better understanding of the current traffic (speeds)

Stakeholders

- City council of Kortrijk (departments Urban planning, Mobility, Communication & Participation, Data & ICT) [government]
- Intercommunal organisation Leiedal [government]
- Neighbourhood residents [civil society]
- Neighbourhood committees [civil society]
- Van Marcke NV (owner of the site) [industry]
- Engineering company SWECO (provider of the EIA report) [industry]
- Companies on site [industry]
- Other Companies in project area [industry]
- Parenting organisations [civil society]
- Schools Athena (Ter Bruyninge/Pottelberg/Zoom Freinet) [civil society]
- School BuSO Ter Bruyninge [civil society]
- School De Kleine Kunstgalerij [civil society]
- School O.L.V. van Vlaanderen [civil society]
- School Provinciaal Technisch Instituut [civil society]
- Residential care center (WCZ De Pottelberg) [civil society]
- Howest students (students in city of Kortrijk who follow course of Smart Cities) [academia]
- Smart Flanders (Steering group of Flanders Smart Region network) [government]
- Flemish Environment Agency [government]
- Flemish Department of Mobility & Public Works [government]
- Flemish Agency for Road Management & Traffic [government]
- Vereniging van Vlaamse Steden en Gemeenten (association of Flemish cities and Municipalities) [government]
- Kenniscentrum Vlaamse steden (association of 13 big Flemish cities) [government]
- V-ICT-OR (Flemish association of local ICT providers & users) [industry/government]
- FLAGIS (Flemish association of professional spatial data users) [industry/government/academia]
- Agoria (Belgian employers' organization for technology companies) [industry]

Full description

Empowering citizens to participate in local traffic and traffic safety policy debates by giving them a leading role in the production of traffic data, evidence and knowledge about mobility in their neighbourhood by providing them with smart traffic sensors and tools.

Citizens count and visualise traffic (pedestrians, bicycles, cars, heavy vehicles) and car speeds automatically (in real-time).

Core features

- Smart sensor technology
 - AI-powered traffic counter.
 - Uses edge computing with an integrated AI chip for real-time object detection and classification.
 - Operates autonomously with built-in mobile data (LTE-M or NB-IoT), no Wi-Fi needed.
- Multimodal Traffic Counting
 - Detects and classifies traffic modes
 - Data is aggregated into broader categories for visualisation: pedestrians, two-wheelers, cars, and large vehicles.
- Privacy and security
 - No identifiable images or videos are stored or transmitted.
 - Only anonymous, aggregate data is sent every 15 minutes.
 - Firmware is stored in read-only memory and updated securely over-the-air (OTA).
- Data & Dashboard
 - Provides real-time traffic data with 15-minute resolution
- Data is accessible via a web dashboard and an API for integration and analysis
- Enables data-driven decision-making for mobility planning, traffic safety, and urban design

User interfaces and functionalities

Table 3 Epics and User Stories of use case 10.

EP	As a citizen	I want to get a user-friendly dashboard for traffic	So I can understand traffic data
US	As a citizen	I want to see traffic counts (pedestrians, bicycles, cars, heavy vehicles) and speeds (cars, heavy vehicles) in real time.	So I can get a better understanding of traffic in my neighbourhood.
US	As a citizen	I want to see the modal split for a chosen day, week and specific period	So I can get a better understanding of the modal split over time
US	As a citizen	I want to share the results on social media	So I can inform my community
US	As a citizen	I want to export the data in an open format	So I can make my own graphs
US	As a city official	I want to create and see the results of selected sensors as a network	So I can analyse traffic data in a particular project area

EP	As a citizen	I want to get a user-friendly dashboard for traffic	So I can understand traffic data
US	As a city official	I want to access the data of a sensor or network through an API	So I can analyse traffic data in our traffic management system
US	As a city official	I want to set up a public network page with a customisable layout	So I can publish the data publicly with the corporate identity of my City
US	As an admin	I want to access user statistics .	So I can inform my clients about the use of our product.

Technologies, platforms and tools

A central tool for this use case is Telraam: www.telraam.net

Telraam is a combined technical and participatory tool designed to empower citizens to contribute to local traffic and mobility policy debates actively. It fulfils this role by placing citizens at the centre of the production of traffic data, evidence, and knowledge in their own neighbourhoods.

There are two types of Telraam sensors: one for indoor placement and one for outdoor placement in public areas. In case of the former, citizens are equipped with smart Telraam traffic sensors, which are installed outdoors in this project use case. Both sensors automatically and continuously count and classify different categories of road users, including pedestrians, bicycles, cars, and heavy vehicles, as well as measure vehicle speeds.



Figure 11 Indoor and outdoor smart traffic count devices

All sensor data is transmitted in real time to an open data platform, where it is processed, aggregated, and visualised.

Citizens can access and interpret traffic data for their own street or neighbourhood, identify trends, and compare patterns over time.

The platform enables residents to interact with the evidence, fostering constructive dialogue with policymakers and other stakeholders. It transforms raw data into actionable insights, supporting evidence-based discussions on traffic safety, mobility planning, and local interventions.

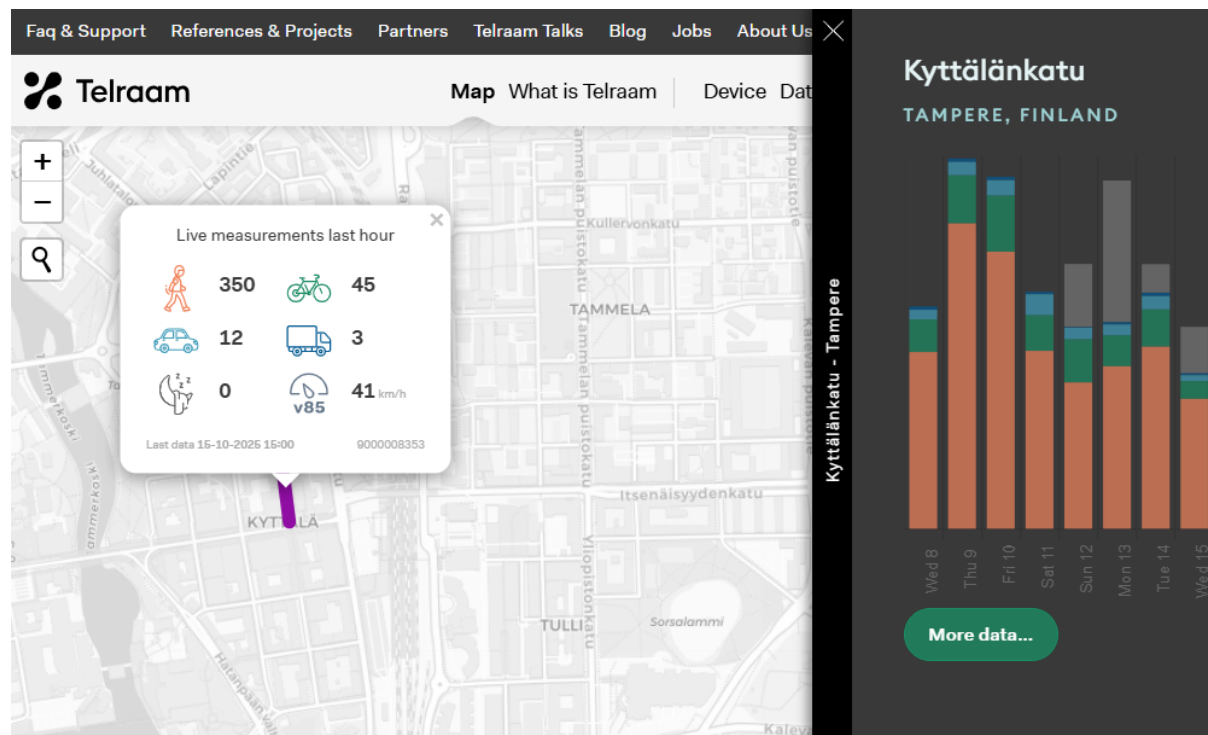


Figure 12 Public Traffic Count Dashboard

In this project, Telraam will be deployed through outdoor sensor installations in participating neighbourhoods. The approach ensures:

High-quality, continuous monitoring of multimodal traffic flows and vehicle speeds.

Citizen empowerment through active roles in data interpretation.

Policy relevance by providing transparent, shared evidence that underpins mobility and traffic safety debates between residents and local authorities.

By combining technical accuracy with citizen participation, Telraam functions not only as a traffic-counting system but also as a civic engagement instrument, bridging the gap between local communities and policymakers.

Use Case 11: Simulate EIA procedure

Short description

Simulate the EIA procedure using an LDT.

Pilot city

Flanders-Mechelen

Domain

Environmental policy

Project coordinator

VLO

Project leader

Karen Bosmans

Success factors

- The Flemish government has a better understanding of which components (datasets, models, software) are available for an operational LDT for EIA procedure (for the domains traffic, air quality and noise) and what obstacles exist
- EIA experts gain more trust in data models (for the domains traffic, air quality and noise)

Stakeholders

- Policy Makers (Flemish Government) [Government]
- City of Mechelen (Government)
- City of Kortrijk (Government)
- Intercommunal organisation Leiedal [Government]
- EIA Centre of expertise (Flemish Government) [Government]
- EIA experts [Government]
- EIA experts [Industry]
- EIA coordinators (providing EIA reports) [Industry]
- EIA advisory boards [Government]
- Spatial planners (Flanders)
- VMx (Flemish association of environment experts) [Industry]
- Vlaamse Vereniging voor Ruimte en Planning (VRP) (Flemish association of urban & spatial planners) [Industry]
- International Association for Impact Assessment (IAIA) (policy makers, EIA experts) [Industry]
- Data custodians/providers (Flemish Government) [Government]

- Standardisation body (Flemish Government) [Government]
- Model providers [Industry]
- Model providers [Academy]
- LDT component providers [Industry]
- Smart Flanders (Steering group of Flanders Smart Region network) [government]
- Flemish Environment Agency [government]
- Flemish Department of Mobility & Public Works [government]
- Flemish Agency for Road Management & Traffic [government]
- Vereniging van Vlaamse Steden en Gemeenten (association of Flemish cities and Municipalities) [government]
- Kenniscentrum Vlaamse steden (association of 13 big Flemish cities) [government]

Full description

Applying the Environmental Impact Assessment (EIA) procedure to the spatial implementation plan "RUP Ragheno", focusing on traffic, air quality, and noise dimensions, using a local digital twin. Creating the EIA report with scenarios, effects and mitigating measures (calculations & graphic display). Experiment with form and structure (underpinning conclusions).

Core features

- Integration with simulation models: integrates with traffic simulation (TML), air quality modelling, and noise modelling systems. This allows for comprehensive analysis and comparison of different traffic mitigation measures.
- Centralised Data Processing and Management: a central hub for data processing and management, ensuring that all relevant data is collected, processed, and utilised effectively.
- Output and visualisation capabilities: output and visualisation capabilities through a 2D Web GIS Viewer and a 3D/XR Viewer. This enables users to visualise the impact of different traffic measures in both 2D and immersive 3D/XR environments.
- Cloud-Native Backend Infrastructure: supports a cloud-native backend infrastructure, which ensures scalability, performance, and reliability.

User interfaces and functionalities

The required functionalities correspond with Epics (EPs) and User Stories (US) that have been identified during functional workshops with the main stakeholders.

Table 4 Epics and User Stories of use case 11.

EP	As a citizen/student	I want to explore content in the Digital Twin .	So I am informed and get new insights .
US	As a citizen	I aim to understand the mobility changes that occur at each stage of the planning process.	So I can help with co-designing solutions for the city.
US	As a citizen	I want to gain access to additional background information .	So I am better informed.

EP	As an admin	I want to monitor user behaviour and keep the DTwin up to date.	So I can fine-tune my communication plan and info is always up-to-date
US	As an admin	I want to add, modify and delete content .	So the information remains up-to-date.
US	As an admin	I want to add or update locations (such as highlights).	So the information remains up-to-date.
US	As an admin	I want to modify overarching model settings .	So the model accuracy improves.
US	As an admin	I want to access user statistics .	So I can adapt my communication plan based on user behaviour.

EP	As a city official	I want to use models to feed the DTwin.	So I can simulate the project's effects at different levels.
US	As a city official	I want access to a protected Digital Twin area where I can do modelling.	So the environment can only be accessed by experts.
US	As a city official	I want to model mobility in a DTwin.	So I can monitor potential traffic changes.
US	As a city official	I want to set model parameters interactively using a dashboard.	So I can simulate the effect of traffic changes by creating different scenarios (e.g., closing streets, changing speed regimes, filtering traffic, etc.).
US	As a city official	I want to be able to add local static traffic data .	So I can train the traffic model, which will result in better air quality and noise modelling.
US	As a city official	I want to be able to add local dynamic traffic (sensor) data .	So I can train the traffic model, which will result in better air quality and noise modelling.
US	As a city official	I want to be able to add local air quality sensor data .	So I can train the air quality model, which will result in better air quality and noise modelling.
US	As a city official	I want to model air quality (NO2, PM2.5, PM10) in a Digital Twin.	So I can simulate the effects on air quality.
US	As a city official	I want to model noise in a Digital Twin.	So I can simulate the effects of noise.
US	As a city official	I aim to clearly and understandably explore the model results within the Digital Twin.	So, we can immediately estimate the AS IS and TO BE situation.

EP	As a city official	I want to use models to feed the DTwin.	So I can simulate the project's effects at different levels.
US	As a city official	I want to see the apparent differences (deltas) before and after the local use case implementations.	So I can see the effects of the project at different stages.
US	As a city official	I want to download the raw model data results.	So I can compare data with calculations made by third parties.
US	As a city official	I want to be able to export visuals .	So I can use them for communication purposes.
US	As a city official	I want models to give output in a reasonable amount of time (max. 15 minutes).	So simulations can be completed efficiently within the available timeframe.
US	As a citizen	I want to use simplified modelling with free access.	So I see the effects of, for example, a school street on traffic, air quality and noise.

EP	As a citizen/student/teacher	I want to experience maximal accessibility .	So I can access and absorb information at my own level and pace.
US	As a disabled citizen	I want to have an accessible user interface (UI) for all x-CITE solutions.	So I can clearly understand the case.
US	As a moderate citizen with whatever background and age	I want to understand the written x-CITE content correctly without being highly educated.	So I get easily informed at my level.
US	As a moderate citizen with whatever background and age	I want to be able to use the UI intuitively and logically , avoiding complexity.	So I get easily informed at my level.
US	As a city official	I want to get interoperable x-CITE solutions.	So I can reuse the solutions or continue working on them after completing the x-CITE project.

Technologies, platforms and tools

Final selection to be confirmed in Deliverable D4.2.

Scalability considerations

Final selection to be confirmed in Deliverable D4.2.

Compatibility with CitiVerse environment

To be analysed

Integration with EU LDT toolbox development project

To be analysed

Use Case 12: Roadmap for EIA LDT

Short description

The initiative aims to develop a comprehensive roadmap for operationalising a Local Digital Twin (LDT) tailored to Environmental Impact Assessments (EIA). This involves a thorough evaluation of accessible open models, datasets, components, and standards relevant to key environmental factors such as traffic, air quality, and noise.

As part of this effort, both a model catalogue and a data catalogue will be initiated to structure and centralise available resources. Additionally, the project will identify and begin developing any missing open standards necessary for effective implementation. A critical focus will be placed on ensuring transparency in the models used, to avoid “black box” scenarios and foster trust and confidence in the results produced by the LDT.

Pilot city

Flanders-Mechelen

Domain

Environmental policy

Project coordinator

VLO

Project leader

Karen Bosmans

Success factors

- The Flemish government has a better understanding of which components (datasets, models, software) are available for an operational LDT for EIA procedure (for the domains traffic, air quality and noise) and what obstacles exist
- The x-CITE consortium assesses the interoperability of LDT components (to test at least the integration of preferred components; e.g., integration test between an open-source data management module and a model and asset registry)
- The Flemish government knows how to organise the governance of LDT components (datasets, models, standards and marketplace)
- EIA experts gain more trust in data models (for the domains traffic, air quality and noise)

Stakeholders

- Policy Makers (Flemish Government) [Government]
- City of Mechelen (Government)
- City of Kortrijk (Government)
- Intercommunal organisation Leiedal [Government]
- EIA Centre of expertise (Flemish Government) [Government]
- EIA experts [Government]
- EIA experts [Industry]
- EIA coordinators (providing EIA reports) [Industry]
- EIA advisory boards [Government]
- Spatial planners (Flanders)
- VMx (Flemish association of environment experts) [Industry]
- Vlaamse Vereniging voor Ruimte en Planning (VRP) (Flemish association of urban & spatial planners) [Industry]
- International Association for Impact Assessment (IAIA) (policy makers, EIA experts) [Industry]
- Data custodians/providers (Flemish Government) [Government]
- Standardisation body (Flemish Government) [Government]
- Model providers [Industry]
- Model providers [Academy]
- LDT component providers [Industry]
- Smart Flanders (Steering group of Flanders Smart Region network) [government]
- Flemish Environment Agency [government]
- Flemish Department of Mobility & Public Works [government]
- Flemish Agency for Road Management & Traffic [government]
- Vereniging van Vlaamse Steden en Gemeenten (association of Flemish cities and Municipalities) [government]
- Kenniscentrum Vlaamse steden (association of 13 big Flemish cities) [government]

Full description

The initiative aims to develop a comprehensive roadmap for operationalising a Local Digital Twin (LDT) tailored to Environmental Impact Assessments (EIA). This involves a thorough evaluation of accessible open models, datasets, components, and standards relevant to key environmental factors such as traffic, air quality, and noise.

As part of this effort, both a model catalogue and a data catalogue will be initiated to structure and centralise available resources. Additionally, the project will identify and

begin developing any missing open standards necessary for effective implementation. A critical focus will be placed on ensuring transparency in the models used, to avoid “black box” scenarios and foster trust and confidence in the results produced by the LDT.

Core features

N/A (not a technical solution)

User interfaces and functionalities

N/A (not a technical solution)

Technologies, platforms and tools

N/A (not a technical solution)

Scalability considerations

N/A (not a technical solution)

Compatibility with CitiVerse environment

N/A (not a technical solution)

Integration with EU LDT toolbox development project

N/A (not a technical solution)

Proposal for “architectural hypothesis” approach in use cases

The special proposal using an “architectural hypothesis” approach in use case studies have been made during this deliverable writing period. This means creating research scenarios for areas where technology solutions are not yet clear. The aim is to try out new things and gather information before deciding on the best technology to use, instead of choosing one too soon.

Looking at eleven x-CITE use cases, the analysis shows that many of them share similar needs and challenges. These are mainly about making systems work well together, protecting intellectual property, and supporting cultural engagement. Most of the technology needed is already available and reliable, so guidance can rely on best practices and existing standards. However, when different technology stacks as like

extended reality and local digital twins are combined, new problems with interoperability appear. The proposal recommends focusing on these “Pivotal Points of Interoperability” and using frameworks such as Minimal Interoperability Mechanisms (MIMs) to help find solutions.

The proposal highlights three main areas for research: protecting and managing intellectual property in XR and real-world environments, achieving true cultural interoperability in settings with many languages and cultures, and making sure simulated results lead to fair real-world experiences. By developing architectural hypotheses in these areas, projects can carefully test solutions, collect reliable results, and build reference architectures with proven methods that others can use. This approach also supports teamwork, reduces repeated work, and helps ensure that solutions can be used in different situations.

For the x-CITE project, this method can offer strong and flexible guidance for both known and unknown issues. By encouraging cooperation and focusing on research instead of fixed solutions, x-CITE and similar projects can build reliable and ready-to-use technologies that fit the complex needs of today’s cities. In the end, these suggestions aim to help x-CITE create innovative, compatible, and inclusive applications that other organisations and governments can also use. Our target can be to study and test this approach in some selected use case designs.

Summary

This report provides a comprehensive study of use case development within the x-CITE project, focusing on the creation of practical demonstrators that integrate Extended Reality and Local Digital Twin platforms. Each chapter delivers valuable knowledge and guidance, ensuring that developers, city stakeholders, and readers understand both the conceptual and technical foundations needed for successful implementation.

The opening part introduces the goals and structure of the x-CITE project, explaining how joint development and collaboration across pilot cities are essential for building meaningful solutions. Readers learn how participatory approaches and integration with the Local Digital Twin Toolbox establish responsible practices and support the growth of digital urban environments. This foundation is important, as it gives a clear view of how collaborative processes and feedback help shape effective urban technology.

The next parts describe the conceptual design process, showing how user needs and project requirements are translated into actionable solutions. Here, detailed explanations of system analysis, stakeholder engagement, and design principles guide the reader through every step involved in planning and building demonstrators. The information helps use case developers understand the importance of aligning software, hardware, and data integration with open standards and modularity. This not only ensures technical compatibility but also prepares solutions for future scalability.

The part dedicated to UI and UX design provides accessible knowledge about building user interfaces that are inclusive and intuitive. These chapters highlight practical methods for creating immersive XR experiences that are easy to use and engaging for all audience groups. Emphasis is placed on accessibility, usability, and inclusivity, ensuring that digital services reach and serve diverse users. The reader gains a clear understanding of how thoughtful design leads to higher user adoption and satisfaction, which is essential for successful deployment of XR and digital twin solutions.

Technical and governance requirements are covered in detail, offering practical insights into building secure, interoperable, and robust digital ecosystems. The chapters discuss architectural components, integration points, and emerging standards, helping developers and planners meet the expectations of both technical reliability and ethical responsibility. This knowledge is crucial for aligning local implementations with EU-level standards and supporting long-term sustainability.

The report then moves into the pilot use cases, providing real-world examples from Tampere, Rotterdam, and Flanders. Each chapter outlines the local context, objectives, and strategies used to engage stakeholders, develop XR features, and integrate digital twin technologies. These sections offer lessons from practical experience, showing how iterative feedback, data integration, and participatory design can lead to meaningful outcomes in urban cultural, educational, and environmental projects. The information is valuable for anyone wanting to apply similar approaches in other cities or seeking

inspiration for new use cases. This technical depth provides a solid reference for developers and researchers aiming to push the boundaries of digital urban innovation.

Throughout the report, the alignment with the Local Digital Twin Toolbox and EU standards is emphasized. The study demonstrates how modularity, open interoperability, and shared best practices form the backbone of successful digital transformation. By documenting both principles and practical experience, the report sets a clear baseline for future use case development studies across Europe. It shows how knowledge gained here can be reused and adapted for new demonstrators, ensuring consistency and progress in building citizen-centric digital environments.

In conclusion, this report is much more than a technical review. It is a practical guide and a foundational resource for use case developers, city stakeholders, and European innovators. By serving as a use case development study, it supports the creation of demonstrators that drive responsible digital urban transformation. At the same time, it offers a baseline for future studies and implementations with Local Digital Twin Toolbox demonstrators, ensuring that the lessons, frameworks, and standards described here will benefit cities and communities throughout the EU for years to come.

References

- [1] Corbillon, X.; Simon, G.; Devlic, A.; Chakareski, J. Viewport-adaptive navigable 360-degree video delivery. In Proceedings of the 2017 IEEE International Conference on Communications (ICC), Klagenfurt, Austria, 10–13 May 2017; pp. 1–7.
- [2] Windows Mixed Reality Platform. Available online.
- [3] ARTE. Available online: <https://www.arte.tv/en/>.
- [4] Abid Yaqoob, Ting Bi, Member, Gabriel-Miro Muntean, A Survey on Adaptive 360° Video Streaming: Solutions, Challenges and Opportunities, July 2020, IEEE Communications Surveys & Tutorials, July 2020, pp(99):1-1.
- [5] Federico Chiariotti, A Survey on 360° Video: Coding, Quality of Experience and Streaming, Elsevier Computer Communications, February 17, 2021.
- [6] Rabia Shafi, Wan Shuai and Muhammad Usman Younus, 360-Degree Video Streaming: A Survey of the State of the Art, *Symmetry* 2020, 12(9), 1491; <https://doi.org/10.3390/sym12091491>
- [7] Moatasim Mahmoud, Stamatia Rizou, Andreas S. Panayides, Nikolaos V. Kantartzis, George K. Karagiannidis, Pavlos I. Lazaridis, AND Zaharias D. Zaharis, A Survey on Optimizing Mobile Delivery of 360° Videos: Edge Caching and Multicasting, *IEEE Access*, 10.1109/ACCESS.2023.3292335.
- [8] Fanglue Zhang, Junhong Zhao, and Yun Zhang, A Survey on 360° Images and Videos in Mixed Reality: Algorithms and Applications, *Journal of Computer Science and Technology* 38(3): 473–491 May 2023. DOI: 10.1007/s11390-023-3210-1.
- [9] S. Mangiante, G. Klas, A. Navon, Z. GuanHua, J. Ran, and M. D. Silva, “VR is on the edge: How to deliver 360 videos in mobile networks,” in Proceedings of the Workshop on Virtual Reality and Augmented Reality Network. ACM, 2017, pp. 30–35.
- [10] G. J. Sullivan, J.-R. Ohm, W.-J. Han, T. Wiegand et al., “Overview of the high efficiency video coding (HEVC) standard,” *IEEE Transactions on circuits and systems for video technology*, vol. 22, no. 12, pp. 1649– 1668, 2012.
- [11] V. Sze, M. Budagavi, and G. J. Sullivan, “High efficiency video coding (HEVC),” *Integrated Circuit and Systems, Algorithms and Architectures*. Springer, vol. 39, p. 40, 2014.

[12] G. J. Sullivan, "Video coding standards progress report: Joint video experts team launches the Versatile Video Coding project," *SMPTE Motion Imaging Journal*, vol. 127, no. 8, pp. 94–98, 2018.

[13] Fraunhofer FOKUS, "Cloud-based 360° Video Playback," 2016, Retrieved 10. [Online]. Available: <https://www.fokus.fraunhofer.de/go/360>

[14] Bernet, Y.; Ford, P.; Yavatkar, R.; Baker, F.; Zhang, L.; Speer, M.; Braden, R.; Davie, B.; Wroclawski, J.; Felstaine, E. A Framework for Integrated Services Operation Over Diffserv Networks; Technical Report; RFC 2998; 2000.

[15] Blake, S.; Black, D.; Carlson, M.; Davies, E.; Wang, Z.; Weiss, W. An Architecture for Differentiated Services. 1998. Available online: <https://www.semanticscholar.org/paper/An-Architecture-for-Differentiated-Services-Blake-Black/13c3630c03bec0c3e443ad5a3dc6d1951db74c20> (accessed on 5 August 2020).

[16] Braden, R.; Zhang, L.; Berson, S.; Herzog, S.; Jamin, S. Resource ReSerVation Protocol: (RSVP); Version 1 Functional Specification; December 1997. Available online: <https://tools.ietf.org/html/rfc2205>.

[17] Schulzrinne, H.; Casner, S.; Frederick, R.; Jacobson, V. RTP: A Transport Protocol for Real-Time Applications. Network Working Group; Technical Report; 2003. Available online: <https://www.rfc-editor.org/rfc/rfc3550.pdf>.

[18] Schulzrinne, H.; Rao, A.; Lanphier, R. Real Time Streaming Protocol (RTSP). April 1998. Available online: <https://www.rfc-editor.org/info/rfc2326> (accessed on 5 August 2020).

[19] Postel, J. Rfc0793: Transmission Control Protocol. Internet Engineering Task Force (IETF); Technical Report; September 1981. Available online: <https://tools.ietf.org/html/rfc793> (accessed on 5 August 2020).

[20] Skupin, R.; Sanchez, Y.; Podborski, D.; Hellge, C.; Schierl, T. Viewport-dependent 360 degree video streaming based on the emerging Omnidirectional Media Format (OMAF) standard. In *Proceedings of the 2017 IEEE International Conference on Image Processing (ICIP)*, Beijing, China, 17–20 September 2017; p. 4592.

[21] Roche, L.; Gal-Petitfaux, N. Using 360 video in physical education teacher education. In *Proceedings of the Society for Information Technology & Teacher Education International Conference*. Association for the Advancement of Computing in Education (AACE), Austin, TX, USA, 5 March 2017; pp. 3420–3425.

[22] Kelling, C.; Väättäjä, H.; Kauhanen, O. Impact of device, context of use, and content on viewing experience of 360-degree tourism video. In *Proceedings of the 16th International Conference on Mobile and Ubiquitous Multimedia*, Stuttgart, Germany, 26–29 November 2017; pp. 211–222.

- [23] Tan, T.K.; Weerakkody, R.; Mrak, M.; Ramzan, N.; Baroncini, V.; Ohm, J.R.; Sullivan, G.J. Video quality evaluation methodology and verification testing of HEVC compression performance. *IEEE Trans. Circuits Syst. Video Technol.* 2015, 26, 76–90.
- [24] Seshadrinathan, K.; Soundararajan, R.; Bovik, A.C.; Cormack, L.K. Study of subjective and objective quality assessment of video. *IEEE Trans. Image Process.* 2010, 19, 1427–1441.
- [25] Azevedo, R.G.A.; Birkbeck, N.; De Simone, F.; Janatra, I.; Adsumilli, B.; Frossard, P. Visual distortions in 360-degree videos. *arXiv* 2019, arXiv:1901.01848.
- [26] Bates, E.; Boland, F. Spatial Music, Virtual Reality, and 360 Media. In *Proceedings of the Audio Engineering Society Conference: 2016 AES International Conference on Audio for Virtual and Augmented Reality*; Audio Engineering Society, Los Angeles, CA, USA, 1 October 2016.
- [27] Huang, H.; Solah, M.; Li, D.; Yu, L.F. Audible panorama: Automatic spatial audio generation for panorama imagery. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, Glasgow, UK, 4–9 May 2019; pp. 1–11.
- [28] Google VR Software Development Kit. Available online: <https://developers.google.com/vr> (accessed on 23 May 2020).
- [29] Facebook spatial Workstation. Available online: <https://facebook360.fb.com/spatial-workstation/> (accessed on 23 May 2020).
- [30] He, J. *Spatial Audio Reproduction with Primary Ambient Extraction*; Springer: Berlin, Germany, 2017.
- [31] Riaz, H.; Stiles, M.; Armstrong, C.; Chadwick, A.; Lee, H.; Kearney, G. Multichannel Microphone Array Recording for Popular Music Production in Virtual Reality. In *Proceedings of the 143rd Audio Engineering Society Convention - Jacob K. Javits Convention Center*, New York, NY, USA, 18–20 October 2017.
- [32] Frank, M.; Zotter, F.; Sontacchi, A. Producing 3D audio in ambisonics. In *Proceedings of the 57th International Conference: The Future of Audio Entertainment Technology—Cinema, Television and the Internet*, Hollywood, CA, USA, 6–8 March 2015.
- [33] Zielinski, S.K.; Lee, H. Automatic Spatial Audio Scene Classification in Binaural Recordings of Music. *Appl. Sci.* 2019, 9, 1724.
- [34] Xie, B. *Head-Related Transfer Function and Virtual Auditory Display*; J. Ross Publishing: Richmond, VA, USA, 2013.

- [35] Jeong, J.; Jang, D.; Son, J.; Ryu, E.S. 3DoF+ 360 video location-based asymmetric down-sampling for view synthesis to immersive VR video streaming. *Sensors* 2018, 18, 3148.
- [36] M. Gänsluckner, M. Ebner, and I. Kamrat, “360 Degree Videos within a Climbing MOOC.” International Association for Development of the Information Society, 2017.
- [37] A. Hebbel-Seeger, “360 Degrees Video and VR for Training and Marketing within Sports,” *Athens Journal of Sports*, vol. 4, no. 4, pp. 243–261, 2017.
- [38] E. Domínguez, “Going beyond the classic news narrative convention: The background to and challenges of immersion in journalism,” *Frontiers in digital humanities*, vol. 4, p. 10, 2017.
- [39] N. De la Peña, P. Weil, J. Llobera, E. Giannopoulos, A. Pomés, B. Spanlang, D. Friedman, M. V. Sanchez-Vives, and M. Slater, “Immersive journalism: immersive virtual reality for the first-person experience of news,” *Presence: Teleoperators and virtual environments*, vol. 19, no. 4, pp. 291–301, 2010.
- [40] Statista, "Virtual Reality (VR) - Worldwide," 2024.