DIDYMOS XR
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DIGITAL, DYNAMIC AND RESPONSIBLE TWINS FOR XR

D2.3 – Requirements and validation methods v2

[WP2 – User-centric development]

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About the project

The digital transformation and the availability of more diverse and cost-effective methods for 3D capture has led to the creation of digitised representations of parts of our public spaces, machinery and processes, so-called Digital Twins (DTs). These DTs are an important basis for building advanced extended reality (XR) applications for cityscapes and the industrial environments. These XR applications need high-fidelity models for accurate localization, which are kept in-sync with the real world. The vision of DIDYMOS-XR is to enable advanced, more realistic and more dynamic XR applications, powered through artificial intelligence. The project thus focuses on advancing technologies for creating large-scale digital twins, synchronised with the real world. DIDYMOS-XR will research and develop methods for reconstruction and mapping from heterogeneous inputs, including static and mobile sensors, AI-based data fusion, scene understanding and rendering. Digital twin based XR applications also require means of accurately positioning in the environment, aware of the dynamics of the scene, also addressed by the project. The capture of scenes at scale, as well as using cameras and other sensor data for synchronising the digital representation, bears the risk of capturing personal and sensitive data. Hence, the technologies resulting from DIDYMOS-XR must be and will be ethical and privacy-aware by design. In order to demonstrate and validate the enabling technologies researched and developed in DIDYMOS-XR, the project will address use cases of XR applications in two domains that differ in their scale and characteristics. One is urban planning and smart mobility, the other is the collaboration with autonomous mobile robots at an industrial production facility.

Abstract

This updated version of the DIDYMOS-XR Requirements and Validation Methods deliverable represents a continuation and enhancement of the foundational work established in the first iteration. It reflects the project's progression by refining and expanding the defined technical and user requirements, as well as the validation plans for the final validation. These revisions are informed by continuous engagement with stakeholders, insights gained from the technical development, and testing results obtained during the initial project phases.

While the original personas—representing key user archetypes—remain valid and unchanged, the requirements have been critically reviewed and adapted to reflect new technical insights and evolving project priorities. The validation plan has been revised to align with updated requirements, specifying refined methods, metrics, and test scenarios that will guide the assessment of system components moving forward.

It is important to note that this document does not include new user flows or finalized use case descriptions. These elements, which were initially introduced in the first version, will be completed and fully detailed in the subsequent deliverable D5.2. Therefore, this deliverable serves as a living artifact in the requirements engineering process—providing an up-to-date reference point for all project partners.

Table of Contents

Table of Contents 5
1 Introduction 10
1.1 Background 10
1.2 Purpose and Scope 10
1.3 Deliverable Structure 11
2 Stakeholder Engagement 12
Purpose of Stakeholder Involvement 12
2.1 Workshops – Ongoing Dialogue and Feedback 12
3 Use Cases for DIDYMOS-XR 13
3.1 Design Thinking and Use Case Development 13
3.2 Refinement and Validation Feedback 14
4 Personas 15
4.1 General Motivation 15
4.2 Persona Recap by Use Case 15
5 Requirements for DIDYMOS-XR 16
5.1 Requirement Gathering 16
6 User Journey and User Flow 30
7 Validation Methods 31
7.1 Objectives 31
7.2 Organization 31
Validation Plans 31
Recruitment 31
Execution 32
7.3 Methodology 32
Data collection 32
Questionnaires 32
Test locations 35

Procedure 35
Scientific Standards 36
Ethical Guidelines 36
7.4 Use Case Validation Plans 36
Digital Twin Creation 36
City Planning 38
City Maintenance 39
Virtual Reality Virtual Tour 40
Augmented Reality Virtual Tour 41
Industry DT Maintenance 43
8 Conclusion 45
9 Annex - Persona Visualisations 46
10 Annex – Interview Questionnaires 50

Executive summary

This deliverable marks the culmination of over two and a half years of intensive work on requirements engineering and validation within Work Package 2 (WP2) of the DIDYMOS-XR project. As the final report on requirements and validation, it consolidates the extensive outputs and lessons learned throughout this critical project phase, providing a mature and comprehensive reference for all subsequent development activities.

DIDYMOS-XR is driven by the digital transformation made possible by accessible and cost-effective 3D capture technologies. The creation of digital twins—precise, dynamic representations of public spaces, machinery, and processes—has been central to enabling advanced XR applications in both urban and industrial environments. The project's vision is to support more realistic, adaptable, and context-aware XR experiences powered by AI, underpinned by robust, up-to-date digital twins.

This deliverable synthesizes the technical and user requirements that have been progressively refined through ongoing stakeholder engagement, iterative technical development, and validation activities spanning the entire duration of WP2. Key project domains include urban planning and smart mobility, as well as industrial collaboration with autonomous mobile robots. Throughout, the consortium has prioritized a user-centric approach, grounded in real-world use cases, detailed user personas, and active co-design with stakeholders.

The document presents a thorough and structured overview of the final functional and non-functional requirements, as well as an updated and validated requirements catalog. The outcomes of extensive stakeholder workshops and validation exercises are systematically documented, supporting both transparency and traceability. The deliverable also details the evolution and refinement of the validation plan, specifying methods, metrics, and test scenarios that will guide the final validation.

While this deliverable finalizes the requirements and validation phase, detailed user flows and finalized use case descriptions will be presented in the upcoming deliverable D5.2, aligned with the project's development timeline. As such, this document serves as both a comprehensive record of the WP2 achievements and a practical guide for the next phases of DIDYMOS-XR.

List of figures

Figure 1. Affective Slider
Figure 2. User Persona - Linda Robertson
Figure 3. User Persona - Brandon McDermott
Figure 4. User Persona - Stefan Wolff
Figure 5. User Persona - Mia Becker
Figure 6. User Persona - Chiara Valentini
Figure 7. User Persona - Samuel Lee
Figure 8. User Persona - Marcos Fernandez
Figure 9. User Flow Diagrams for the Digital Twin Creation Use Case
Figure 10. User Flow Diagrams for the City Planning Use Case
Figure 11. User Flow Diagrams for the City Maintenance Use Case
Figure 12. User Flow Diagrams for the AR Virtual Tourism Use Case
Figure 13. User Flow Diagrams for the VR Virtual Tourism Use Case
Figure 14. User Flow Diagrams for the Industrial Use Case

List of tables

Table 1. List of acronyms
Table 2. Glossary of terms
Table 3. Personas overview
Table 4. Requirement list
Table 5. Use Case Possibilities – Tourism
Table 6. Use Case Possibilities – Urban planning
Table 7. Use Case Possibilities – Smart Mobility
Table 8. Use Case Possibilities – Collaboration with AMR

List of acronyms/abbreviations

Abbreviation	Explanation
DIDYMOS-XR	Digital, Dynamic and Responsible Twins for Extended Reality
WP	Work Package
UC	Use Case
IoT	Internet of Things
AI	Artificial Intelligence
KPI	Key Performance Indicator
AR	Augmented Reality

Abbreviation	Explanation
VR	Virtual Reality
XR	Extended Reality
VE	Virtual Environment
DT	Digital Twin
POI	Point of Interest
IoU	Intersection over Union
FPS	Frames per Second

Table 1. List of acronyms/abbreviations

Glossary of terms

Term	Explanation
Digital Twin	A digital representation of an intended or actual real-world physical product, system, or process
Stakeholder	A relevant actor (persons, groups, or organisations) who: (1) is affected by the project's results and findings; (2) have the potential to use or exploit the project's results and findings; or (3) have a stated interest or stake in the project results and findings.
End-user	A person, group or organisation who has the potential to use or exploit the project's results and findings. Each stakeholder is thus also an end-user, but not vice-versa.
Use Case	A use case is a written description of how a system or project will be used to achieve a specific goal from the perspective of an end user.
Persona	A persona is a fictional character created to represent a typical user in a specific demographic, capturing their behaviors, goals, and motivations to guide the design and development of a product or service.
Design Thinking	Design thinking is a problem-solving approach that involves understanding user needs, redefining problems, and creating innovative solutions through a process of ideation, prototyping, and testing.
Requirement	In the field of user-centric development, a requirement describes a specific functionality, feature or characteristic that a system or product must have to meet the expectations and preferences of its user.

Table 2. Glossary of terms

1 Introduction

Fundamentally, DIDYMOS-XR aims to transform how we interact with industrial environments and public spaces by leveraging the power of real-time, sensor-driven Digital Twins enhanced through Augmented and Virtual Reality. This deliverable builds on the foundation laid in the initial requirements report, providing updated insights, refined content, and a more mature understanding of the system and its users.

While the original document introduced the key components—functional requirements, user personas, and illustrative use cases—this version reflects iterative improvements informed by validation feedback, stakeholder engagement, and technical advancements achieved over the past development phase. In this regard, the deliverable maintains its dual role: offering both a technical specification and a reporting perspective to contextualize the system's application and relevance.

The revision also continues the effort to humanize technological discussions, highlighting the role of user personas, collaborative stakeholder workshops, and interactive sessions that helped refine system goals. Rather than presenting a static specification, this document should be understood as a living artifact—a curated snapshot of a system in progress, enriched by multidisciplinary collaboration and continuous validation.

1.1 Background

The vision of DIDYMOS-XR originates from the growing demand to apply advanced digital technologies in smart city management, industrial automation, and urban experience design. At the center of this initiative is the concept of Digital Twins, digitally replicated environments that are dynamically linked to their physical counterparts via IoT, AI, and data analytics.

While the foundational background remains consistent with the initial deliverable, the present document reflects the evolution of this vision—now informed by more detailed technical exploration and stakeholder validation. In particular, the refinement of use cases, system functions, and validation targets has clarified how DIDYMOS-XR can improve operational efficiency, planning, and engagement across different domains.

1.2 Purpose and Scope

The primary objective of this updated deliverable is to refine and consolidate the project's strategic and technical direction. It provides an updated view of the five core use cases, clarifies how the user personas and functional requirements have

remained or evolved, and outlines how validation input has shaped the development of the DIDYMOS-XR framework.

It serves as a bridge between early concept definition and final implementation planning—capturing both what has remained constant and what has been adjusted to reflect real-world constraints and opportunities. This document also continues to serve as a reference point for partners, supporting internal alignment and offering external stakeholders a structured overview of the project's scope, architecture, and anticipated benefits.

1.3 Deliverable Structure

This deliverable retains the overarching structure of its predecessor while incorporating updated insights, refinements, and validation-informed revisions across all major components. It is organized as follows:

- Chapter 2 – Stakeholder Engagement: Describes the continued involvement of the Stakeholder Board and Ethics Advisory Board, including newly conducted workshops and their influence on system refinement.
- Chapter 3 – Use Cases: Summarizes the approach for use cases development and refinement.
- Chapter 4 – User Personas: Provides a recap of the established user personas, which remain unchanged, reaffirming their relevance and alignment with the current use cases.
- Chapter 5 – Requirements: Updates the functional and non-functional requirements based on recent iterations of use cases, user flows, and early feedback from validation activities.
- Chapter 6 – User Journeys and Flows: Summarizes the refined user journeys and flows for each use case, noting that updated diagrams and descriptions will be fully presented in Deliverable D5.2.
- Chapter 7 – Validation Methods: Outlines the methodological framework for the final validation of all DIDYMOS applications, including metrics, test procedures, and user-centered evaluation strategies.
- Chapter 8 – Conclusion and Future Directions: Concludes the deliverable by summarizing key updates and describing how this document feeds into the final specification and validation deliverable (D5.2).
- Chapter 9 – Annexes: Includes supplementary materials such as detailed workshop reports, interview guides, user flows.

2 Stakeholder Engagement

Engaging stakeholders throughout the design and development phases of the DIDYMOS-XR project remains a cornerstone of the project's user-centered and ethically sound approach. As outlined in the first iteration of the deliverables, a Stakeholder Board (SB) and an Ethics Advisory Board (EAB) were established to ensure that the interests of users, industry representatives, technical partners, and ethical experts are continuously reflected in project decisions.

Purpose of Stakeholder Involvement

Stakeholders bring essential perspectives and domain expertise to the project, supporting:

- A deeper understanding of user needs and behavioural patterns
- More informed and relevant design choices
- Early identification of risks and usability issues
- Continuous alignment between system development and real-world goals
- Ethical oversight regarding data collection, privacy, and long-term user impact

The Stakeholder Board is composed of consortium members, external business partners, and representatives from target user groups. It ensures that diverse viewpoints guide the use case design, requirement elicitation, and validation strategy. The Ethics Advisory Board, comprising legal, academic, and domain experts, provides independent oversight of ethical compliance. Its guidance is especially important given the project's ongoing handling of real-time, potentially sensitive data.

2.1 Workshops – Ongoing Dialogue and Feedback

Since Deliverable D2.1, one workshop was held with members of the stakeholder board. During this workshop, stakeholders were asked to test two online applications (Digital Twin Creation and City Planning) fill in user experience questionnaires. Afterwards there was a discussion round where additional feedback was gathered. The meetings with the ethics advisory board will be discussed in Deliverable D2.4 .

Stakeholder Board Workshop
Date: 04/12/2024
Modality: online workshop
Tool used: online board
Goal: User validation for the use cases "Digital Twin Creation" and "City Planning"

3 Use Cases for DIDYMOS-XR

The DIDYMOS-XR project builds upon five distinct use cases that explore how digital twins, augmented reality (AR), and virtual reality (VR) can create immersive, context-aware solutions across different domains—including industry, urban planning, city maintenance, and tourism. These use cases form the foundation for requirement elicitation, persona development, user flow modelling, and ultimately, system validation.

In the first project phase, the use cases were generated through a design thinking methodology, encompassing stakeholder interviews, iterative ideation, and collaborative workshops. This process ensured that each use case aligned with real user needs (desirability), could be technically implemented (feasibility), and provided tangible value (viability).

3.1 Design Thinking and Use Case Development

The initial creation of the use cases followed a structured design thinking approach:

- Empathize – Through interviews with stakeholders across all project partners
- Define – Synthesis of pain points and opportunities into concrete problem statements
- Ideate – Exploration of diverse solution scenarios and AR/VR-enabled experiences
- Prototype & Test – Presentation of early use case drafts at project meetings and stakeholder workshops

This collaborative effort led to the definition of five initial use cases, covering a wide spectrum of application contexts:

- UC1 – Real-time Industrial Mapping with HIL
- UC2 – Digital Twin Creation
- UC3 – City Planning via Simulation
- UC4 – City Maintenance Based on Sensor Feedback
- UC5 – Virtual Tourism in AR and VR

These use cases were initially presented during the Thessaloniki project meeting (May 2023) and subsequently refined based on feedback collected during two stakeholder workshops and the Patras project meeting (September 2023). Their development also informed the generation of user personas and validation scenarios.

3.2 Refinement and Validation Feedback

Since their first iteration, all five use cases have undergone targeted revisions based on early validation insights. The initial user feedback—gathered through workshops and early implementation discussions—prompted a re-evaluation of certain assumptions, interactions, and technical configurations within each scenario.

In particular, the updates focus on:

- Improving clarity and realism of user actions and system behavior
- Reflecting technical developments (e.g., sensor integration, device choices, simulation tools)
- Strengthening the alignment between user needs and system functionalities
- Better defining data flows and interactions with AR/VR environments

4 Personas

4.1 General Motivation

User personas continue to play a central role in aligning system development with the needs, goals, and contexts of future users. Developed during the first iteration of the project, these fictional yet research-based representations help ensure that technical and functional decisions remain grounded in user-centric perspectives. By translating data and user research into relatable characters, personas serve to enhance empathy within the development team and maintain a consistent design focus across diverse use cases.

In the context of the DIDYMOS-XR project, personas have been especially valuable for:

- Guiding the design of XR-based tools in industrial, civic, and tourism contexts
- Supporting use case-specific decisions during workshops and requirement refinement
- Acting as a shared reference during interdisciplinary collaboration, particularly across distributed teams

Although project requirements and technical solutions have evolved over time, the user personas themselves have not changed. Their consistency has provided a stable foundation for validating user needs across various development stages.

4.2 Persona Recap by Use Case

The original set of seven personas remains unchanged and continues to provide a comprehensive representation of the primary user types involved across the six use case scenarios:

Industry Use Case	Industry (UC1)	User Persona 1 - Linda Robertson User Persona 2 - Juan McDermott
City Use Case	Virtual Tourism (UC5)	User Persona 3 - Marcos Fernandez User Persona 4 - Chiara Valentini
	Digital Twin Creation (UC2)	User Persona 5 - Samuel Lee
	City Planning (UC3)	User Persona 6 - Mia Becker
	City Maintaince (UC4)	User Persona 7 - Stefan Wolff

Table 3. Distribution of personas per use case scenario

5 Requirements for DIDYMOS-XR

5.1 Requirement Gathering

Requirement gathering remains a core activity within DIDYMOS-XR's user-centered design approach, ensuring that the system meets both technical standards and real-world user expectations. In this second iteration, the process has evolved based on the insights gained during validation activities and finalized use case definitions.

The updated list of requirements presented in this deliverable reflects a more focused perspective on user interaction and final system features. It incorporates partner feedback, highlights cross-domain priorities, and integrates practical considerations derived from stakeholder workshops, early technical evaluations, and realistic deployment planning.

The second iteration of requirements draws from three key sources:

- Finalized Use Cases: The revised use cases provided clarity on functional expectations and context-specific needs across domains.
- Validation Feedback: Insights from WP5 validation planning helped identify performance thresholds, technical constraints, and usability requirements.
- Partner Consultation: A collaborative review of the updated requirements was conducted with all project partners to ensure feasibility and alignment across work packages.

This version serves as a near-final specification baseline before implementation and testing.

The following table presents the revised and expanded list of both technical and user-focused requirements as of project month 32.

Code	Title	Description
TNF1v2	Reconstruction accuracy	The system shall achieve an average reconstruction error of ~15 cm
TNF2v1	Minimum number of scenarios	At least 5 use case that showcase the creation and the usage of the digital twins
TNF3v2	Segmentation pixel accuracy	The system shall achieve a segmentation pixel accuracy of at least 0.8 in realistically complex scenes.
TNF4v2	Segmentation Class Support	The segmentation system shall support more than 500 classes, achieving a minimum mean Average Precision (mAP) of 0.1 at an Intersection over Union (IoU) threshold of 0.5.
TF5v1	Camera and Sensor Support	The system shall support integration with at least 10 different types of camera or sensor streams.

Code	Title	Description
TNF6v2	Digital twin update rate	The system shall support a digital twin update rate of at least 5 fps for real-time applications and at least x fps for non-real-time applications.
TNF7v2	Volumetric data alignment	The alignment of volumetric data with the real-world scene shall be performed at a minimum rate of 15 frames per second (fps).
TNF8v2	Data Transfer rate	The system shall maintain a data transfer rate not exceeding 100 Mbps at 15 fps.
TNF9v1	Reliability	Reduce catastrophic failures in localization and the ability to re-initiate tracking
TNF10v1	Texture Robustness	The system shall exhibit increased robustness against poorly textured environments, with performance degradation not exceeding 10% compared to well-textured scenarios.
TNF182v1	Respected bandwidth	Respected bandwidth of x for realtime applications and bandwidth of x for non-realtime applications
TNF183v1	Frame resolution	The system shall support a FHD resolution for the initial capture and FD resolution frame resolution of at least X pixels per frame for both real-time and non-real-time applications.
TNF184v2	Voxel Handling Rate	The system shall be capable of processing at least 10 million voxels per second for real-time applications and 40 million voxels per second for non-real-time applications.
TNF185v2	Compression ratio	The system shall achieve a data compression ratio of at least 3.5 times compared to the raw data.
TNF186v2	Compression Quality - Geometry	The geometric compression of the digital twin data shall maintain a Peak Signal-to-Noise Ratio (PSNR) of at least 40 decibels (dB).
TNF187v2	Compression Quality - Color	The color compression of the digital twin data shall maintain a PSNR of at least 40 dB.
TNF11v2	Localization Accuracy	High accuracy localization mean error <5cm
TNF12v2	Smartphone Support	Real-time rendering support on state of the art mobile phones (Android)
UNF13v1	Stakeholder involvement	Stakeholder analysis and list of at least 500 relevant stakeholders in the EU
UF14v1	Approval from the EAB	The Ethics Advisory Board shall approve the legal, ethical, and data protection measures of the system.
UNF15v1	User Engagement	At least 50 users engaged and consulted in the design of the technologies by M12
UNF16v2	Minimum Validation Users	At least 24 users shall participate per domain in validation.
TF17v1	Validation in real environment	Five XR applications validated in realistic environment
UF19v2	Remapping of production line	The system should provide a feature to remap or recapture the 3D data of the digital twin

Code	Title	Description
UF20v1	Simulation Report Generation	The system should generate a comprehensive report to evaluate the impact of new devices on various aspects such as investment optimization, time optimization, and production time.
UNF21v2	Investment and Time Optimization	The application should quantify the improvement (gain xx%) in performance
UNF22v2	Error Prevention	The system should have features that help identify and prevent errors
UF23v2	Addition of New POI	The system should provide functionality to easily create and define new POIs, requiring a minimal number of interactions.
UNF24v2	POI location accuracy	The system should ensure that the POI information is accurately represented within a maximum of 10-15 cm margin of error in the VE.
UNF25v1	User Experience and Interaction with POIs	The system should provide a user-friendly interface that allows easy interaction with the POIs even for users with limited technical expertise.
UNF26v2	Clear Information for improved work performance	The system should provide workers with easily accessible information, instructions, and guidelines to improve their work performance, as assessed by the QUIS/SUS metrics.
UF30v1	Guidance for Workers	The system should provide workers with guidance through the factory.
UNF35v1	Worker Responsibility	The system should facilitate worker responsibility by providing them with clear tasks and goals.
UNF36v1	Worker Application Feedback Mechanism	The system should have a feedback mechanism that allows workers to receive application performance feedback without direct interaction with the manager.
UF37v1	Remote Monitoring and Adjustment of DT Parameters	The system should allow remote monitoring and adjustment of the DT parameters (3D map) enabling managers to make necessary changes without being physically present.
UF39v1	Identification of Bottlenecks	The system should provide tools or analytics that help managers identify areas of improvement (missing parts to be scanned)
UF40v2	Pothole Detection	The system shall detect potholes.
UF43v1	Traffic simulation	The system should accurately model city traffic flow with road networks, lights, pedestrians, and transport
UF44v1	Parking Space Impact Simulation	The system should be able to simulate the effects of removing or adding parking spaces in specific areas of the city.
UF48v1	Safety and Risk Management	The system should provide tools to identify and mark areas of risk, including accident-prone locations
UNF50v1	Preventive Measures for	The system should incorporate preventive measures for potentially vulnerable targets, such

Code	Title	Description
	Vulnerable Targets	as places of worship, by hiding sensitive information or blurring image content.
UF52v1	Temperature and CO2 emission monitoring	The system shall monitor and display real-time temperature and CO^2 emission data from multiple city areas.
UNF53v1	Seamless Data Integration	The system should have a robust data integration process and allow the merging of diverse datasets.
UF54v2	Real-time Sensor Data Integration	The system should continuously update with the latest sensor information, enabling observation of real-time changes and dynamic behavior. (e.g. crowd information, traffic conditions, weather updates, and pollution levels.)
UF55v1	Integrated Data Collection	The system shall collect point clouds, high-resolution images, and 360-degree panoramas to support digital twin creation.
UF56v1	Virtual Museum Analytics	The system should monitor and analyze user interaction with exhibits in the virtual museum to make data-driven evaluation
UF57v1	Tourism Information Support	The system should provide essential information such as museum availability, ticket prices, and highlights of exhibits.
UF58v2	Crowd Control data for museums	The system should offer real-time crowd data to optimize crowd control for museums.
UF60v2	Augmented Reality Guided Exploration	The system should include a wayfinding features and enable the creation of interactive AR routes, guiding tourists to lesser-known zones of interest and hidden places.
UF61v1	Advertisement Integration in AR Pathway	The system should support (targeted) advertisements during the AR pathway to promote other museums or tourist attractions.
TF66v1	Mobile Shops Tracking	Develop a tracking system for mobile shops to help locals and tourists find them based on crowd and traffic information.
TNF68v1	VR Application Platform	Develop the application to work on major VR platforms (at least two), such as Oculus, HTC Vive, or other compatible headsets.
TF69v2	3D Scanning and Rendering	The system shall utilize 3D scanning technologies to create detailed virtual representations of urban areas and landmarks.
TF72v1	Location-Based Services	The system shall present location-specific content using GPS.
TF73v1	Museum and Shop Information	Integrate a database of museums, shops, and restaurants with their opening hours and relevant details.
TF77v2	User preference recommendations	Users should receive recommendations based on preferences, such as avoiding crowded places or choosing public transportation over private vehicles.
TNF78v1	Realistic VR Experience	The application should offer an immersive and realistic experience, providing a detailed

Code	Title	Description
		representation of the city's small areas and monuments.
TF79v2	Adaptive AR Content	AR content should adapt dynamically based on real-time factors and location based triggers, based on weather conditions, time of year, and the number of visitors at a location.
TF80v1	Group Planning and Tour Organization	The application should facilitate group planning for tourists, allowing them to organize tours efficiently based on various factors like crowd density and transportation options.
TF84v2	Smart City Lights Simulation	The system should simulate smart city lights with variable positions and synchronization.
TF91v1	Data Analysis Tool for Traffic scenarios	Implement data analysis tools to compare different traffic scenarios and draw meaningful insights.
TF92v1	Autonomous Vehicle Integration	Integrate autonomous vehicles into the simulation environment with varying levels of autonomy.
TNF96v2	Simulation Scalability	Ensure that the simulation environment is scalable and capable of handling an increasing number of vehicles and complex scenarios.
TNF97v1	Performance Optimization	Optimize the performance of the simulation to provide real-time or near-real-time results.
TF100v1	Realistic Simulation Environment	Users expect the simulation environment to closely replicate real-world traffic behavior, considering factors like vehicle interactions, pedestrian crossings, and traffic rules.
TF102v2	Data Visualization and Analysis	Users need visualizations and analysis tools to evaluate simulation results and understand the impact of different factors on traffic and parking.
TF110v2	Data Analytics and Visualization	The system shall include tools to analyze issue data.
TF112v1	Mobile Application for Maintenance Teams	Create a web app for maintenance teams to receive and update tasks related to city maintenance, such as street maintenance
TF114v2	Infrastructure Notifications	Implement a notification system to alert maintenance teams about sensible sites that require immediate attention (e.g. rubbish accumulation, broken infrastructure)
TF118v2	Geolocalization for Maintenance (T)	Detected issues shall be geolocated using GPS.
TNF119v1	Efficient City Maintenance	The system should help maintenance teams efficiently plan and execute tasks related to city maintenance, saving time and resources.
TNF125v1	Data Security and Privacy	The system shall handle all data securely, especially location-based and personal information.
TF131v1	3D Reconstruction and Modeling	The system shall include algorithms for 3D reconstruction and modeling using sensor data.

Code	Title	Description
TF133v1	Update Verification Mechanism	All updates to the digital twin shall be verified through a validation process for quality (human in the loop).
TF135v2	Integration with Simulation Software (e.g., Carla):	The system should allow seamless integration with simulation software like Sumo or Omniverse to test the process of updating the digital twin.
TF137v1	Version Control for Digital Twin	The system shall track changes to the digital twin using version control mechanisms.
TF138v1	Data Sources audit	The system shall provide auditing capabilities to trace the history of all data.
TNF143v1	Data Quality Assurance	Users should be able to rely on the system's data verification mechanism to ensure the accuracy and reliability of the digital twin updates.
TF144v2	Export for Simulation Testing	The system shall support export to external simulation environments (SUMO) for testing and validation
TNF146v2	Simultaneous Sensor Performance	The system shall concurrently process data from multiple heterogeneous sensors without significant delay.
TF149v1	Error Reporting and Logging	The system shall include tools for users to report bugs or technical problems.
TF150v1	Troubleshooting Guidance	Clear error messages and help documentation shall assist users in resolving common issues. TF150v1
TF151v1	Device Compatibility	The AR application should support both tablets and headsets with AR capabilities.
TF152v1	OS Compatibility	The application must be compatible with major operating systems (e.g., iOS, Android).
TF153v2	Factory 3D Scanning and Rendering	The application should provide real-time 3D scanning of the factory environment using the device's camera.
TNF154v1	Scanning of large environments	The 3D scanning process should be efficient and capable of handling large factory environments.
TF156v1	Digital Twin Integration	The application must have a seamless integration with the existing digital twin of the factory.
TF158v1	Overlay changes in realtime	Users should be able to view the digital twin alongside the scanned environment and overlay the changes in real-time.
TF159v1	Error Correction Functionality	The AR app should allow users to identify and correct misalignments, obstacles, and other errors found during scanning.
TF160v1	3D objects manipulation	Users should be able to manipulate 3D objects in the scanned environment to adjust their positions accurately.
TF161v1	Hidden/Covered Area Scanning	The application should support scanning of uncaptured areas within the factory environment.

Code	Title	Description
TF162v2	Update of the model	The system shall process scanned data and update the digital twin accordingly.
TNF165v1	Efficient Data Management¬†	The system shall manage large datasets effectively, ensuring high performance and responsiveness.
TF166v1	Cloud Storage	The system should support cloud storage integration for managing the digital twin and scanned environment data.
TNF167v1	Performance and Stability	The AR app should be optimized for performance to ensure smooth AR experiences.
TNF168v1	Long-Term Stability	The system shall operate reliably over extended periods without significant crashes or slowdowns.
TF169v1	Intuitive User Interface	The system shall provide a clear, intuitive user interface designed for non-technical users.
TF171v1	Clear Scanning Instructions	The app should provide clear instructions on how to perform the 3D scanning effectively.
TF173v2	Visual Feedback and Guidance	The application should provide visual feedback during the scanning process to indicate the accuracy and alignment of scanned objects with the digital twin and identify erros during the process
TF177v1	Realistic Representation	The AR app should provide a realistic representation of the factory environment in AR, making it easier for users to identify issues and make updates.
TF178v2	Save Functionality	Users should have the option to save their progress during scanning and error correction and to later pick up from that state.
TF179v1	Redo/Undo Functionality	The system shall support undo and redo operations for editing actions.
UF189v1	Desktop Access	The system shall be accessible via a standalone desktop application or web interface.
UF191v1	Customizable Twin Settings	Users shall be able to adjust quality settings related to the digital twin.
UF192v2	Model Update Capability	The system shall allow users to update specific models within the digital twin.
UF194v1	City or Area Twin Generation	Users shall be able to generate a full digital twin of a city or a specific area.
UNF195v1	Environment Modification	Users shall have the option to modify terrain, buildings, and objects in the twin.
UNF196v1	Model Selection Tools	The user interface shall provide tools to select and substitute models within the twin.
UF197v1	3D Model Import Support	Users shall be able to import external 3D models into the digital twin.
TF199v1	Mouse Interaction	The system shall support mouse-based interactions for camera movement and object selection.
TNF200v1	Keyboard Navigation	Keyboard input shall be available for navigation through the virtual environment.

Code	Title	Description
UNF201v1	Scroll-Based Zoom	Users shall zoom in and out using mouse or trackpad.
UNF203v1	Mini-map Overview	A mini-map shall display an overview of the digital twin.
UF204v1	Day/Night Cycle Control	Users shall be able to change the time of day.
UF205v1	Weather Simulation Options	Users shall be able to change weather conditions (sunny, rainy, foggy, snowy).
UNF206v1	Shadow and Lighting Control	Users shall control shadow and lighting settings.
UF209v1	Progress Saving and Loading	Users shall be able to save progress and reload previously saved digital twins.
UNF210v1	Export Functionality	Users shall have the option to export the digital twin for other applications.
TF211v1	Partial Update Capability	The system shall allow users to update specific areas of the digital twin without regenerating the entire model.
TF212v1	Cross-Platform Desktop Support	The application shall be fully compatible with both Windows and macOS platforms.
TF213v1	3D Engine Integration	The digital twin environment shall be powered by a real-time engine such as Unity or Unreal Engine.
TF215v1	Automatic Model Placement	The system shall support automatic placement of models based on real-world data.
TF216v1	Model Replacement Tools	The system shall allow users to select individual models and replace them.
TF217v1	Standard Format Support	The system shall support standard 3D file formats including FBX, OBJ, and GLTF.
TNF218v1	Low-Latency Changes	Modifications made by the user shall be applied in real time or with minimal delay.
TNF219v1	Free Camera Control	The interface shall allow unrestricted camera movement throughout the environment.
TNF220v1	Keyboard-Based Movement	WASD or arrow key navigation shall be supported.
TNF221v1	Zoom Control	Zoom functionality shall be precise and smoothly responsive.
TF222v1	Camera Mode Switching	Users shall be able to switch between first-person and third-person modes.
TNF224v1	Weather Effects Simulation	The system shall simulate weather conditions realistically.
TNF225v1	Shader Effects for Realism	Shader effects shall be available for visual enhancement.
UNF226v1	Web-Based Access	The website shall be developed using modern web technologies (React, Angular, or Vue.js).
UNF227v1	2D City Visualization	The system shall be accessible through a website.
UF229v1	Interactive Issue Map	Users shall be able to interact with the map to inspect issues in different areas.

Code	Title	Description
UF230v1	Issue Detail Inspection	Users shall be able to click on an issue marker to view detailed information.
UF231v1	Issue Validation by Users	Users shall be able to label issues as True or False to validate them.
UNF232v1	Parking Violations Detection	The system shall detect and report parking violations.
UF233v1	Map Navigation Tools	Users shall be able to zoom, pan, and search for specific areas in the city.
UNF234v1	Issue Filtering	Users shall be able to filter the types of issues displayed.
UNF235v1	Mobile Responsiveness	The system shall be mobile-responsive for smartphone access.
UNF236v1	Cross-Browser Compatibility	The platform shall be optimized for Chrome, Firefox, Edge, and Safari.
TF237v1	Interactive Markers	Sensors and vehicle-reported issues shall be displayed as interactive markers.
TF238v1	Detailed Marker Info Access	Users shall be able to click on markers to see detailed information.
TNF239v1	Multi-Source Data Integration	The system shall integrate data from different data sources
TF240v1	Binary Issue Labeling System	A binary (True/False) input method shall be used for validation.
TNF241v1	Issue Confidence Score	A confidence score shall be calculated for each issue based on user input.
TNF242v1	Integrate Parking Space Information	The system shall incorporate parking space information (rules)
TF243v1	Scalability for Concurrent Users	The system shall support thousands of simultaneous users.
UF244v1	Simulation Execution in Digital Twin	Users shall be able to run simulations in the digital twin of the city.
UNF245v1	Real-Time Simulation Visualization	The digital twin shall provide a real-time visualization of changes applied by the user.
UF246v1	Interactive Simulation Controls	Users shall be able to interact with the simulation using mouse and keyboard.
UF247v1	Vehicle Density Adjustment	Users shall be able to adjust the number of cars in different areas of the city.
UNF248v1	Traffic Flow Simulation	The system shall simulate traffic flow changes based on user inputs.
UF249v1	Traffic Light Configuration	Users shall be able to change traffic light settings at roundabouts.
UNF250v1	Real-Time Congestion Feedback	The impact of changes shall be visualized in real-time (e.g., congestion increase/decrease).
UF251v1	Lighting Control Interface	Users shall be able to control city-wide lighting

Code	Title	Description
UF253v1	Scenario Comparison Feature	Users shall be able to compare different simulation scenarios.
TNF256v1	Cross-Platform Compatibility	The desktop application shall be compatible with Windows and macOS.
TF258v1	Multi-Threading Capability	The platform shall support multi-threading for handling real-time calculations.
TNF259v1	Physics-Based Traffic Simulation	The system shall support real-time physics-based traffic simulation.
TF260v1	Dynamic Traffic AI	A traffic AI system shall be used to simulate vehicle behavior dynamically.
TNF261v1	Scenario Flexibility	The system shall allow predefined and custom traffic scenarios.
TNF262v1	Traffic Light Control	Traffic lights shall be adjustable in real-time, affecting road congestion.
TNF263v1	Dynamic Road Network Update	The system should suggest road network optimization based on car flow changes.
TNF264v1	Vehicle Pathfinding System	The simulation shall use realistic vehicle AI for pathfinding.
TF265v1	Centralized Lighting Panel	City lighting shall be controlled using a centralized UI panel.
TF268v1	Traffic Flow Visualization Tools	The system shall include charts and heatmaps to visualize traffic flow.
TNF269v1	Exportable Simulation Reports	Users shall be able to export simulation results for further analysis.
TNF271v1	Support for Large Simulations	The system shall support large-scale simulations of hundredsof vehicles.
TNF273v1	Minimum Frame Rate	Simulations shall run at a minimum of 30 FPS for smooth performance.
TNF274v1	Local Simulation Settings Storage	User simulation settings shall be stored locally and retrievable.
TNF275v1	Simulation Log Management	Simulation logs shall be saved for historical analysis.
TNF276v1	Data Integrity Assurance	The system shall ensure data integrity and prevent unauthorized changes.
UNF277v1	Meta Quest 3 Compatibility	The system shall be fully compatible with Meta Quest 3.
UF278v1	Immersive City Exploration	Users shall be able to explore digital twin cities of Etteln and Villanova in an immersive VR environment.
UNF279v1	VR Controller Support	The experience shall support VR controllers for interactions.
UF280v1	Teleportation Movement	Users shall be able to move using teleportation mechanics.
UF281v1	Virtual Camera	Users shall be able to take photos using a virtual camera.

Code	Title	Description
UF282v1	Weather Change Functinality	Users shall be able to change weather conditions
UNF283v1	In-Game Map Access	Users shall have access to an in-game map for navigation.
UF284v1	Object Interaction	Users shall be able to interact with objects such as doors, signs, or information panels.
UF285v1	Time of Day Control	Users shall be able to change the time of day (Morning, Afternoon, Evening, Night).
UNF286v1	Dynamic Environment Update	The environment shall dynamically update based on selected conditions (weather, time).
UF288v1	Teleportation and Smooth Movement	Users shall be able to move using teleportation or smooth movement.
UNF289v1	Tutorial Availability	The system shall include a tutorial explaining movement and interactions.
UNF290v1	Minimal UI Design	The UI shall be designed for ease of use, with minimal menus for immersion.
TNF294v1	72 FPS Minimum	The VR experience shall run at a minimum of 72 FPS for smooth performance.
TNF295v1	LOD Optimization	The system shall use Level of Detail (LOD) optimization to improve rendering performance.
TNF296v1	Occlusion Culling	Dynamic occlusion culling shall be implemented to improve frame rates.
TNF297v1	Motion Sickness Prevention	The experience shall be optimized to minimize motion sickness.
TNF298v1	High-Fidelity Digital Twins	The cities of Etteln and Villanova shall be developed as high-fidelity digital twins.
TNF299v1	Optimized 3D Models	3D models of buildings, streets, and landmarks shall be optimized for VR rendering.
TNF301v1	Real-Time Weather Effects	Weather effects shall be created using real-time shaders and particle systems.
TF304v1	Physics-Based Object Interaction	The system shall support real-time physics interactions for interactive objects.
TNF305v1	VR-Native UI	The user interface shall be built using Unity UI (Canvas) or a VR-native UI system.
TNF309v1	Local Photo Storage	Captured photos shall be saved locally on the Meta Quest 3 storage.
TF312v1	Seated and Standing Play	The system shall support both seated and standing play modes.
TNF314v1	Custom Movement Settings	Adjustable movement speeds and snap-turning options shall be available.
TNF315v1	Mobile Compatibility	The system shall be compatible with Android smartphones.
UF316v1	AR City Exploration	Users shall be able to experience AR-based tourism in one of the two digital twin cities: Etteln or Villanova.
UF317v1	Real-Time AR Interaction	The experience shall provide real-time interaction with AR elements.

Code	Title	Description
UF318v1	Monument Recognition	Users shall be able to scan/frame a monument using their smartphone camera to receive historical or cultural information.
UNF319v1	Information Overlay	The system shall display information as an overlay in AR (text, images, or video).
UNF320v1	Interactive AR UI	Users shall tap on AR elements for more detailed content.
UF321v1	AR Portals	Users shall be able to open a virtual portal in front of specific buildings to see their interiors in AR.
UNF322v1	360-Degree Interior View	The portal shall display a 360-degree view of the inside of the building.
UF323v1	Virtual Portal Exploration	Users shall be able to walk through the portal to explore the building virtually.
UF324v1	POI Selection	Users shall be able to select an area of interest on the map.
UNF325v1	AR Compass Guidance	The system shall display an AR compass (floating pointer) to guide users toward their selected location.
UNF326v1	Dynamic Compass Updates	The AR compass shall update dynamically based on user movement.
UNF327v1	Lighting-Adaptive Elements	AR content shall remain visible under different lighting conditions
UNF329v1	Minimal Interaction UI	The UI shall be designed for ease of use with minimal interaction needed while walking.
TNF330v1	ARKit & ARCore Support	The system shall use ARCore (Android) for AR functionality.
TNF332v1	Monument Tracking	Monuments shall be recognized using image tracking and GPS positioning.
TNF333v1	Multimedia Overlays	Information overlays shall support text, 3D models, and video pop-ups.
TNF334v1	Monument Data Storage	The system shall include a database of monuments with relevant historical and cultural data.
TNF335v1	360¬∞ Portals & 3D Models	The AR portal shall use 360-degree images or 3D models of building interiors.
TNF336v1	Accurate AR Anchoring	The portal system shall anchor accurately to real-world locations using GPS and AR tracking.
TF337v1	Interior Navigation	The system shall support basic movement inside the virtual portal (e.g., rotation, zooming, or stepping forward).
TNF338v1	GPS & Device Sensor Use:	The system shall use GPS and device sensors for positioning, tracking, and orientation.
TNF339v1	Persistent AR Compass	The AR compass shall be persistent and dynamically update as the user moves.
TNF340v1	Non-Obstructive Compass	The pointer shall be visually distinct and easy to follow without obstructing real-world vision.
TNF341v1	Minimum Frame Rate:	The AR experience shall run at a minimum of 30 FPS to ensure smooth interaction.

Code	Title	Description
TNF342v1	Battery Optimization	The system shall optimize battery usage to avoid excessive drain during extended use.
TNF343v1	Indoor/Outdoor Support	The app shall function in both outdoor and indoor environments with proper lighting adjustments.
TNF344v1	Local Monument Data	Monument data shall be stored locally with periodic online updates.
TNF345v1	Offline AR Functionality	The system shall function offline for basic AR experiences (e.g., monument recognition).
TNF346v1	Online Update Features	Online features (e.g., new content updates) shall require an internet connection.
UF347v1	Scan Environment	User can initiate scan of the industrial environment using AR wearable device.
UF350v1	Edit Mismatched Area	User can rescan or manually correct mismatched parts of the environment.
UF351v1	Add POIs	User can add new points of interest (e.g., charging stations, loading docks) to the digital twin.
UF352v1	Delete POIs	User can delete outdated or incorrect POIs from the digital twin.
UF353v1	Edit POIs	User can edit existing POIs including name, location, or type.
UF354v1	Add 3D Assets	User can add new 3D industrial assets to the virtual environment.
UF355v1	Delete 3D Assets	User can remove outdated or incorrect 3D assets from the virtual environment.
UF356v1	Edit 3D Assets	User can modify existing 3D assets in the digital twin.
TNF363v1	Security Compliance	System must comply with industrial data security standards.
TNF364v1	Hololens 2 Compatibility	System must be fully compatible and tested with Microsoft Hololens 2.
TNF365v1	iPad Pro Compatibility	System must be fully compatible and tested with Apple iPad Pro (latest generation).
UF366v1	Hand-based Interaction (Hololens 2)	Users shall interact with the system through hand gestures when using Microsoft Hololens 2.
UF367v1	Touch-based Interaction (iPad Pro)	Users shall interact with the system through touch gestures on the screen when using Apple iPad Pro.
UF368v1	Environment Scanning via Device Camera	Users shall scan the environment using the built-in camera(s) of the device in use (Hololens 2 or iPad Pro).
TF369v1	Integrate 3DGS Viewer	The system shall integrate a 3DGS viewer for enhanced spatial visualization.
UF370v1	Visualization of Result Images	The system shall allow users to view result images linked to detected issues.
UF371v1	Issues Representation	Issues shall be represented with icons or images in the digital twin.
UF372v1	Configurable Representation	The system shall allow toggling between image and icon-based representations.

Code	Title	Description
TF373v1	Trash Detection Engine	The system shall use visual or sensor data to detect litter or trash accumulation in the environment.
TF374v1	Sidewalk Condition Detection	The system shall report damage or obstructions on sidewalks.
TF375v1	Street Marking Detection	The system shall detect different street markings (e.g., zebra-crossings).
TF376v1	Street Marking Quality	The system shall evaluate the confidence for the different street markings detected
UF377v1	Update Status of Issues	The system shall allow issue status to be updated (e.g., resolved, in-progress).
UF378v1	Geolocation for Maintenance (U)	Users shall be able to view and use GPS-based issues locations in the interface for efficient navigation.
UF379v1	Trash Detection Display	Detected trash areas shall be displayed on the interface for user awareness or validation.

Table 4. List of all requirements.

6 User Journey and User Flow

In the first iteration of the deliverables, we introduced the process of defining user journeys and user flows as a critical step in bridging the gap between high-level use case definitions and the concrete actions required for validation. These elements helped clarify user interactions, decision points, and system behaviors across the six core use cases of the project, including virtual tourism, digital twin creation, city planning and maintenance, and industrial applications.

As part of the ongoing refinement process, updated versions of both the user journeys and user flows have been developed. These updates reflect the latest developments in the definition of the use cases, incorporating feedback from stakeholder workshops and evolving technical requirements.

The need for updated versions emerged from the iterative nature of the project, where ongoing stakeholder engagement, system prototyping, and initial validation efforts revealed the need to adjust certain assumptions about user actions, system behavior, and decision paths. In particular, the maturing of the technical architecture and UI concepts necessitated changes to the flows to ensure they accurately represent real-world interactions and are aligned with the envisioned system functionalities.

The revised versions will be presented in the final deliverable (D5.2), alongside the finalized use case descriptions, to serve as a complete foundation for implementation and evaluation.

7 Validation Methods

The outlined validation plans serve as a framework for conducting the final validation phase of the project. They build upon the methodology and preliminary results documented in the intermediate evaluation, which are detailed in Deliverable D5.1. In addition, the project's approach to evaluation methodologies has been disseminated through a peer-reviewed short paper, presented at the AIxVR 2025 conference held in Lisbon, Portugal.

7.1 Objectives

Similar to the first validation, the primary objective of the final validation is to evaluate the usability of the developed applications. Each use case will be tested with real target users, following a dedicated validation plan tailored to its specific context. A range of user experience metrics, such as emotional response and task load, will be assessed using both standardized (e.g., UEQ-S, NASA-TLX) and custom-designed questionnaires. Additionally, user behavior and the interaction with the applications will be observed to gain deeper insights. For selected use cases that qualify for comparative analysis (e.g., evaluating different user devices), controlled studies will be conducted.

7.2 Organization

Validation Plans

The validation plans for the final evaluation are built upon those developed for the first validation and were collaboratively designed by TUB and HSHL. Based on initial drafts, individual meetings were conducted for each use case to refine and tailor the plans in close coordination with project partners. These discussions involved both the partners responsible for participant recruitment and execution, as well as the technical partners associated with each specific use case, ensuring alignment across all operational and technical aspects of the validation process.

Recruitment

The primary responsibility for participant recruitment lies with the FIWARE Foundation, VNG Neàpolis (Vilanova), and IW (Idealworks). The target groups include local residents from the city of Etteln, members of the VNG colleagues network, and colleagues from IW. To ensure a sufficient number of participants for meaningful validation, TUB will additionally support the process by conducting one of the user validation sessions with individuals recruited through the university's participant portal. Further recruitment efforts are planned to involve students from partners universities

such as UPAT or AUB, colleagues from the technical partners' organizations, and members of the project's stakeholder board. These combined approaches aim to ensure a diverse and representative user base for the final validation phase.

Execution

The user evaluation is planned to be carried out by FIWARE, VNG, IW, and TUB. If the desired sample sizes cannot be achieved through the current recruitment strategy, the involvement of additional partners will be considered to support participant acquisition. As several use cases are not dependent on a specific physical location, user testing can be conducted remotely, allowing for greater flexibility and broader participation.

7.3 Methodology

Data collection

The data collected during the user evaluations consists primarily of subjective self-reports provided by participants. Each use case employs a tailored set of standardized questionnaires, complemented by custom-designed questions to address specific aspects of the user experience. This combination enables a comprehensive and nuanced understanding of users' perceptions and interactions. In addition to questionnaire-based feedback, the partners responsible for conducting the evaluations are tasked with observing participant behaviour and engaging in informal conversations during the sessions. These interactions help gather valuable first-hand insights and contextual feedback that may not be captured through written responses alone.

Questionnaires

The following questionnaires will be used for the validations:

Demographics: The demographic questionnaire collects general information, including age, gender, profession, country of residence and prior experience with XR technologies. Additionally, users will be asked if they participated already in the first validation phase.

ATI: The Affinity for Technology Interaction (ATI) scale offers valuable insights into how interested and experienced individuals are in interacting with technology and technical systems. It assesses users’ comfort levels, preferences, and familiarity with technology-related tasks. The tool consists of a 9-item questionnaire, with each item rated on a 7-point Likert scale. These responses are used to calculate an overall ATI score, which reflects the individual’s general tendency to engage with and embrace technological systems.

NASA-TLX: The NASA Task Load Index (NASA-TLX) is a widely recognized, subjective, and multidimensional assessment tool developed to measure perceived workload during task performance. It evaluates six key dimensions that together provide a comprehensive picture of cognitive and physical demands. Mental demand refers to the amount of mental and perceptual activity required, such as thinking, deciding, or calculating. Physical demand assesses the level of physical effort needed to complete the task. Temporal demand captures the time pressure experienced while performing the task. Performance reflects the individual's self-assessment of how successfully they accomplished the task, while effort measures the amount of work exerted to reach that level of performance. Lastly, frustration level encompasses feelings of stress, irritation, or annoyance encountered during the task. Participants rate each dimension, and the results are combined to create an overall workload score.

UEQ-S: The UEQ-S is a short version of the original User Experience Questionnaire, designed for situations where a quick yet reliable assessment of user experience is required. It measures two key dimensions of user experience. The first, Pragmatic Quality, relates to usability factors such as efficiency, clarity, and dependability, focusing on how effectively users can achieve their goals. The second, Hedonic Quality, captures the product's ability to engage and stimulate users, reflecting emotional responses such as excitement, creativity, and innovation. The UEQ-S consists of 8 items, each presented as a pair of contrasting adjectives—for example, "complicated" versus "easy." Participants indicate their impression by rating each pair on a 7-point scale, providing a balanced overview of both functional and emotional aspects of the user experience.

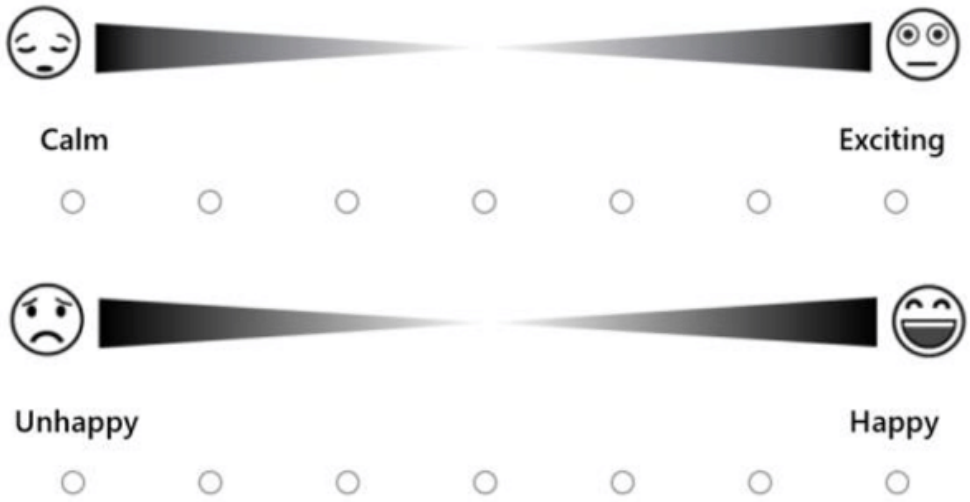

Figure 1: Affective Slider as a 7-point scale.

Affective Slider: The Affective Slider is a self-assessment tool designed to measure emotional responses along two key dimensions: valence and arousal. Valence reflects the degree of pleasantness or unpleasantness experienced, while arousal indicates the level of emotional intensity or activation. Participants rate their current emotional state using a 7-point Likert scale for each dimension, providing a structured yet intuitive way to capture affective responses (see Figure 1). This format makes the tool suitable for both quick assessments and integration into larger studies.

CSQ-VR: The Cybersickness in Virtual Reality Questionnaire (CSQ-VR) is a brief and targeted tool designed to assess symptoms of cybersickness experienced during virtual reality exposure. It evaluates three main categories of symptoms: nausea, oculomotor discomfort, and vestibular disturbances. Nausea includes sensations such as stomach discomfort and the urge to vomit, while oculomotor symptoms involve issues like eye strain, blurred vision, and headaches. Vestibular symptoms reflect feelings of dizziness and confusion. Each category is assessed using two questions, with participants rating their symptoms on a 7-point Likert scale ranging from “1 – absent feeling” to “7 – extreme feeling.” The CSQ-VR yields a total score along with sub-scores for each symptom category, providing a comprehensive overview of the severity and nature of cybersickness.

IPQ: The Igroup Presence Questionnaire (IPQ) is a well-established tool used to measure a user’s sense of presence within a virtual environment. It focuses on a general presence assessment and three additional dimensions: spatial presence, involvement, and experienced realism. Spatial presence refers to the sensation of physically being in the virtual space, while involvement captures the level of attention, focus, and emotional engagement a user maintains during the experience. Experienced realism reflects how authentic and lifelike the virtual environment appears to the user. Participants rate their experience using a 7-point Likert scale, with higher scores indicating a stronger sense of presence.

Digital Twin Questionnaire: The Digital Twin Questionnaire is a custom-developed selection of questions designed to assess user perceptions of digital twin systems. It focuses on key characteristics such as the perceived dynamicity and factual representation of the replicated system, as well as the fidelity of its visual appearance and overall usefulness of using a DT. Participants are asked to rate a series of statements using a 7-point Likert scale. This targeted approach aims to provide insights into how users interpret and interact with the digital twins across the different use cases and applications.

Custom Questionnaire: Each user study concluded with a final questionnaire regarding specific aspects of the applications. Participants will be asked to rate their overall satisfaction and the ease of use and usefulness of the implemented features as well as personal impression concerning privacy. Lastly, participants will be asked for additional open-end feedback and comments.

Test locations

The locations for conducting the user tests vary across use cases. Some applications are location-independent and can therefore be tested in controlled laboratory settings at the facilities of all participating institutions. To increase participant numbers during the initial validation phase, remote testing sessions were conducted with stakeholders who were not required to travel. Instead, they participated in moderated online sessions from their homes or offices. This remote approach remains a viable option for the final validation phase as well.

However, two specific use cases require testing exclusively in their intended target environments. These use cases demand live, in-the-field evaluations involving on-site participants. In such scenarios, potential disturbances, such as the influence of bystanders or environmental distractions, cannot be entirely avoided and are acknowledged as part of the real-world testing context.

Procedure

While each use case has specific requirements, the general procedure for user validation follows a consistent structure. It begins with welcoming participants at the test location, followed by an introduction to the project and the respective use case. Participants are then informed about the pseudonymized storage of their data, their right to withdraw from the study at any time without consequence, and are asked to sign a consent form if they agree to the terms. Next, participants complete a demographics questionnaire and the ATI (Affinity to Technology Interaction) questionnaire. They are then guided to interact with the applications. For Virtual Reality use cases, a brief introduction to the head-mounted display (HMD) is provided beforehand, and the correct setup of the device is ensured. Participants are given a series of tasks to complete within the applications. Upon completion, they fill out both standardized and custom questionnaires to capture their user experience. For validations designed as comparative studies, this procedure includes a second cycle of testing and questionnaire completion to facilitate comparison between conditions.

Scientific Standards

The executing partners are requested to adhere to the following scientific standards whenever feasible: Participants should be tested individually and isolated from others to prevent group influence on behaviour. To ensure comparability of results, all participants testing a specific application within a use case should be evaluated in the same location. Additionally, users should be exposed to the application for a similar duration. While the testing phase concludes upon task completion, it is important to ensure that no participant exceeds a maximum duration of X seconds.

Ethical Guidelines

When conducting XR user studies, it is essential to ensure participants are treated with care and respect, starting with a clear and accessible informed consent form outlining the study's purpose, potential risks, data use, and the right to withdraw at any time. Participants must be allowed to exit the study without penalty, and any collected data should be securely stored, pseudonymized, and handled according to privacy regulations. The XR setup must be physically safe and hygienic, with correctly adjusted headsets and monitored usage to prevent discomfort or injury. Researchers should minimize risks like motion sickness and provide thorough debriefing afterward. Special attention must be given to vulnerable populations, and all procedures should promote transparency, safety, and participant well-being.

7.4 Use Case specific Validation Plans

Digital Twin Creation

The study design will follow an exploratory usability testing approach. The experiments will be moderated and can be conducted remotely, with a preference for a controlled laboratory environment. Two distinct applications in the context of the digital twin creation use case will be tested in a pseudo workflow. Both applications feature a version for Etteln and one for Vilanova. Ideally, tech-prone participants will be recruited and asked to complete specific tasks within each application and subsequently answer subjective questionnaires for data collection. The evaluation will involve descriptive statistics and correlation analysis to interpret the collected data.

Applications

- Digital Twin Creation App from DTT (Features both Etteln and Vilanova)
- Point Cloud Editing Tool from CAP (Features both Etteln and Vilanova)

Locations

- Any remote location (laboratory environment)

Technical setup

- PC or powerful laptop
- Chrome browser
- Credentials for DTT app

Questionnaires

- Demographics
- ATI
- UEQ-S
- NASA-TLX
- Affective Slider
- Digital Twin Questionnaire
- Custom Questionnaire

Participants

- Tech-prone users (tech students, stakeholders, co-workers)

Tasks

- Load point-cloud
- Merge two point-clouds
- Label the point cloud
- Create mesh from point cloud

Test Procedure

1. Introduction
2. Demographic, ATI
3. CAP application
4. UEQ-S, NASA-TLX, Affective Slider, Custom Questionnaire
5. DTT application
6. UEQ-S, NASA-TLX, Affective Slider, Custom Questionnaire

Organization

- Recruiting and execution by VNG, FIWARE
- Data analysis by TUB, HSHL

City Planning

The study design will follow an exploratory usability testing approach. The experiments will be moderated and can be conducted remotely, with a preference for a controlled laboratory environment. One application will be tested that features both a version for the DT of Vilanova and Etteln each. Ideally, participants from a city related field will be recruited and asked to complete specific tasks within the application and subsequently answer subjective questionnaires for data collection. The evaluation will involve descriptive statistics and correlation analysis to interpret the collected data. If feasible it is recommended to test this use case in a subsequent session with the city maintenance use case.

Applications

- City Planning app from DTT (Features both Etteln and Vilanova)

Locations

- Any remote location (Laboratory environment)

Technical setup

- PC or laptop

Questionnaires

- Demographics
- ATI
- UEQ-S
- NASA-TLX
- Affective Slider
- Digital Twin Questionnaire
- Custom Questionnaire

Participants

- Users from the field of city management/planning
- Participants from other cities (sister projects, stakeholders, FIWARE cities, city students)
- Vilanova diverse sample group (city council, tourism, economic promotion, gastronomy, museum, university, i2cat employees)

Tasks

- Change environment parameters
- Traffic planning, traffic jam simulation

- Export statistics to file

Test Procedure

1. Introduction
2. Demographic, ATI
3. Test application
4. UEQ-S, NASA-TLX, Affective Slider, Custom Questionnaire

Organization

- Recruiting and execution by VNG, FIWARE
- Data analysis by TUB, HSHL

City Maintenance

The study design will follow an exploratory usability testing approach. The experiments will be moderated and can be conducted remotely, with a preference for a controlled laboratory environment. One application will be tested for the city of Vilanova. Ideally, participants from a city related field will be recruited and asked to complete specific tasks within the application and subsequently answer subjective questionnaires for data collection. The evaluation will involve descriptive statistics and correlation analysis to interpret the collected data. If feasible it is recommended to test this use case in a subsequent session with the city planning use case.

Applications

- City Maintenance app (Vilanova)

Locations

- Any remote location (Laboratory environment)

Technical setup

- PC or laptop

Questionnaires

- Demographics
- ATI
- UEQ-S
- NASA-TLX
- Affective Slider
- Digital Twin Questionnaire
- Custom Questionnaire

Participants

- Users from the field of city management/planning
- Participants from other cities (sister projects, stakeholders, FIWARE cities, city students)
- Vilanova diverse sample group (city council, tourism, economic promotion, gastronomy, museum, university, i2cat employees)

Tasks

- Localize issue on the map
- Review source image
- Set state + description
- Update issue

Test Procedure

1. Introduction
2. Demographic, ATI
3. Test application
4. UEQ-S, NASA-TLX, Affective Slider, Custom Questionnaire

Organization

- Recruiting and execution by VNG, FIWARE
- Data analysis by TUB, HSHL

Virtual Reality Virtual Tour

The study design will follow an exploratory usability testing approach. The experiment will be moderated and conducted remotely in a controlled laboratory. Two applications will be tested, one for Vilanova and one for Etteln. Participants will be asked to complete specific tasks within the application and subsequently answer subjective questionnaires for data collection. The evaluation will involve descriptive statistics and correlation analysis to interpret the collected data.

Applications

- Etteln VR application
- Vilanova VR application

Locations

- Remote Laboratory at TUB

Technical setup

- Meta Quest 3 and powerful PC

Questionnaires

- Demographics
- ATI
- UEQ-S
- IPQ
- CSQ-VR
- Affective Slider
- Digital Twin Questionnaire
- Custom Questionnaire

Participants

- No specific requirements for population
- Recruited through TUB test subject portal

Tasks

- Start on the 3D map view
- Enter to street level view
- Visit all POIs, access additional information
- Environment Changes, Snapshot feature

Test Procedure

1. Introduction
2. Demographic, ATI
3. Test application
4. UEQ-S, IPQ, CSQ-VR, Affective Slider, Custom Questionnaire

Organization

- Recruiting and execution by TUB
- Data analysis by TUB, HSHL

Augmented Reality Virtual Tour

The study design will follow a comparative testing approach with two conditions. The experiment will be moderated and conducted in the field in Etteln and Vilanova. Two versions of the application will be tested in the respective city, one on smartphone and one on the a HMD. Participants will be asked to complete specific tasks within the applications and answer subjective questionnaires after each condition. The evaluation will involve descriptive statistics, comparative analysis and correlation analysis to interpret the collected data.

Applications

- Etteln AR application for smartphone
- Etteln AR application for HMD
- Vilanova AR application for smartphone
- Vilanova AR application for HMD

Locations

- In the field Etteln (Zwetschgenfest)
- In the field Vilanova (Museu Víctor Balaguer)

Technical setup

- Smartphone
- Meta Quest 3 (Etteln)
- Meta Quest 2 or Quest Pro or Pico Neo 2 (Vilanova)

Questionnaires

- Demographics
- ATI
- UEQ-S
- IPQ (Realism)
- CSQ-VR (For HMD)
- Affective Slider
- Digital Twin Questionnaire
- Custom Questionnaire

Participants

- No specific requirements for population
- Recruited ad-hoc on the Zwetschgenfest (Etteln)
- Vilanova diverse sample group (city council, tourism, economic promotion, gastronomy, museum, university, i2cat employees)

Tasks

- Navigate to the POI/portal in the physical world using the map and compass feature
- Step inside the portal by walking in physical world
- Find a piece of information (e.g., Windmill display in Etteln, Painting in Vilanova)

Test Procedure

1. Introduction

2. Demographic, ATI
3. Test condition 1
4. UEQ-S, IPQ, CSQ-VR, Affective Slider, Custom Questionnaire
5. Test condition 2
6. UEQ-S, IPQ, CSQ-VR, Affective Slider, Custom Questionnaire

Organization

- Recruiting and execution by FIWARE, VNG
- Data analysis by TUB, HSHL

Industry DT Maintenance

The study uses a within-subjects design to compare three apps for viewing and editing warehouse point clouds on HoloLens, iPad, and laptop. Participants perform editing tasks. On the HoloLens and iPad, the point cloud appears as an AR overlay aligned to the real scene while the laptop shows the point cloud in a desktop viewer without real scene. Edited models are saved and compared to a laser scan as ground truth to measure geometric accuracy. After each session participants complete a demographics questionnaire and a NASA-TLX for each platform.

Applications

- AR application for HoloLens
- AR application for iPad
- 3D editing application for Laptop

Locations

- At the research center of IDEALworks

Technical setup

- HoloLens
- iPad
- Laptop
- Laser scan of the testing environment

Questionnaires

- Demographics and experience
    - Age
    - Gender
    - Previous experience with HoloLens/XR

    - Previous experience with mobile AR (iPad)
    - Previous experience with 3D editing software (Laptop)
- NASA-TLX for the HoloLens
- NASA-TLX for the iPad
- NASA-TLX for the laptop

Participants

- No specific requirements for population
- Recruited randomly from IDEALworks staff members

Tasks

- Participants will have to identify and correct discrepancies between the visualized pointclouds and the real environment using the three platforms

Test Procedure

1. Introduce the participants to the experiment.
2. Fill the demographic questionnaire from the survey.
3. Prepare the testing area (Laser scan, QR placement and devices setup)
4. Using each platform, participants should apply necessary edits on the pointcloud based on what they can identify.
5. For the laptop phase, users will be allowed to measure the discrepancies from the real environment, since no overlay is provided using that platform.
6. A NASA-TLX survey will be filled after completing each platform.

Organization

- Recruiting and execution by IDEALworks and AUB
- Data analysis by AUB

8 Conclusion

This deliverable focuses on the refined versions of the requirements and the validation plans for the final validation phase of the DIDYMOS-XR project. These elements are central to the project's user-centred development approach and have been iteratively improved based on feedback gathered through stakeholder engagement, internal reviews, and early technical implementation.

The validation plans have been revised after the results from the first validation phase as outlined in deliverable D5.1 to better assess data and improve insights on user experience. The user personas remain unchanged but continue to serve as a stable reference point, ensuring alignment between system functionalities and user needs. The requirements—both functional and non-functional—have been updated in line with the evolving technical understanding and improved use case definitions.

With these elements in place, the project's focus now transitions toward execution of the validation. Preliminary validation strategies have been outlined in this document, and ongoing discussions with consortium partners are guiding the development of comprehensive validation methods. These will inform the testing activities in Work Package 5 (WP5), where the actual performance and user experience of the XR applications will be evaluated.

This document does not stand as a static reference but as part of a living, evolving process. The final specification of use cases, updated user flows, and complete validation methodologies will be consolidated and reported in Deliverable D5.2, which will serve as the definitive reference point for the project's implementation and evaluation strategy.

9 Annex - Persona Visualisations

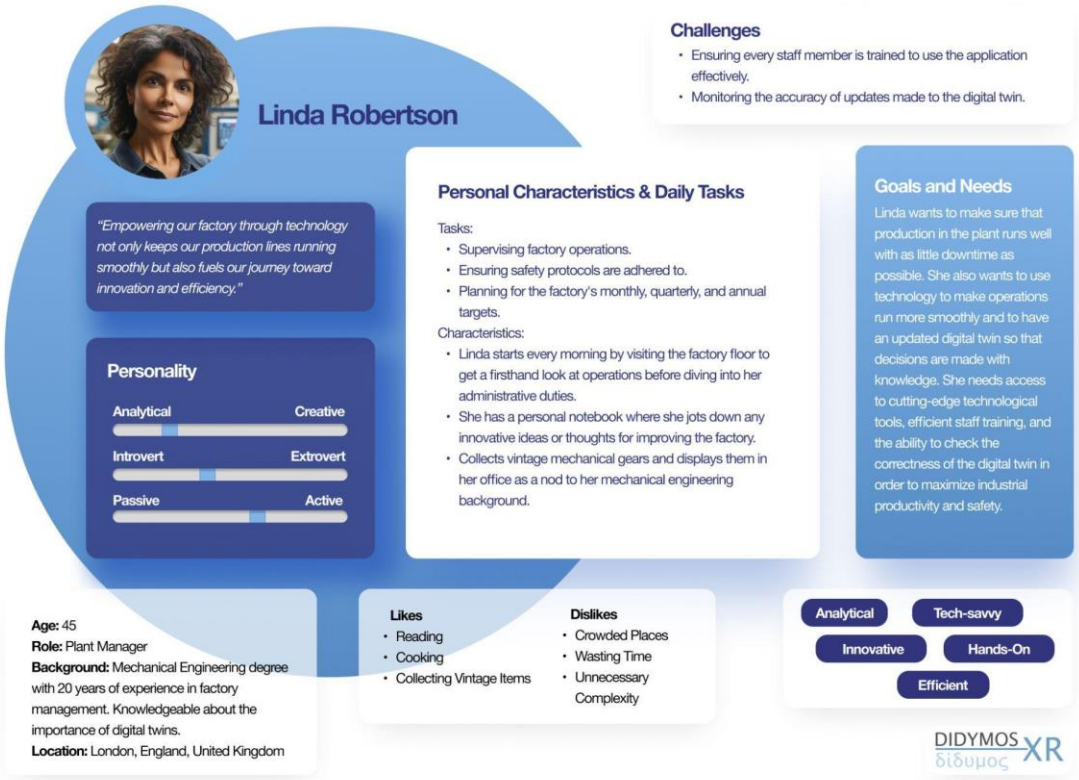

Figure 2. User Persona - Linda Robertson

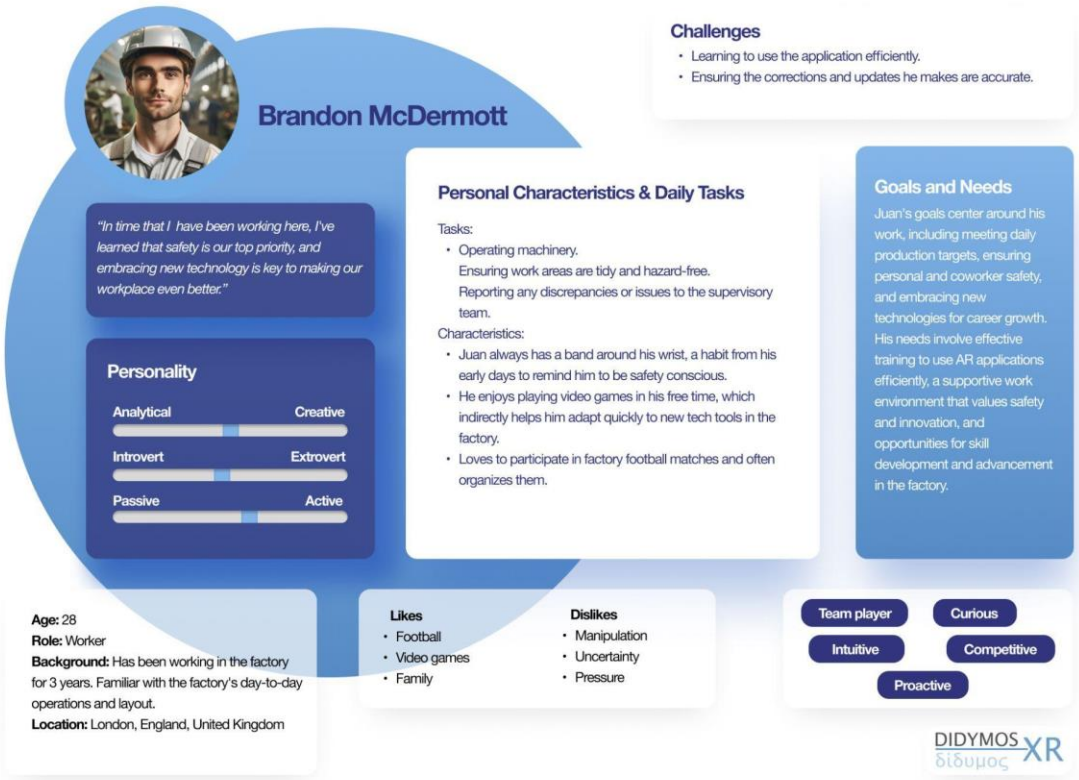

Figure 3. User Persona - Brandon McDermott

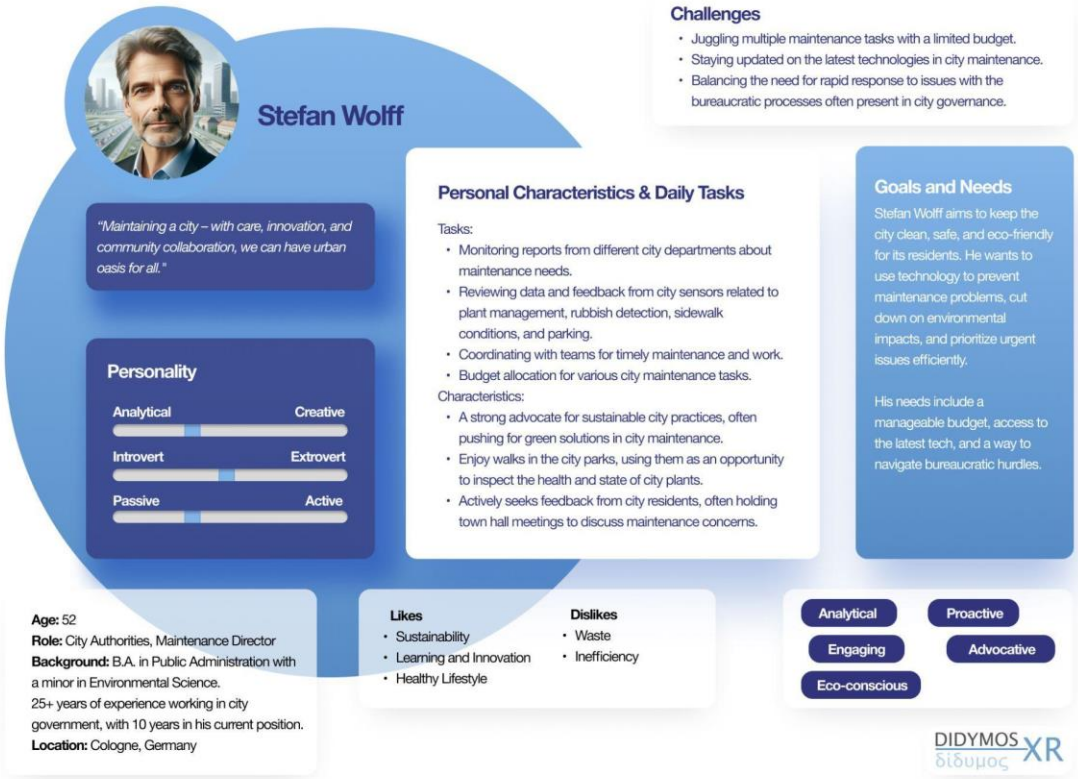

Figure 1. User Persona - Stefan Wolff

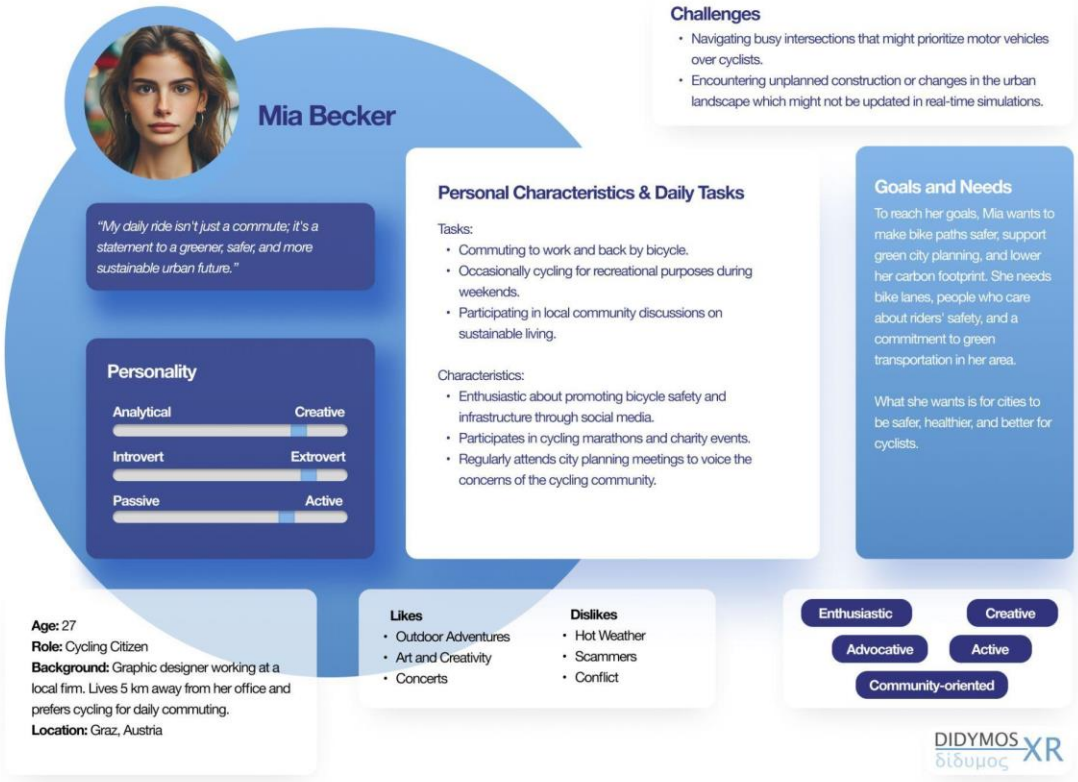

Figure 2. User Persona - Mia Becker

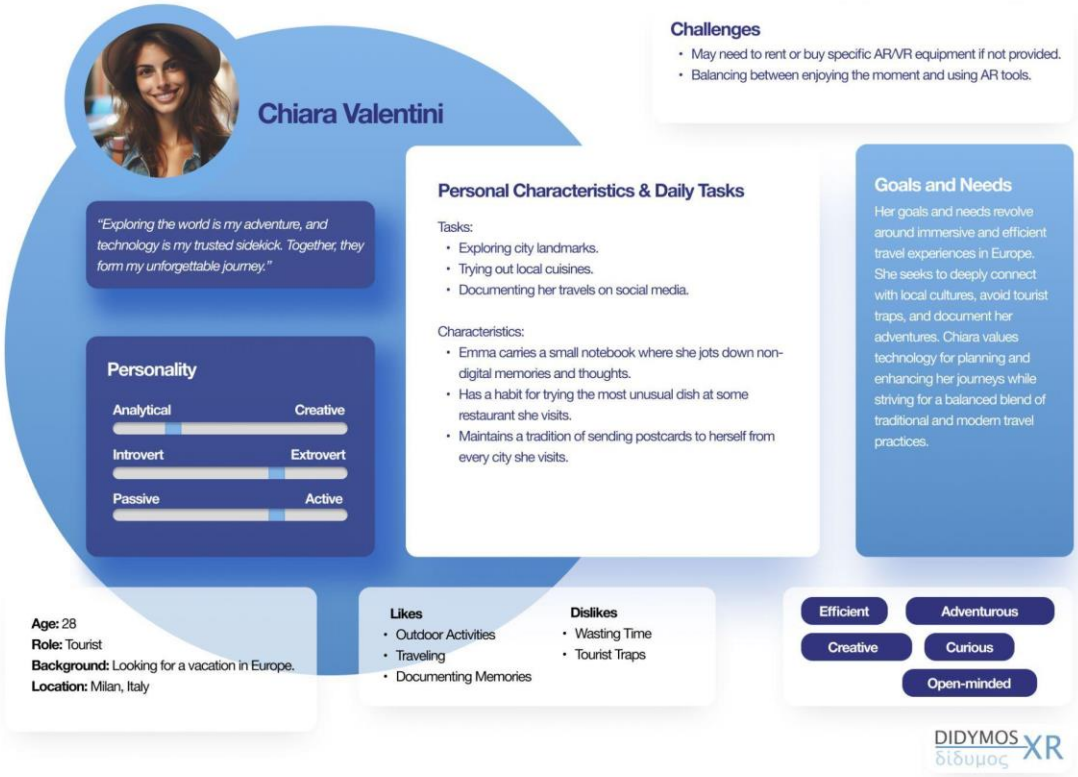

Figure 3. User Persona - Chiara Valentini

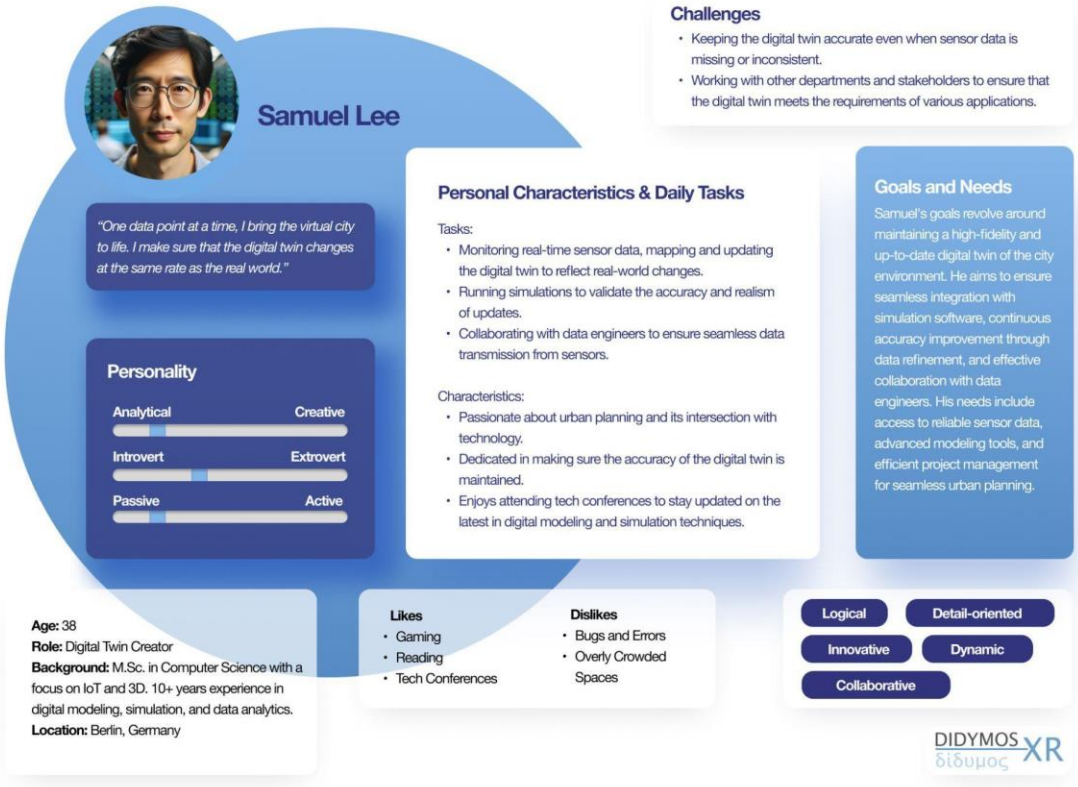

Figure 7. User Persona - Samuel Lee

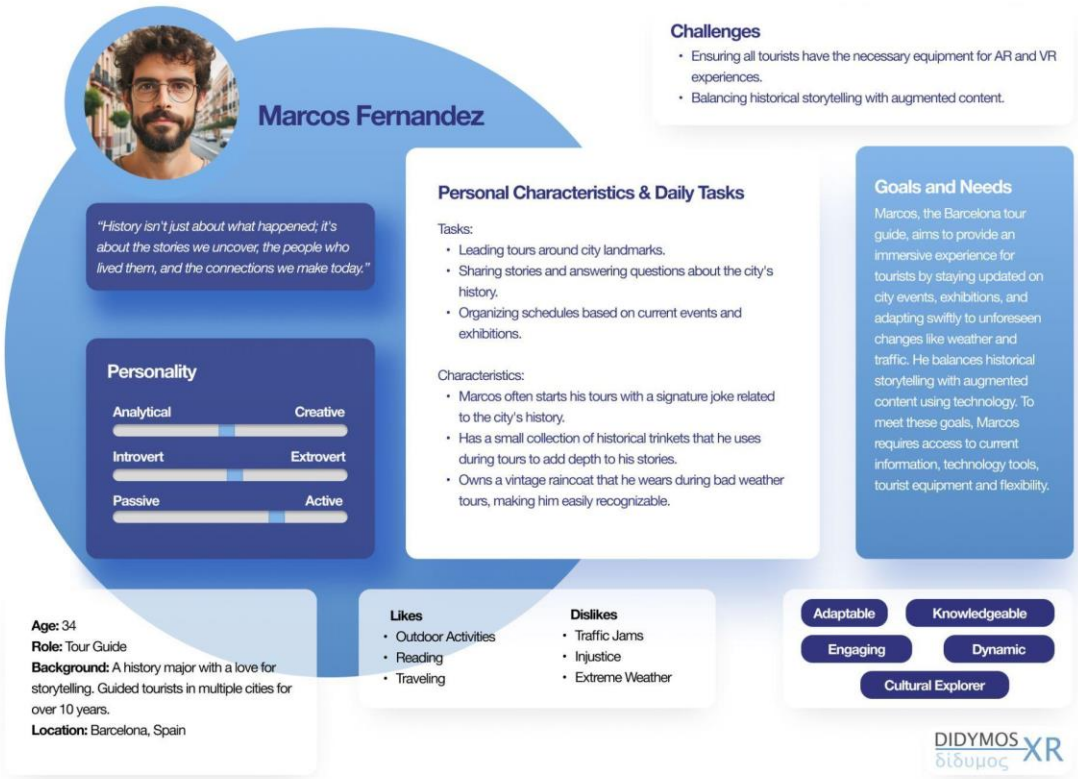

Figure 4. User Persona - Marcos Fernandez

10 Annex – Interview Questionnaires

Applications for citizen involvement in urban planning, tourism, and smart mobility in cities/villages, and collaboration with autonomous mobile robots in industrial production environment.

Tourism	
Historical and cultural heritage	Provide a rich and interactive learning experience for tourists by giving historical and cultural information about a location. This can include information on the architecture, art, and local customs of a destination.
Personalized Experience	Create personalized experiences for tourists based on their preferences and interests. For example, a digital twin of a city could suggest personalized itineraries for visitors based on their interests, making their trip more enjoyable and memorable.
Virtual Tours	Provide virtual tours of tourist destinations, allowing potential visitors to experience the location before they arrive. This can help travelers make more informed decisions about their travel plans and increase interest in less well-known destinations.
Sustainable Tourism	Promote sustainable tourism practices by providing information on eco-friendly activities and highlighting the impact of tourism on the local environment. This can help visitors make more responsible choices and reduce their carbon footprint.
Improved Navigation	Provide accurate navigation for tourists within a destination. This can include real-time updates on traffic, public transportation schedules, and other relevant information that can help visitors better navigate the area.

Choose among two of the following use case related to tourism

- ☐ Historical and cultural heritage
- ☐ Personalized Experience
- ☐ Virtual Tours
- ☐ Sustainable Tourism
- ☐ Improved Navigation
- ☐ Other proposal: …

Sort these use cases from the one you preferred most to the one you preferred least

Urban Planning	
Environmental Planning	Monitor and analyze environmental data, such as air quality, noise levels, and water usage. By simulating the impact of proposed developments on the environment, planners can identify the most sustainable solutions and minimize the negative effects on the ecosystem.
Infrastructure Planning	Enable real-time monitoring of urban infrastructure, such as transportation networks, energy systems, and water supply. Planners can use this information to optimize the performance of existing infrastructure and make informed decisions about future investments, ensuring efficient and sustainable development.
Land Use Planning	Provide a holistic view of the urban landscape, integrating data on land use, zoning, and development. This helps planners to balance competing demands for space, such as residential, commercial, and recreational uses, while minimizing conflicts
Emergency Response Planning	Simulate the impact of natural disasters or other emergencies to help planners to design more resilient urban environments. In the event of an emergency, real-time data and digital twin simulations can inform response efforts
Community Engagement	Create interactive visualizations of proposed urban projects, allowing the public to better understand and engage with the planning process. This can improve the overall quality of urban plans by incorporating valuable feedback from the community

Choose among two of the following use case related to urban planning:

- ☐ Environmental Planning
- ☐ Infrastructure Planning
- ☐ Land Use Planning
- ☐ Emergency Response Planning
- ☐ Community Engagement
- ☐ Other proposal…

Sort these use cases from the one you preferred most to the one you preferred least

Smart Mobility	
Mobility as a Service	Simulate and test new MaaS models, such as ride-sharing and on-demand transportation services. This can help to optimize the use of vehicles and infrastructure, and provide more convenient and affordable transportation options for users.

Risk Assessment	Assess the risks associated with different transportation scenarios, such as traffic accidents and disruptions. This can help to develop strategies to mitigate these risks and improve the safety and resilience of the transportation system.
Autonomous Vehicle Testing	Simulate and test autonomous vehicles in a safe and controlled environment, before they are deployed on public roads. This can help to ensure that autonomous vehicles are safe and reliable, and can operate effectively in a range of different conditions.
Traffic Optimization	Simulate and optimize traffic flow in real-time, based on current and predicted traffic patterns. This can help to reduce congestion, improve travel times, and minimize the environmental impact of transportation.
Predictive Maintenance	Monitor the condition of vehicles, infrastructure, and other components of the transportation system in real-time. This can help to identify potential issues before they become major problems, and schedule maintenance and repairs more efficiently.

Choose among two of the following use case related to smart mobility:

- ☐ Mobility as a Service
- ☐ Risk Assessment
- ☐ Autonomous Vehicle Testing
- ☐ Traffic Optimization
- ☐ Predictive Maintenance
- ☐ Other proposal…

Sort these use cases from the one you preferred most to the one you preferred least

Industry

Collaboration with AMR	
Real-time Data Analytics	Collect and analyze real-time data from the production process, including data from sensors and other sources. This information can be used to optimize the production process and improve overall efficiency.
Quality Control	Monitor the quality of production output and identify potential defects. This information can be used to optimize the production process and improve product quality.
Predictive Maintenance	Monitor the condition of AMRs and predict when maintenance will be needed. This can help prevent

	breakdowns and reduce downtime, ensuring that the production process remains efficient.
Training and Simulation	Simulate different scenarios and train workers on how to collaborate effectively with AMRs. This can include simulating different production scenarios and teaching workers how to program and operate the robots.
Monitoring and Control	Monitor the status of AMRs, including their location, speed, and battery life. This information can be used to optimize the performance of the robots and ensure that they are operating safely and efficiently.
Beyond AMR	Human in the loop can overcome the limitation of AMR improving the output of processes

Choose among two of the following use case related to industry:

- ☐Real-time Data Analytics
- ☐Quality Control
- ☐Predictive Maintenance
- ☐Training and Simulation
- ☐Monitoring and Control
- ☐Beyond AMR
- ☐Other proposal…

Sort these use cases from the one you preferred most to the one you preferred least

Questions

User → who is going to use the application
Related to the use case:
What kind of user is involved in the experience?
What should be is Affinity to the technology? Is an evaluation needed (ATI scale)

Is the user active or passive in the experience?

- ☐active: interacts with the system
- ☐passive: only content visualization

If active what can the user do?

If passive what does the user see?

What XR technology you would like to use?

- ☐Augmented Reality (AR): Computer-generated and Real world are combined
- ☐Virtual Reality (VR): Computer-generated world
- ☐Mixed - AR+VR → **Constraint**: Cross-reality device

User Interaction in the XR experience → what the user can do in the experience?

Related to the technology chosen:
Can the user move in the virtual environment?

- ☐Yes
- ☐No

If yes, how do you imagine movement?

- ☐Continuos movement
- ☐Real mapped movement
- ☐Teleport movement

What interaction enabler can the user use during the experience?

- ☐Gaze
- ☐Hands
- ☐Controllers
- ☐Voice

Which user senses are involved in the experience?

- ☐Haptic
- ☐Visual
- ☐Auditory

Augmented Reality specific

How addictive information is presented?

- ☐Constructive: additive to the natural environment
- ☐Destructive: masking of the natural environment

Which device you would like to use?

- ☐Headset: Hololens2, nReal glasses, Magic Leap
- ☐Projectors
- ☐Handheld/Mobile

Virtual Reality specific

How the environment should be presented to the user? (This will depend also from the data capturing and rendering technique)

- ☐Real capturing/360
- ☐Virtual/3D

Which device you would like to use?

- ☐Headset: 1. tethered: HTC, 2. wireless: Pico, MetaQuest
- ☐CAVE
- ☐ Mobile/Desktop