Welcome to the Citiverse

Deliverable **D 4.2**

Use case solution test and assessment

Document Identification	
Project name:	Expanding the Experience of Citizens through Extended Reality (x-CITE)
Project number:	101167756
Duration:	December 2024 – May 2027
Delivery date:	31/01/2026
Responsible beneficiary:	Nokia
Contributing beneficiaries:	All consortium partners
Dissemination level:	Public
Version:	1.0
Status:	Final

Co-funded by the European Union

Co-funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

Document History

Version	Date	Contributor	Description
0.1	03/12/2025	Jukka Saarinen (Nokia)	Initial text descriptions for Nokia Arena Use Case as example
0.2	11/12/2025	Jukka Saarinen (Nokia)	Initial text proposals for introduction and summary
0.3	19/12/2025	Jukka Saarinen (Nokia)	Initial text version after Tampere and Rotterdam contributions
0.4	02/01/2026	Jukka Saarinen (Nokia)	Version after Tampere and Nokia updates
0.5	15/01/2026	All partners	Updates from all partners to create the review version of the document
0.6	22/01/2026	Jukka Saarinen (Nokia)	Final version for the internal review process
0.7	04/02/2026	Jukka Saarinen (Nokia)	Version based on internal review comments
0.8	10/02/2026	All partners	Final comments and editions after final checking round
0.9	11/02/2026	Inge Willemsen (OASC)	Final formatting
1.0	13/02/2026	Sebastian Valkama (TAMP)	Final version for submission

Table of Contents

List of Figures

List of acronyms

Abbreviation /acronym	Description
AI	Artificial Intelligence
API	Application Programming Interface
AR	Augmented Reality
EIA	Environmental Impact Assessment
EP	Epic
HMD	Head-Mounted Display
LDT	Local Digital Twin
MIM	Minimal Interoperability Mechanisms
MR	Mixed Reality
OUP	Open Urban Platform
QoE	Quality of Experience
TML	Traffic simulation
UI	User Interface
US	User Story
UX	User Experience
VR	Virtual Reality
WebXR	WebXR is an emerging technology standard designed to make XR experiences accessible through the web
XR	Extended Reality
3D	Three Dimensional

Executive summary

Testing and assessment play a pivotal role in the x-CITE project, underpinning the reliability and transferability of the solutions developed. Use cases are evaluated through a phased approach, beginning in controlled simulations and gradually expanding into authentic urban settings. Technical assessments, such as interoperability and scalability testing, are conducted alongside stakeholder and user feedback sessions to ensure that both the functional and experiential aspects of the CitiVerse environment are validated. The results of these assessments inform ongoing refinements and contribute to the broader EU objective of developing digital environments where citizens, policymakers, and industry partners can collaborate effectively.

A systematic approach to scenario preparation underpins the quality assurance process, with each test scenario designed to reflect real-world urban conditions and user interactions. These scenarios are crafted based on detailed analyses of user systems and local requirements, ensuring both relevance and representativeness. The process is iterative, involving ongoing stakeholder engagement to adapt to emerging needs and technological advancements. User interface and experience design is equally prioritised, with accessibility and inclusivity guiding the development of intuitive, engaging solutions for diverse user groups. Iterative feedback loops, informed by end-user input, allow for the continuous refinement of interfaces, ensuring ease of use and broad adoption.

Functional and technical testing is comprehensive, employing a range of methodologies to validate both individual components and their integration within the broader architecture. The process is closely linked with the principles of modularity and interoperability, facilitating the identification and resolution of integration challenges. User feedback is systematically collected and analysed, supporting agile responses to usability issues and technical limitations. Performance assessments are rigorous and data-driven, employing both quantitative and qualitative measures to evaluate system efficiency, scalability, and responsiveness under varying conditions. These assessments inform risk mitigation strategies and support decision-making around the broader deployment of x-CITE solutions.

Security and privacy are integral to the x-CITE framework, with a dedicated assessment regime aligned with EU data governance standards and security-by-design principles. The framework encompasses technical safeguards such as encryption, authentication, and access controls, as well as organisational policies to ensure user consent and confidentiality. Regular audits and vulnerability assessments are conducted to address emerging threats, ensuring that the digital environments developed are both trustworthy and resilient.

In summary, the x-CITE project's structured approach to joint development, integration, testing, and assessment sets a new benchmark for responsible digital transformation in European cities. By embedding the principles of interoperability, scalability, modularity,

and user-centricity throughout the development lifecycle, the project ensures that its solutions are not only innovative but also robust, adaptable, and ready for scalable deployment. The comprehensive test and assessment methodology described provides a clear roadmap for evaluating the quality and impact of digital urban solutions, supporting the EU's ambition to harness digital technologies for the benefit of all citizens.

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	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 solution test and assessment in the x-CITE project

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

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. 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 project targets 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 Citiverse concepts, 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 test and assessment

The introduction to the test, quality assurance, and assessment report for the x-CITE project provides a comprehensive overview of the objectives, methodology, and underlying principles guiding the evaluation of the project's use case implementations. This report outlines the rationale for systematic testing and quality assurance, detailing how these processes underpin the delivery of robust, interoperable, and user-centric solutions in alignment with the broader goals of the x-CITE initiative.

The testing and assessment of use cases within x-CITE are central to ensuring that project outcomes deliver measurable value to cities, stakeholders, and end-users. The scope of this activity encompasses the systematic evaluation of technical solutions, user interactions, and system integration, with the clear objective of validating both the functional and experiential dimensions of the CitiVerse environment. By embedding assessment processes early and throughout the development lifecycle, x-CITE

establishes a feedback-driven culture that supports continuous refinement and adaptation.

The role of testing extends beyond technical compliance, serving as a mechanism for verifying interoperability between modular components, ensuring alignment with the LDT Toolbox, and facilitating the reuse of best practices across different urban contexts. This approach ensures that the solutions developed are not only fit for purpose in their pilot settings but are also designed to be adaptable and scalable for broader deployment across Europe. In this way, testing and assessment become the foundation for building trust among stakeholders, demonstrating the reliability, inclusiveness, and sustainability of the x-CITE project's digital urban solutions.

The following subchapters offer an in-depth exploration of each key aspect, from the specifics of scenario preparation to user experience considerations, technical and functional validation, performance evaluation, and the critical areas of security and privacy. Each subsection demonstrates how the project's commitment to interoperability, modularity, accessibility, ethics, digital inclusion, and continuous improvement is operationalised within the context of the European Union's Local Digital Twin (LDT) Toolbox standards and the overarching ambitions for scalable, transferable urban digital solutions.

Preparation of test scenarios

The preparation of test scenarios is a fundamental step in the x-CITE quality assurance process, designed to simulate the diverse conditions and use cases that the CitiVerse environment will encounter in real-world urban settings. Every test scenario is carefully developed through thorough analysis of user systems and the particular needs of the pilot cities, guaranteeing both relevance and representativeness. The process involves defining realistic user journeys, operational workflows, and data flows that reflect the anticipated interactions between citizens, stakeholders, and technological systems.

Alignment with the CitiVerse concepts ensures that scenario design leverages established templates, best practices, and interoperability standards, facilitating the consistent evaluation of system behaviour across different contexts. Scenario preparation also takes into account the modularity and reusability of components, enabling the assessment of individual modules as well as their integration within larger system architectures. Through iterative refinement and stakeholder engagement, the test scenarios are validated and adjusted to capture emerging needs, regulatory changes, and technological advancements, thus maintaining the relevance and rigour of the assessment process.

User interface and user experience design for test scenarios

Designing user interfaces (UI) and user experiences (UX) for test scenarios is a critical element in ensuring that the x-CITE solutions are not only technologically sophisticated but also accessible, intuitive, and engaging for a broad spectrum of users. The design

process adheres to the principles of inclusivity and accessibility, guided by the recommendations and standards embedded in the LDT Toolbox. Test scenarios are developed to rigorously evaluate the usability and accessibility of interfaces across various devices, platforms, and user groups, including those with differing abilities or digital literacy levels.

User-centric design is prioritised, with iterative feedback loops allowing for the continuous refinement of UI/UX elements based on direct input from end-users and stakeholders. This approach ensures that the final solutions are both functionally robust and capable of delivering seamless, meaningful experiences that foster engagement, trust, and broad adoption. The focus on modular UI components also supports the scalability and adaptability of solutions, enabling their integration into diverse urban environments across Europe.

Functional and technical testing setups and user feedback

The functional and technical testing setup in x-CITE is structured to comprehensively validate system performance against defined requirements, ensuring that each solution operates reliably within its intended context. This setup encompasses a range of testing methodologies, including unit, integration, system, and acceptance testing, all designed to assess both individual components and their interactions within the broader CitiVerse architecture. The testing protocols are aligned with the interoperability and modularity principles, facilitating the identification of integration issues, performance bottlenecks, and compliance gaps.

User feedback is systematically integrated into the testing process, with structured mechanisms for collecting, analysing, and acting upon input from end-users and stakeholders during pilot deployments. This feedback-driven approach enables the rapid identification of usability challenges and functional limitations, supporting agile, iterative improvements to both technical solutions and user interfaces. Ultimately, the functional and technical testing process ensures that the x-CITE solutions meet the highest standards of quality, reliability, and user satisfaction, while remaining adaptable and scalable for future urban applications.

Performance assessment evaluation setups for test cases

The evaluation of performance within x-CITE test cases is a systematic and data-driven process, designed to measure the efficiency, scalability, and responsiveness of the deployed solutions under varying operational conditions. Performance assessment is conducted using a suite of quantitative and qualitative metrics, including system throughput, latency, resource utilisation, and user-perceived responsiveness. The evaluation setup is tailored to the specific needs and technical characteristics of each use case, drawing upon the standardised measurement frameworks and benchmarking tools provided by the LDT Toolbox.

The process involves controlled simulations, real-world pilot deployments, and stress testing to rigorously evaluate the system's ability to handle diverse workloads and user demands. Results from performance assessments are analysed in the context of interoperability, modularity, and reusability, ensuring that solutions not only meet immediate project requirements but are also optimised for future scaling and integration. The insights gained from performance evaluation inform ongoing improvements, risk mitigation strategies, and decision-making regarding the broader adoption and replication of x-CITE solutions.

Security and privacy assessments

Security and privacy considerations are integral to the x-CITE project's commitment to responsible, trustworthy digital urban environments. The security and privacy assessment framework is designed to identify, evaluate, and mitigate risks associated with data protection, system integrity, and user confidentiality across all test cases. This framework is aligned with EU data governance standards and the security-by-design principles articulated in the LDT Toolbox and project guidelines. Assessments encompass a thorough review of technical safeguards, including encryption, authentication, access control, and audit mechanisms, as well as organisational policies and user consent procedures.

Particular attention is given to the challenges of managing sensitive urban data, user-generated content, and cross-domain data exchanges in an interoperable, modular environment. Security and privacy testing is an ongoing process, with regular audits, vulnerability assessments, and compliance checks ensuring that emerging threats are proactively addressed and that solutions remain resilient in the face of evolving risks. This rigorous approach not only protects end-users and stakeholders but also contributes to building public trust and supporting the sustainable adoption of x-CITE technologies.

Summary

In summary, the introduction to this report establishes a comprehensive foundation for understanding the objectives, processes, and critical success factors underpinning the testing, quality assurance, and assessment of x-CITE use cases. Each subchapter articulates a key dimension of the evaluation framework, demonstrating how the project's commitment to interoperability, modularity, accessibility, and user-centricity is operationalised in alignment with the EU LDT Toolbox and broader digital urban transformation goals.

The structured approach to scenario preparation, interface design, technical and functional testing, performance evaluation, and security and privacy assurance ensures that solutions are not only innovative but also robust, reliable, and ready for scalable deployment. This introduction sets the stage for the detailed analyses and findings presented in subsequent chapters, providing stakeholders, technical teams, and

evaluators with a clear roadmap for assessing the quality and impact of the x-CITE project's digital urban solutions.

Scalability and interoperability are foundational principles in the development of digital urban solutions, serving as key enablers for both immediate effectiveness and long-term sustainability in use case deployment. Scalability ensures that solutions designed for specific pilot scenarios can be expanded to accommodate larger user bases, increased data volumes, and new functionalities without compromising performance or reliability.

This adaptability is crucial as urban environments evolve and demands change, allowing technologies to remain relevant and impactful beyond their initial scope. Interoperability, meanwhile, guarantees that digital systems can seamlessly integrate with diverse platforms, datasets, and service providers, facilitating efficient information exchange and collaborative innovation across sectors and domains.

By embedding these principles into the design and testing of use cases, projects like x-CITE foster environments where new solutions can be easily adopted, replicated, and connected, reducing the risk of technological silos and supporting the broader goals of digital transformation.

Ultimately, prioritizing scalability and interoperability not only maximizes the return on investment for urban technology initiatives but also reinforces the capacity for rapid adaptation, inclusive participation, and sustainable growth in complex city ecosystems.

A portion of the testing activities has already been carried out in practice for specific use cases. The remaining tests will be conducted in accordance with the methodologies and frameworks described in this document, ensuring consistency and alignment with the established evaluation approach.

Tampere use cases

The Tampere CitiVerse use cases focus on digital cultural experiences. 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 experience centre.

Use case 1: Digital public art map

The City of Tampere's public art collection, managed by the Tampere Art Museum, includes more than 130 works such as sculptures, murals and 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. Access to public art is a question of cultural equity. In the Public Art on the Map pilot, we aim to improve accessibility through digital solutions, enabling inclusive participation and ensuring that everyone has the right to meaningful cultural experiences.

The project focuses on gathering, producing and publishing information and digital content about public art in Tampere. This content will be made available through a new map-based online platform, which will showcase the city's public art collection and provide detailed information about each piece, accessible via smart devices. The project consists of three main phases:

Data collection and digitization

While Tampere's public artworks have previously been accessible via a website and the Finna service, there is a need for a more user-friendly platform optimized for mobile devices and capable of hosting diverse materials. In addition, intangible cultural heritage – such as citizen experiences and oral histories – remains largely undocumented. These stories represent a living, evolving heritage and a shared cultural experience.

The project will digitize existing materials and create new content, including texts, images, videos, maps, interviews and conservation records. Participatory methods will be used to capture the personal and communal significance of public art. Selected artworks will also feature XR content, offering immersive experiences and new ways to engage with art. All materials will be published on the online platform.

Building the online platform

This phase involves creating a map-based platform that displays public artworks across Tampere. Users can zoom in to explore neighbourhoods and individual pieces, with varying content provided for each artwork. The platform will encourage physical exploration of public art while also enabling remote access. The aim is to deliver an accessible, user-friendly, and engaging solution for a wide audience.

Developing a coordination model

The project will also define a coordination model for public art processes in Tampere. This model will outline principles for producing public art and incorporate insights gathered from audiences during the project. It aims to create a transparent and equitable foundation for future initiatives, enhance citizen participation and establish channels for sharing experiences.

Augmented Reality – Expanding the experience

Augmented Reality (AR) offers a new dimension to experiencing public art, adding playfulness, immersion, and accessibility. With AR, art can transcend physical limitations, enhance existing works, or even revive lost pieces. By integrating AR and 3D scanning, the project seeks to enrich public art through digital overlays, interactive features, and gamified elements.

During the data collection phase, AR content will be developed for selected artworks, depending on resources. Full implementation will be determined later.

Test, quality assurance and assessment for digital public art on the map

Preparation of test scenarios

The first phase of testing focuses on the preparation of test scenarios, ensuring that all activities are purposefully aligned with the pilot objectives. The process begins with defining testing objectives, which are directly derived from the project's core aims: enhancing digital accessibility, fostering citizen engagement, and facilitating the discovery and appreciation of public art through innovative digital means.

Identifying representative user groups is a critical step, encompassing e.g. local citizens, tourists, museum professionals and Tampere residents, thus reflecting the broad spectrum of anticipated platform users. User journeys are carefully mapped to interactions considering scenarios where users access artworks on-site via smart devices or remotely engage with the digital map and optional AR features.

The selection of test environments accounts for desktop and mobile platforms, various operating systems and differing network conditions to ensure robustness. Success criteria are established, drawing on metrics such as ease of access, completeness of information and user satisfaction. Participatory methods involving citizens are integrated into the scenario preparation.

Accessibility is embedded throughout scenario development, with considerations for multilingual content. When feasible, alignment with GDPR and the EU LDT Toolbox ensures that all test scenarios adhere to prevailing data protection and interoperability standards, establishing a foundation for trustworthy and scalable solution deployment.

UI and UX design

The information architecture is clearly organised, allowing for efficient retrieval of artwork details, artist backgrounds and historical context without cognitive overload. Responsive design is implemented to guarantee optimal performance across desktops, tablets and smartphones, adapting seamlessly to varying screen sizes and orientations.

Multilingual support is integral to the UI/UX framework, with core navigation and content available in both Finnish and English. Accessibility features such as adjustable font sizes and high-contrast modes are tested, ensuring compliance with accessibility statutes and universal usability. Engaging content presentation is achieved through the integration of e.g. high-resolution images, embedded videos and (optional) 3D models presented in a visually coherent manner. The seamless integration of AR/XR content is planned, with user flows accommodating the transition from map exploration to immersive experiences without friction.

Feedback mechanisms are embedded within the interface, enabling users to report issues, suggest improvements or share their experiences directly through the platform. Consistency across platforms is enforced by adhering to established design systems and branding guidelines, ensuring a uniform look and feel regardless of access point.

Functional and technical testing

The functional and technical testing setup is organised to validate all operational aspects of the Public Art on the Map application, with a strong emphasis on collecting actionable user feedback. Platform compatibility testing covers a wide spectrum of devices, operating systems and browsers, ensuring that the platform performs reliably in diverse user contexts. Location tracking features, where enabled, are tested for accuracy, privacy compliance and seamless integration with map-based navigation.

The optional 3D modelling and photogrammetry elements are subject to careful validation, assessing the fidelity of digital replicas and their rendering performance across devices. The optional AR elements are tested for e.g. localisation, stability and interaction.

The content management functionalities of the online admin tool are tested for ease of updating, moderation and version control, supporting agile content production and curation. Multilingual functionality is assessed through language switching, translation accuracy and content completeness in both Finnish and English.

User feedback collection is systematised, with optional surveys and/or questionnaires feeding directly into the iterative development cycle. Iterative testing is embedded in the project workflow to address problems, refine features and ensure continuous improvement in response to user input.

Performance assessment evaluation

Performance assessment is critical to the platform's scalability, reliability and user satisfaction. Load testing simulates high-traffic scenarios, measuring the system's ability to handle concurrent users and large volumes of data requests without degradation.

Resource utilisation is monitored, with particular attention to memory, CPU and network consumption during typical and peak usage. The performance of optional AR features is separately assessed, focusing on e.g. rendering quality and the impact on device battery life especially on mobile platforms.

Data throughput is measured to ensure efficient transfer and synchronisation of multimedia assets, supporting smooth user interactions and rapid content updates. User concurrency tests validate the stability of collaborative features such as simultaneous content submissions or feedback channels.

Platform stability is evaluated over extended periods and under varying conditions, identifying and addressing potential points of failure. Error rate monitoring tracks the frequency and severity of system errors, crashes or failed transactions, providing insights for targeted optimisation. Finally, optimisation strategies are formulated based on test results, prioritising performance enhancements that directly impact user experience and operational resilience.

Security and privacy assessments

User consent management is reviewed with clear, transparent mechanisms for obtaining, recording and revisiting user permissions, particularly regarding location tracking. When feasible, compliance with GDPR and the EU LDT Toolbox is systematically assessed, thereby confirming the platform's readiness for public launch and cross-border collaboration.

Conclusions and lessons learned

Public Art on the Map pilot's testing objectives are directly derived from its core aims: enhancing digital accessibility, fostering citizen engagement and facilitating the discovery and appreciation of public art through innovative digital means. The preparation of suitable test scenarios ensures relevance and inclusivity, while the UI/UX design principles lay the groundwork for an accessible and engaging user experience.

Functional and technical testing confirms the platform's reliability, adaptability and responsiveness to user feedback, with iterative cycles driving continuous improvement. Performance assessment underscores the system's robustness and readiness for scalable deployment. Security and privacy assessments validate the project's commitment to data protection and compliance, reinforcing user trust and institutional accountability.

Use case 2: Art biennial

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.

For the 2025–2026 cycle, Tampere Art Museum takes the lead in production. The exhibition will be presented across two venues in Tampere: 1) Finlayson factory Area – a historic industrial setting in the city center, and 2) Haihara manor – a cultural site located in Tampere's suburbs. In addition, selected works will appear in public urban spaces and on digital platforms, extending the experience beyond traditional galleries.

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 included 15 members: staff from the three museums, independent artists, partners and local residents outside the art field who applied to join the process. From the applications, the 100 most-voted works were shortlisted, followed by final selections 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 designers from Moido Games.

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.

Test, quality assurance and assessment for art realm/urban AI art

Preparation of test scenarios

The foundation of the assessment process lies in the careful preparation of test scenarios that reflect the multifaceted objectives of Urban AI Art. The starting point involves a thorough analysis of anticipated interactions, ensuring that each scenario is anchored in real-world application and the lived experiences of diverse audience segments.

Central to this approach is the identification of key elements for scenario development, including access via mobile platforms and participatory creation experiences. Particular attention is devoted to accessibility and inclusivity, with scenarios encompassing users with varying abilities, language preferences and degrees of digital literacy.

In this way, the test scenario suite provides a robust framework for validating the project's capacity to meet its stated goals while accommodating the complexity of its collaborative and experimental nature.

UI and UX design

A central component of the assessment is the examination of UI and UX design as they relate to the test scenarios. The interface must facilitate effortless navigation, allowing users to engage with AI-generated cityscapes via large screens and personal devices without technical friction.

Device compatibility is also a critical factor, with interfaces optimised for desktop, mobile and tablet experiences. Public and digital interface considerations extend to the physical context of urban installations, where high-visibility displays support spontaneous audience interaction.

The design supports diverse user groups, including children, older adults and those unfamiliar with digital art, through clear instructions and intuitive iconography. Each design element is evaluated for its contribution to a cohesive, accessible and engaging user experience that aligns with the Art Realm's mission of expanding artistic participation and redefining audience roles in the creation and appreciation of visual art.

Functional and technical testing

At the core of the use case is the AI-driven image generation engine, which must be tested for the accuracy, originality and consistency of its outputs, as well as its ability to operate continuously without error.

Public display modules require verification of real-time rendering and seamless integration with the urban environment. Mobile and web platform integration is tested for cross-device compatibility, ensuring that users can access personalised image streams and interact with the artwork regardless of their location or hardware.

Performance assessment evaluation

System behaviour is evaluated under varied operational conditions. Load and stress testing are conducted to determine the platform's resilience during periods of high user activity, particularly at major cultural events or during peak times for public installations. Scalability can be assessed through simulations of feature expansion and the onboarding of new cities or partners, ensuring that the modular architecture can accommodate growth without degradation in service quality.

Response times are measured for core interactions such as image generation, with a focus on maintaining a seamless experience even under network constraints. System robustness can be tested by introducing controlled failures, such as network interruptions or hardware faults, and monitoring the platform's ability to recover gracefully.

Together, these elements provide a comprehensive framework for ensuring that the Urban AI Art solution remains performant, reliable and scalable in real-world deployment.

Security and privacy assessments

User consent management is reviewed with clear, transparent mechanisms for obtaining, recording and revisiting user permissions. When feasible, compliance with GDPR and the EU LDT Toolbox is systematically assessed, thereby confirming the platform's readiness for public launch and cross-border collaboration. Secure data storage practices are validated.

Conclusions and lessons learned

The preceding chapters collectively establish a rigorous framework for the test, quality assurance and assessment of the Tampere Art Realm and Urban AI Art use case.

Preparation of test scenarios demonstrates a participatory, inclusive methodology that aligns with the project's collaborative vision and commitment to accessibility. Detailed UI and UX design principles ensure that platform interactions are intuitive, inclusive and effective across diverse user groups and contexts.

Functional and technical testing confirms the reliability and adaptability of core systems, with robust feedback loops supporting continuous improvement and co-creation. Performance assessment verifies the platform's capacity for scalable, resilient operation, offering critical insights for ongoing optimisation and sustainable growth. Security and privacy assessments validate the project's adherence to high standards of data protection and regulatory compliance, reinforcing user trust and institutional accountability.

Use case 3: Cathedral 1918 - Civil war storytelling

In 1917, World War I 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, it also descended into civil war.

The Finnish Civil War was fought in January-May 1918 between the forces led by the Finnish Senate and the Finnish People's Delegation. The Senate's armed forces were also known as the White forces and the People's Delegation's forces as 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.

Museum center Vapriikki has already published several virtual exhibitions on the 1918 Civil War theme (www.tampere1918.fi/en). In the x-CITE project, the storytelling will be extended with the role of Tampere Cathedral.

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

Tampere Cathedral and its surrounding areas will be 3D modelled, and scenes depicting the stories of civilians will be filmed with live action actors. The scenes will be placed in the virtual 3D cathedral for the users to experience. When feasible, existing 3D scans of the city of Tampere will be used as resources for the 3D model. Parts of the exhibition will also be gamified.

The main development platform of the project is Unreal Engine 5. In addition to manual modelling, we will also experiment with photogrammetry, camera-equipped drones and laser scanning. The possibility of combining parts of the virtual exhibition with physical tours in the cathedral as well as the use of AR technologies are also being investigated.

Test, quality assurance and assessment for Cathedral 1918

Preparation of test scenarios

The preparation of test scenarios for the Cathedral 1918 virtual exhibition requires a methodical approach that ensures comprehensive coverage of functional, experiential and technical requirements. Firstly, the objectives of testing must be articulated,

encompassing both the validation of immersive storytelling and the effective integration of gamification elements without compromising historical accuracy.

The intended user groups are to be clearly identified, including school children, history enthusiasts, general museum visitors and international audiences, each with varying digital literacy and expectations. The test environments should be defined to mirror real-world usage, spanning desktop, tablet and smartphone devices.

Success criteria for each scenario must be set, such as seamless navigation, accurate historical representation and high user engagement as measured by feedback and interaction data. The selection of representative content and features such as the branching storylines, interactive narratives and virtual 3D environments must be prioritised for scenario inclusion to ensure that all critical functionalities are exercised.

Risk identification and mitigation strategies should be embedded within each scenario, considering potential technical failures or content inaccuracies.

UI and UX design

The evaluation of UI and UX elements forms the backbone of user-centred testing for the Cathedral 1918 exhibition. Intuitive navigation is crucial, ensuring that users can move seamlessly through the virtual environments. Accessibility is a core consideration, with the interface supporting screen readers, closed captioning for audio content and adjustable text sizes to promote inclusivity.

Multilingual support must be rigorously tested, ensuring that Finnish, English and potentially Swedish language options are correctly implemented across all content and navigation elements. Responsive design is critical, guaranteeing optimal display and interaction across a spectrum of devices regardless of the used language.

On-screen prompts should be evaluated for their effectiveness in guiding users through interactive narratives and gamified components. Interactive elements, such as branching storylines and object discovery, require careful review to ensure they are both discoverable and engaging, without overwhelming the user.

Feedback mechanisms must be embedded within the UI, providing users with effortless ways to share their experiences and support ongoing platform refinement.

Functional and technical testing

A robust setup for functional and technical testing underpins the reliability and adaptability of the Cathedral 1918 exhibition. Unreal Engine 5 serves as the primary development tool, necessitating targeted tests on rendering fidelity, asset loading and compatibility with WebXR for browser-based access.

The 3D modelling and photogrammetry components, utilising high-resolution scans from Tampere Infra and Kelluu, must undergo validation for accuracy, performance and seamless integration within the virtual environment. Browser-based delivery demands

thorough cross-platform testing, ensuring consistent performance and feature availability across all major browsers and devices.

The AI integration, although optional and resource-dependent at this stage, should be prepared for future testing on accuracy, contextual relevance and adherence to academically approved sources.

Gamification elements require functional testing to confirm engagement without disrupting the narrative flow. The live-action storytelling modules should be assessed for e.g. realism and impact on user immersion.

Accessibility features are to be tested for compliance with standards and real-world usability by individuals with varying needs. Content management integration, such as versioning and translation workflows via a headless CMS, must be evaluated for robustness and ease of updates.

Finally, user feedback loops are essential: for example surveys, forms, in-scenario prompts and analytics collection can be implemented to capture both qualitative and quantitative insights, supporting iterative enhancements and co-creation with stakeholders.

Performance assessment evaluation

Performance assessment for the Cathedral 1918 exhibition is centred on ensuring scalability, resilience and high-quality user experience under varying load conditions. Load testing is fundamental, simulating peak usage scenarios such as school group visits, to verify that the platform remains responsive and stable.

Device compatibility is evaluated across a spectrum of hardware profiles, from entry-level mobile devices to computer setups. Network resilience is scrutinised by simulating variable connectivity and ensuring graceful degradation of features. The system's ability to handle concurrent user sessions without data loss or performance degradation is rigorously tested. Backup and recovery protocols are validated to ensure minimal disruption in the event of system failures.

Security and privacy assessments

While the Cathedral 1918 is free to use and requires no login, security and privacy form the foundation of user trust. Thus, data protection strategies must be validated, ensuring that all personal information such as feedback submissions are stored securely within controlled environments. When feasible, regulatory compliance with GDPR is systematically assessed.

Conclusions and lessons learned

The comprehensive test, quality assurance and assessment setup for Cathedral 1918 establishes a rigorous framework for evaluating and optimising the exhibition platform.

The preparatory phase ensures that all critical scenarios are defined with clear objectives, stakeholder engagement and robust risk management. UI and UX testing prioritises intuitive, accessible and inclusive experiences, supporting broad public engagement and educational value.

Functional and technical testing confirms the integrity and adaptability of the platform's advanced features, while user feedback mechanisms drive ongoing improvement. Performance assessment guarantees that the exhibition can scale effectively, maintain resilience under load and deliver seamless experiences across diverse devices and network conditions. Security and privacy evaluations reinforce user trust.

Use case 4: Culture and children (Art Arc)

Art Arc (Taidekaari) is City of Tampere's cultural education programme tied to the curriculum of basic education and early childhood education. 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 three 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.

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.

Art Arc will also develop practical pedagogical methods to plan and execute educational content for virtual and AR exhibitions. The 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.

During and after the workshop tours, Art Arc will collect 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.

Comprehensive test, quality assurance and assessment for art arc

Preparation of test scenarios

Art Arc will reinforce other Tampere use cases by bringing in young visitors. Thus, it is not a technical solution. However, Art Arc will develop practical pedagogical methods to plan and execute educational content utilising XR elements. The aim is to find a balance between immersive content and working in a group, to include both virtual and real-life creating and sharing. To achieve these goals Art Arc co-operates with the Tampere pilots, schoolteachers and freelance art educators who work with children in Art Arc.

UI and UX design

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

Functional and technical testing setup

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

Performance assessment evaluation

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

Security and privacy assessments

When testing the other Tampere pilots, data protection protocols are central, ensuring that all personal information of minors is handled in strict accordance with GDPR and local regulations. Parental consent processes are meticulously managed, with clear communication and record-keeping to guarantee legal compliance for all forms of documentation and feedback collection.

Conclusions and lessons learned

The Art Arc pilot will reinforce other Tampere use cases by bringing in young visitors. In addition, the pilot will develop practical pedagogical methods to plan and execute educational content utilising XR elements.

Use case 5: Nokia Arena

The Nokia Arena XR use case is a pioneering initiative that aims to transform how audiences experience live events by leveraging immersive 360-degree video, spatial audio technologies, and advanced network infrastructure. Centered in Tampere, Finland, Nokia Arena is a state-of-the-art venue equipped to host a wide range of cultural, sporting, and entertainment events. Through the integration of six 360° cameras, high-resolution real-time streaming, and 5G mmWave connectivity, the project seeks to

deliver an authentic arena atmosphere to both onsite participants and remote viewers, regardless of their physical location.

The system is architected for flexibility and scalability, supporting desktop browsers, mobile devices, and head-mounted displays, with features such as viewport-dependent streaming, user-controlled perspectives, and robust recording/playback capabilities. By enabling audiences to attend concerts, sports matches, and other events virtually, the Nokia Arena use case addresses accessibility challenges, expands participation beyond venue capacity, and opens new revenue streams for event organizers.

The project also explores the potential for immersive content in various domains, including education, sports, and media production, while highlighting the need for innovative solutions to challenges such as bandwidth optimization, quality of experience, and integration with broader digital ecosystems. Overall, the Nokia Arena XR use case represents a significant step toward redefining event experiences in the digital age, harnessing cutting-edge technology to foster greater inclusion, engagement, and operational efficiency.

Testing the Nokia Arena XR use case from multiple perspectives is essential to ensure that the system meets its ambitious objectives and delivers a seamless, secure, and engaging user experience.

The preparation of test scenarios forms the foundation for meaningful evaluation by replicating the complex conditions of live events and accounting for factors such as crowd movement, lighting variations, and acoustic dynamics. Careful scenario design enables technical teams to assess system behavior under diverse and realistic circumstances, ensuring reliability and repeatability in results.

UI and UX designs play a critical role in shaping how users interact with the platform; thorough testing of these elements helps refine interfaces for intuitive navigation, accessibility, and satisfaction for both onsite and remote participants.

Functional and technical testing setups, combined with the systematic collection of user feedback, are vital for validating that all features operate as intended across a range of devices and network conditions, and for identifying areas where the user experience can be further optimized.

Performance assessment evaluation is necessary to measure key parameters such as latency, video and audio quality, and system scalability, ensuring that the platform can deliver high-fidelity, low-latency content to a large and geographically distributed audience.

Finally, security and privacy assessments are indispensable, particularly given the handling of personal data and compliance with regulations such as GDPR. Rigorous testing in this area safeguards user information, maintains trust, and ensures that all legal and ethical standards are upheld.

By approaching the testing process from these complementary perspectives, the project not only mitigates technical and operational risks but also maximizes the potential for successful deployment, user adoption, and long-term impact.

Preparation of test scenarios

The Nokia Arena XR use case represents a pioneering application of immersive 360° video and virtual reality event experiences within a large-scale, technologically advanced venue. Located in Tampere, Finland, Nokia Arena serves as a next-generation hub for sporting, cultural, and entertainment events, accommodating up to 10,000 spectators and hosting over a million visitors annually.

The arena's infrastructure is distinguished by its integration of state-of-the-art digital and network technologies, including a highly capable 5G mmWave network. This digital foundation enables the development and delivery of real-time, high-resolution 360° video and spatial audio streams, intended to replicate the authentic atmosphere of live events for both onsite and remote participants.

The rationale for a rigorous and comprehensive approach to test scenario preparation is rooted in the complex interplay between technical and experiential requirements inherent in immersive media. Unlike conventional video streaming, the immersive context demands careful orchestration of spatial and acoustic authenticity, user agency, and seamless integration across diverse platforms.

The system is designed to empower users with unprecedented control over their viewing experience, allowing them to select camera perspectives, navigate virtual environments, and engage with high-fidelity audio-visual content from any location. This ambition necessitates the meticulous definition of test scenarios that accurately reflect the unique spatial, acoustic, and operational characteristics of both live sporting and entertainment contexts at the arena.

Central to scenario design is the strategic deployment of four-six 360° cameras and advanced spatial audio capture technologies. These elements are positioned to authentically mirror the perspectives and soundscapes encountered by live audiences, ensuring that the virtual experience is both compelling and true to the original event.

Test scenarios must account for the dynamic movement of crowds, variable lighting conditions, and the complex acoustics of a multi-purpose venue. Furthermore, the robust 5G infrastructure, developed in partnership with leading telecommunications providers, underpins the ability to deliver ultra-high-resolution, low-latency streams to a broad array of devices, including smartphones, XR headsets, and web-enabled screens.

The preparation of test scenarios also requires a careful balance between technical repeatability and experiential realism. Scenarios must be designed to evaluate system behaviour under a range of network conditions, device capabilities, and usage patterns, reflecting the realities of live event environments. By rigorously specifying the physical

and digital layouts, defining camera and microphone placements, and simulating the operational flow of events, the groundwork is laid for meaningful and repeatable assessments. This foundation is critical not only for technical validation but also for ensuring that user experiences meet the high expectations associated with world-class arena events.

The background for test scenario preparation is defined by the convergence of immersive 360° video and audio technologies, spatial and acoustic fidelity, and the demands of real-time, cross-platform content delivery. A robust scenario design process is essential to capture the full spectrum of technical and experiential variables, ensuring that the Nokia Arena XR use case can be rigorously evaluated and iteratively improved in line with its ambitious objectives.

Selected elements for preparation of test scenarios

This subchapter outlines the selected essential elements for constructing robust test scenarios for immersive 360° video and audio experiences during ice hockey and pop concert events at Nokia Arena. The approach ensures both technical and experiential dimensions are addressed for realistic and repeatable assessments. By carefully defining the event environment, the test scenarios will capture the unique spatial and acoustic characteristics of both sporting and entertainment contexts. Strategic positioning of 360° cameras and spatial audio equipment is vital to authentically replicate live audience perspectives and arena acoustics.

The scenarios also incorporate comprehensive network infrastructure planning, ensuring sufficient 5G mmWave coverage and minimal latency for seamless streaming of high-fidelity content. User experience is rigorously evaluated by distributing a variety of viewing devices, including XR headsets and web-enabled screens, to both onsite attendees and remote participants. Additionally, test user recruitment and clear assignment of operational roles help guarantee that the collected data reflects a wide range of real-world usage patterns and technical conditions. These measures collectively support in-depth analysis and continuous improvement of immersive media solutions within the Nokia Arena use case.

- Event environment definition: Specify the physical and digital layout for both ice hockey and concert scenarios, including arena zones, audience locations, and camera placements.
- 360° camera deployment: Position four/six 360° cameras strategically to capture optimal action and audience perspectives relevant to each event type.
- Audio equipment setup: Install spatial audio recording devices (e.g., Ambisonics microphones) to authentically capture arena acoustics and performances.
- Network infrastructure: Ensure 5G mmWave coverage, assess bandwidth requirements, and verify low-latency connectivity for real-time streaming.
- Viewer device allocation: Distribute XR headsets, mobile devices, and web-enabled screens to test both onsite and remote user experiences.
- Test user recruitment: Select diverse participants (VIPs, general attendees, remote viewers) representing target demographics for each event scenario.

- Role assignment: Define roles (event operator, camera controller, network administrator, user support) and responsibilities within the test operation team.
- Logistics and scheduling: Develop a detailed timeline for equipment setup, event simulation, and test execution for both sports and concert events.
- Data collection protocols: Establish procedures for recording technical metrics, user interactions, and feedback during each scenario.
- Contingency planning: Identify risk points (device failures, network outages) and define mitigation strategies to ensure test continuity.

UI and UX designs for test scenarios

The design of user interfaces (UI) and user experiences (UX) within the Nokia Arena XR use case presents a unique set of challenges and opportunities, shaped by the immersive nature of 360° video and virtual reality event participation. Unlike traditional media consumption, immersive environments demand interfaces that facilitate intuitive navigation, real-time interaction, and seamless transition between multiple viewpoints and audio-visual streams. The overarching goal is to create an experience that is both accessible and deeply engaging, catering to a diverse audience that spans onsite attendees, remote viewers, and users with varying levels of technical proficiency.

Key to the UI and UX design is the principle of universality. The system must be compatible with a wide range of devices and platforms, from desktop and mobile browsers to advanced head-mounted displays (HMDs). This cross-platform requirement influences every aspect of interface design, from layout and navigation to the integration of spatial audio controls and multi-view camera selection. The web-based viewer is intentionally crafted to require no installation, supporting direct access through standard browsers and enabling easy embedding into third-party platforms. In contrast, the native XR viewer for HMDs allows for deeper integration and customisation, adapting streaming parameters and interface elements to the capabilities of each device and the preferences of individual users.

Accessibility and engagement are further enhanced by the inclusion of real-time feedback mechanisms and customisation options. Users are empowered to control their camera perspectives, select from multiple viewing angles, and interact with overlays and supplementary content. The interface supports adaptive streaming, ensuring that video resolution and audio quality are dynamically optimised to match network conditions and device performance. This adaptability is crucial for maintaining a consistent and high-quality user experience, regardless of the viewer's location or technical environment.

The immersive context also introduces new considerations for interface design, particularly in terms of spatial orientation and user agency. Navigating a virtual representation of a live arena requires clear visual cues, responsive controls, and intuitive transitions between different zones and camera feeds. The integration of spatial audio further complicates the interface, necessitating controls that allow users to adjust audio positioning and balance in real time. These requirements are addressed through a

combination of well-defined user journeys, context-sensitive overlays, and robust backend support for synchronising audio and video streams across devices.

Ultimately, the UI and UX design for test scenarios must not only facilitate technical assessment but also serve as a proving ground for user-centred innovation. By prioritising accessibility, engagement, and adaptability, the design process supports the broader objective of delivering a truly immersive and inclusive event experience, laying the groundwork for meaningful user feedback and continuous refinement.

Selected elements for UI and UX designs for test scenarios

This subchapter presents key user interface (UI) and user experience (UX) considerations to ensure the immersive platform is intuitive, accessible, and engaging across both event types. The design approach prioritises straightforward navigation, enabling users to easily select viewpoints, switch between camera feeds, and explore the arena environment regardless of their familiarity with immersive technology. Responsive layouts are essential to deliver consistent usability and visual appeal across all viewer devices, from XR headsets to mobile phones and web browsers.

The inclusion of real-time feedback mechanisms, such as loading indicators and status messages, helps users remain informed and confident throughout their experience. Accessibility features, including adjustable text sizes, high-contrast modes, and audio descriptions, are integrated to cater for a wide range of user needs and preferences.

Immersive audio controls allow participants to personalise spatial sound settings, enhancing realism and individual comfort. Where appropriate, event-specific themes and dynamic overlays such as live scores or artist information can be tailored to each scenario, further deepening user engagement and relevance.

- Intuitive navigation: Design clear controls for viewpoint selection, camera switching, and arena navigation, suitable for both novice and advanced users.
- Responsive layouts: Optimise interface layouts for various devices (web browsers, XR headsets, mobiles) to maintain usability and immersion.
- Real-time feedback: Provide immediate system responses (e.g., loading indicators, status messages) to user actions.
- Accessibility features: Incorporate adjustable text sizes, contrast modes, and audio descriptions to support diverse user needs.
- Immersive audio controls: Allow users to manage spatial audio settings, including volume, balance, and focus zones.
- Event-specific themes (optional): Tailor UI elements (colours, icons, overlays) to reflect the context of sports or concert events for enhanced engagement.
- Seamless onboarding (optional): Integrate guided tutorials and tooltips to support first-time users in understanding core features.
- Custom data overlays (optional): Enable dynamic overlays (e.g., live scores, artist info) relevant to each event, with user control over visibility.

- Interaction logging (optional): Capture user interactions for later analysis to inform iterative UI/UX improvements.
- User feedback channels (optional): Embed feedback forms and quick rating options directly within the experience for real-time input.

Functional and technical testing setup and user feedback

The functional and technical testing setup for the Nokia Arena XR use case is predicated on the integration of advanced media processing pipelines, network infrastructure, and user interface components. At the core of the system is a modular architecture comprising media connectors, media processors, system managers, and a suite of viewers tailored for both web and XR platforms. This architecture is designed to support real-time, viewport-dependent streaming of high-resolution 360° video and spatial audio, optimising bandwidth usage while maintaining low latency and high fidelity.

A critical aspect of the testing setup is the validation of synchronisation between video and audio streams, particularly given the complexity of spatial sound rendering and the need for precise alignment with user-controlled viewpoints. The system leverages a robust 5G mmWave network, enabling the rapid transmission of large data volumes required for 8K video and multi-channel audio. This infrastructure is tested across a spectrum of scenarios, from peak-load event simulations to variable network conditions, ensuring reliability and performance at scale.

Device and platform diversity is a central consideration in the testing process. The system is evaluated on a wide array of endpoints, including desktop browsers, mobile devices, and HMDs, each presenting unique challenges in terms of compatibility, performance, and user interaction. Test scenarios are constructed to capture these variations, with particular attention to adaptive streaming, error correction, and the seamless delivery of content across heterogeneous environments.

User feedback mechanisms are embedded throughout the testing process, enabling the collection of qualitative and quantitative data on user experience, system usability, and content quality. Feedback is gathered through structured surveys, direct observation, and real-time reporting tools, providing a comprehensive view of user interactions and satisfaction. This iterative approach supports continuous improvement, allowing technical teams to refine system components, interface elements, and operational procedures in response to real-world usage patterns and preferences.

The functional and technical testing setup is thus characterised by a holistic approach that encompasses infrastructure validation, cross-platform compatibility, audio-visual synchronisation, and user-centred assessment. By systematically addressing each of these dimensions, the testing process ensures that the Nokia Arena XR use case is robust, scalable, and aligned with the evolving needs of its diverse user base.

Selected elements for functional and technical testing setup and user feedback

This subchapter details the core technology components, test focus areas, and user feedback mechanisms essential for comprehensive quality assurance. It explores the strategies used to optimise interface layouts for different devices, ensuring both usability and immersion across web browsers, XR headsets, and mobile platforms. Particular attention is paid to the integration of real-time feedback and accessibility features, catering to a diverse range of user needs.

Furthermore, the chapter discusses the importance of immersive audio controls and custom data overlays, which allow for a tailored and engaging user experience. Testing methodologies such as real-time 360° streaming validation, spatial audio synchronisation, and adaptive streaming performance are also described. Finally, the chapter highlights the significance of capturing and analysing user interactions and feedback to drive iterative improvements and maintain high standards of quality throughout the system's lifecycle.

- Real-time 360° streaming validation: Test viewport-dependent streaming for low latency and accurate video synchronisation.
- Spatial audio synchronisation: Assess the fidelity and directionality of spatial audio with respect to user movement and viewpoint.
- Cross-Platform functionality: Validate system compatibility across desktop browsers, mobile devices, and XR headsets.
- Recording and playback: Verify chunked recording, seamless playback, and export options for both live and on-demand content.
- Camera management tools: Test remote camera control, switching, and layout configuration workflows for event operators.
- User and access management: Assess authentication, authorisation, and group-based permissions for different user roles.
- Adaptive streaming performance: Evaluate system response to varying network conditions, including bitrate adaptation and error correction.
- API integration: Test external API connectivity for analytics, overlays, and third-party service integration.
- Collaging and multi-view features: Assess usability and performance of collaged streams and multi-view layouts.
- User feedback collection: Deploy structured surveys, in-experience prompts, or post-session interviews to capture qualitative and quantitative user insights.

Performance assessment evaluation setup

Evaluating the performance of the Nokia Arena XR system requires a multi-faceted methodology that encompasses both technical metrics and user-centred indicators of quality. The assessment framework is designed to capture the full spectrum of system

behaviour, from network latency and bandwidth utilisation to device compatibility and overall quality of experience (QoE).

Latency is a primary concern in immersive streaming environments, as even minor delays can disrupt the sense of presence and engagement. The system's reliance on a high-capacity 5G mmWave network, coupled with bandwidth-efficient streaming techniques such as viewport-dependent delivery, is subjected to rigorous measurement under various load conditions. Performance metrics are collected for end-to-end latency, jitter, packet loss, and adaptive bitrate behaviour, providing a detailed picture of system responsiveness and resilience.

Scalability is another critical dimension, particularly given the potential for large-scale events with thousands of concurrent viewers. The modular architecture supports distributed deployment, enabling the system to flexibly scale resources in response to fluctuating demand. Performance assessments include stress testing, failover simulations, and resource allocation analysis to ensure that the infrastructure can accommodate peak loads without compromising quality or reliability.

Device compatibility is evaluated through systematic testing across all supported platforms, with a focus on maintaining consistent user experiences and interface functionality. Adaptive streaming and error correction mechanisms are scrutinised to verify their effectiveness in mitigating the impact of network variability and device limitations.

Structured user feedback is integrated into the performance assessment process, providing valuable insights into perceived quality, usability, and engagement. Quantitative data from surveys and usage analytics are complemented by qualitative feedback gathered through interviews and observational studies. This comprehensive approach enables the identification of strengths and areas for improvement, informing the ongoing refinement of system components and operational procedures.

In essence, the performance assessment evaluation setup is grounded in a rigorous, data-driven methodology that balances technical precision with user-centric evaluation. By systematically measuring and analysing key performance indicators, the process ensures that the Nokia Arena XR use case meets the highest standards of quality, scalability, and user satisfaction.

Selected elements for performance assessment evaluation setup

This subchapter defines the methodology for evaluating the Nokia Arena XR system's performance under diverse operational conditions. The approach encompasses both functional and non-functional testing, ensuring comprehensive coverage of the system's capabilities. Key performance metrics, such as spatial audio synchronisation, adaptive streaming, and recording integrity, are systematically assessed to reflect real-world usage scenarios. Cross-platform compatibility is validated through benchmarking on desktop browsers, mobile devices, and XR headsets, allowing identification of any platform-specific limitations.

Additionally, user and access management workflows are tested to confirm robust authentication and authorisation processes for various user roles. The methodology also integrates structured user feedback collection, combining qualitative and quantitative insights to inform iterative system improvements.

- Latency measurement: Record end-to-end video and audio streaming delays during peak and off-peak times.
- Bandwidth utilisation: Monitor network throughput for viewport-dependent and full-frame streaming modes.
- Concurrent user load: Simulate and assess system stability with increasing numbers of simultaneous viewers.
- Device compatibility: Benchmark performance across a spectrum of supported devices and operating systems.
- Error rate analysis (optional): Track packet loss, frame drops, and audio glitches under varying network and hardware conditions.
- Quality of Experience (QoE) (optional): Conduct subjective and objective assessments.
- Adaptive bitrate effectiveness (optional): Test system responsiveness to fluctuating bandwidth and its impact on user experience.
- Resource usage: Measure CPU, GPU, and memory consumption on client devices during intensive scenarios.
- Recording and playback integrity: Verify the completeness and quality of recorded streams and playback fidelity.
- System scalability: Evaluate the ability to scale infrastructure (cloud, edge, local) to meet event demands.

Security and privacy assessments

Security and privacy are foundational considerations in the design and operation of the Nokia Arena XR system, particularly given the sensitive nature of event attendance data, user interactions, and multimedia content. The system is architected to comply with the strictest standards of data protection, including the General Data Protection Regulation (GDPR) and relevant local legislation.

Authentication and access control mechanisms are implemented to ensure that only authorised users and administrators can access system resources, manage devices, and interact with event streams. Robust user and group management interfaces support the assignment of granular permissions, enabling fine-tuned control over access rights and operational roles. These controls are complemented by comprehensive logging and audit trails, facilitating the monitoring of system activity and the detection of unauthorised access or anomalous behaviour.

Secure streaming protocols are employed to safeguard the transmission of video and audio content, leveraging encryption and secure key management to prevent

interception and tampering. The system's modular architecture supports deployment on private networks, further reducing exposure to external threats and enhancing operational privacy. Data at rest, including event recordings and configuration files, is protected through the use of secure storage solutions such as S3-compatible object storage with robust access controls and encryption.

Privacy by design is a guiding principle throughout the system's development lifecycle. User consent is obtained and recorded in accordance with GDPR requirements, with clear communication regarding the collection, processing, and storage of personal data. The system is designed to minimise data collection wherever possible, retaining only the information necessary for operational purposes and user experience enhancement. Incident response strategies are established to address potential breaches or data loss, including predefined procedures for notification, mitigation, and recovery.

In summary, the security and privacy assessment framework is characterised by a proactive, comprehensive approach that integrates regulatory compliance, technical safeguards, and operational best practices. This ensures that the Nokia Arena XR use case not only delivers cutting-edge immersive experiences but also upholds the highest standards of trust and responsibility.

Selected elements for security and privacy assessments

This subchapter addresses the identification and mitigation of vulnerabilities, ensuring compliance with data protection standards and user trust. Comprehensive security reviews are undertaken to uncover potential threats within the streaming infrastructure, including both software and hardware components. Regular penetration testing and vulnerability scanning are implemented to proactively detect and remediate weaknesses before they can be exploited.

The system's authentication and access control mechanisms are rigorously assessed to prevent unauthorised access and privilege escalation. Furthermore, the adoption of secure streaming protocols and encryption safeguards the integrity and confidentiality of video and audio content across public and private networks. Continuous monitoring and incident response plans are established to respond promptly to emerging security incidents, thereby reinforcing the platform's commitment to safeguarding user data and maintaining regulatory compliance.

- Data protection compliance: Ensure GDPR alignment for all user data collection, processing, and storage activities.
- Authentication and access control: Assess robustness of user authentication, authorisation mechanisms, and privilege management.
- Secure streaming protocols: Validate encryption and integrity of video/audio streams over public and private networks.
- Privacy by design (optional): Evaluate system architecture for minimal data exposure, user consent management, and anonymisation where appropriate.

Conclusions and lessons learned of Nokia Arena use case test and assessment

The synthesis of test and assessment outcomes for the Nokia Arena XR use case is informed by the rigorous methodologies, technical innovations, and user-centred practices outlined in the preceding chapters. The comprehensive testing and evaluation process provides a holistic understanding of system performance, user experience, and operational resilience, enabling stakeholders to identify both strengths and opportunities for further enhancement.

Analysis of test results highlights the effectiveness of the modular, scalable architecture in delivering high-quality, low-latency 360° video and spatial audio experiences across a diverse array of devices and network conditions. The integration of advanced streaming technologies, adaptive interfaces, and robust feedback mechanisms ensures that both technical and experiential objectives are met, supporting the Nokia Arena's vision of a world-class, digitally enabled event environment.

User feedback plays a central role in the assessment process, providing actionable insights into usability, engagement, and satisfaction. The iterative refinement of system components and interface elements, guided by real-world user input, ensures that the platform remains responsive to evolving needs and expectations. At the same time, the system's robust security and privacy controls reinforce stakeholder confidence and regulatory compliance, safeguarding both data integrity and user trust.

Infrastructure scalability is validated through stress testing and scenario-based assessments, demonstrating the system's capacity to support large-scale events and accommodate future growth. Recommendations for ongoing development focus on the continued enhancement of streaming efficiency, expansion of device compatibility, and further integration with external platforms and analytics tools.

Selected key elements for Nokia Arena use case test and assessment

This subchapter synthesises the outcomes from all test and assessment activities, highlighting strengths, identifying areas for improvement, and providing actionable recommendations for future Nokia Arena XR deployments. It presents a short analysis of system performance, including the reliability of real-time streaming, adaptive bitrate management, and multi-view capabilities. The evaluation further details the platform's commitment to security and privacy, with particular emphasis on GDPR compliance and robust access control measures. User feedback is integrated to inform future enhancements, especially in the areas of personalisation and event overlay features. Additionally, scalability of the underlying infrastructure is assessed, with opportunities identified to optimise for large-scale events and legacy device integration. The insights provided aim to guide ongoing development and ensure the platform continues to deliver immersive, accessible, and secure experiences for all users.

- Immersive experience: The platform delivers high-fidelity 360° video and spatial audio, offering engaging experiences for participants in ice hockey and concert events.
- UI/UX strengths: Intuitive navigation and cross-device compatibility support broad user accessibility.
- Functional robustness: Core functionalities, including real-time streaming, adaptive bitrate handling, and multi-view options, perform reliably across tested scenarios.
- Performance: Low latency and high bandwidth efficiency are achieved, though continued optimisation is needed for large-scale concurrent usage and legacy device support.
- Security and privacy: The system demonstrates strong compliance with security and privacy standards.
- User feedback: Participants report high satisfaction with immersion and ease of use. Requests for enhanced personalisation and richer event overlays suggest future development directions should consider.
- Future targets and optional considerations:
    - Expand device compatibility and accessibility features.
    - Continue to optimise adaptive streaming for variable network conditions.
    - Enhance user feedback loops for continuous UX improvement.
    - Leverage analytics to inform event-specific UI/UX enhancements.

In conclusion, the summary of the Nokia Arena XR use case test and assessment encapsulates the project's achievements in advancing immersive event experiences, while charting a clear path for sustained innovation and operational excellence. The insights gained from the comprehensive evaluation process serve as a foundation for future deployments, ensuring that the Nokia Arena remains at the forefront of digital transformation in the cultural, sporting, and entertainment sectors.

Overall, the Nokia Arena XR use case testing performance should demonstrate a stable and scalable platform for immersive event experiences with clear pathways for technical and experiential enhancements to maximise stakeholder and user value via x-CITE project developments.

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

The City of Rotterdam develops an immersive and interactive 3D environment together with Krill-o.r.c.a, Future Insight B.V 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.

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.

Introduction of the test and assessment approach for Rotterdam

This section outlines the test and assessment approach for Rotterdam. The focus is on validating the end-to-end workflow from content/data onboarding in the Open Urban Platform (OUP) and Digital Twin integration, to multi-device 2D/3D/XR experiences that enable participatory engagement and accessible interfaces. In our testing we will take the local check-and-balances into account, meaning our SPIDER approach (security, privacy, information maintenance, data management).

Preparation of test

Interations based testing will reflect realistic engagement moments in Oud-Mathenesse and the B&D City. For each iteration, we will pay attention to:

- Learning about the developed iterations and contexts together with users
- Testing of Iterations with clear how things were and could become.
- Inputs required: e.g. OUP tilesets, GIS layers, curated content, event schedules.
- Defining outputs & indicators: e.g. engagement, content reach, qualitative feedback e.g. sentiment, accessibility compliance checks.
- Legibility of privacy zones: this requires a set of indicators.

UI/UX design

The UI/UX assessment aligns with Rotterdam's user stories (free or restricted access depending on the privacy zone], multi-device, filtering, XR on-site/remote, avatar guidance, accessibility). In the UX approach the double diamond approach or process is applied, a constant reiteration.

We will examine how:

- Users can access scenes and interpret overlays clearly.
- Admins can manage content and configurations in a controlled, maintainable way.
- Comfort & safety for users: clear avatar codes of conduct, report/mute tools, and session-level safeguards, clear and practical concepts for enhancement in line with general rules.
- Governance is facilitated in a transparent manner.

Functional and technical testing setups

End-to-end functional and integration testing will examine:

- Use case lifecycle: attach assets from OUP, publish, run event/workshop, capture feedback, and export/share results.
- Data ingestion checks: correct mapping of tiles/GIS to the neighbourhood scene.
- Visualisation checks: verify 2D maps/dashboards and 3D/XR rendering, overlays readability, avatar presence, and QR deep-link flows.
- Governance check: in line with governance principles

Performance assessment

Performance assessment prioritises practical usability for e.g events, neighbourhood sessions:

- Client performance: verify responsiveness of 2D and 3D/XR clients.
- Concurrency: a way to validate usability under selected groups.
- Accessibility performance: confirm no degradation when enabling accessibility features.

Security and privacy assessments

Security and privacy assessment will confirm that:

- Access control is organised and actions are traceable where needed.
- User safety is supported by configurable safeguards, consent prompts, and minimal data exposure.
- Data presentation uses appropriate aggregation levels for public content;
- Compliance alignment with GDPR and CitiVerse/LDT governance principles.

Conclusions and lessons learned

Rotterdam pilots an immersive 3D neighbourhood platform enabling citizens to engage, interact, and co-create urban projects via avatars, fostering inclusive decision-making. Testing uses iterative, user-centered evaluations of UI/UX, privacy zones, performance, and governance through SPIDER principles and feedback loops.

This approach is designed for a structured and transparent execution of the cases. Though testing the project validates key functionalities, performance indicators and user acceptance in realistic conditions. It also enables risk identification and mitigation. The assessment phase translates test results into outcomes and lessons learned, supporting evaluation and continuous improvement.

The generated results will also assess the scalability and replicability of aim of the project across different contexts ensuring value and contribution to future policy and implementation decisions.

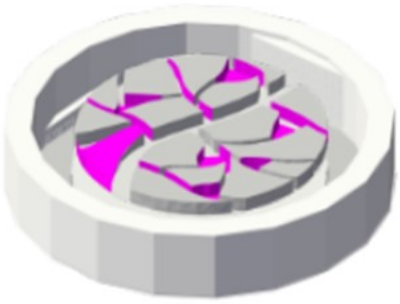
Use case 7: Students engagement

The City of Rotterdam develops an immersive 3D environment together with Krill-o.r.c.a, Future Insight B.V, Zadkine B&D City 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 City 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.

The 3D environment of B&D City 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.



Introduction of the test and assessment approach for Rotterdam

This section outlines the test and assessment approach for Rotterdam. The focus is on validating the end-to-end workflow from content/data onboarding in the Open Urban Platform (OUP) and Digital Twin integration, to multi-device 2D/3D/XR experiences that enable participatory engagement via avatars and accessible interfaces. In our testing we will take the local check-and-balances into account, meaning our SPIDER approach (security, privacy, information maintenance, data management).

Preparation of test

Interations based testing will reflect realistic engagement moments in Oud-Mathenesse and the B&D City. For each iteration, we will pay attention to:

- Learning about the developed iterations and contexts together with users
- Testing of Iterations with clear how things were and could become.
- Inputs required: e.g. OUP tilesets, GIS layers, curated content, event schedules.
- Defining outputs & indicators: e.g. engagement, content reach, qualitative feedback e.g. sentiment, accessibility compliance checks.
- Legibility of privacy zones: this requires a set of indicators.

UI/UX design

The UI/UX assessment aligns with Rotterdam’s user stories (Free or restricted access depending on the privacy zone], multi-device, filtering, XR on-site/remote, avatar

guidance, accessibility). In the UX approach the double diamond approach or process is applied, a constant reiteration.

We will examine how:

- Users can access scenes and interpret overlays clearly.
- Admins can manage content and configurations in a controlled, maintainable way.
- Comfort & safety for users: clear avatar codes of conduct, report/mute tools, and session-level safeguards, clear and practical concepts for enhancement in line with general rules.
- Governance is facilitated in a transparent manner.

Functional and technical testing setups

End-to-end functional and integration testing will examine:

- Use case lifecycle: attach assets from OUP, publish, run event/workshop, capture feedback, and export/share results.
- Data ingestion checks: correct mapping of tiles/GIS to the neighbourhood scene.
- Visualisation checks: verify 2D maps/dashboards and 3D/XR rendering, overlays readability, avatar presence, and QR deep-link flows.
- Governance check: in line with governance principles

Performance assessment

Performance assessment prioritises practical usability for e.g events, neighbourhood sessions:

- Client performance: verify responsiveness of 2D and 3D/XR clients.
- Concurrency: a way to validate usability under selected groups.
- Accessibility performance: confirm no degradation when enabling accessibility features.

Security and privacy assessments

Security and privacy assessment will confirm that:

- Access control is organized and actions are traceable where needed.
- User safety is supported by configurable safeguards, consent prompts, and minimal data exposure.
- Data presentation uses appropriate aggregation levels for public content;
- Compliance alignment with GDPR and CitiVerse/LDT governance principles.

Conclusions and lessons learned

Rotterdam creates an immersive 3D B&D City for, enabling students and creators to collaborate safely via avatars. Testing applies iterative UX/UI evaluations, privacy zone

checks, and SPIDER-based security, ensuring inclusive engagement and governance compliance.

This approach is designed for a structured and transparent execution of the cases. Though testing the project validates key functionalities, performance indicators and user acceptance in realistic conditions. It also enables risk identification and mitigation. The assessment phase translates test results into outcomes and lessons learned, supporting evaluation and continuous improvement.

The generated results will also assess the scalability and replicability of aim of the project across different contexts ensuring value and contribution to future policy and implementation decisions.

Flanders use cases

Two pilot sites

The Flemish government is using *CitiVerse* technology to develop an immersive Local Digital Twin (LDT) solution that supports the Strategic Environmental Assessment (SEA) process and its associated public participation activities. This *CitiVerse*-based SEA approach will be tested at two locations, each representing a typical SEA case type. The immersive technology aims to improve the clarity of information, enhance citizen engagement, and strengthen both the SEA process and the quality of its outcomes.

- In **Kortrijk**, a procedure for a SEA is underway in preparation for a municipal spatial implementation plan (RUP) to transform a former industrial zone (*LandMarck* site) into a multifunctional area for work, living, and public spaces, while preserving historical elements. The Kortrijk city council, the intermunicipal organisation Leiedal, and the x-CITE project are developing, testing, and evaluating *CitiVerse* solutions **to strengthen public participation** around the spatial implementation plan. To serve the primary goal of strengthening public participation, three use cases were developed, along with four supporting tools.
- In the second pilot in Mechelen, a SEA was conducted to support the development of a major new urban district near the main train station. Within x-Cite, the digital twin tools particularly the integrated simulation tools for traffic and air quality are being used to evaluate how effective these digital twin instruments are in assessing efficiency and impact based on an existing, representative real-world case.

Five Flemish use cases

The Kortrijk case covers **use cases 8 to 10** and focuses on supporting the SEA public participation procedure using immersive tools and digital twins.

The Mechelen case, covering **use cases 11 and 12**, targets the use of Digital Twins to test their effectiveness in SEA procedures.

Four software tools, referred to as Tools A, B, C and D, are developed to support the use cases.

User testing

In addition to internal testing by the technical partners, structured user feedback was collected, and dedicated user test sessions were organised. These insights served as the basis for subsequent updates and improvements to the x-CITE tools.

- During the **bi-weekly Flanders pilot calls**, new tool features/functionalities are demonstrated, feedback is gathered, and the alignment with the use cases, pilot needs, expectations, success factors and stakeholders is guarded.
- During the **bi-weekly technical meetings** for the Flanders pilot, knowledge and best practices, approaches and obstacles are shared concerning core features, UI/UX, technologies, scalability considerations, compatibility with the *CitiVerse* environment and the integration with the EU LDT Toolbox. Approaches are synchronised in a coordinated/standardised manner, and tools are tweaked based on all feedback gathered and collaborations established.
- During the **monthly management calls**, broader, pilot-overarching information is gathered, and approaches are aligned, also impacting the tool development.
- On 27 October 2025, all tools were demonstrated to the city of Kortrijk in a **dedicated session**. Feedback and clear guidelines were received from urban planners and IT specialists to improve and fine-tune tools A, B, C, and D.
- On 5 December 2025, a **guest lecture workshop** was held with a focus group of urban planning students from Hogeschool Howest in Kortrijk. The workshop had three main objectives: firstly, to collaborate on traffic mitigation measures (anticipating changes in traffic conditions at the future site); secondly, to test the supporting digital tools and provide feedback to enhance their usability and functionality; and thirdly, to test and further elaborate the concept for future participative initiatives with the citizens of Kortrijk.

Figure 1: The co-creative design of mitigation measures and x-CITE tool testing for the Kortrijk site, with Hogeschool Howest urban planning students in Kortrijk on 5 December 2025.

Use case 8: Insightful spatial implementation plan

Use Case 8 focuses on **visualising** the phased development of urban projects over a period of more than 20 years. By using mixed reality (XR) and 3D Digital Twin technology, the aim is to help the public better understand and accept the spatial implementation plan. Together with the City of Kortrijk and the intermunicipal organisation Leiedal, we will assess whether this approach effectively improves citizens' understanding and acceptance of the plan.

The **Augmented Reality (AR) app** (referred to as **Tool A,** see figures below) supports this use case by enabling citizens to view the spatial development plan in 3D. By scanning a QR code on-site, users can access an interactive AR experience that overlays the proposed developments onto live camera views on their smartphones or tablets. In addition, the underlying Digital Twin model will be accessible online via a dedicated viewer, enabling remote exploration and a deeper understanding of the project.

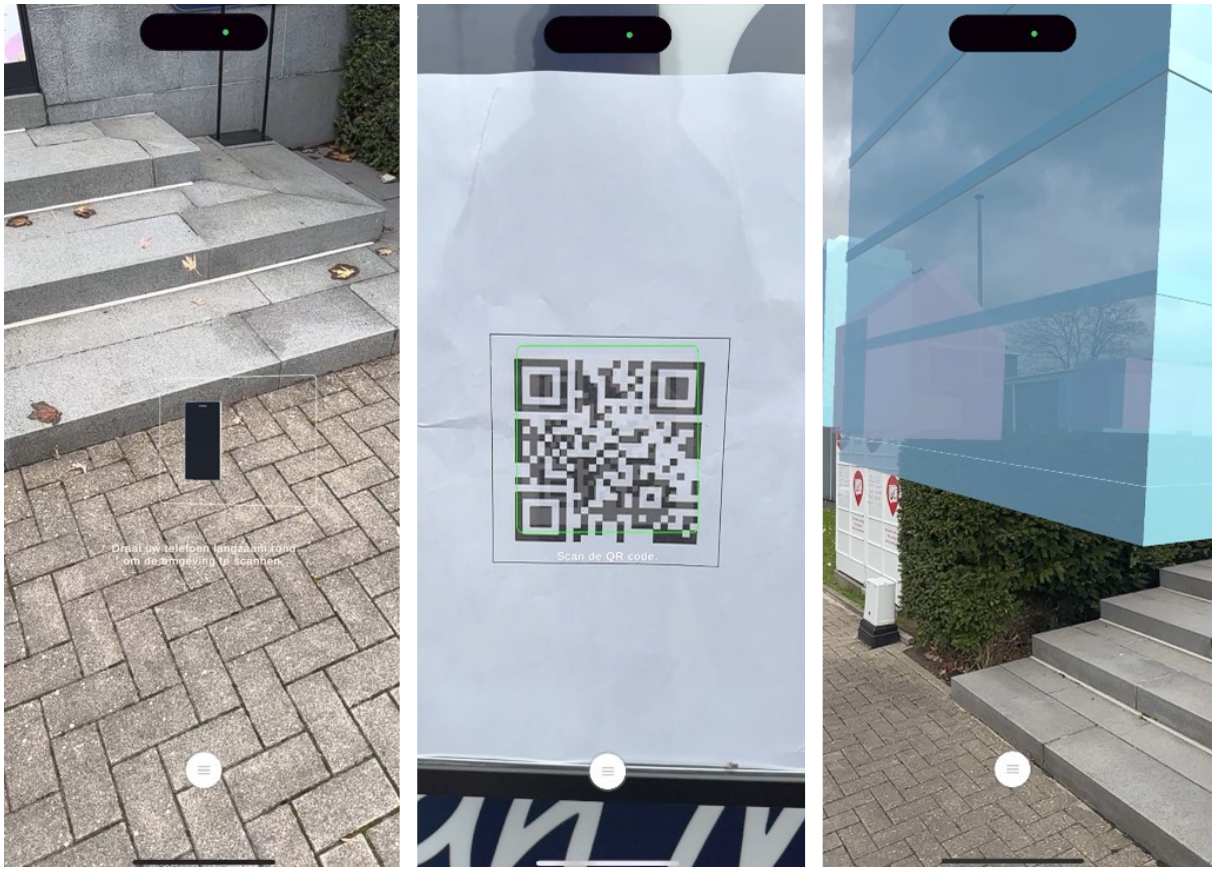


Figure 2: To test the Tool A procedure, a QR code was installed at the entrance of the pilot site (see middle image), allowing users to launch the tool on a smartphone or tablet. Subsequently, users are instructed to move their device for calibration purposes (see left image), ensuring that the buildings are correctly positioned within the AR environment for a full immersive experience (see right image).

Citizens can easily use their smartphones to view what is happening on-site, while the application highlights upcoming changes and provides clear information about the new buildings.

Tool A's core features include exploring the neighbourhood on a 2D map (showing the user's current location), viewing the modelled future buildings in 3D for the pilot site, using a flyover mode to overview the planned development, and experiencing the AR mode, which projects the future model onto live camera views from a smartphone.

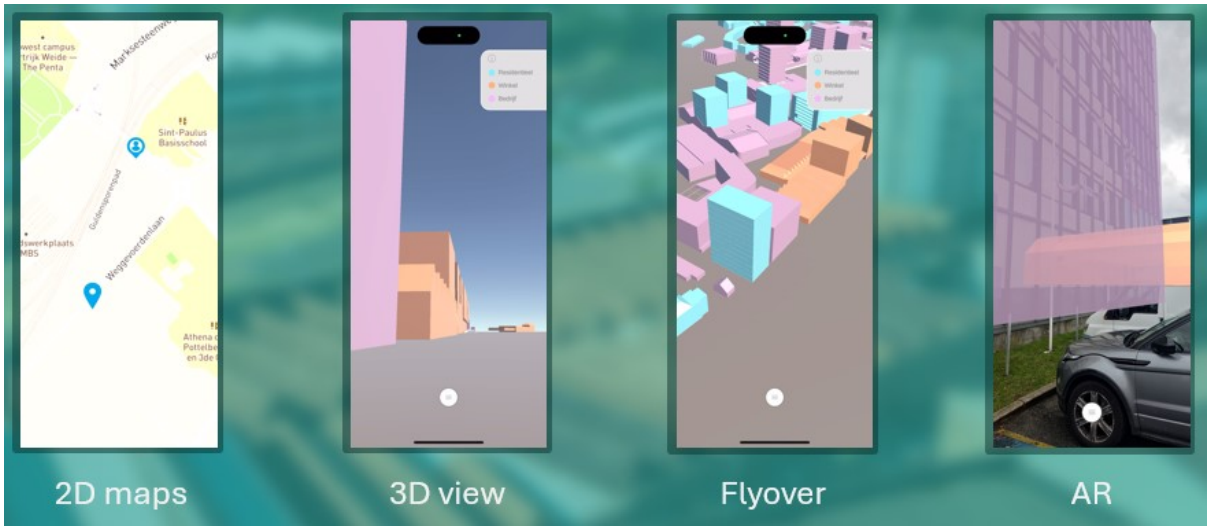


Figure 3: Tool A offers several viewing options, shown from left to right: a 2D map visualisation, a 3D view of the future site, a flyover mode of the planned development, and an immersive AR experience that combines the digital model with the live camera view.

Different approaches have been developed to access additional information on navigation and buildings on the site, as shown in the figure below. Information buttons let users view basic information about the site and specific buildings. A colour-coded legend further helps citizens understand the different types of modelled buildings.

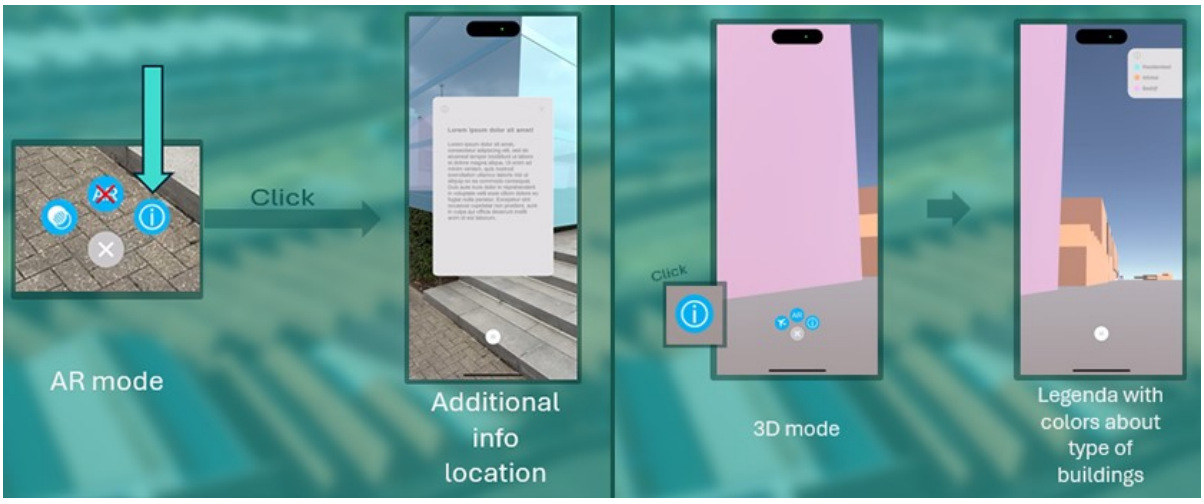


Figure 4: Tool A provides additional information to users through information buttons, pop-up text boxes, and colour-coded legends.

The next figure summarises the UI/UX steps required to access the app's functionalities and illustrates the functionality of the navigation buttons displayed on the user's screen.

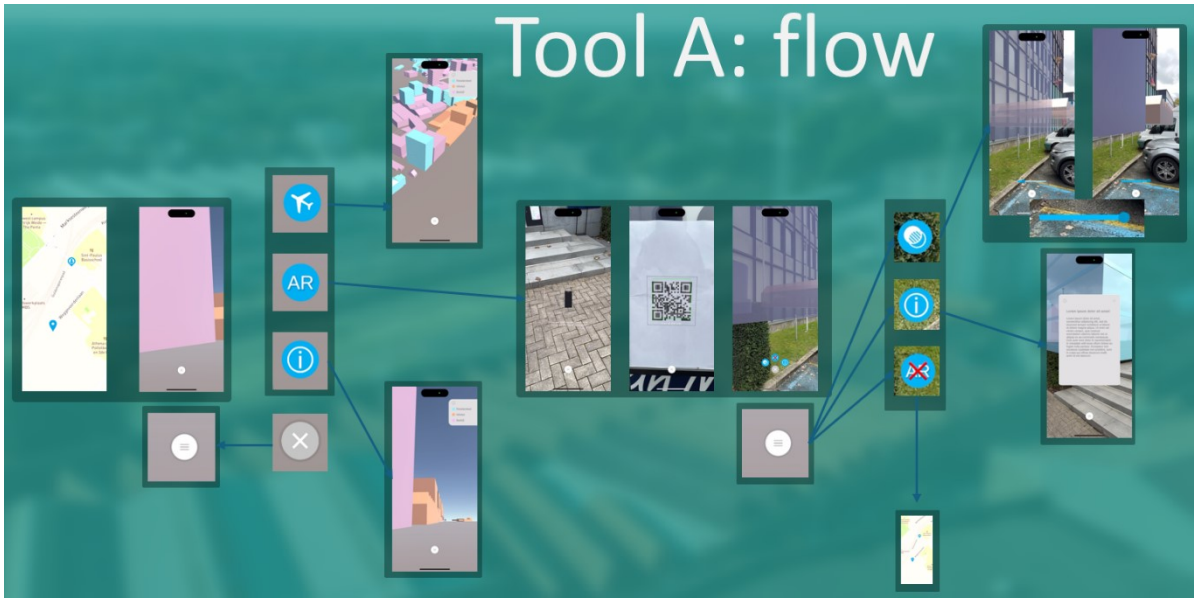


Figure 5: Overview of Tool A's UI/UX flow, illustrating the steps required to access the available functionalities.

Use Case 8 solution test and assessment

Preparation of test scenarios

The test scenario consists of a QR code placed near the selected area and a smartphone or tablet that supports the application. The test group can walk around the zone and explore the surroundings using the app's various features. The goal of the test is to observe which functionalities work well for citizens. Devices running both Android and iOS were provided during the testing.

UI and UX designs for test scenarios

The design focuses on simple, easy-to-understand icons that clearly reflect their functions. The interface is intentionally minimalistic to avoid clutter on the screen and to ensure that users can see as much of the digital environment as possible. The overall design prioritises accessibility and ease of use.

The icons change depending on the mode:

- **Plane icon (3D mode)**: Activates the flyover mode, which zooms out and rotates around the area.
- **Information button (3D mode)**: Displays a legend that uses colours to indicate the purpose of each building.
- **Information button (AR mode)**: Shows a pop-up with written information about the selected building.
- **Two intersecting circles (AR mode)**: Allows users to adjust the transparency of the 3D buildings.

- **‘AR’ button**: Turns AR mode on or off, switching between AR and the 2D map view.

Functional and technical testing setup

The setup is minimal, as it mainly involves starting the app and walking to the designated location(s). Once the AR mode is activated, the app guides users through the necessary steps. After calibration, the AR function is no longer tied to a single spot, allowing users to move freely and experience the full scale of the buildings within the digital environment. During testing, the user group explored the system's boundaries by walking beyond and around the original QR code location.

Performance assessment evaluation (setup)

One of the main challenges is ensuring smooth performance on mobile devices. To achieve this, the graphics and the 3D model's size have been optimised and split into smaller parts to ensure the app runs without delays. This ensures that users can explore all functionalities with minimal interruptions and enjoy a seamless experience.

Security and privacy assessments

This topic is less of a focus because the app does not collect user data, except for location information needed to show the user’s position on the 2D map. The application does not require any other personal data.

Conclusions and lessons learned

Some adjustments can be made to optimise the **visualisation** and make it easier to reproduce, such as placing the QR code at ground level, where users also perform the calibration. Other improvements such as updating information or modifying the 3D model may depend on external factors.

Hogeschool Howest students tested the augmented reality app on the *LandMarck* site. Guided by a technical developer from Howest, they learned how to scan the on-site QR code, calibrate the AR functionality, and explore the planned new buildings in full 3D. Their hands-on use of the app on a tablet also provided valuable insights into the UI/UX and helped identify potential improvements. By combining direct feedback from the students with observations during testing, we gathered the following potential improvements:

- The application should begin with a brief information screen and a step-by-step guide, including a colour code for easy reference. Users should be able to access clickable AR information buttons, similar to those in popular games, that provide basic details about each building on the site. At the introduction, it is important to manage users’ expectations regarding both the tool and the *LandMarck* site, and to clearly explain the need for calibrating the app by “pointing towards the ground,” as improper calibration can cause the buildings to appear to float above the site.
- On-site, prominent information boards should be installed, displaying a simple 2D map with zoning colours, a “you are here” marker, the QR code, and an explanation

of what visitors can expect. These boards should stand out and make it clear that the aim is to provide an overview of the site layout—the “big blocks”—without going into detail. Consider providing benches for less mobile and older visitors. The boundaries of the SEA (MER) area should be clearly indicated, and the lines marked on the ground should correspond with the zoning colours for consistency.

- Finally, a feedback option should be available for citizens, allowing them to submit comments about the site as a whole, specific buildings or layouts, and their experience using the app.

Use case 9: Co-design traffic mitigation measures

Use case 9 centres on co-designing **traffic mitigation measures** with citizens and policymakers, where a **Local Digital Twin** solution is tested as a decision-making tool to simulate, visualise and compare the effects of these measures on traffic, air quality, and noise. It also explores how **XR technology** can be used to inform and consult the public about the environmental and safety impacts of such measures.

Two tools support Use Case 9: Tool B and Tool C.

Tool B

Using Tool B (illustrated in the figures below), simulations of a wide variety of traffic scenarios can be run in a Digital Twin Environment using modelling. The integrated simulation models are:

- Traffic simulations: state-of-the-art traffic simulation software from Traffic Scout (TML). Data sources for Traffic Scout traffic model: traffic counts delivered by the city of Kortrijk and SWECO, OpenStreetMap, traffic-light control schemes, Telraam traffic counts, Regional Traffic Model Flanders origin-destination matrices (DMOW), ‘Meten-in-Vlaanderen’ motorway traffic counts (AWV);
- Air quality modelling: VITO Quark model for emissions/NO_2/PM deltas; and
- Noise modelling systems.

Effects can be calculated and visualised in a 2D environment.

Figure 6: Screenshot of the 2D web-GIS dashboard showing motorised traffic intensity as a map layer, with a legend for absolute values, location markers, and a time slider to explore historical data.

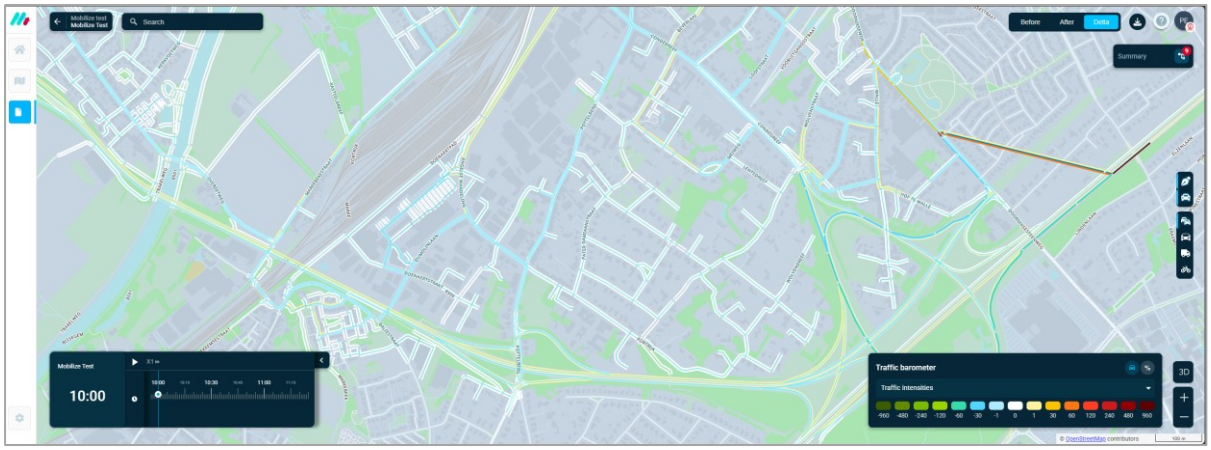


Figure 7: Example simulation result showing the traffic barometer view, where road segments are colour-coded by traffic intensity and an interactive toggle enables comparison between the baseline (“Before”), the scenario (“After”), and the change (“Delta”) for the same area and time.

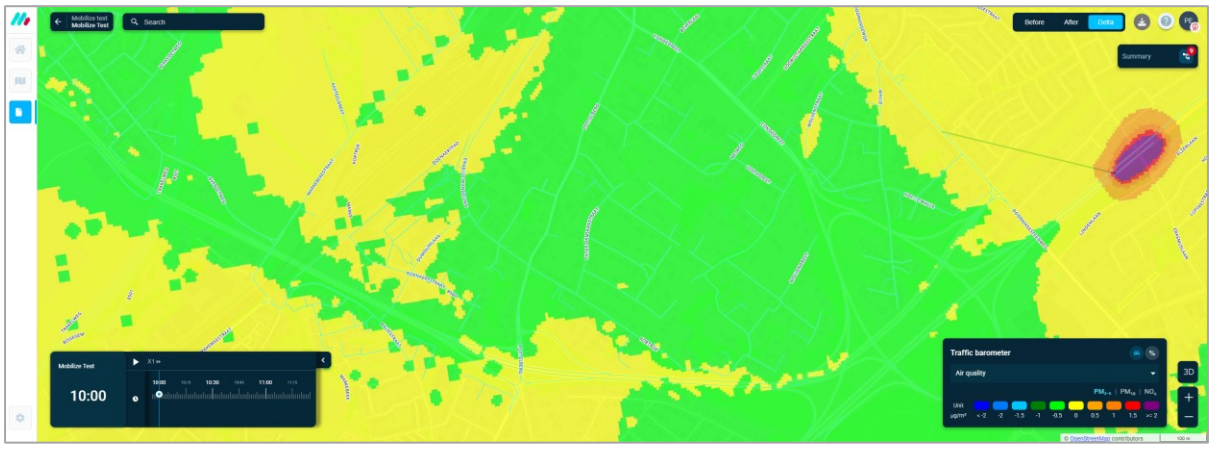


Figure 8: Example simulation result showing the air-quality barometer, presenting a spatial heatmap over the road network with pollutant selection (e.g., $PM_{2.5}$ / PM_{10} / NO_2), a colour-scale legend, and a Before/After/Delta comparison mode supported by time navigation.

For the Kortrijk site of the Flanders pilot, these functionalities are implemented through the *Mobilize* platform developed by Cegeka. This platform integrates XR visualisation, expert-level 2D data visualisation, and the creation, orchestration, and management of

simulations. *Mobilize* also supports XR connectivity (connecting with Tool C) and serves as the core scenario engine within the Local Digital Twin (LDT) architecture.

Tool C

Tool C is connected to tool B. This tool aims to provide a **3D simulation experience** for citizens that maximises their perception and understanding of how mitigation measures affect traffic, air quality, and noise, focusing on experimental **visualisation** techniques.

Figure 9: Example simulation visualisation showing the traffic flow on an intersection in Kortrijk.

Use Case 9 solution test and assessment

Co-design traffic mitigation measures (Mobilize / Tool B with XR visualisation via Tool C)

This section outlines the test and assessment approach for Use Case 9, focusing on validating the end-to-end workflow from scenario definition and simulation orchestration in *Mobilize*, with traffic simulations in Traffic Scout (Tool B), to 2D/3D/XR visualisation of the results. *Mobilize* acts as the scenario engine and integration backbone and is designed to connect datasets, simulations, and scenario runs to user-facing experiences.

Integration points in scope (interfaces under test)

The following connections will be treated as explicit integration test points, to ensure traceability from inputs → scenarios → outputs → visualisation:

- Data ingestion & governance: traffic counts / FCD, environmental (air quality/noise)
- Simulation services: traffic simulation in Traffic Scout (TML), air quality modelling (VITO), and noise modelling inputs/results as available for the selected scenarios.

- Scenario management & orchestration (Cegeka – *Mobilize* Core): scenario creation, parameterisation, execution orchestration, and comparison.
- Visualisation: 2D comparisons and XR/3D viewer consumption of scenario outputs (Tool C).
- Identity, access and auditability: role-based access
- Read-only XR/3D visualisation of *Mobilize* scenario outputs via API

Preparation of test scenarios

The testing will be scenario-based, reflecting realistic policy questions in Kortrijk. For each test scenario, the following will be defined and recorded:

- Scenario purpose and intended decision context.
- Baseline ("as-is") and at least one alternative ("to-be") configuration, including key parameters and assumptions.
- Input required and their data.
- Expected outputs and indicators: traffic intensities, air quality, and noise.
- Scenarios will be maintained with clear identifiers so that results can be traced back to a specific scenario definition and simulation run.

User interface and user experience design for test scenarios UI/UX assessment will be aligned with the user story set for Use Case 9. The assessment will check that:

- City officials/mobility experts can configure scenarios and interpret the results in a clear and accountable way.
- Experts can manage content and configuration in a controlled and maintainable manner.
- Residents can explore and understand traffic scenarios through an intuitive XR/3D visualisation (Tool C).

Functional and technical testing setup

Functional and integration testing will validate the end-to-end:

- Scenario lifecycle: create/update scenario, set parameters, launch computation, store outputs, compare baseline vs alternative, and export/share results.
- Data ingestion checks: correctly mapped to the area of interest and usable by the simulation chain.
- Orchestration checks: confirm that *Mobilize* triggers and tracks the simulation chain (traffic/air quality/noise where applicable) and that outputs are registered.

- Integration checks: confirm that scenario input in *Mobilize* is correctly transferred and interpreted in the Traffic Scout integration.
- Visualisation checks: confirm that outputs are correctly rendered in 2D (maps/dashboards) and are consumable by Tool C for 3D/XR experiences.
- XR/3D visualisation checks: confirm that Tool C correctly consumes scenario outputs via the *Mobilize* API and renders traffic indicators consistently with 2D results.
- User interaction checks (residents): confirm that navigation and basic interaction in Tool C allow residents to explore scenario outcomes without requiring expert configuration.

Performance assessment evaluation (setup)

Performance assessment will focus on practical usability for policy iteration and citizen engagement:

- Scenario turnaround time: measure end-to-end runtime for baseline and alternative scenarios, including queueing and post-processing where applicable. A practical target is to keep baseline scenarios within a "reasonable" timeframe for workshop use (as captured in the user stories), supported by pre-computation and caching where appropriate.
- Client performance: verify acceptable responsiveness for 2D and 3D/XR (Tool C) viewing on typical devices, including performance optimisations described for Tool C.
- Concurrency (as applicable): validate that the solution remains usable under expected workshop, distinguishing compute load from viewing load (web/XR clients (Tool C)).

Security and privacy assessments

Security and privacy assessment will confirm that:

- Access control is role-based where needed, and actions are traceable where needed and possible, time/budget-wise.
- Outputs are presented at an appropriate aggregation level.

Conclusions and lessons learned

The test and assessment approach for Use Case 9 is designed to provide a clear and repeatable validation of (1) interoperability and traceability across data → scenario → simulation → outputs, (2) usability for experts, (3) performance suitability for participatory sessions, and (4) security/privacy compliance. Quantitative results and final acceptance evidence will be captured during pilot execution and can be added as the implementation matures.

The Use Case 9 pilot indicates that the Digital Twin workflow supports co-design of traffic mitigation measures by enabling stakeholders to compare scenario impacts on traffic intensity and air-quality indicators through a consistent 2D web-GIS interface. The Before/After/Delta visualisations and time navigation help facilitate shared interpretation of results in both expert and participatory settings. Key lessons learned include the importance of baseline and input data quality, and the need to clearly communicate modelling assumptions and limitations when discussing scenario outcomes.

Howest students tested Tools B and C during a guest lecture on 12 December. They translated mitigation scenarios step-by-step into real mobility and air-quality model simulations within the Digital Twin environment (Tool B), supported by technical guidance from Cegeka and TML. They also explored how the developers at Howest created and refined Tool C to visualise traffic density in a way that makes the outcomes of Tool B's scenarios as clear and understandable as possible for citizens.

By observing the students as they used the tools and by gathering their direct feedback, we identified the following potential improvements:

Tool B

- **General remarks:** Creating new connecting roads between existing roads is straightforward, such as adding a new cycle path on the site.
- **Tool limitations:** Creating a mandatory right turn at a junction is complex, and adding a roundabout is not possible—though at the meso level, the difference between a roundabout and a standard junction is negligible. Interpreting the data can be challenging, especially for non-specialists, so expert guidance remains important. Implementing workarounds, such as adjusting the road network, can make interpreting results more difficult.
- **General evaluation of the tool:** The interface is intuitive, with clearly labelled and logically positioned buttons, and the tool works well on the existing street network. It is primarily designed for experts, but when combined with Tool C, it enables more comprehensive scenario interpretation. The accuracy of the underlying road network (OSM) is crucial; for example, missing representations of key cycle routes along the *LandMarck* site can affect results. A strategy is needed to determine where adjustments to calculations should be made, either by using the tool's editing function or by editing a local OSM version in advance to simulate desired changes.
- **Tool functions:** Key functions include a navigation feature (compass rose) and the ability to model air quality, which is a clear added value. Future enhancements could include more traffic functions, such as easily changing turn directions at junctions and converting standard junctions to roundabouts (even if the traffic engineering change is minimal, users perceive a difference in the model). Additionally, future modelling of noise would also be beneficial.

Tool C

- The tool should allow multiple viewpoints, as it is currently limited to three. It would also be beneficial to improve the representation of heavy vehicles among car traffic, as the current display gives a somewhat distorted impression. Additionally, distinguishing between cars and buses—such as by setting percentages—would be useful, especially given the proximity of the *De Lijn* bus depot, where there are more buses than lorries in this area compared to elsewhere in the city. The visualisation of Trucks will be added, but distinguishing between cars/trucks and buses is harder and depends mostly on whether the *Mobilize* data includes that information.
- The tool adds value in terms of building public support for the project.
- Introducing a snapshot or replay function would be helpful, enabling users to capture and review shorter periods of traffic build-up when playing back an existing scenario. A replay functionality will be added, allowing users to scrub through a timeline to view traffic at different points in time.

Use case 10: Enhance the quality of the traffic debate

Use case 10 empowers citizens to take an active role in local discussions about traffic and traffic safety policy by equipping them with smart traffic sensors and tools, enabling them to **collect and share data**, evidence, and knowledge about mobility in their neighbourhood.

The central tool for this use case is *Telraam*: www.telraam.net (Tool D). *Telraam* is a combined technical and participatory tool designed to empower citizens to actively contribute to local traffic and mobility policy debates. 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 use and one for outdoor installation in public areas. In this use case, we mainly installed outdoor sensors in public spaces and a small number of indoor sensors in school buildings. Both sensor types automatically and continuously count and classify different categories of road users—including pedestrians, cyclists, cars, and heavy vehicles—and also measure vehicle speeds.

Figure 10: Outdoor smart traffic *Telraam* counting devices.

All sensor data is transmitted in real time to an **open data platform**, where it is processed, aggregated, and visualised in a **dashboard**. Through this dashboard, all (local) stakeholders can access and interpret traffic data for their street or neighbourhood, project area, or policy plan. They can identify trends and compare patterns over time.

The platform enables stakeholders—including citizens—to engage directly with the data, fostering constructive dialogue with policymakers and other actors. By transforming raw data into actionable insights, it supports evidence-based discussions on traffic safety, mobility planning, and local interventions.

Use Case 10 solution test and assessment

In preparation for implementation and field testing, **five outdoor and two indoor traffic sensors were installed** (December 2025) along the access roads to the *LandMarck* site in Kortrijk. The map below depicts the precise location of the road segments on the local road network.

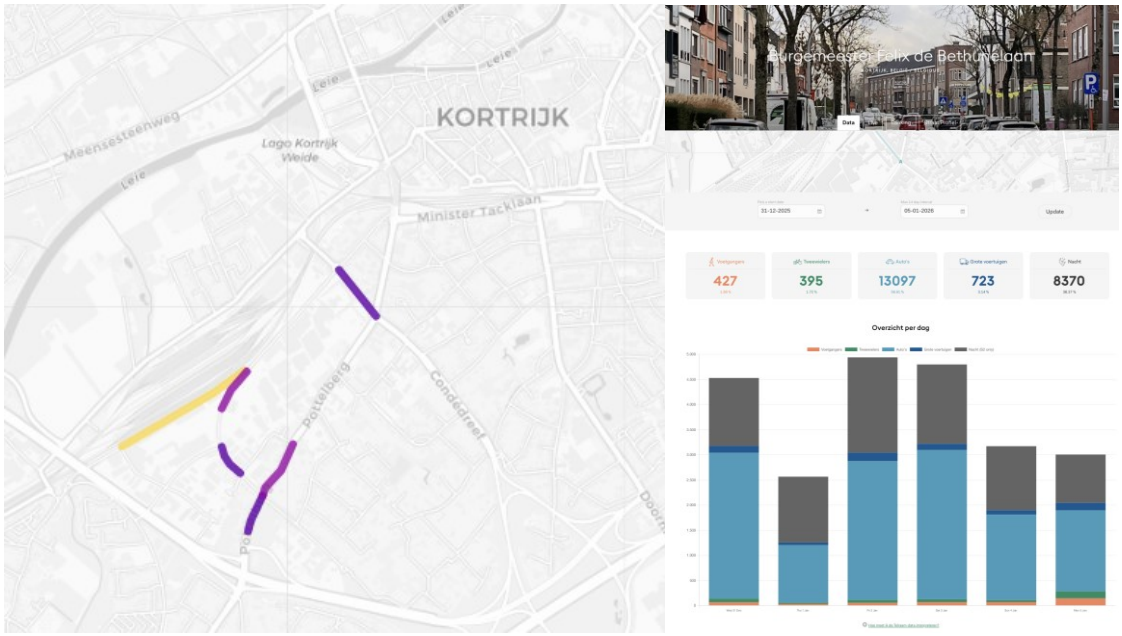


Figure 11: Traffic Counting Dashboard | Detailed information.

The *Telraam* **dashboard** allows for the retrieval of a historical overview of the counting data for each road segment where a *Telraam* traffic counting sensor is located. The dashboard interface is the result of user testing, experiences from previous research projects, and input from the *Telraam* user community. The user testing comprises testing the UX, the readability and completeness of the graphs, and their use in mobility studies.

The dashboard provides a complete overview of the aggregated data output from the *Telraam* device (indoor or outdoor) and has already been extensively tested. The added value of testing the *Telraam* data lies in the following aspects:

- Its application as a data stream for local traffic modelling
- Necessary local coverage to achieve reliable measurement results for the entire area (combining data from multiple *Telraam* sensors)
- New visualisation applications based on aggregated *Telraam* data as part of a digital twin and extended reality application
- Use of the visualisation applications with *Telraam* data as part of a public participation process

Preparation of test scenarios

Outdoor sensors were installed at five locations, equipped with solar panels and batteries to be self-powered.

The locations were determined in consultation with the City of Kortrijk.

In addition, two indoor sensors were installed in the two schools located in this project zone. The school management gave its approval for the indoor sensors.

This network at these locations enables multimodal traffic to be counted in the immediate vicinity of the *LandMarck* site. The count data for the four main categories is open data that is accessible to all relevant local stakeholders, including residents, at hourly intervals over a 14-day period.

UI and UX designs for test scenarios

In 2026, the *Telraam* dashboard is focused on shifting from hardware-centric monitoring to a person-centred "citizen science" experience. The UI/UX is designed to empower local communities and professionals with intuitive traffic data.

2026 UI/UX Design & Features

- Citizen-Science Centricity: Following a heavy focus on the S2 sensor in 2025, the 2026 roadmap prioritises the "people central" approach, improving engagement tools for the volunteers who host devices.
- Inclusive Data Visualisation: The interface uses a brand guide developed to be accessible, specifically avoiding problematic colour combinations for the 1 in 10 men with colour blindness (e.g., avoiding red-green or blue-yellow overlaps).
- Advanced Traffic Categorisation: The dashboard now supports 10 distinct traffic modes (including strollers, motorcycles, and trailers) instead of the previous four broad categories, providing more granular insights for urban planning.
- Night Counting Display: A new "night count" feature displays a dedicated black bar in the charts, representing cumulative motorised vehicle counts captured during dark hours by the S2 sensor.
- Project Timelines & Trajectories: The updated backend allows for visual timelines of specific projects and the division of traffic data into different trajectories for clearer street-level analysis.

Core Management Functionalities

- Network Admin Tools: Professionals can manage large fleets through a pull-down menu to switch between networks, interactive maps of segments, and a "Users" tab to monitor installation status or send batch emails to volunteers.
- Data Reliability Labels: For better data quality assessment, the dashboard now includes "uptime" labels (low vs. good) in reports and exports, ensuring researchers use the most reliable datasets.
- Open Data & API Integration: Data is accessible via an interactive map and a public API, allowing for integration into external mobility policy tools and third-party research.
- S2 Hardware Integration: The interface is optimised for the *Telraam* S2, which features a built-in LCD screen for instant on-device visualisation and uses LTE-M (no Wi-Fi needed) for consistent data syncing to the dashboard.

For a live demo of these features, you can explore the *Telraam* Sandbox Network or visit the official dashboard.

Functional and technical testing setup

Validation Methodology:

- *Telraam* uses manual traffic counts where citizens note passing road users by direction and traffic mode (Telraam), alongside pneumatic tube measurements for ground truth validation
- For the S2 device, *Telraam* employs a debugging tool that emulates firmware performance on recorded video files from various locations (GitHub), allowing systematic testing without repeated field deployments
- *Telraam* conducts controlled experiments with multiple devices at the same location to measure device-to-device consistency

Key Testing Metrics:

- **Precision**: Testing shows high device-to-device consistency with minimal scatter between identical installations
- **Accuracy**: In optimal conditions, typical accuracy is around 85-90% for cars and heavy vehicles (Telraam), with potential to reach 90-95% in perfect setups.

Common Setup Challenges:

- Region of Interest (ROI) configuration can be difficult, depending on the local circumstances, to position the sensor
- Installation requires careful attention to placement criteria (first floor, unobstructed view, proper angle)

Support Infrastructure:

- Community-driven "*Telraam* Talks" forum for peer support
- Users can validate their own data and share results with the team
- Feedback mechanisms integrated into the platform for continuous improvement

The system emphasises community participation in both deployment and validation, with users actively contributing to data quality by manually validating counts.

Performance assessment evaluation (setup)

Testing Infrastructure:

Telraam uses a debugging tool that emulates firmware performance on video files recorded with GoPro cameras GitHub. This allows them to test new firmware versions on a standardised dataset without repeatedly deploying physical devices.

Test Dataset:

- 12 short videos (2-6 minutes) covering various streets across Leuven, Brussels, and London (GitHub).
- Locations range from cycling/pedestrian areas to multi-lane express roads
- Videos represent various traffic and weather conditions
- Ground truth derived through manual counting

Validation Approach:

- **Debug Tool Validation**: Tests firmware performance on recorded videos before field deployment
- **Device-to-Device Consistency**: Eight *Telraam* S2 devices installed at the same location with identical settings to measure device-to-device scatter and precision (GitHub).
- **Parallel Ground Truth**: GoPro recordings synchronised with actual device counts for comparison

Performance Metrics:

- **Overall Object Count**: 99.5% accuracy (0.5% error)
- **By Category**:
- Heavy vehicles: 90%
- Cars/light trucks: 95%
- Bicycles/motorcycles: 90%
- Pedestrians: 85%

User Validation Tools:

Users can conduct "Quick validation" counts, manually counting traffic for 15 minutes and comparing it against their device using a standardised error calculation formula (FAQ). If performance falls outside expected ranges, users are encouraged to submit video validations for further analysis.

This systematic approach allows continuous firmware improvement while maintaining transparency about device performance.

Security and privacy assessments

Privacy-by-Design Architecture:

Telraam implements true "edge computing" where camera images are processed immediately at the source, with only strictly necessary information retained (Telraam). This architectural approach is central to their privacy protection:

- Camera images are never stored, and the camera films in low resolution, so it does not recognise faces or license plates. (Telraam Talks)
- Images are converted into object properties (size, speed in pixels) instantaneously on the device
- Only anonymised 15-minute aggregate traffic counts are transmitted to the database

Independent Security Audits:

Several ethical hackers have vetted *Telraam*, enabling them to improve the device further and make it more secure (Telraam). The company actively encourages security review through:

- **Open-Source Transparency**: All software running on *Telraam* devices is completely open source
- Device owners can physically connect to verify processes
- Public code repository allows community scrutiny

Regulatory Compliance:

- **GDPR Compliance**: Personal data and privacy are protected in accordance with Belgian and European regulations, including the General Data Protection Regulation (GDPR) (Telraam).
- **Data Protection Authority Approval**: Belgium's Data Protection Authority (GBA-APD) responded that "based on the additional information provided, the use of the cameras as explained does not appear to involve any processing of personal data" (FAQ).

Privacy Safeguards:

- **No Personal Data Storage**: System cannot identify individuals, faces, or license plates
- **Community Transparency**: Information materials provided for users to inform neighbours

Data Security Limitations:

Telraam acknowledges that "the security and protection of your personal data can never be fully guaranteed" (Telraam), maintaining transparency about inherent limitations while implementing comprehensive safeguards.

Conclusions and lessons learned

The sensors have only been actively counting for a month. At this point, it is too early to draw any conclusions.

The city services were involved in the installation, and afterwards, there was satisfaction with the data provided in the network dashboard.

To draw conclusions about traffic volumes and speeds, it is important to have at least three months of counting data.

Use case 11: Simulate SEA procedure, scientific and policy outcomes

The primary objective of this use case is to simulate the scientific and policy outcomes of the SEA procedure using a Local Digital Twin of the "RUP Ragheno" spatial implementation plan, focusing on traffic, air quality, and noise. The aim is to determine whether a Digital Twin–based approach can produce results comparable to those of the traditional, time-consuming SEA process carried out by specialised consultants, who handle data collection, processing, simulation, interpretation, and the development of mitigation measures.

To support this use case, **Tool B** will be used.

Use Case 11 solution test and assessment

Since this use case also relies on Tool B—the same tool used in Use Case 9—the information in this chapter is fully identical to the details provided in the chapter "*Use Case 9: Co-design traffic mitigation measures.*"

Use case 12: Roadmap for SEA LDT

The initiative aims to develop a comprehensive roadmap for operationalising a Local Digital Twin (LDT) tailored to SEAs. 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.

For Use Case 12, no software or hardware development or installation is required, as the roadmap is solely a descriptive document. Consequently, UC 12 does not include core

features, user interface elements, functionalities, specific technologies, platforms, or tools.

Similarly, capability considerations, compatibility with the CitiVerse environment, and integration with the EU LDT Toolbox development project do not apply.

Use Case 12 solution test and assessment

N/A (not a technical solution).

Summary

This summary distils the primary strategies, methodologies, and results linked to the evaluation of use case solutions as outlined in this document. It is crafted to provide stakeholders, evaluators, and project contributors with a clear outline of the essential principles and insights gleaned from the testing process, emphasising the pivotal role of thorough validation in achieving project goals. The review covers the justification for conducting tests from the perspective of each use case, the detailed planning and documentation of scenario-based assessments, the integration of user interface and experience analysis, the alignment of functional and technical verification with stakeholder contributions, the deployment of performance measurement techniques, inclusion of security and privacy checks, and a final synthesis of all tested solutions.

From the outset, the project has treated testing as a continuous, embedded activity, rather than a standalone phase. This seamless integration ensures that the transition from conceptual design to practical implementation is grounded in real-world conditions, enhancing the dependability and applicability of each use case. Such an approach not only demonstrates the robustness of the solutions but also instils confidence among all involved parties regarding the outcomes' relevance and credibility.

Test scenario planning began with a structured exploration of primary user interactions and likely operational sequences. This groundwork ensured that each scenario mirrored genuine working conditions, supporting the creation of tests that are both practical and repeatable. Every scenario was meticulously recorded to guarantee transparency and enable collaborative scrutiny, supporting the strategic priorities of the project and laying the foundation for ongoing refinement.

User experience considerations were prioritised during scenario design, with a focus on making interfaces intuitive and accessible to all user types. Scenarios were specifically designed to identify potential usability challenges and ensure that feedback channels were effectively embedded, allowing for rapid integration of user suggestions. Through this iterative process, both the interface and experience aspects of each solution were gradually optimised to meet the needs of a diverse user base.

Functional and technical assessments were carried out using a combination of hands-on and automated testing, ensuring both feature compliance and robust infrastructure performance. These activities validated that specifications were met and that systems responded appropriately under varied conditions. The collaborative inclusion of user feedback during these stages allowed for the timely identification of issues, promoting a sense of shared responsibility and trust within the project team.

To address system efficiency, performance testing was systematically embedded within the framework, utilising realistic workloads to identify limitations and optimise system resources. This process was underpinned by objective measurement tools and real-time analytics, providing actionable insights to guide future development and resource planning.

Security and privacy were treated as integral to the entire assessment process, aligned with recognised standards and best practices. Security testing included risk analysis, vulnerability detection, and checks on authentication, authorisation, and data handling procedures. These proactive measures ensured comprehensive protection and informed the implementation of targeted safeguards, reinforcing the resilience of each use case solution.

The overall testing methodology adopted throughout the project can best be understood as a well-choreographed narrative, where each phase and component plays a crucial role in advancing the story from concept to completion. From the very beginning, testing was not an afterthought or a final checkpoint but instead wove itself into the very fabric of the project's lifecycle. At the project's outset, careful attention was given to planning test scenarios that would accurately reflect how real users would interact with the proposed solutions. This meant identifying day-to-day operational sequences and user journeys, capturing them with fidelity so that tests would not be abstract exercises, but rather genuine mirrors of actual working environments. Each scenario was meticulously recorded, ensuring that every step could be scrutinised, repeated, and improved upon. This thorough documentation fostered a culture of openness, enabling all stakeholders to contribute meaningfully to the refinement of the approach.

As the narrative continued, user experience became a central theme, guiding the design of interfaces with a view to making them as intuitive and accommodating as possible. The inclusion of iterative feedback channels acted like a dialogue between users and developers, allowing suggestions and concerns to be swiftly addressed and integrated. This conversation not only improved the usability of each solution but also instilled a sense of ownership and confidence among those who would ultimately rely on the system. Alongside usability, the methodology incorporated both functional and technical assessments, blending manual testing with automated routines. This combination ensured that every feature, function, and underlying system component was checked for compliance, resilience, and readiness for real-world demands. By actively involving users in these stages, the project was able to quickly identify and remedy issues, reinforcing trust and shared commitment to quality.

Performance testing added its own chapter to the methodology, employing realistic workloads and sophisticated measurement tools to uncover bottlenecks and optimise resource usage. Rather than relying on hypothetical benchmarks, testers drew on practical, context-rich data to inform and refine their strategies, ensuring that the final solutions would be both efficient and adaptable in practice. Security and privacy, meanwhile, formed an ever-present thread running throughout the narrative. Drawing on industry standards and best practices, the methodology embedded risk analysis, vulnerability checks, and robust controls for authentication and data management at every stage of the process. This vigilant, proactive stance meant that security was never left to chance but was instead built into the core of each use case solution. Ultimately, the story of testing in this project is one of seamless integration, continuous dialogue, and shared responsibility, resulting in a resilient framework prepared to meet both current and future challenges with confidence.

In conclusion, the evaluation activities described here serve as the backbone of the project's commitment to producing solutions that are reliable, user-centred, and secure. By embracing an iterative, context-driven approach that values stakeholder input and continuous improvement, the project has created a resilient framework ready to support future developments and adapt to emerging needs. The combined efforts in scenario design, usability testing, functional and technical validation, performance analysis, and security assurance demonstrate a holistic commitment to quality and sustainability, assuring stakeholders that the solutions will remain relevant and effective as requirements evolve.

References

No References