Ref. Ares(2024)9180685 - 20/12/2024

HUMAN-CENTRIC AI-ENABLED EXTENDED REALITY APPLICATIONS FOR THE INDUSTRY 5.0 ERA

D2.2 – REFERENCE ARCHITECTURE MODEL AND TECHNICAL SPECIFICATIONS

Lead Beneficiary	UBI
Work Package Ref.	WP2 – Specifications, Architecture and EU XR Platform Integration
Task Ref.	T2.2, T2.3 – Technical Specifications of XR5.0 Components and Technologies, Reference Architecture Model for XR5.0 Applications
Deliverable Title	D2.2 – Reference Architecture Model and Technical Specifications
Due Date	2024-12-31
Delivered Date	2024-12-20
Revision Number	3.0
Dissemination Level	Public (PU)
Type	Report (R)
Document Status	Release
Review Status	Internally Reviewed and Quality Assurance Reviewed
Document Acceptance	WP Leader Accepted and Coordinator Accepted
EC Project Officer	Ms. Tunde LEVY

HORIZON-CL4-2023 Research and Innovation Action

This project has received funding from the European Union's Horizon Europe Research and Innovation Programme under grant agreement no 101135209.

DISCLAIMER

COPYRIGHT MESSAGE

CONTRIBUTING PARTNERS

Partner Acronym	Role[1]	Name Surname[2]
UBI	Lead Beneficiary	Nikolaos Tousert, Dimitra Lipitaki, Thanos Giannakopoulos, Xanthi Papageorgiou, Dimitris Ntalaperas
IML	Contributor	Jorge Oliveira, Tomaz Saraiva
GFT	Contributor	
KUKA	Internal Reviewer	
SSF	Internal Reviewer	
OCU	Contributor	
HOLO	Contributor	
SYN	Contributor	
LXS	Contributor	
UNP	Contributor	
INNOV	Contributor	
ATB	Contributor	
UPRC	Quality Assurance and Internal Reviewer	Thanos Kiourtis, Argyro Mavrogiorgou
IPIA	Contributor	
CYENS	Contributor	
SUPSI	Contributor	
ALMER	Contributor	
SIE	Contributor	
TOG	Contributor	

[1] Lead Beneficiary, Contributor, Internal Reviewer, Quality Assurance
[2] Can be left void

REVISION HISTORY

Version	Date	Partner(s)	Description
0.1	2024-09-10	UBI	ToC Version
1.0	2024-11-12	UBI, IML	1st Version
1.1	2024-11-29	UBI, IML, GFT, OCU, HOLO, SYN, LXS, UNP, INNOV, ATB, UPRC, IPIA, CYENS, SUPSI, ALMER, SIE, TOG	Inputs and Additions
1.2	2024-12-6	UBI	Version for Peer Reviews
2.0	2024-12-13	UBI	Version for Quality Assurance
3.0	2024-12-20	UBI, UPRC, GFT	Version for Submission

LIST OF ABBREVIATIONS

Acronym	Definition
ADM	Architecture Development Framework
AI	Artificial Intelligence
AMT	Active Management Technology
API	Application Programming Interface
AR	Augmented Reality
BLE	Bluetooth Low Energy
CAD	Computer-Aided Design
CI/CD	Continuous Integration/Continuous Deployment
CRM	Customer Relationship Management
CSV	Comma-Separated Values
DTLS	Datagram Transport Layer Security
ERP	Enterprise Resource Planning
ETL	Extract, Transform, Load
GATT	Generic Attribute Profile
HDM	Historical Data Manager
HTTPS	Hypertext Transfer Protocol Secure
IDE	Integrated Development Environment
IoT	Internet of Things
IT	Information Technology
JDBC	Java Database Connectivity
JSON	JavaScript Object Notation
JWT	JSON Web Token
LLM	Large Language Model
MQTT	Message Queuing Telemetry Transport

MR	Mixed Reality
MRTK	Mixed Reality Toolkit
ODBC	Open Database Connectivity
OS	Operating System
PLC	Programmable Logic Controller
SAP	Systems, Applications and Products in Data Processing
SLAM	Simultaneous Localization and Mapping
SLB	Server Load Balancer
SRTP	Secure Real-Time Transport Protocol
SSO	Single Sign-On
STUN	Session Traversal Utilities for NAT
TCP	Transmission Control Protocol
TOGAF	The Open Group Architecture Framework
TURN	Traversal Using Relays around NAT
UDP	User Datagram Protocol
WebRTC	Web Real-Time Communication
XAI	eXplainable Artificial Intelligence
XR	Extended Reality

EXECUTIVE SUMMARY

Deliverable D2.2, titled "Reference Architecture Model and Technical Specifications", is a cornerstone of the XR5.0 project, providing essential guidance for the development and integration of the platform. It serves as a central reference for developers and stakeholders, ensuring seamless connectivity and robust design principles across Industry 5.0 use cases such as product design, remote maintenance, production simulations and XR-based training.

The architecture emphasizes flexibility, scalability and interoperability. It integrates inputs from six pilots, aligning with their diverse needs and incorporating widely recognized standards like a high-level approach to design architecture framework with The Open Group Architecture Framework (TOGAF), an architecture modeling language ArchiMate and C4 model for visualising software architecture. The deliverable presents:

- A business-focused Enterprise Architecture offering strategic alignment across processes, applications and technologies.
- A Solution Architecture detailing system components, external integrations and information flows.

Additionally, the deliverable includes technical specifications of tools and new technologies used, ensuring modularity and compatibility. It outlines how XR5.0 aligns with existing industry standards while preparing for integration with the upcoming EU XR platform to support collaboration and innovation in Industry 5.0.

TABLE OF CONTENTS

LIST OF FIGURES

List of Tables

1. INTRODUCTION

The content of this Deliverable serves three purposes: to act as an Architecture reference point for XR5.0 developers, to document the design and integration work in the context of WP2 and to serve as a blueprint for future endeavors in building systems that will try to address Industry 5.0 use cases by making use of XR and AI technologies.

The Deliverable first introduces the reader to the Architectural design process and the approach used for building the diagrams of the Architecture through requirements engineering. All user stories which have been created according to the needs of the 6 pilots have been reported since they played a major role in the design of the Business Layer of the Enterprise Architecture. Then, the standards and specifications used by the Architecture are listed and documented. More specifically, the TOGAF, ArchiMate and C4 specifications are analyzed in order for the user to be able to interpret the diagrams.

The technical specifications of the partners' tools have also been included in this document in high detail. Tools dedicated to various operations such as training, management of the XR environment, asset storage, AI processing, orchestration, etc. have been extensively documented in order to depict their integration in the ArchiMate Application Layer. In the context of this Deliverable, these tools are considered to be generic enough and modular in the sense that they could be replaced by similar tools with the same functionalities. To this end, the title given to the tools in the Architecture Application Layer reflects the functionality of the tool within the XR5.0 system.

After the presentation of the specifications employed by the Architecture (TOGAF, ArchiMate, C4), the diagrams of the Enterprise and Solution Architectures are presented and explained. These 2 architectural categories are supplementary and they design and describe the same system through different viewpoints, each tailored to different aspects and levels of detail. The Enterprise Architecture offers guidance, alignment, and a holistic context, defining the organization's strategic goals and overall IT landscape, while the Solution Architecture provides operational design, delivering the system-level structure necessary to implement specific capabilities and business processes. Together they ensure that the solution is both strategically aligned and technically sound.

Furthermore, well-known standards in Industry 5.0, Industry 4.0, XR, and AI are included and briefly described in the document and their alignment with XR5.0 Architecture has been analyzed. Moreover, recommendations are being made in order to have in the future a standard capable of boosting compliance and interoperability with future Industry 5.0, XR and AI solutions

Finally, the XR5.0 Architecture has been structured to ensure future compatibility and alignment with the EU XR platform. This forward-looking approach aims to promote seamless interoperability and collaboration with the broader Industry 5.0 ecosystem.

1.1 Objectives of the Deliverable

The objectives of this Deliverable are the following: to set the basis and the reference point for partners' development and integration efforts, to depict the transformation of various user stories derived from the needs of 6 different pilots into a comprehensive architectural business layer, to present how different tools can synergize and cooperate so as to deliver the so called XR5.0 platform that will boost the training, the effectiveness in troubleshooting and maintenance and the monitoring of the production line in Industry 5.0 environments. Moreover, this deliverable aims at reviewing current standards in Industry 5.0, Industry 4.0, XR and AI domains and examines their capabilities or deficiencies in supporting XR and AI-enabled Industry 5.0 person-centric applications.

Moreover, the Deliverable's objectives are to ensure all partners align on key architectural principles and are aware of how each tool fits within the overall XR5.0 architecture, as well as aligning the reference architecture with relevant European and international standards, ensuring compliance and fostering wider adoption. The Architecture and the technical specification of the tools have been documented in a manner that is accessible and understandable to all partners, including non-technical stakeholders. Furthermore, it acts as a reference document for onboarding new stakeholders in the project. Finally, the goal is through this document to provide a roadmap and guidelines for further development and enhancement of the tools and the architecture and ensure that the Deliverable can serve as a foundation for subsequent project phases or follow-up initiatives.

1.2 Insights from Other Tasks and Deliverables

This Deliverable entitled "Reference Architecture Model and Technical Specifications" has been published in the context of WP2, named "Specifications, Architecture and EU XR Platform Integration". To this end, along with the other tasks of WP2, it contributes to preparation of architectural guidelines that will drive the further development of the tools and their integration into a unified interoperable platform. The Deliverable was heavily based on the work of task T2.1 "Analysis of Reference XR Scenarios for Industry 5.0 Apps" which has been documented in the Deliverable D2.1 [2], entitled "Requirements and Reference Scenarios Analysis". Thereafter, the user stories of reference XR scenarios which have been gathered by the 6 pilots of the project were the cornerstones for building the architecture and especially for designing the business layer which represents the operational and strategic aspects of the project.

In addition to task T2.1, this deliverable has also been influenced by the findings of task T2.2, entitled "Technical Specifications of XR5.0 Components and Technologies" in the sense that the partners' tools form the building blocks of the system and shape the design and operational aspects of the architecture in several ways: the architecture must be designed to accommodate the tools capabilities within XR5.0 platform, the tools influence what modules or services need to be created for proceeding with the integration and determining the needed interfaces. Moreover, since each tool may depend on specific requirements (software, hardware, etc.), the architecture must ensure compatibility across all tools, and if tools require shared datasets, the architecture should include centralized storage.

Task T2.4 entitled "Cloud/Edge and BigData Infrastructures for XR5.0 Apps" also played a huge role in shaping the architecture and more specifically in designing the Enterprise Technology Layer. The task T2.4 which is responsible for the integration and more specifically for specifying the pipelines and workflows to seamlessly deploy XR5.0 platform across a wide range of industrial settings, was a roadmap for designing the architecture in the lowest level (i.e. Technology Layer) by depicting the resources, network and other tools needed for deployment and the continuous integration purposes.

The content of this Deliverable and more specifically the schema of the tools integration will feed the activities of task T2.5 "Design, Implementation and Documentation of Open APIs" which reports on the set of APIs that will facilitate the integration and communication between XR5.0 components and between XR5.0 and existing industrial systems. According to the Application Layer of this Deliverable, T2.5 will specify and document the APIs in order to facilitate the integration.

Moreover, the specification of the architecture is designed in a way that will boost compliance and interoperability with the EU XR platform, and thereafter, this document is highly relevant with the activities of the task T2.6 entitled "Integration to the EU XR Platform".

The design of the Architecture and the content of this Deliverable are also in line with the Technical Management activities of task T1.2 and the goal is to constitute the blueprint for the activities of the technical packages WP3, WP4, WP5. Finally, the results of the Architecture will be evaluated and validated through the activities of WP6 and more specifically through the deployment in 6 diverse and representative pilots.

1.3 Structure

Chapter 2 presents the methodology used for designing XR5.0 Architecture. The review of standards in Industry 5.0 and Software Systems Architecture, the study of available XR5.0 documents and the collaboration with the partners are highlighted in this chapter. Moreover, an explanation is being provided for employing TOGAF and ArchiMate specifications for designing the Enterprise Architecture, and for employing C4 for designing the Solution Architecture. The process of Requirements Engineering and the list of XR5.0 user stories are also included in this chapter.

Chapter 3 presents the technical specifications of XR5.0 components and technologies. More specifically, the description, functionalities, interfaces, internal architecture, the dependencies and the authentication mechanisms employed by each component are all listed in this chapter.

Chapter 4 explores the application of "The Open Group Architecture Framework" (TOGAF) [6] within the XR5.0 project. It is explained that TOGAF provides a structured methodology for developing and governing enterprise architectures. Moreover, five phases of TOGAF's iterative Architecture Development Method (ADM) are implemented in XR5.0, each contributing to the alignment of IT investments with Industry 5.0 goals.

Chapter 5 addresses the Enterprise Architecture of XR5.0. The various layers (business, application and technology), the vision of the Architecture and the organization viewpoint are presented in this chapter. Moreover, this chapter presents the translation of the user stories into business processes (business layer) and the integration of the various tools within the whole XR5.0 platform.

Chapter 6 includes the Solution Architecture which consists of the System Context diagram and the Container diagram. The major architectural components (containers) and their responsibilities as well as the big-picture view of the solution are illustrated in this chapter.

Chapter 7 presents the various standards used in Industry 5.0, Industry 4.0, XR and AI and describes the alignment of the Reference Architecture with those existing standards.

Finally, chapter 8 addresses the plan for integrating the XR5.0 Reference Architecture with the EU XR platform. It highlights the forward-looking strategies for ensuring interoperability, compliance and alignment with the EU XR platform's anticipated framework. Thereafter, it outlines initial steps, future plans and considerations to foster collaboration and compatibility.

2. DOCUMENTATION OF THE PROCESS

The development of the system's architecture followed a structured methodology, ensuring alignment with the project's goals and stakeholder expectations. This chapter outlines the steps undertaken to gather, analyze and document the necessary inputs for the architecture design. The process combined the review of foundational project documents, active participation in collaborative workshops and discussions, and iterative refinement based on stakeholder feedback. Key inputs for this process included:

- ➢ Review and selection of the appropriate standards and specifications for the definition of XR5.0
- ➢ The Description of Action (DoA) of the project, which defined the overarching objectives and scope.
- ➢ Deliverable D2.1 entitled "Requirements and Reference Scenarios Analysis" [2] which provided user stories and scenarios critical for defining the system's functionality and behavior.
- ➢ Documentation from co-creation workshops conducted for the six pilots, which highlighted specific use cases and contextual needs.
- ➢ Insights and decisions derived from teleconferences and discussions with project partners, which played a pivotal role in refining the architecture design

More specifically, the first step began with the selection of the specifications and standards used for designing XR5.0 Architecture. The choice was to employ TOGAF [6] and ArchiMate [3] for defining the Enterprise Architecture. TOGAF is a widely adopted and well-established enterprise architecture framework with a comprehensive approach to structuring a project's architecture. On the other hand, ArchiMate is the official modeling language for TOGAF, providing a visual tool for representing architectural concepts, relationships and layers. The main reasons for using TOGAF (and consequently ArchiMate) for designing the XR5.0 Enterprise Architecture are the following:

- ➢ **Holistic Approach to Architecture**: TOGAF provides a holistic approach to aligning business and IT strategies with technical design and implementation. This is crucial for XR5.0, which aims at integrating human-centric solutions with advanced technologies (AI, IoT, XR, etc.)
- ➢ **Support for complex and evolving technologies**: TOGAF supports the development of flexible architectures that can evolve with these cutting-edge technologies. Flexible architectures are essential in XR5.0 considering the need for integrating with EU XR platform and diverse industrial settings
- ➢ **Cross-Disciplinary collaboration**: XR5.0 involves a diverse group of stakeholders across industries, research institutions, SMEs and countries. TOGAF (and thereafter ArchiMate) supports cross-functional collaboration through its structured methodology for governance, stakeholder engagement and decision-making processes.
- ➢ **Scalability and Flexibility**: XR5.0 accommodates a wide variety of actors, technologies and use cases. TOGAF offers adaptability in designing architectures that are both scalable and flexible, making it easier to incorporate new technologies, standards, or business processes as the project progresses. Moreover, ArchiMate enables clear communication of how changes at one level (e.g. XR integration) affect other areas (e.g. business processes, applications, etc.)
- ➢ **Alignment with European standards and regulations**: As the project is European, TOGAF provides a framework that is aligned with international standards and practices, ensuring compliance with EU regulations and standards, such as GDPR or the EU Digital Strategy. ArchiMate also supports this, since it provides a standardized notation for modeling that can be used across different countries and institutions within the EU, promoting consistency and interoperability.
- ➢ **Risk Management and Governance**: With a project of this scale and complexity, proper governance and risk management are vital. TOGAF has a strong focus on risk management, ensuring that architectural decisions are made with a full understanding of potential challenges, including technological, financial and operational risks.
- ➢ **Open and Community-driven**: Both TOGAF and ArchiMate are open frameworks with active communities. This ensures continuous development and support, along with access to a broad base

of knowledge and best practices. For a research project such as XR5.0, the ability to stay up to date with the latest trends and advancements in architecture is a major advantage.

Thereafter, these 2 architectural frameworks provide a robust, flexible and standardized approach to designing and managing the Enterprise Architecture of a complex European research project such as XR5.0. They ensure that the project can adapt to emerging technologies, foster collaboration across disciplines and align with industry and regulatory standards, while maintaining a human-centric focus and robust governance framework.

In addition to incorporating these specifications for defining the Enterprise Architecture, it has been decided to also include a separate section entitled “Solution Architecture” which makes use of the specification C4[4]. With C4 specification, the goal is to provide a more practical and actionable design for XR5.0 development teams, to provide a common understanding for both business and technical stakeholders, ensuring alignment across different levels of the project, and also to provide simple diagrams that help technical teams understand system components, interactions and dependencies. Moreover, C4 gives more specific, system-level design details (how the system operates and integrates). Thereafter, the reasons for choosing C4 (the Context, Containers, Components, and Code model) for the Solution Architecture alongside TOGAF and ArchiMate seems to be a beneficial approach for the following reasons:

- ➢ **Clear and Understandable Visual Representation**: The C4 model is designed to provide a clear, hierarchical set of diagrams that are easy to understand, even for stakeholders who may not be technically savvy. The focus is to provide diagrams that present a high-level overview of the system and its core components without overwhelming the XR5.0 audience with too many details, something extremely important in collaborative research environments with diverse stakeholders, including developers, industrial partners and researchers.
- ➢ **Focus on System Boundaries and External Interactions**: The diagrams presented in the context of the Solution Architecture through C4, as shown in chapter 6, establish system boundaries clearly. More specifically they focus on how XR5.0 interacts with external entities (users, pilots, etc.) and they highlight the **actors** and their relationships with the system, ensuring that all interactions, whether they are human-centric (such as XR interfaces) or machine-based (AI) are well understood.
- ➢ **Simplicity and Agility for Early-Stage Research Projects**: The C4 model that represents the Solution Architecture, with its 2 diagrams (System Context and Container) allows for a simplified approach that is agile and flexible, which is ideal for early-stage design work or projects where the exact specifications and technologies may evolve over time. XR5.0 falls into this category, and focusing only on these 2 diagrams keeps the design process light and adaptable, avoiding unnecessary complexity while still allowing for the necessary system design communication and iteration as the project progresses.
- ➢ **Complementing TOGAF and ArchiMate:** TOGAF and ArchiMate provide comprehensive enterprise architecture views, focusing on business, application and technology layers. These frameworks give a broad view of how the enterprise works, how processes are aligned and how technologies support the business. By adding C4 model for the Solution Architecture, the architecture is enriched with a focused, system-specific view of how the core technology operates within the larger context. Thereafter, C4 bridge the gap between Enterprise Architecture and actual Solution Architecture, allowing to translate high-level enterprise objectives into the design of specific systems and components.

To this end, using C4 diagrams allow to complement the Enterprise Architecture with a focused, clear and flexible view. This enables stakeholders to understand the core system architecture, the external interfaces and the high-level components in a way that is accessible, scalable and adaptable to the evolving needs of XR5.0.

After the selection of the tools and standards for the definition of XR5.0 architecture that have been described above, the process continued with a detailed review of the project documents to identify key objectives and requirements. These documents include the Description of Action (DoA), the Deliverable

D2.1[2] “Requirements and Reference Scenarios Analysis” and documentation of the co-creation workshops. Deliverable D2.1 provided to the Architecture high-level goals, user stories and scenarios that defined the functional scope of the system. Additionally, the co-creation workshops documentation captured pilot-specific use cases, offering an even deeper understanding of user needs and challenges.

It has to be mentioned that the collaborative nature of the process was central to its success. Regular telcos and discussions with project partners allowed for the validation and refinement of requirements, ensuring alignment with both technical feasibility and stakeholder expectations. This iterative approach ensured that the Architecture evolved in response to insights from all XR5.0 partners. Figure 1 illustrates the process undertaken to design the XR5.0 Architecture. **Document Analysis** serves as the foundation, incorporating static inputs such as the Description of Action (DoA), Deliverable D2.1 (which includes the user stories), and insights from co-creation workshops. These inputs feed into **Partners Collaboration,** which involves ongoing discussions with partners through telcos and other meetings to refine system requirements and validate architectural decisions. Then, the process includes the Architecture Design which consists of the Enterprise Architecture and the various layers (business, application, technology, strategy) and the Solution Architecture. It has to be noted that an iteration loop is indicated, showing how feedback from architecture design informs further partners collaboration, ensuring the design aligns with XR5.0 goals and evolving requirements.

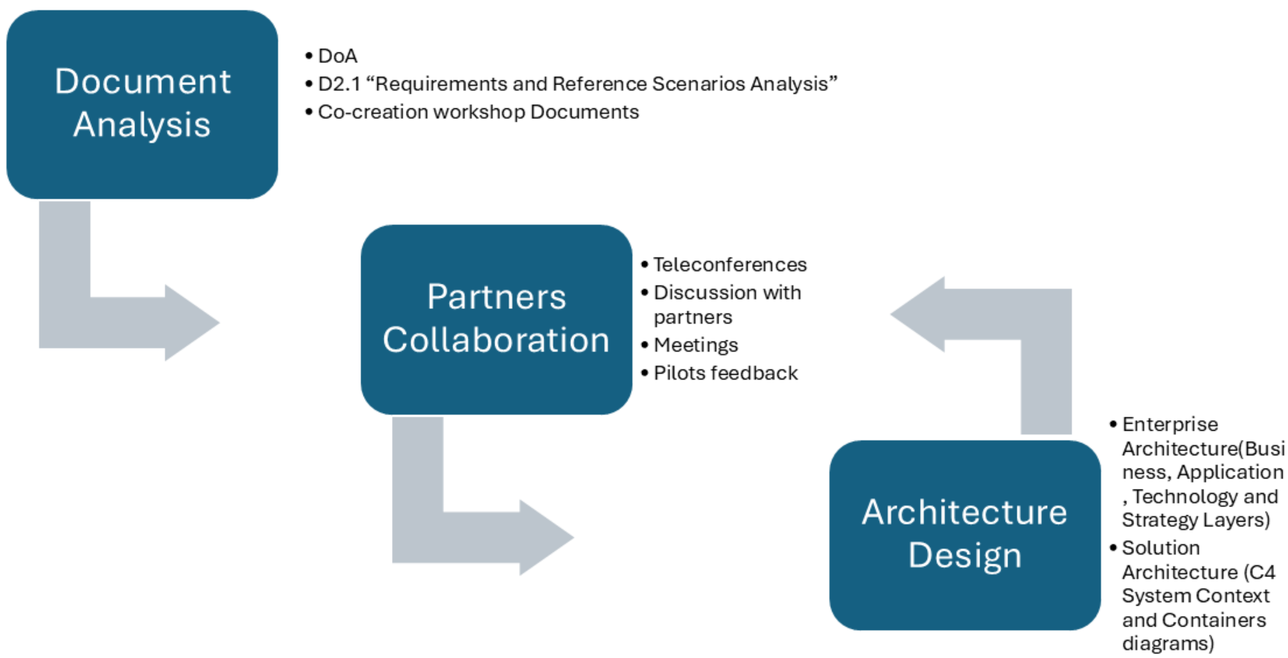


Figure 1: Key Steps in XR5.0 Architecture Design

2.1 Requirements Engineering Process

This section documents the requirements engineering (RE) methodology and underlying basics which are applied to the XR5.0 project. To utilize the potential of existing structures and at the same time harmonize the RE process across the different technical stakeholders in the project, the RE methodology is primarily based on the international standards “ISO/IEC/IEEE 29148-2018 - Systems and software engineering — Life cycle processes – Requirements engineering”. Furthermore, the standard “ISO/IEC/IEEE 24765-2017 - System and software engineering – Vocabulary” is used as a clarification basis on Systems Engineering (SE) terminology. In accordance with ISO/IEC/IEEE 29148-2018, the XR5.0 project has adopted an iterative RE model which clusters the requirements engineering into three main steps (Figure 2) The steps are sequential; however, the iteration loops are designed so that they may include only certain steps.

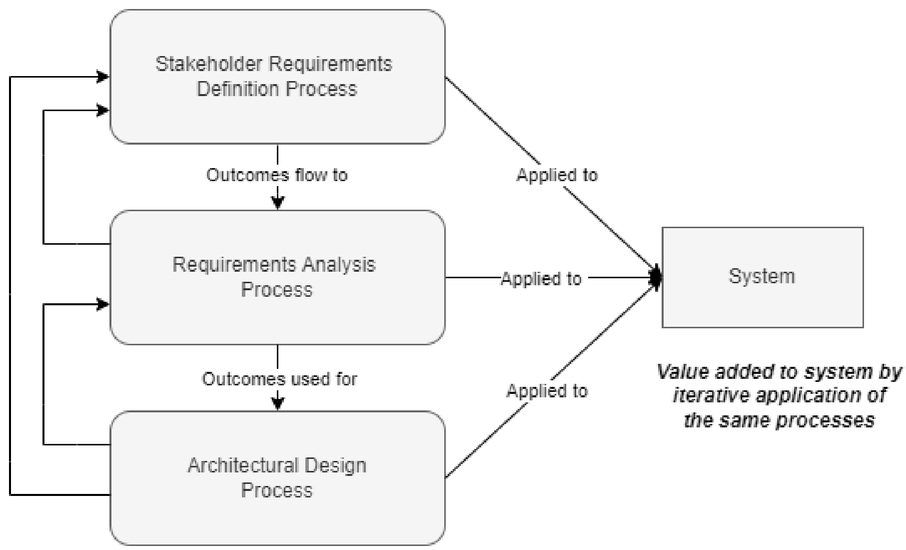


Figure 2: Iterative systems engineering processes

This iterative approach to requirements engineering allows the project to adapt both the requirements engineering process and the systems development process to the changing dynamics of the three business cases. The process is not specific only to RE but is also applied to all development activities in XR5.0.

The objective of the requirements' engineering process is to develop a model of requirements that facilitates an agreed understanding between stakeholders (e.g., operators, customers, managers, virtual commissioners, etc.). This model must be validated against real-world needs, be implementable, and provide a basis for verifying designs and accepting solutions.

The identification and analysis of the requirements of reference XR scenarios within the context of Industry 5.0 has been presented in Deliverable D2.1 [2]. This analysis outlined how XR5.0 can effectively address these challenges, providing a comprehensive framework for integrating XR technologies in Industry 5.0 applications. The Deliverable D2.1 presents many XR5.0 aspects, such as pilot descriptions, background technologies and reference scenarios, but from the perspective of architecture, the user stories defined in D2.1 are considered of utmost importance since they serve as a foundation for designing the business layer of the enterprise architecture.

XR5.0 user stories encapsulate the key requirements, objectives and behaviors that the system must support to deliver value to stakeholders (i.e. operators, training managers, etc.). By focusing on user-centric goals and outcomes, these stories translate business needs into actionable features and processes. Each story typically defines "who" the user is, "what" they need, and "why" it matters, which helps architects prioritize functionalities and design modular, scalable components. In the enterprise business layer, user stories guide the alignment of services, workflows and data models to ensure they fulfill real-world use cases. This iterative and incremental approach fosters collaboration across teams, improves understanding of complex business requirements and ensures the resulting architecture is both adaptable and user focused. For a complete reference of the user stories, the user can refer to Deliverable D2.1 [2].

3. TECHNICAL SPECIFICATIONS OF XP5.0 COMPONENTS AND TECHNOLOGIES

This section elaborates on the technical specifications of the technologies used in XR5.0. This will describe each component in detail to inform the reference architecture for XR5.0. The structure of this description is provided according to the following sections:

Section 3.1. Description and Functionalities and Components, introduces the purpose and utility for each component. This description is provided to demonstrate how technology supports XR5.0. Most of the technologies are software components, but some hardware technologies are also considered.

Section 3.2. APIs and Interfaces describes how each component interacts within XR5.0, highlighting protocol support and methods for external systems to interact with XR5.0.

Section 3.3. Input and Output Data Formats outlines the data formats for input and output across components to enable interoperability between platforms.

Section 3.4. Schematics and Internal Architecture contains the architecture and schematics of each component, including logical flow diagrams, interactions between components, and structural layouts.

Section 3.5. Software Requirements and Dependencies details the requirements, including required or compatible versions, operating systems, and libraries for use by each component.

Section 3.6. Authentication Mechanisms provides a summary on the security protocols and authentication mechanisms related to every described component such as encryption algorithms or authentication protocols.

3.1 Description and Functionalities of the Components

For Section 3.1 depicting the Description and Functionalities of Components of XR5.0, an overview of each technology's intended use and its role within the project is provided, illustrating how each element contributes to achieving XR5.0's objectives. The following technologies represent different hardware and software components, each uniquely integrated to support XR5.0's goals in data processing, remote assistance, user interactions, XR and explainable AI (XAI) capabilities.

Hardware and Operating Systems

The Hardware and Operating Systems section describes the underlying technologies that will support XR5.0 XR immersive and functional scenarios. This hardware consists of sophisticated XR wearables and operating systems that together improve usability, data capture, and user experience in different industry contexts. The Almer Arc 2 is a second-generation head-mounted display from Almer Technologies being a lightweight and ergonomic device, optimized for prolonged, hands-free use in environments ranging from logistics to remote support. This device is coupled with Almer OS, an Android-based OS specifically devised to optimize the interaction with AR capabilities, providing seamless and intuitive use for real-world applications. Moreover, Wearable OS based on InfiniTime OS, powers the PineTime SmartWatch, which enables a fast and lean execution on low-power devices, while capturing data from different sensors including behavioral and physiological data The combination of these hardware and operating systems provides high-performance a user-friendly infrastructure of XR5.0.

Augmented and Virtual Reality Platforms

The Augmented and Virtual Reality Platforms section describes the technologies that drive XR5.0 featuring advanced, hands-free, immersive tools for industry use cases. The solutions combine real-time guidance, high-end streaming, and high-quality visualizations, addressing a range of use cases from remote support to training modules in off-the-job and on-the-job training. TeamViewer Frontline running on the Almer Arc 2 headsets, supports hands-free interaction via the overlay of digital instructions over physical environments to improve workflow efficiency for field workers and technicians.

Another technology used in XR5.0 that supports management and streaming of high-fidelity visualizations is the HOLO's XR solutions. The following figure illustrates three core components: Hololight Space, Hololight Stream and Hololight Hub (Figure 3).

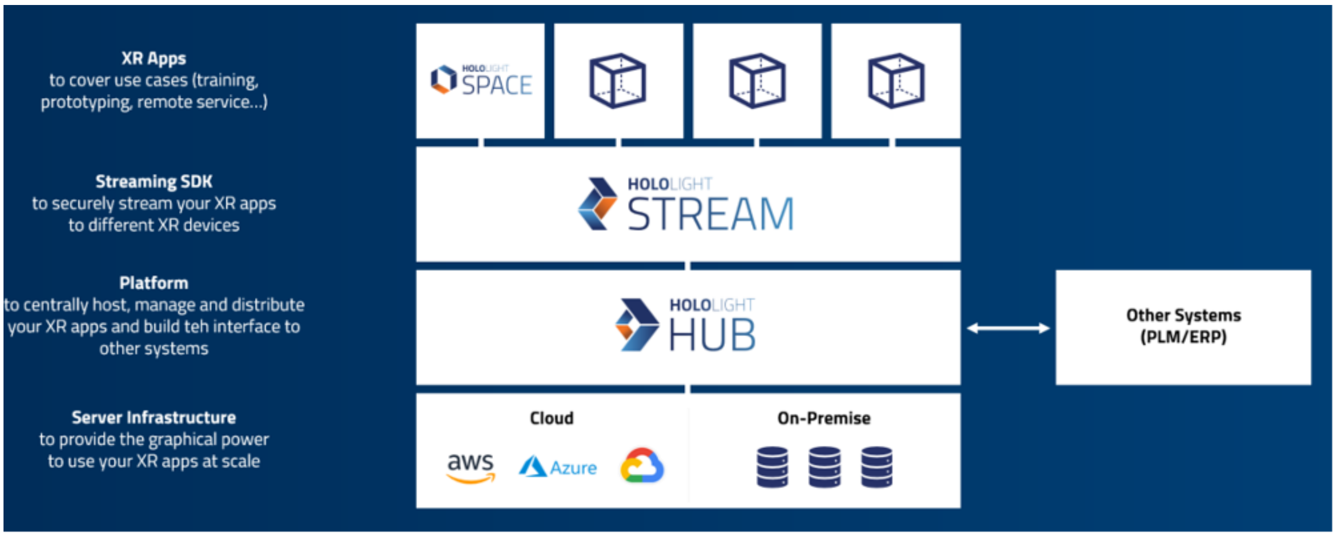


Figure 3: HOLO's components supporting XR solutions in XR5.0

Hololight Hub and Hololight Stream provide flexible, scalable solutions for streaming and managing XR applications, giving users an effortless experience with low-latency visualizations, while Hololight Space provides high-fidelity, interactive 3D visualizations that enhance engineering and development workflows.

In addition, a Virtual Reality Training module for Aircraft Maintenance Technicians offers a step-by-step procedure for guidance in essential tasks, thereby promoting hands-on learning and skill refinement. Overall, these platforms improve XR5.0's training, usability, and real-time support capabilities.

Smart Service, IoT, and IIoT Integration

Smart Service, IoT and IIoT Integration section outlines the technologies that support connectivity, monitoring and collaboration through XR5.0. Ultron is a smart assistant that adds context-sensitive and responsive assistance to AR and mobile devices to support user workflow and experience. Oculavis SHARE provides device-agnostic connectivity for remote troubleshooting and operational efficiency between equipment manufacturers, technicians and experts from locations around the globe. Clawdite is an extensible and flexible IIoT-based platform supporting the creation of customized data representations of production systems and their entities, including humans. It also enables dynamic and quasi-static data management. On the other hand, the Service Connector Core enables integration across clouds, databases, APIs, and services, allowing for real-time data acquisition, which is critical for XR5.0 monitoring and data-driven applications.

Explainable AI (XAI) and Machine Learning Technologies

The Explainable AI (XAI) and Machine Learning Technologies section describes the advanced AI models that enhance transparency, adaptability, and user understanding within XR5.0. The integration of Explainable AI (XAI) and Deep Learning Models, XR5.0 contributes to explainable predictions using advanced AI models. That improves transparency in the AI decision-making process and enhances trust of the system. Generative AI as a Service component adds a next level of interactivity within XR environments, providing context-aware responses that adapt based on the user's environment, inputs, and tasks, thus potentially contributing to user engagement. Another XAI with Domain-Specific Knowledge component uses ontologies, knowledge graphs, and domain-specific knowledge to create context-specific explanations for the user to support their decision-making and understanding. Last, Integration and Visualization of AI/XAI provide these AI explanations and recommendations in a clear manner in the XR environment to follow the open science principles and to support the user with understanding of the AI-driven process.

Data Management and Analytics

The Data Management and Analytics section describes the infrastructure supporting XR5.0 to handle large datasets and provide insight in real-time, crucial for data-driven and immersive experiences. This is supported by the Ultra-Scalable Relational Database – LeanXcaleDB and the Training Repository. The LeanXcaleDB is a technology able to handle big data with high efficiency. It includes scalability capabilities for retrieving, processing, and storage, necessary for the real-time analytics that support XR5.0's functionalities. The Training Repository is a cloud base storage solution that will host XR & conventional training materials.

3.2 Specification of APIs and Interfaces provided and exposed by each Component

For Section 3.2 related to Specification of APIs and Interfaces Provided and Exposed by Each Component, describes the communication protocols, APIs, and interfaces available for each technology integrated within XR5.0. The components span the area types identified above where the technologies of XR5.0 are organized.

Hardware and Operating Systems

The Almer Arc 2 devices are supported by a customer-facing application available as an APK, facilitating installation and access to AR functionalities on Android-based devices.

Almer OS is compatible with a wide range of Android applications, allowing users to install and operate standard Android apps directly on their AR devices without additional integration components, apart from compatible AR hardware. As for the other OS, Wearable OS, communication between Bluetooth Low Energy (BLE) devices is managed using the Bluetooth GATT (Generic Attribute Profile) protocol, enabling efficient and low-power data exchange, ideal for wearable applications.

Augmented and Virtual Reality Platforms
The TeamViewer Frontline APK is compatible with any AR hardware running Almer OS or Android OS version 9 or higher, making this component compatible with a wide range of AR devices. This platform easily integrates with enterprise systems like ERP (Enterprise Resource Planning) and CRM (Customer Relationship Management) platforms to enable efficient data capture, compliance, and workflow optimization.

Streaming: The following image illustrates the XR streaming approach of Hololight Stream for real time streaming of XR applications cloud server to an XR device. A high-level overview of the components and data flow in the system is depicted in Figure 4.

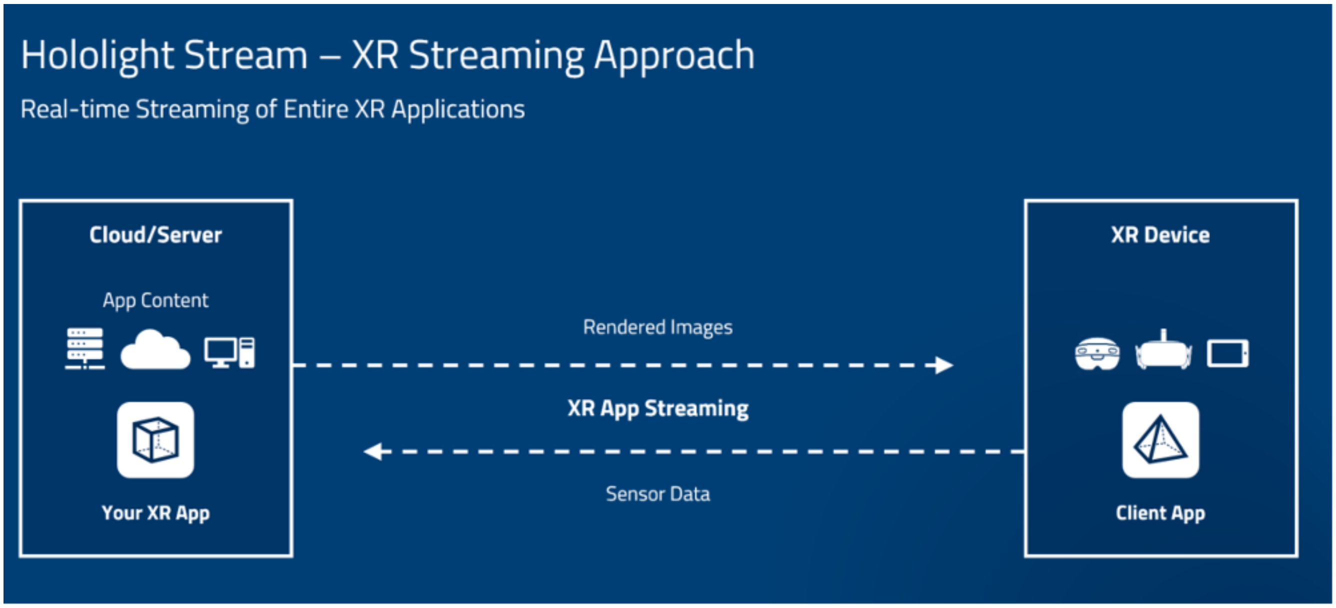


Figure 4: Hololight Stream – XR Streaming Approach

Hololight Hub uses Web Real-Time Communication (WebRTC) protocols for secure and low-latency streaming, providing instantaneous access to data and visuals. In addition, Secure Real-Time Transport Protocol (SRTP) and Datagram Transport Layer Security (DTLS) are also implemented to ensure data integrity and confidentiality. Web Access is based on HTTPS for reliable web interactions. This component provides APIs to allow integration with other services, enabling customized extensions and ensuring compatibility with systems in XR5.0. See also Figure 5 for more details about the Training platform that use the above components.

Hololight Stream supports Unity Plugin and Software Development Kit (SDK) integrations, offering a developer-friendly environment for incorporating high-quality streaming into XR applications. It also supports Mixed Reality Toolkit (MRTK), facilitating development for mixed reality. Hololight Stream utilizes WebRTC for efficient real-time streaming, optimized to deliver high-quality visuals with low latency. Communication signaling occurs on port 9999.

Smart Service, IoT, and IIoT Integration

Ultron requires Almer OS or an Android operating system version 9 or higher, making it accessible across a range of compatible Android devices. Installation of the Ultron APK on the desired hardware enables the smart assistant's functionality, with Almer Arc devices being pre-deployed with this technology for streamlined setup and integration. Ultron enhances user interactions by delivering context-aware, responsive support on AR devices, allowing for smooth operation in various professional environments.

Oculavis SHARE provides Oculavis API and standard connectors for integration with major enterprise platforms, including Salesforce, SAP, and Microsoft systems. This setup facilitates seamless communication between devices and enterprise systems, allowing for robust, device-agnostic remote collaboration that enhances troubleshooting, maintenance, and support capabilities.

Clawdite supports integration through two main APIs: the Orchestrator API and the HDM (Human Data Model) API. It also features MQTT broker for data saving a modules communication. These APIs allow for the customization and creation of data representations for production systems, including human interactions. Through these interfaces, Clawdite enables enhanced monitoring and control over connected industrial environments, aligning human and machine data for optimal operational insights.

The Service Connector Core uses MQTT (Message Queuing Telemetry Transport) as its primary protocol, a lightweight messaging protocol ideal for IoT environments where low bandwidth and reliable data exchange are critical. Its architecture is easily extendable, allowing for the addition of further services or APIs, supporting scalability, and ensuring compatibility with various IoT and IIoT applications within XR5.0.

Explainable AI (XAI) and Machine Learning Technologies

The Active Learning component operates as a web service where data is exchanged in JSON format. NeuroSymbolic AI also functions as a web service, with JSON as the primary data format for communication with other components.

The Generative AI as a Service system is built using FastAPI and supports components such as OpenAI API, ChromaDB/Pinecone, Redis Chat Store, LlamaIndex, LangChain, and Hugging Face Transformers. The service is accessible via a RESTful API, enabling scalable, flexible interaction with external applications for generating context-aware responses. This REST API setup provides developers with a standardized method to access and implement generative AI capabilities within XR5.0.

Explainable AI (XAI) with Domain-Specific Knowledge component offers multiple interfaces to ensure comprehensive integration and functionality. The Data Collection Interface integrates with various data sources, supporting the flow of relevant information into the XAI system. Ontology/Knowledge Graph Interface allows for creating, editing, managing, and querying knowledge structures, supporting the development and use of domain-specific knowledge within the AI system. Context Extraction Interface manages context models, using standardized data to load and interpret contextual information, enhancing the relevance and accuracy of explanations provided by the XAI system.

Integration and Visualization of AI/XAI component supports API calls using JSON for structured data exchange and integrates various multimedia services, such as Speech to Text and Text to Speech for audio interactions, and Virtual multimedia content support (3D models, images, metadata, sounds, videos) to enhance the user experience and provide rich, visual explanations within XR5.0's environment.

Data Management and Analytics

The LeanXcaleDB component is designed to be integrated into diverse environments, adhering to industry standards for communication and data processing, such as JDBC/ODBC communication protocols providing also a standard python-based driver. It is already integrated with popular data processing frameworks (i.e. Apache Spark, Flink, Kafka, etc.). This combination of industry-standard communication protocols, versatile API specifications, and integration with popular data frameworks ensures that LeanXcaleDB is highly adaptable and meets the demands of modern data-intensive environments. The Training Repository Storage Solution is based on Web Distributed Authoring and Versioning (WebDAV) which is an HTTP-based protocol allowing users to collaboratively edit and manage files stored on a remote server. The service availability will be done through RESTful APIs.

3.3 Description of each Component input and output data format

In this section related to the Description of Each Component Input and Output Data Format, the data formats used by each XR5.0 component for both input and output is depicted in a structured table (Table 1).

Table 1 Hardware and Operating Systems

Technology	Input	Output	I/O data format and samples
Almer Arc 2	Camera Microphone Inertial Sensors Voice control Programmable buttons	Display HD Audio Remote support	-- --
Almer OS	Via Android applications Voice commands	Interface optimized for AR interactions	--
Wearable OS	Accelerometer PPG Heart Rate Sensor	Executes small-factor algorithms directly on the device Open to community contributions for customization	Bluetooth GATT protocol

Table 2 Augmented and Virtual Reality Platforms

Technology	Input	Output	I/O data format and samples
TeamViewer - Frontline	Voice Commands and gesture controls Gathers real-time data from the environment and devices	Displays instructions, highlights objects, and provides real-time annotations Offers step-by-step instructions, checklists, and guided workflows for consistent and accurate task execution	--
Hololight Hub	Web Interface: -User data -Application data -Training data (files, workflows, assets) XR Client: -User input	User session data Application instance on cloud	--
Hololight Stream	User Input	Pixel Stream	--
Hololight Space	3D models (CAD/Digital Twin files) User input through interaction Custom data - AI enhanced content, JSON, text/image/speech, PDFs etc. Sensor data - camera, microphone	XR representation/XR space; Sensor data - head pose, SLAM, user input; Visualization of 3D models	--
SLB for AMT training	User input through interaction with XR device	3D visualization	--

Table 3 Smart Service, IoT, and IIoT Integration

Technology	Input	Output	I/O data format and samples
Ultron - Smart Assistance	Gathers information about its environment from the sensors of the AR platform Voice commands Detects the state of the user including emotions	Provides information access in the device Allows communication with others Manages device operations Over API to any given service	--
Oculavis SHARE	Input from technicians and experts for remote guidance Data from maintenance processes managed through the integrated ticketing and work order system User Data for Login	Provides virtual elements overlaying the real world to guide technicians Delivers precise instructions during visual assistance calls User Session Data Provides a platform for resolving support tickets and accessing knowledge resources (Service and machine documentation)	--

Clawdite	Streams data from devices such as smartphones, Raspberry Pi, PLCs, etc., through dedicated agents Collects and manages historical data from gateways and functional modules	Offers components for modeling digital twins that can be reused and extended. Supports modular integration, allowing for additional functionalities as needed Interface with Clawdite APIs and JSON data format	JSON data format
Service Connector Core	Collects data from different clouds, databases, APIs, and services. Each connector can have specific options passed as arguments to providers, parsers, and consumers	Data conversion Engine for data interoperability across various systems	MQTT JSON; Easily extendable to support other data formats

Table 4 Explainable AI (XAI) and Machine Learning Technologies

Technology	Input	Output	Input/Output data format and samples
Active Learning	Labels dataset Human annotations to the model It will be a web service, the data transferred to the Web Service would be in a JSON format	Trained model with better predictions and accuracy	--
NeuroSymbolic AI	Web Service that will take as inputs images / texts / videos. Recognizes and processes attributes such as color, shape, and size to make predictions.	Identifies and recognizes images, attributes, and produces results based on the embedded representations	JSON
Generative AI as a Service	Chat messages via OpenAI API Data formats JSON, CSV, PDF, TXT Proprietary knowledge for LLMs Use-case specific metadata for context User input/query in text form	Generated text responses to be rendered in XR	Chat messages via OpenAI API Data formats JSON, CSV, PDF, TXT Proprietary knowledge for LLMs Use-case specific metadata for context
Explainable AI (XAI)	Ontology/Knowledge graph interface for creating, editing, managing and querying ontologies/knowledge graphs Context extraction interface for loading and managing context models based on standardized data	Generates explanations contextualized to specific domains and knowledge	--
Integration and Visualization of AI/XAI	Input of 3D virtual content for rendering Data regarding user interactions within the XR environment Inputs from speech-to-text and text-to-speech services for AI	AI/XAI visualizations rendered in XR environments Rendering of virtual multimedia content including 3D models AI-driven recommendations displayed within the XR environment	--
	API calls (i.e. json)		

Table 5 Data Management and Analytics

Technol ogy	Input	Output	Input/Output data format and samples

LeanXcal eDB	Historical data that can be ingested for further analytical processing or real-time data generated by the XR devices	Provides real-time analytical results while ensuring data consistency	Standard JDBC/ODBC Python drivers Integration with Spark, Flink, Kafka via the usage of custom connectors
Training Repository	--	--	JSON, XML

3.4 Schematics and Internal Architecture/Design of each Component

In this section that concerns to the Schematics and Internal Architecture/Design of each Component, the information is described for the different categories of technologies in XR5.0.

Hardware and Operating Systems

This schematic provides an overview of the Almer OS technology stack for AR devices, showing the various components and stakeholders involved, along with their functions (Figure 5).

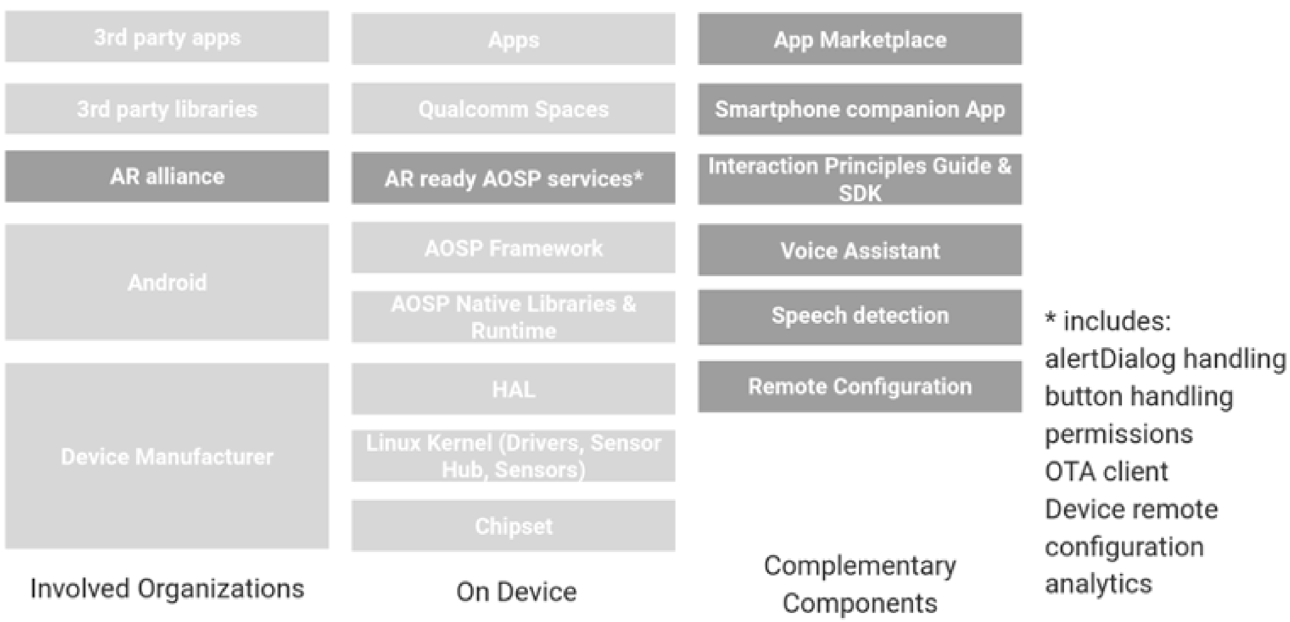


Figure 5: Schematics concerning the Almer OS component

Almer OS Technology integrates hardware and software for a flexible, Android-based AR platform. This consists in partnerships with third parties and uses Qualcomm's AR technologies, creating a robust environment for developers. The architecture of the device also includes basic components for voice-control, remote configuration and a smartphone companion app that can make it feasible in a wide range of AR settings.

Augmented and Virtual Reality Platforms

The below figure (Figure 6) depicts a modular and integrated approach for the XR training environment using XR5.0 technologies. This training platform is scalable and adaptable to different training needs being a centralized interface for XR managing applications and accessing training resources. This platform will be accessible by a Custom Frontend Admin View providing an administrative view, allowing admins to monitor and configure various elements on the platform as the available XR applications, Cloud Repository for accessing training assets, Training programs, and User management and Settings panels. API connections will be done by Backend APIs connect the Hololight Hub, Cloud Repository, and Training Assets & Programs modules to the main training platform, whereas 3rd Party Provider Authoring Tool also integrates with the platform, enabling content from external providers to be accessible within the training environment.

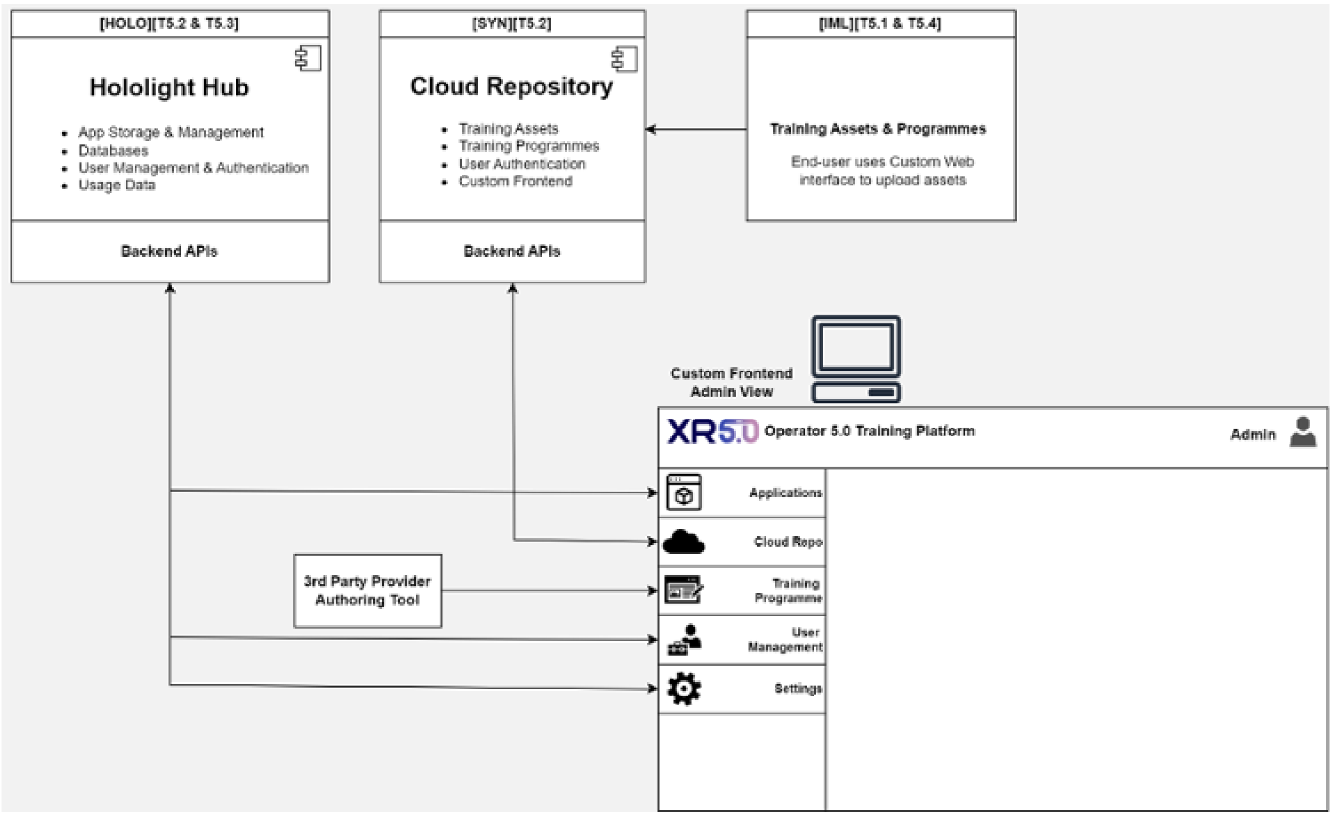


Figure 6: Visual schema of the XR5.0 Operator 5.0 Training Platform

The architecture of the XR5.0 Operator 5.0 Training Platform integrates various components to deliver XR applications for training. This setup provides a cloud-based solution to deliver XR training applications, allowing resource-intensive XR experiences to run on lightweight XR devices. The centralized architecture enables scalability and AI driven models allowing to create a powerful training environment that leverages cloud computing and streaming technology. The components are the Human-Centric Digital Twin, AI Models and Cloud Repository (WP5): Stores training assets, applications, and related data, making them accessible for XR applications. An AWS Cloud Server allows multiple XR apps to operate in parallel and provides scalability to handle high-performance needs. The streaming will be done by the Hololight Stream streaming of XR applications directly from the cloud to XR devices, ensuring that computationally intensive tasks are processed remotely, while the XR device only handles the display and interaction. The Hololight Hub acts as the central hub for managing and storing applications. Figure 7 illustrates the architecture of the XR5.0 Operator 5.0 Training Platform.

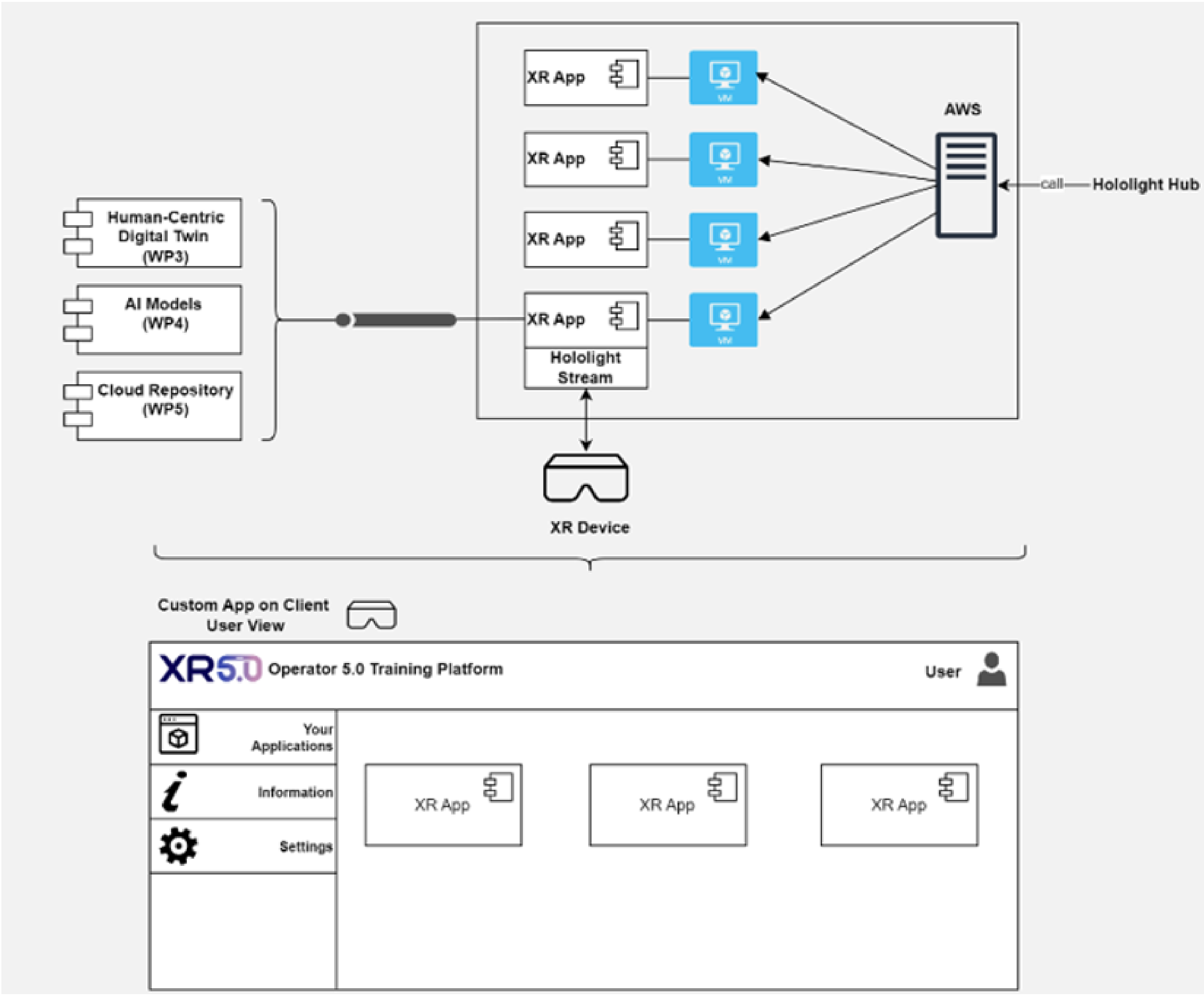


Figure 7: Architecture of the XR5.0 Operator 5.0 Training Platform

Smart Service, IoT, and IIoT Integration

The Star Topology Call is an important component of Oculavis SHARE. The Star Topology Call Component is designed for a real-time communication system. It integrates multiple services to manage effectively peer-to-peer connections, media streaming, and signaling (Figure 8).

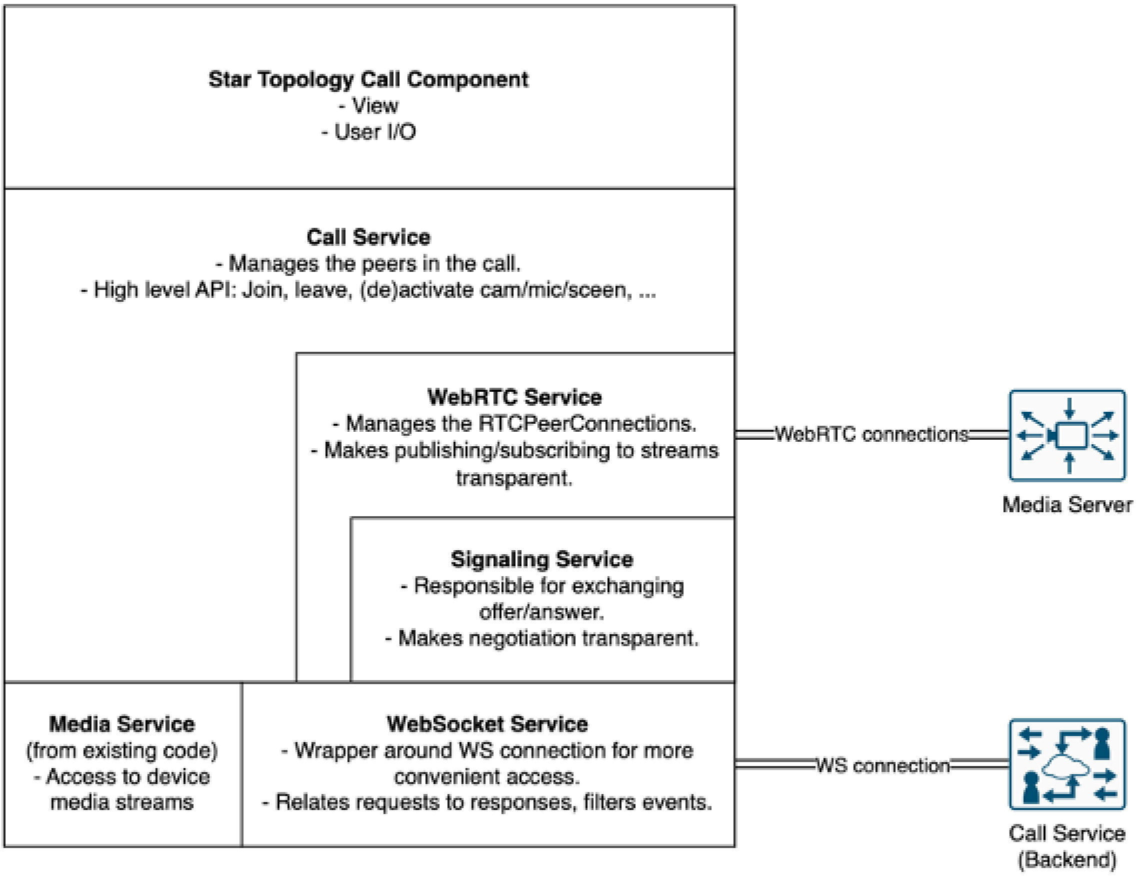


Figure 8: Logic flow of the Star Topology Call Component

The general architecture of Oculavis SHARE is described in the following image. This provides a holistic view of the entire system, emphasizing multi-platform client integration and additional services such as 3D asset delivery (Figure 9).

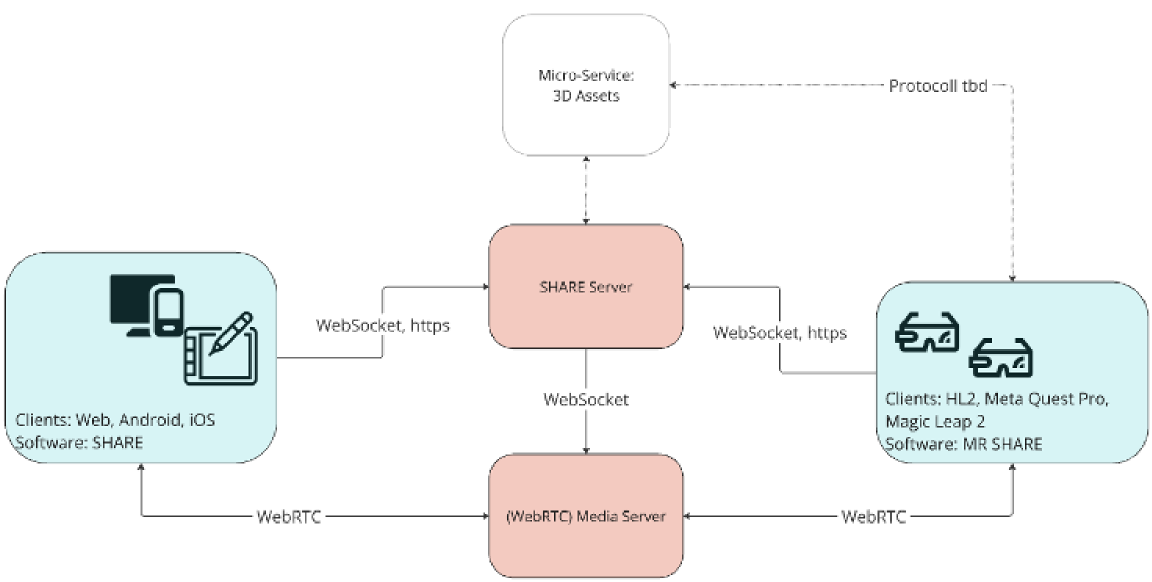


Figure 9: General architecture of Oculavis SHARE

The Clawdite platform architecture offers a modular and adaptable framework optimized for Industrial IoT use cases. It focuses on facilitating data exchange, across different industrial systems to ensure interoperability and scalability. Its core components are as follows: i) Gateways: Act as interfaces to stream data to the IIoT Middleware in predefined formats. They can be deployed on various devices like Raspberry Pi, smartphones, tablets, and PLCs; ii) IIoT Middleware: Manages and distributes data streams across architectural components, integrating different middleware solutions to suit specific application needs; iii) Historical Data Manager (HDM): Stores and retrieves historical data from Gateways and Functional Modules, enabling reporting and analytics since most middleware solutions lack this functionality; iv) Orchestrator: Oversees platform organization and management, including Digital Twin instances, installed modules, sensors, workers, and adopted message schemas; and v) Functional Modules: Pluggable external components that enhance the platform's capabilities (e.g., fatigue monitoring). They process data from the Middleware and Orchestrator and share the results with the platform. Figure 10 depicts these components.

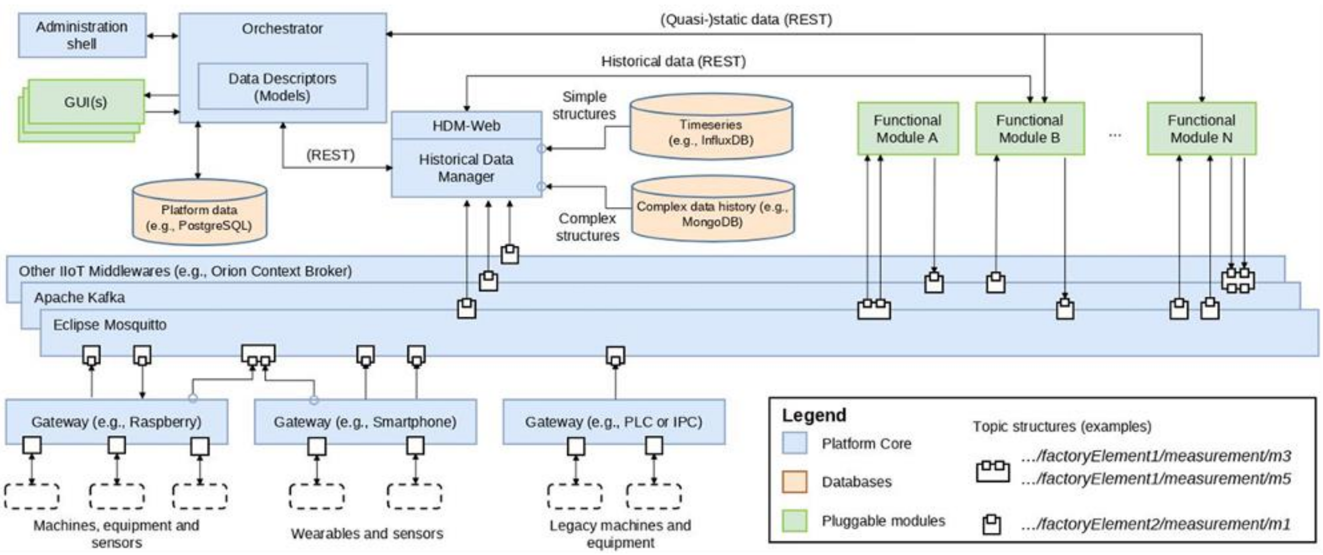


Figure 10: Architecture of Clawdite

The architecture of the Service Connector Core enables efficient and flexible data processing by integrating the data from different sources, parsing and sending this data to end-users or applications in real-time. This setup is crucial for XR5.0, which would require real-time monitoring and data-driven decisions for adapting training programs to the user. The data flow will be sent from the providers into its corresponding parser, where it is processed and formatted. The parsers send this processed data to the consumers. Therefore, its main features are: i) interoperability: Linking various data sources (providers) to different applications or systems; ii) Real-Time Data Ingestion; and iii) Scalability: where Multiple providers and consumers can be added being adaptable to changing data needs (Figure 11).

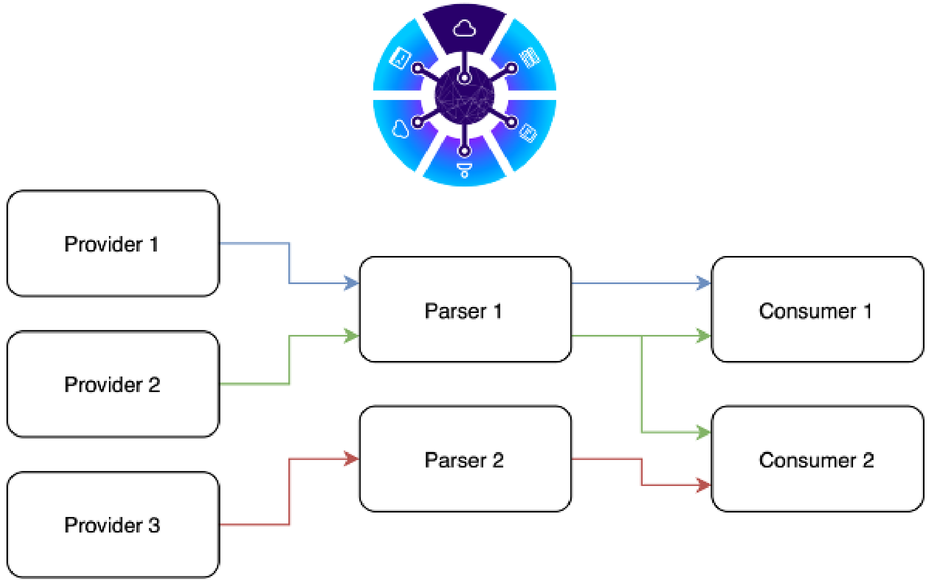


Figure 11: General architecture of the Service Connector Core

Explainable AI (XAI) and Machine Learning Technologies

Generative AI as a Service joins expert domain-specific knowledge with advanced language processing to provide real-time and personalized context-driven responses. XR-AI API combined with LLM Pipeline Engine provides a natural conversational interface to the XR environment enhancing user experience within the XR environment. In the example architecture illustrated in Figure 12, Domain Specific Knowledge is integrated with an LLM Pipeline Engine to provide contextualized responses for an XR System through an XR-AI API.

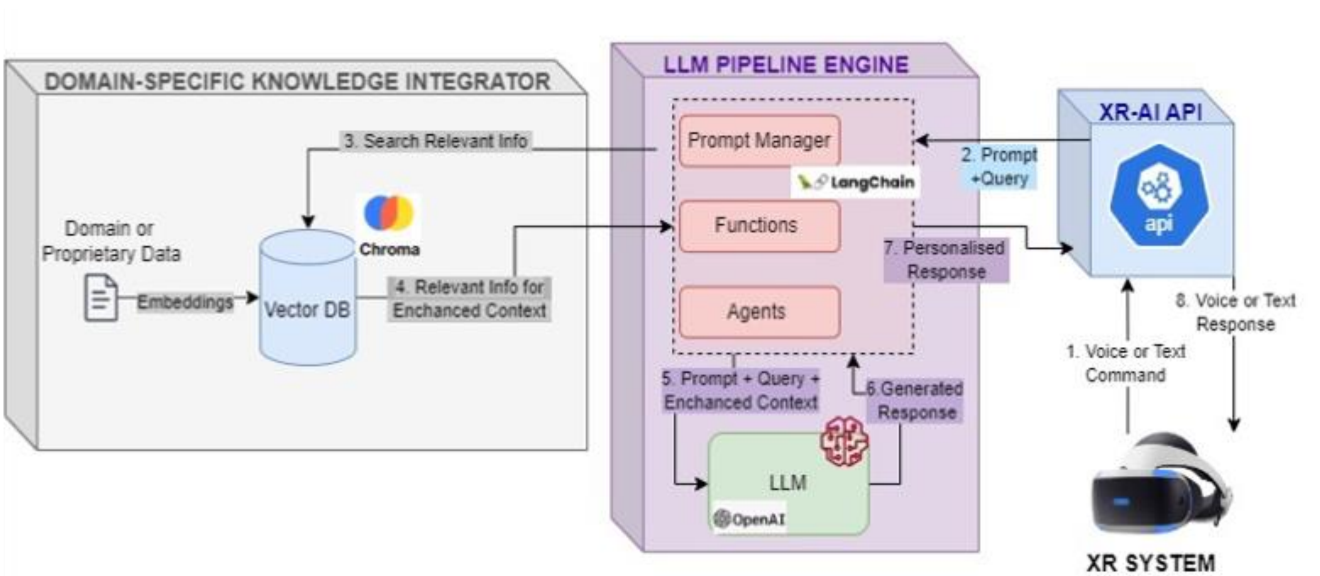


Figure 12: Architecture of Generative AI as a Service

A potential application within XR5.0 project is for transforming user manual PDFs into an AI-accessible, queryable format, allowing for interactive, context-aware responses to user questions. The integration of text chunking, embeddings, and a vector database ensures that the information is stored and queried efficiently. This diagram illustrates a workflow for processing a User Manual (PDF) and making it accessible through a query AI agent using OpenAI embeddings and a Chroma DB for document indexing and querying.

This diagram (Figure 13) illustrates a workflow for processing a User Manual (PDF) and making it accessible through a queryable AI agent using OpenAI embeddings and a Chroma DB for document indexing and querying.

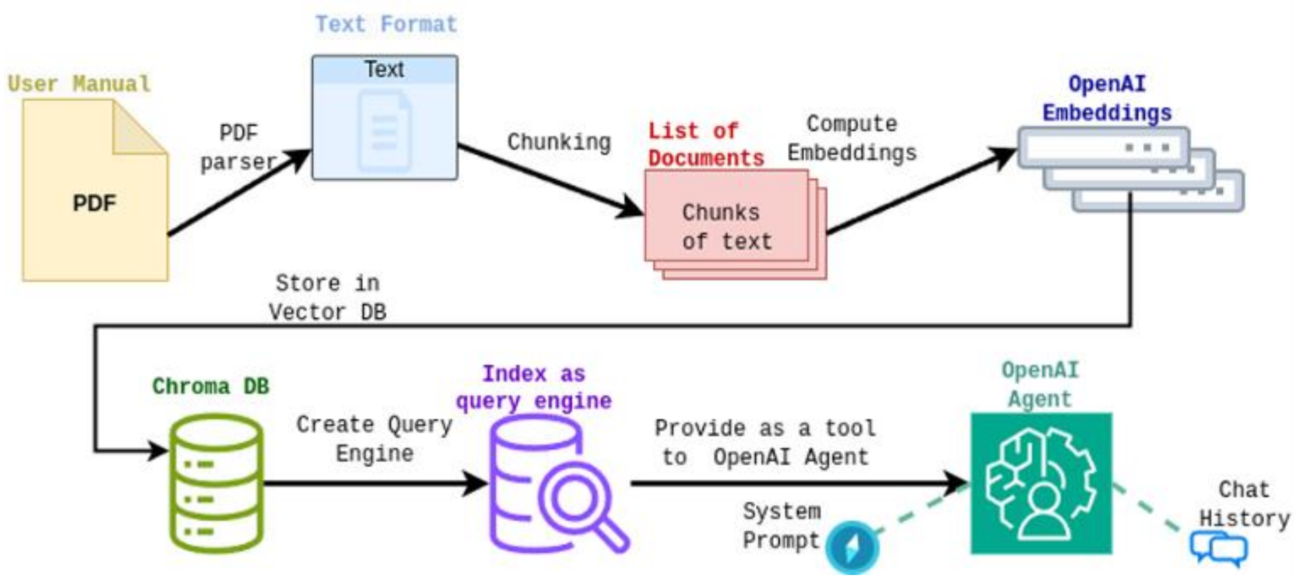


Figure 13: Logic workflow for processing PDF text using Generative AI

ATB's Explainable AI (XAI) uses a Context Awareness Approach by building upon interaction and flow between different modules responsible for providing, extracting, modeling, and monitoring contextual data to enhance the interpretability and usability of the XAI system. This context-awareness approach enhances the XAI component by dynamically adapting explanations to align with the specific situation, environment, or user preferences. This approach is described in Figure 14.

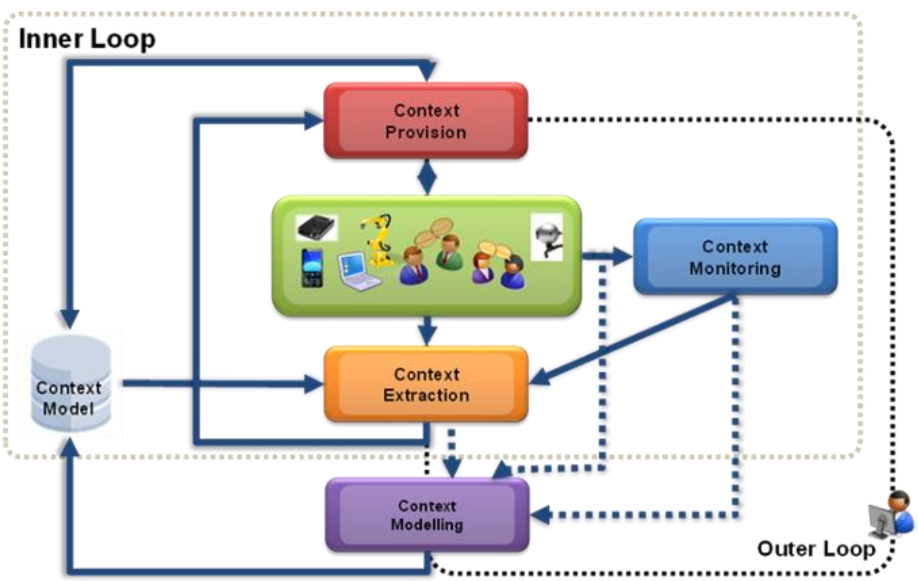


Figure 14: Schema describing ATB's Explainable AI (XAI)

Figure 15 illustrates the architecture of the context-aware system applied to the ATB's Explainable AI (XAI) component to enhance its service by dynamically adapting to environmental and situational factors. It focuses on how context information is collected, extracted, monitored, and utilized to deliver a tailored service, with the involvement of a structured Context Ontology to formalize and represent knowledge.

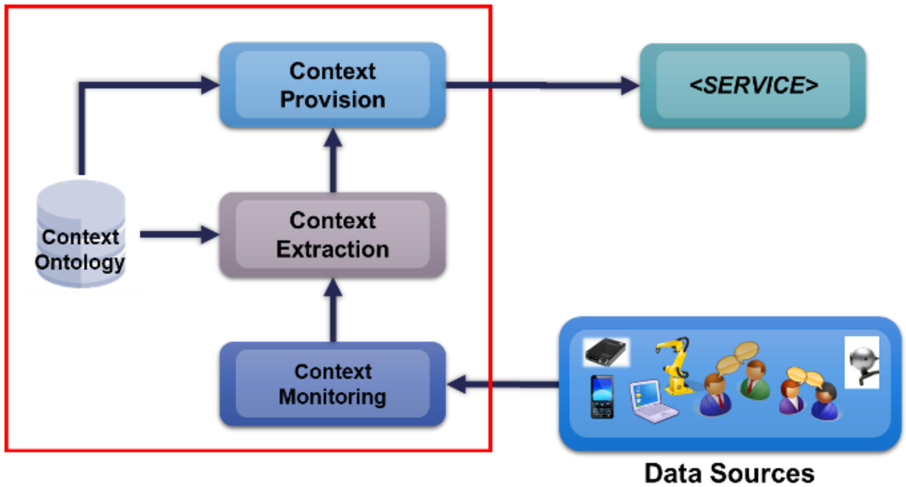


Figure 15: ATB's Explainable AI (XAI) flow diagram

Data Management and Analytics

As for the LeanXcaleDB, the following diagram depicts its components, data flow, and integration with external tools and frameworks. The key components include the i) Data Lake that acts as the main repository for storing data; ii) Query Engines to handle data retrieval and processing, iii) Distributed Data Nodes to store portions of the data and enable distributed query execution; iv) Transactional Engine and Data Node Management to coordinate data node operations; v) Direct API providing unified interface for interacting with external tools and services; vi) Connectors for External Frameworks (i.e. Kafka, Spark, Flink, OData) as Data Sources, Spark Processing, Stream Processing and Mobile Apps.

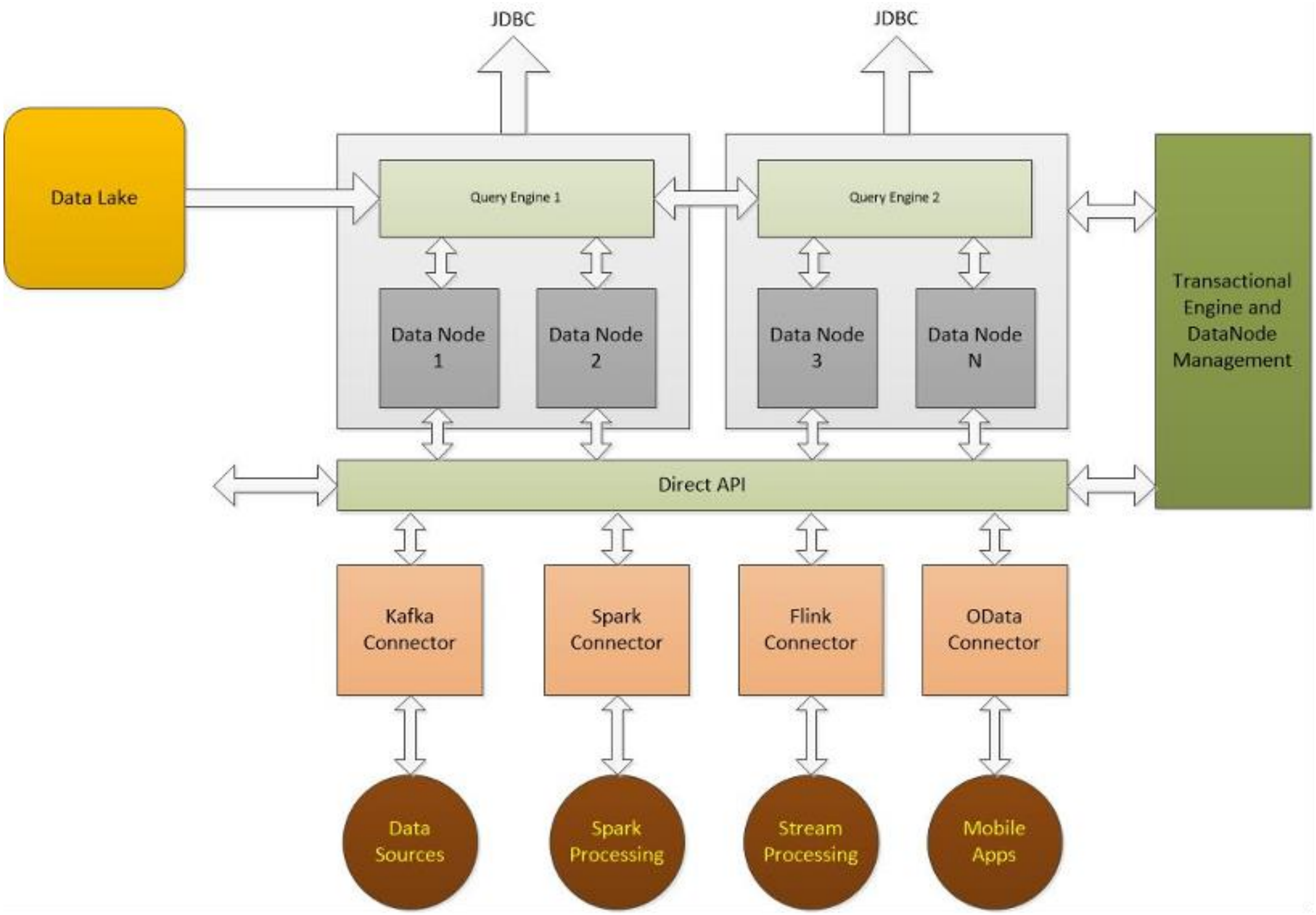


Figure 16: Schema describing LeanXcaleDB

3.5 Software Requirements and Dependencies of each Component

Hardware and Operating Systems

The hardware and operating systems used in the project are complimentary, having unique needs and requirements to work appropriately. The Almer 2 Arc has no software or hardware dependency and only requires a stable Wi-Fi connection. Almer 2 can operate standalone without using any external applications or third-party software components. The Almer OS is designed to operate on an AR hardware, such as the Almer Arc or RealWear Navigator. For compatibility, the AR device must support Android 9 or higher. Since Almer OS relies on the Android operating system environment, the devices should be compatible with this OS specification and have AR capabilities. Beyond this, no additional dependencies are required. The Wearable OS has no specific software or hardware requirements or dependencies

Augmented and Virtual Reality Platforms

For the Augmented and Virtual Reality platforms, namely, TeamViewer Frontline, Hololight Hub, Hololight Stream, Hololight Space, and SLB for AMT training, these have specific requirements and dependencies that are described below. TeamViewer Frontline requires minimal setup, needing only web access and an AR device running at least Android 9. SLB for AMT Training has no specific requirements just the hardware that is based on Meta Quest 3 devices. The requirements for the Hololight technologies are described in Table 6.

Table 6 Requirements for the Hololight technologies

Hololight Hub	**Hardware:** Device-specific client application for XR access. **Network:** A stable, low-latency internet connection. **Software:** Unity-based applications built with Hololight Stream SDK deployed on Microsoft Windows OS.
Hololight Stream	**Hardware** (Minimum): • OS: Windows 10, 11, or Server 2019 • Memory: 16 GB • CPU: Intel i5 8th Gen. (6 Cores) or AMD Ryzen 7 3700X • GPU: NVIDIA GTX 1070Ti or NVIDIA GRID for VMs • Storage: SSD or NVMe • Network (Minimum): • Network: 5 GHz Wi-Fi • Bandwidth: 20 Mbps • Latency: <100 ms **Development Environment**: • IDE: Visual Studio 2019 or 2022 with components for Universal Windows Platform, Unity, and C++ development. • Unity Version: 2021.3.x with Universal Platform Build Support and Windows Build Support IL2CPP. • MRTK Version: 2.7.x or 2.8.x. **XR End-Device**: Requires internet access and must support STUN (Session Traversal Utilities for NAT) and TURN (Traversal Using Relay around NAT) protocols.
Hololight Space	**Server Requirements:** • OS: Windows 10 20H2 or above • DirectX: Version 10 or above • Memory: 8 GB • Graphics Memory: 4 GB on a dedicated graphics card • Processor: x86, Quad-core **Client Requirements:** • OS: Windows 10 version 17763.0 or higher • Architecture: ARM **Connectivity:** • Hololight Stream Ports: Port 9999, UDP and TCP protocols. • WebRTC Ports: Ports 16384-32768 for SRTP/TURN, using UDP for incoming media streams.

	• Standalone Runtime Broker Ports: Port 17321, TCP for the Hololight Space double-click receiver.

Smart Service, IoT, and IIoT Integration platforms

Ultron Smart Assistance and Oculavis SHARE have minimal or no dependencies, making these technologies easy to deploy. Clawdite and Service Connector Core require a more sophisticated setup, based on Docker, NodeJS, and npm to support IIoT functionalities and seamless integration with additional external components.

Ultron - Smart Assistance requires minimal setup, needing only internet access and an AR device running at least Android 9.

Oculavis SHARE is a web-based platform designed for remote collaboration and maintenance tasks. It includes MR applications and dedicated apps for iOS and Android, being accessible across different devices. The supported devices are the following: i) ***Microsoft HoloLens 2*** for immersive MR applications; ii) ***Magic Leap 2*** for advanced AR functionalities; iii) ***Smartphones and Tablets*** where native apps are available for both iOS and Android platforms for mobile access; and iv) PC for accessing through web browsers for desktop use.

Clawdite requires IIoT Middleware to enable connectivity with industrial IoT devices; an Historical Data Manager, Orchestrator; Functional Modules, where additional external components can be plugged in to provide specific functionalities. It also demands the following software requirements: Docker, for containerized deployment, enabling scalability and consistency, and NodeJS, for running JavaScript-based applications and services within the platform. The Service Connector Core is dependent on Node - the runtime environment needed for executing JavaScript code server-side and a Node Package Manager that is used to manage dependencies and install necessary packages, enabling the Service Connector Core to integrate effectively with other components and services.

Explainable AI (XAI) and Machine Learning Technologies

Most components within this suite are designed with minimal or no specific requirements. ATB's Explainable AI (XAI) requires Docker, as the tool is developed in Java and packaged within a Docker container, ensuring compatibility across different environments. ***Generative AI as a Service*** is based on Docker and Python 3.10+. Docker allows containerized deployment, making it easier to maintain consistency and scalability across various systems. The dependency on Python 3.10 or above ensures compatibility with the latest machine learning libraries and frameworks.

Data Management and Analytics

The LeanXcaleDB has no specific requirements, being a flexible component not requiring additional software or hardware. The Training Repository component Docker, OwnCloud, and MySQL/MariaDB. Docker provides a containerized environment. OwnCloud serves as the primary file storage and management platform, while MySQL/MariaDB acts as the database backend.

3.6 Authentication Mechanisms supported by each Component

Hardware and Operating Systems

Almer 2 Arc relies on unique device-based identities managed through MongoDB Realm. Each Almer Arc device has its own identity, which is independent of the end user, ensuring device-level authentication. Wearable OS employs Bluetooth GATT (Generic Attribute Profile) for authentication, supporting low-energy, device-specific connections.

Augmented and Virtual Reality Platforms:

TeamViewer - Frontline uses custom authentication tailored to the platform's specific requirements. Hololight Hub integrates OAuth JWT for secure token-based authentication and supports Microsoft Single Sign-On (SSO) for enterprise-level access. Hololight Stream, Hololight Space, and SLB for AMT training do not require authentication (N/A).

Smart Service, IoT, and IIoT Integration:

Ultron - Smart Assistance does not require authentication, as it is a service that runs directly on the device and operates independently of user-specific credentials. Oculavis SHARE uses Microsoft SSO authentication enabling users to authenticate using their existing Microsoft accounts. Clawdite and Service Connector Core do not require authentication.

Explainable AI (XAI) and Machine Learning Technologies:

Generative AI as a Service employs Auth0 for identity management, JWT for secure token-based authentication, and standard Username/Password credentials for access control. Integration and Visualization of AI/XAI CYENS' technology incorporates authentication mechanisms to ensure secure access, including the following: API Authentication – OAuth (Open Authorization) to allow secure, token-based access to the XAI component's APIs; and Token-based authentication for session management and secure user access. These mechanisms work together to protect data integrity and confidentiality while supporting integration into other project frameworks. Active Learning, NeuroSymbolic AI and ATB's Explainable AI (XAI), and do not require authentication.

Data Management and Analytics

LeanXcaleDB component complies with the standard authentication mechanisms defined in JDBC/ODBC protocols for secure and reliable access to the system. The Training Repository uses Auth0 to manage authentication and authorization; JWT (JSON Web Tokens) a token-based authentication mechanism; Username/Password; or None indicating that no authentication mechanism is implemented or required for specific components.

4. THE ARCHITECTURE DESIGN METHODOLOGY WITHIN TOGAF

The Open Group Architecture Framework (TOGAF) is an established, widely used methodology for developing, managing, and governing enterprise architecture. Initially developed by The Open Group in the mid-1990s, TOGAF has evolved into one of the most recognized and adaptable frameworks for aligning business and IT strategies [6]. Its structured approach provides a comprehensive methodology for designing, planning, implementing, and maintaining enterprise architectures that align IT investments with business goals, enabling organizations to be more agile and responsive in a rapidly changing environment.

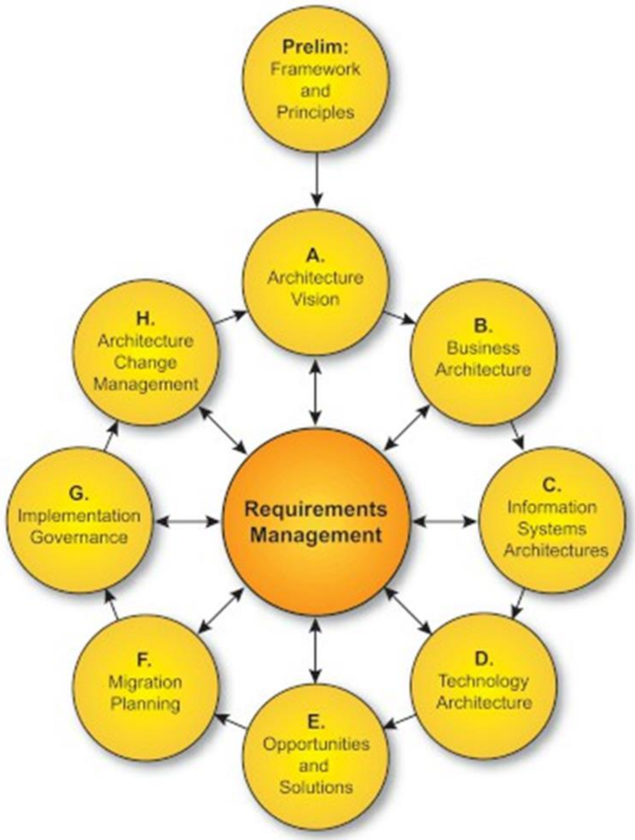


Figure 17: TOGAF Architecture Development Cycle

TOGAF has nine ADM phases of iterative development. This ADM cycle according to TOGAF is depicted in Figure 17. Briefly, the phases can be categorized as follows:

- ➢ The first category consists of the preliminary and phase A, phases that set out the key issues of the problem and serves as a starting point to create the enterprise architecture team and for establishing the vision of the Architecture.
- ➢ The “development” category, which consists of phases B to D. These are phases in which the requirements engineering takes place and in which the various aspects of the architecture are implemented.
- ➢ The “transitional” category, which consists of phases E and F and concerns transitioning and changes of the architecture.
- ➢ The governance category, which establishes how changes in architecture are implemented and how it is maintained.

Not all, but 5 ADM phases were implemented in XR5.0. The following sub-chapters outline the application of TOGAF’s ADM phases in the XR5.0 project, detailing the structured development of Business, Application and Technology layers to achieve Industry 5.0 goals. It is highlighted how foundational principles, stakeholder engagement an iterative design ensured a scalable and integrated architecture leveraging XR and AI technologies.

4.1 Preliminary phase - Framework and principles

The Preliminary Phase establishes the foundational elements necessary for guiding the architectural development process. For this project, this phase involved defining the scope of the architecture, identifying key stakeholders, and aligning with organizational objectives and industry standards.

Key activities included:

- ➢ **Establishing the Architecture Vision**: Ensuring alignment with Industry 5.0 goals to enhance operator effectiveness through XR and AI technologies.
- ➢ **Defining Architecture Principles**: Emphasizing modularity, scalability, and interoperability to support evolving needs and integration across layers.
- ➢ **Identifying Key Stakeholders**: Addressing the needs of operators, training managers, remote experts, and developers as central to architectural design.
- ➢ **Laying the Framework**: Selecting a structured approach incorporating the business, application, and technology layers for iterative development and alignment with TOGAF principles.

This phase provided the necessary framework and principles to ensure the architecture is robust, adaptable, and aligned with project objectives, setting the stage for detailed development in subsequent phases.

4.2 Phase A - Define the architectural vision

Within TOGAF, Phase A serves to define the architecture scope, include stakeholder concerns and establish any hard constraints imposed by any internal (technical) or external source (organizational or legal). It is within Phase A that the adherence to the vision is continuously adhered to.

In XR5.0, we made sure that the vision was well defined in both design and implementation. Moreover, there was a strong effort to requirements being collected and discussed with the pilots before any major design decisions were made.

4.3 Phase B through D - Define the Business, the System and the Technical Architecture

This chapter addresses the detailed architectural development undertaken during the **Business Architecture (Phase B)**, **Application Architecture (Phase C)**, and **Technology Architecture (Phase D)** phases of the TOGAF ADM cycle for the XR5.0 project.

Business Architecture

In Phase B, the project identified the key business functions and services needed to support operators in an Industry 5.0 environment. These include training services, maintenance assistance, and real-time monitoring services. Business services such as **Personalized Training Service**, **Predictive Maintenance**

Service, and **Production Line Monitoring Service** were defined to meet the operational goals of efficiency, safety, and skill enhancement. These services are underpinned by business functions like **Visualization of Augmented Information** and **Fusion of Data and Services into XR Environments**, which access critical business objects such as IoT data, ERP data, and training workflows.

Application Architecture

Phase C focused on mapping the application components and services needed to realize the defined business architecture. The project designed key application components such as:

- **XR Apps**, including training and assistance plugins managed by the Central XR Hub
- **AI Models**, enabling advanced capabilities like generative AI, defect recognition, and process optimization.
- **Cloud Repository**, offering storage and retrieval functionalities for training materials and workflows.

These components collectively deliver services like **XR Visualization Service** and **Data, Image, and Video Processing Service**, ensuring seamless integration of XR and AI technologies into the operator's workflows.

Technology Architecture

In Phase D, the technical foundation supporting the application and business layers was established. A **Kubernetes Cluster** hosts the applications, with automated deployment pipelines leveraging CI/CD principles. The **Virtualization Platform** provides scalable resource provisioning for virtual machines, while communication networks ensure connectivity between external stakeholders and internal systems. Services such as **Application Deployment Service** enable efficient and automated operations across the architecture.

Together, the business, application, and technology layers are integrated to deliver a comprehensive and scalable architecture. This alignment ensures that the XR5.0 framework addresses the project's objectives while remaining adaptable to future enhancements.

5. Enterprise Architecture

Enterprise Architecture serves as a structured approach to align an organization's business goals, application systems and technology infrastructure, ensuring that all components work cohesively to achieve strategic objectives. In this project, Enterprise Architecture is leveraged to design and implement the XR5.0 framework, a cutting-edge solution that integrates AI and XR technologies within Industry 5.0 environments.

The architectural design follows the TOGAF ADM framework [6] introduced in chapter 4 and is represented using ArchiMate [3], a standardized modeling language that facilitates clear and consistent communication between stakeholders. ArchiMate's layered approach ensures that the business, application and technology dimensions are comprehensively addressed, while its viewpoints enable focused exploration of specific concerns, such as organizational roles or value streams. It enables a structured and visual representation of complex systems, and the language supports a layered approach, with the Business Layer capturing the services, processes and functions that deliver value to stakeholders; the Application Layer focusing on the software systems and data flows that support business operations; and the Technology Layer addressing the physical and virtual infrastructure needed to deploy and operate the applications. It also includes a variety of viewpoints, such as the organizational, value and motivation viewpoints, which enable stakeholders to examine the architecture from different perspectives. This flexibility ensures that the architecture remains comprehensive and adaptable to evolving requirements. In this chapter, ArchiMate diagrams are used to convey the XR5.0 architecture in a structured and transparent manner, demonstrating the alignment between Industry 5.0 business goals, innovative applications and the supportive technical infrastructure. This document will not cover ArchiMate in detail, however the reader is encouraged to explore its online documentation [3] or study Annex I which contains a brief explanation of the various ArchiMate elements that were leveraged in order to design the various layers of the XR5.0 in this chapter.

To this end, this chapter presents the Enterprise Architecture of the XR5.0 project, starting with a high-level vision (Chapter 5.1) and an organizational perspective (Section 5.2). Subsequently, the layered architecture is detailed in section 5.3, where the Business, Application and Technology layers are described, emphasizing their interactions and the realization of Industry 5.0 services.

Through this structured design, the architecture ensures that business requirements are effectively realized through robust applications and reliable technical infrastructure. The use of ArchiMate models supports the clarity and traceability of design decisions, enabling future iterations to build upon this initial framework.

5.1 Vision of the Architecture

The architecture is designed to align with XR5.0 strategic objectives, ensuring efficient delivery of value to all stakeholders. The Vision of Architecture provides a high-level overview of how key processes, capabilities and technologies work together to achieve the desired outcomes. This vision serves as the foundation for the subsequent design and implementation phases.

The value stream diagram included in this section illustrates how value is created and delivered, offering a clear understanding of the flow of activities and the enabling capabilities. The value stream diagram is a critical tool that visualizes:

- The stages where value is created or transformed within the project.
- The XR5.0 capabilities and resources required at each stage.
- The flow of value from initial inputs to final delivery to stakeholders

By providing a holistic view, the diagram ensures that the architecture remains focused on delivering value efficiently and effectively. For better comprehension of the diagram in figure 18, we provide the following definitions which are directly aligned with both ArchiMate's modelling language and TOGAF.

- **Activity (represented by an arrow, indicating the flow of task):** The specific tasks or actions performed at each stage of the value stream to transform inputs into outputs. The activity describes what is being done to create or deliver value.
- **Capability (depicted as a rectangle with rounded corners):** The skills, processes, systems or resources required to perform the relevant activity effectively. A set of capabilities ensure that XR5.0 can support the relevant activity and deliver the intended outcomes.
- **Value (represented by a rectangle with an ellipse inside):** The benefit or outcome delivered to XR5.0 stakeholders (training managers, operators, trainees, etc.) at each stage of the value stream. Value represents the reason the activities are performed, and the capabilities are leveraged.
- **Outcome (represented by a rectangle that includes an arrow pointing towards a target):** This element shows the focus on achieving the desired outcome, which is in XR5.0 the following: "Provision of a full-fledged XR and AI environment for improving Industry 5.0 operations"

According to Figure 18, the key stages of XR5.0 value stream are the following:

- **Stage 1:**
  - **Activities:** Provision of Augmented Information
  - **Capabilities Involved:** Creation of Digital Twins, Integration with IoT sensors and ERP systems, Defect Recognition, Product Variant Detection
  - **Value Delivered:** Improve efficiency and reduce onboarding time
- **Stage 2:**
  - **Activities:** Provision of Immersive Training
  - **Capabilities Involved:** Creation of Training Workflows through Generative AI, Rendering of Training Workflows in XR Environment, Conversion of traditional training assets into XR assets, Provision of environment for manually creating Training Workflows
  - **Value Delivered:** Boost training engagement and reduce failure
- **Stage 3:**
  - **Activities:** Step By Step Guidance
  - **Capabilities Involved:** Provision of a chatbot that guides the operator, recognition of technical components, provision of step-by-step instructions concerning maintenance procedures
  - **Value Delivered:** Increase efficiency and procedural accuracy, reduce complexity of assembly lines
- **Stage 4:**
  - **Activities:** Provision of Remote Assistance
  - **Capabilities involved:** Permission control, provision of industry internal data to remote expert, establishment of remote connection
  - **Value Delivered:** Improve troubleshooting and reduce on-site service
- **Stage 5:**
  - **Activities:** Provision of a handsfree digital assistance 24/7
  - **Capabilities involved:** Automatic production of Training Workflows, adaptation of maintenance tasks to the operator stress level, 24/7 support for maintenance and troubleshooting
  - **Value Delivered:** Increase sustainability and improve troubleshooting
- **Stage 6:**
  - **Activities:** Personalization

- **Capabilities involved:** Make use of personalized operator's feedback, optimization of human-machine interaction, processing and integration of operator's biometric data, adaptation of training workflows based on biometrics

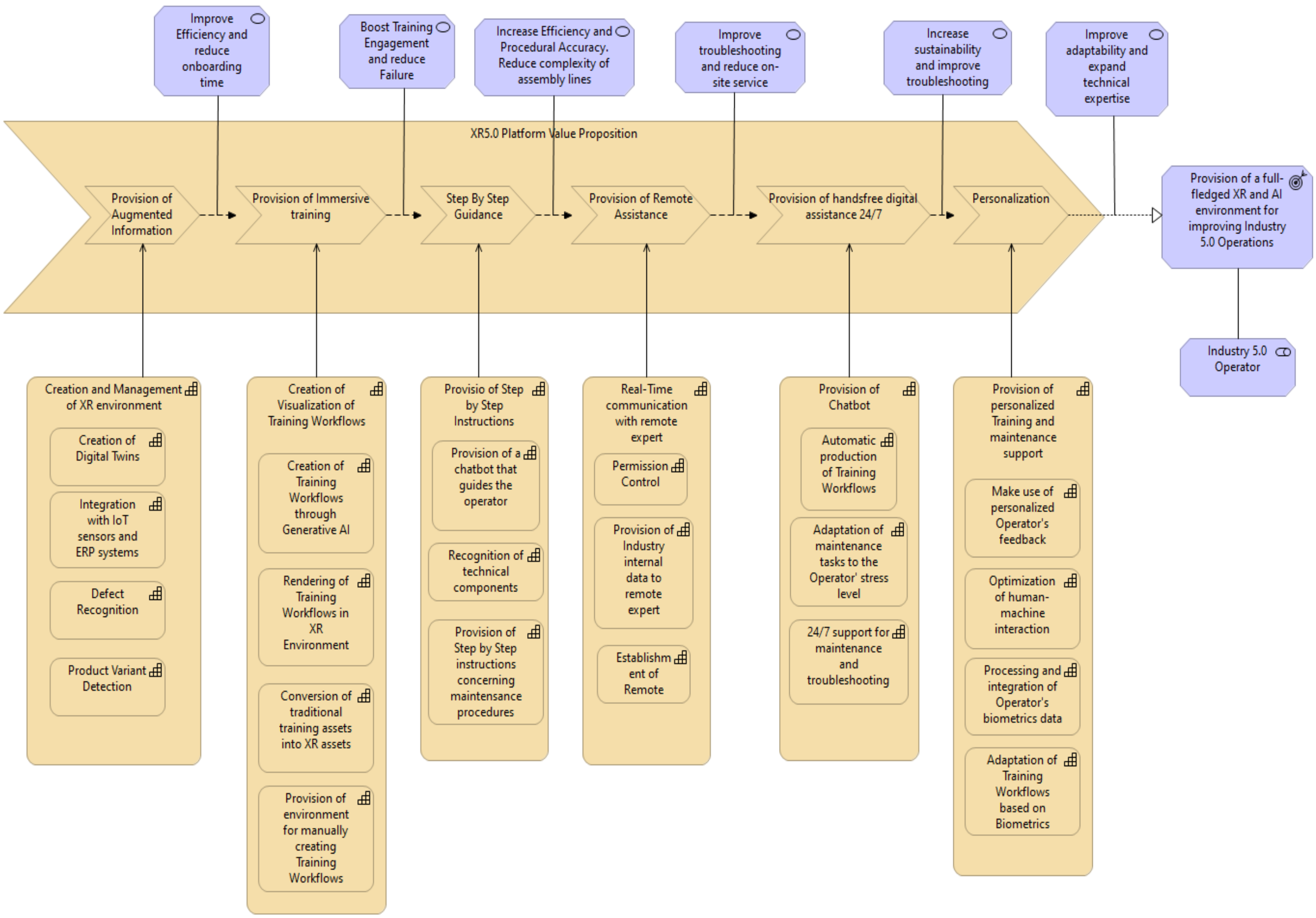


Figure 18: Vision of the XR5.0 Architecture (Value Stream- Strategy layer)

The vision of the architecture sets a clear direction for how this project will deliver value, ensuring alignment between XR5.0 strategic goals, operational processes and supported technologies. The value stream diagram highlights the flow of value and provides a guide for deeper analysis in subsequent chapters. In the next chapters we will explore the specific layers of architecture, namely business, application and technology layers.

5.2 Organization Viewpoint

The Organization Viewpoint focuses on visualizing the organizational structure of an enterprise. It is used to define and analyze the roles, responsibilities, collaborations and hierarchical relationships within an organization. The Organization Viewpoint is particularly valuable for addressing concerns about how the enterprise is structured and how different organizational entities interact. In this document, the Organization Viewpoint models and communicates the organizational structure of typical Industry 5.0

organization based on the feedback provided by the pilots as stated in Deliverable D2.1[2]. The Organization Viewpoint in XR5.0 is shown in Figure 19 and the key characteristics are the following:

- ➢ **Purpose of the diagram:** To model and communicate the organizational structure in Industry 5.0 settings. Also designing, deciding and informing.
- ➢ **Concerns:** Organizational hierarchy and roles, identification of competencies
- ➢ **Elements included:** Business Actors
- ➢ **Scope:** Single Layer/Single Aspect
- ➢ **Stakeholders:** Managers, employees, shareholders

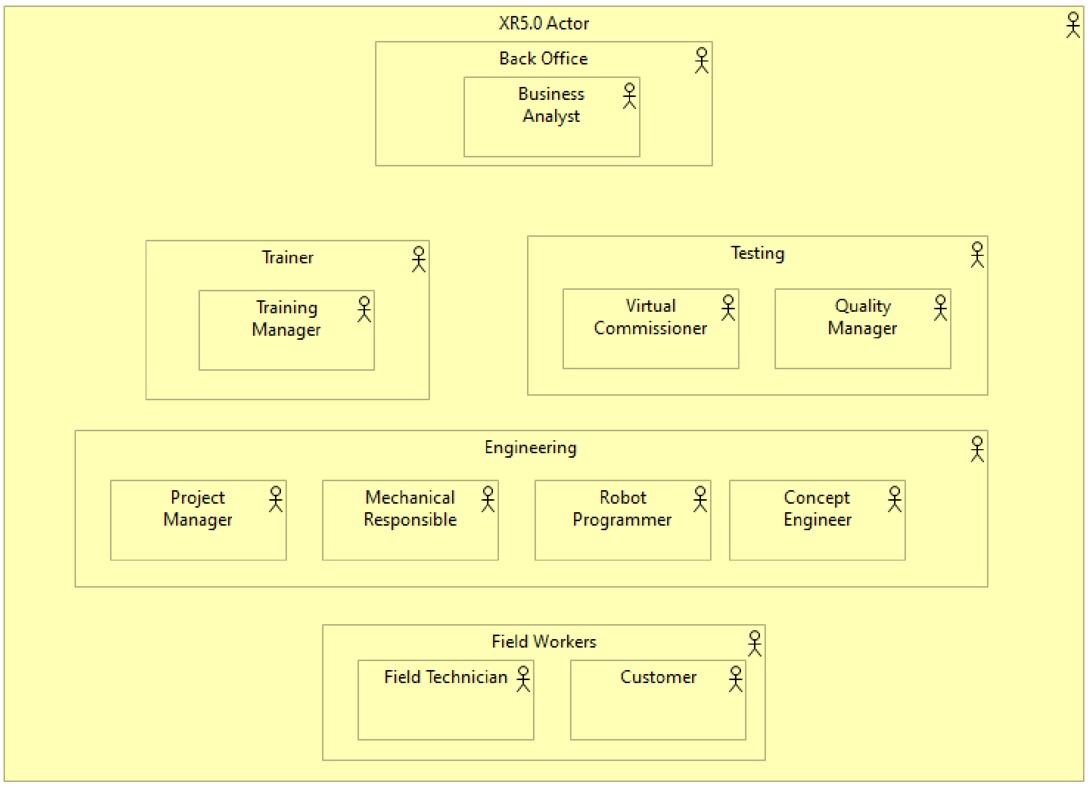


Figure 19: Organization Viewpoint of the Architecture

The interactions of those various actors with the XR5.0 system are described in chapter 6 of the Solution Architecture and more specifically, they are depicted in the System Context diagram.

5.3 Layers

The architecture of XR5.0 is structured using a layered approach, aligning with the principles of the ArchiMate framework. This approach ensures clarity, modularity and consistency across the various aspects of the system, allowing stakeholders to easily understand and analyze the relationships between needs, application capabilities and technological infrastructure.

The layers in this architecture serve distinct but interconnected purposes:

- ➢ **Business Layer**: This layer captures the high-level services, processes and functions that deliver value to stakeholders. It focuses on the activities and objectives of the operator and other roles involved in the XR5.0 ecosystem, emphasizing how the system supports training, maintenance and other business outcomes.

- **Application Layer**: This layer focuses on the software systems and their interactions, ensuring that the business services are effectively supported by well-defined application services, components and data flows. It includes innovative AI models, XR applications and other key components that bridge business needs with underlying technology.
- **Technology Layer**: This layer defines the physical and virtual infrastructure required to support the application layer. It includes elements such as virtualization platforms, communication networks and deployment services, ensuring the seamless operation of the applications and alignment with business goals.

By organizing the architecture into these layers, the result is having a holistic view of the XR5.0 system. Each layer plays a crucial role in achieving the overall vision while maintaining traceability and alignment between XR5.0 strategic objectives, implemented solutions and supporting infrastructure.

5.3.1 Business Layer

The business layer of the architecture presents the foundational services and workflows that empower the operator in an Industry 5.0 environment, leveraging cutting-edge XR and AI technologies. This layer bridges the needs of industrial operators with advanced technological solutions, ensuring efficient training, maintenance, and production monitoring.

The Business Layer diagram includes key ArchiMate elements that represent essential components of business architecture (see also Annex I):

- **Business Function**: Represents a specific activity or operation performed within the business, depicted as a yellow rectangle with an arrow inside pointing on the top.
- **Business Process**: A sequence of tasks or activities that together achieve a specific outcome, typically shown as a yellow rectangle with an arrow inside pointing on the right.
- **Business Object**: Represents information or data used or produced by business processes, shown as a yellow rectangle which holds another rectangle inside.
- **Junction**: Used to indicate decision points or paths where multiple flows converge or diverge, represented by a circle. (circle with black inside is an “and” junction and circle with white inside is an “or” junction)
- **Business Service**: Represents a service provided by the business to external stakeholders, shown as a yellow rectangle with ellipsis inside
- **Actor**: Depicts an entity, typically an individual or role, that interacts with the business, represented by a yellow human-like icon

As shown in figure 20, the business layer is enabling the operator to perform tasks more effectively through enhanced visualization, real-time assistance, and streamlined data integration.

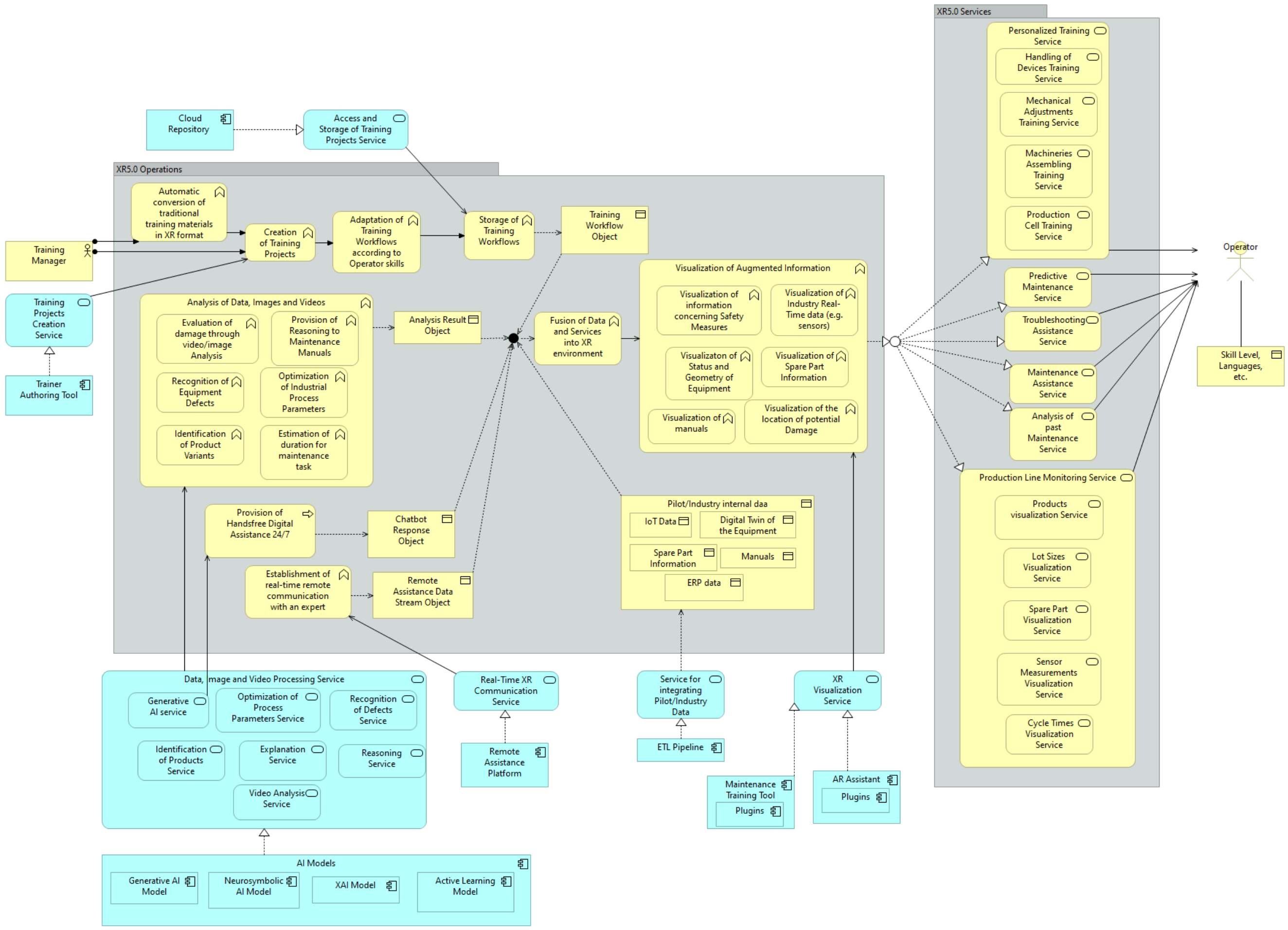


Figure 20: Business Layer of the Architecture

At the heart of the business layer lies the **Visualization of Augmented Information** function, which synthesizes and displays critical industrial data to the operator through XR glasses. This function supports a variety of sub-functions, such as visualizing real-time sensor data, safety measures, equipment geometry, spare part details, manuals, and potential damage locations. These capabilities are powered by the integration of diverse industrial data sources, represented collectively as the **Pilot/Industry Internal Data**, which includes IoT data, digital twins, ERP information, and more.

The **Fusion of Data and Services into XR Environment** function plays a pivotal role, acting as a junction where multiple workflows converge. These workflows ensure that the operator is equipped with accurate and up-to-date information. Inputs to this fusion process include training workflows, analysis results derived from AI-driven image and video processing, chatbot responses for 24/7 digital assistance, and real-time data streams from remote communication with experts. Together, these inputs enable a seamless and immersive XR experience for the operator.

Supporting this ecosystem are a range of business services that cater to the operator's key tasks. For instance, the **Personalized Training Service** delivers tailored training programs, covering areas like device handling, mechanical adjustments, and production cell operations. The **Maintenance Assistance Service** and related services provide proactive and reactive support for industrial equipment, while the **Production Line Monitoring Service** offers insights into product visualization, cycle times, and sensor measurements. These services collectively ensure that the operator has the tools and knowledge needed for effective decision-making.

The business layer is not isolated but tightly integrated with the underlying application layer. Key application components like the **Trainer Authoring Tool**, **Cloud Repository**, **AI Models**, and **ETL Pipeline** provide the technological backbone that realizes the necessary business services. For example, the **Trainer Authoring Tool** facilitates the creation of training workflows, while the **Cloud Repository** ensures storage and access to training materials. Similarly, the **AI Models** application component powers the analysis of data, enabling predictive maintenance and optimized industrial processes.

To further enhance operator capabilities, specific XR applications like the **Maintenance Training Tool** and the **AR Assistant** deliver immersive visualization and real-time assistance. These applications ensure that operators can interact intuitively with complex industrial systems, receiving relevant insights at the right time.

Finally, the inclusion of services like **Real-Time XR Communication** ensures that operators can connect with remote experts for collaborative troubleshooting, leveraging XR for effective guidance.

This business layer is a dynamic and interconnected framework that aligns industrial operations with state-of-the-art technological advancements. By focusing on visualization, real-time assistance, and seamless integration of data and services, it lays the groundwork for achieving the goals of Industry 5.0—enhancing human-machine collaboration and ensuring sustainable, efficient, and human-centric industrial practices.

5.3.2 Application Layer

In ArchiMate, the Application Layer describes the software applications and components that provide functionality to support business and technology operations. It includes application services, data objects, interfaces and relationships among these elements, defining how systems collaborate to meet organizational goals. For XR5.0 project, the Application Layer outlines the integration of AI models, XR applications, cloud resources and supporting platforms to deliver interactive and intelligent solutions.

As shown in figure 21, the Application Layer for XR5.0 project comprises a sophisticated ecosystem of software components and services that collectively support the creation, management and deployment of XR content and AI functionalities. The architecture is designed to facilitate immersive operator training, maintenance assistance and advanced AI-driven insights. The key elements and their roles are summarized below:

- **AI Models and Services:**
    - The **AI Models** application component consists of four specialized models: The **Generative AI**, **NeuroSymbolic AI**, **Active Learning** and **XAI Models**.
    - These models produce the **AI Produced Data**, which comprises data objects such as **Generated Content**, **Explanations**, **Learning Data**, **Symbolic Knowledge** and **Malfunction Detection Data**.
    - The AI Models also realize the **AI Services** grouping element, which includes the following services: (i) **Content Generation Service**, (ii) **Explanation Service,** (iii) **Model Update Service,** (iv) **Reasoning Service** and (v) **Video Analysis for Malfunction service**
    - These AI services are consumed by the **AR Apps** grouping element to enhance user experiences.
- **XR Apps and the Central XR Hub:**
    - **XR Apps** is a grouping element that integrates various plugins and application components for immersive content creation and streaming. Key components include:
        - **Streaming Solution Plugin:** It interfaces with **WebRTC Interface** to stream XR content, enabling rendering on the server rather than the XR glasses.
        - **Cloud Repository Plugin**: It facilitates content retrieval from the **Cloud Repository** application component.
        - **XR Training Plugin**: It is a plugin useful for visualizing training workflows.

    - **AR Assistant**: It visualizes the location of the damage and it also utilizes AI for damage recognition. Furthermore, it renders sensor data and checklists.
    - **Virtual Training Tool**: It processes and renders training programs using the XR Training Plugin. By using this tool, the operator can utilize a step-by-step guidance tool that enhances his training and improves his efficiency in maintenance actions. Also, it visualizes 3D models and AI recommendations.
  - All XR Apps are orchestrated by the **Central XR Hub and Orchestration Platform,** which manages and integrates XR applications. As shown in figure 21, the hub provides the following functionalities:
    - It provides **User Management and Authentication** as well as **Orchestration and Management** of the **XR Apps**.
    - It delivers the service "**Update and Configuration of Embedded XR Apps**" which is consumed by the actor XR **App Developer** in order to be able to configure the various XR apps that have been integrated into the hub.
- **Cloud Repository and Training Management**:
  - The **Cloud Repository** serves as a central storage and retrieval platform. It stores training materials and training programs, and it exposes the interface "**Storage API**". Through this interface, the **Cloud Repository plugin** is able to retrieve the content of the repository which comprises PDFs, videos, 3D models and training workflows. As shown in figure 21, the training workflows are authored by the Trainer Authoring Tool which is a web application that provides the service "**Training Programs Creation**" to be consumed by the actor named **Training Manager.** Furthermore, the repository also provides authentication functionalities.
- **Pilot Environment and Sensor Data Integration**:
  - The **Pilot Environment** exposed the interfaces named "Pilot Interfaces" which is an ArchiMate group element. This element comprises the following interfaces:
    - The **Sensors API Interface** which exposes sensor data available in the industrial environment (e.g. air quality sensors, temperature and humidity sensors, etc.)
    - The **Biometrics Interface** exposes through wearable sensors measurements related to heart rate, temperature, motion, etc. in order to monitor the operator's stress levels, health and safety.
    - The **Gesture Data Interface** monitors the operator's movements, posture and actions in order to deliver those measurements back to XR Apps so as to update the XR experience and thereafter to enhance the operator's productivity and efficiency.
  - Through the aforementioned interfaces, the **ETL Pipeline Tool** which acts as a data pipeline tool, can access the pilot data, transform them in a suitable format and deliver the measurements in the in the XR Apps for further processing
- **Remote Assistance Platform**:
  - Finaly, as shown in the figure below, XR5.0 also offers the **Remote Assistance Platform** application component which establishes communication between the operator and a remote expert. This enables real-time assistance through XR technologies, enhancing operational support and troubleshooting.
- **Application Deployment Service:** This is a service produced in the Technology Layer (see chapter 5.3.3). The service is depicted also in the Application Layer in order to denote that the Kubernetes cluster, and especially the worker nodes offer deployment service to the application components entitled "**AI Models**", "**Cloud Repository**", "**Central XR Hub**" and "**XR Apps**". In other words, this means that the infrastructure resources, as described in the Technology Layer in chapter 5.3.3, support the deployment of the aforementioned XR5.0 tools and this is achieved through well-defined CI/CD procedures and cloud provision. To this end, the **Application Deployment Service** is the ArchiMate element that connects the Application and Technology Layers.

A small description of each of the ArchiMate elements used in the figure below is the following (see also Annex I):

- **Application Service**: Represents a service provided by an application to support business processes, depicted as a rectangle with an ellipsis inside.
- **Application Component:** A modular part of an application, shown as a rectangle, indicating a specific software element responsible for functionality (e.g. Central XR Hub and Orchestrating Platform).
- **Group**: Represents a collection of elements within the application layer, typically shown as a dashed box enclosing related components.
- **Application Interface**: Defines interaction points between application components, depicted as a rectangle with a circle inside (e.g. WebRTC Interface)
- **Application Function**: Represents a unit of behavior or activity performed by the application shown as a rounded rectangle with an arrow inside which points to the top.
- **Data Object**: Represents an item of information used or produced by application functions, shown as a rectangle, which has another rectangle inside.
- **Junction**: Represents a decision point or flow diverging/converging, shown as a circle (a solid circle is an "and" junction while an empty circle is an "or" junction)

It has to be noted that all elements in the Application Layer in this document are depicted in light blue.

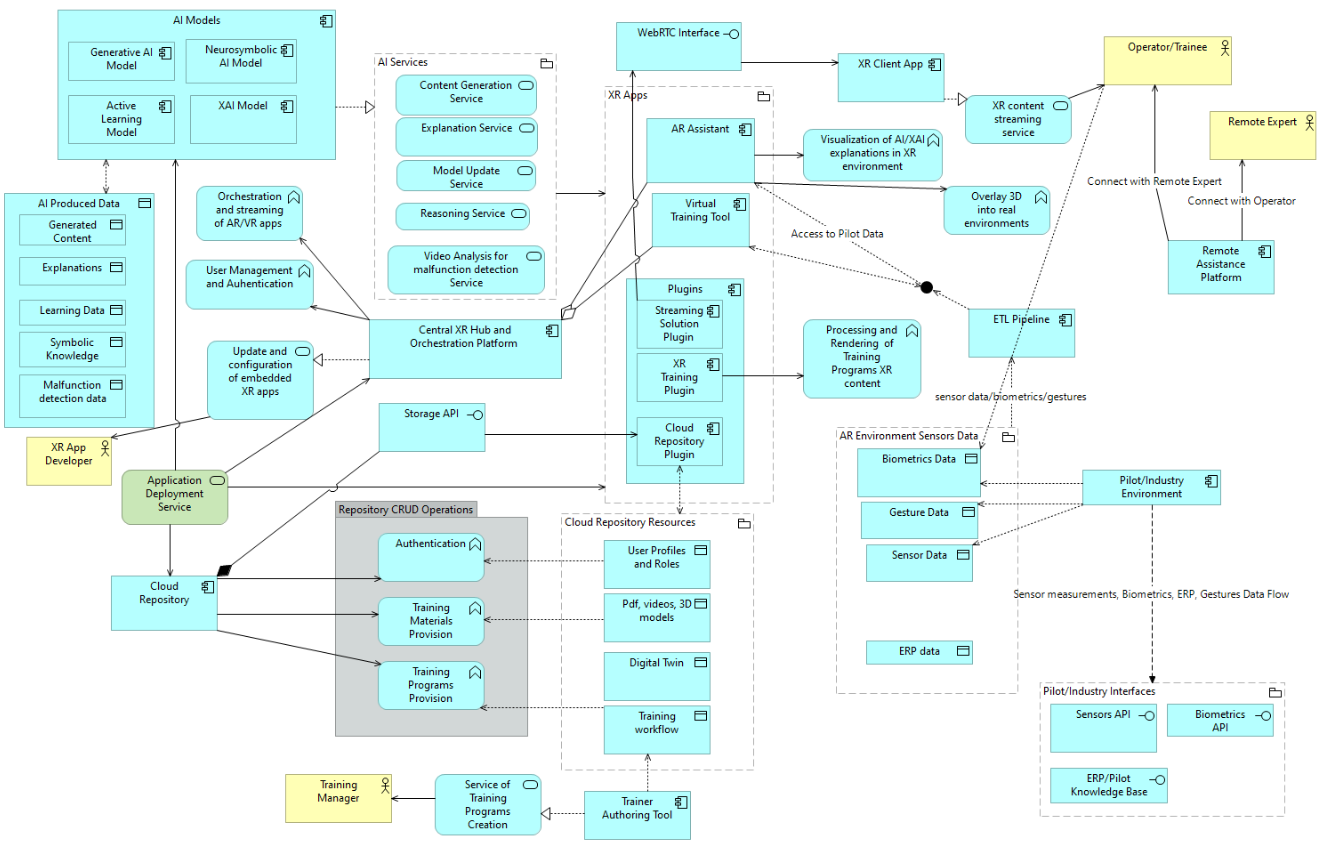


Figure 21: Application Layer of the Architecture

As a result, the XR5.0 Application Layer establishes a robust and interconnected architecture to deliver advanced AI-driven XR experiences. By integrating AI models, XR apps, cloud-based repositories and remote assistance capabilities, the design supports interactive operator training, maintenance and decision-making processes. Each component is carefully orchestrated to ensure scalability, seamless integration and alignment with project goals.

5.3.3 Technology Layer

The Technology Layer in ArchiMate defines the infrastructure services and physical or logical components that support application and business processes. This layer describes elements such as devices, nodes, system software, networks, and their relationships, providing a foundation for higher layers in the enterprise architecture. In this context, the Technology Layer illustrates the project's virtualized infrastructure and network connectivity, which supports DevOps practices and automated deployment pipelines.

A description of the elements used in the following figure is the following (also refer to Annex I):

- ➢ **Node**: Represents a physical or virtual computational resource, depicted as a rectangle with a 3D box inside.
- ➢ **System Software**: Software that supports the operation of applications, shown as a rectangle with 2 circles inside.
- ➢ **Artifact**: Represents an actual piece of data or software deployed, depicted as a rectangle with a document symbol inside.
- ➢ **Technology Service**: A service offered by technology components, shown as a rectangle with rounded corners and ellipsis inside.
- ➢ **Device**: Represents hardware devices like servers or workstations, depicted as a rectangle with a computer symbol inside.
- ➢ **Communication Network**: Represents communication infrastructure, shown as a rectangle with network symbol inside.
- ➢ **Group**: Represents a collection of technology elements, shown as a dashed box.
- ➢ **Technology Function**: Represents a technology-specific function or task, shown as a rounded rectangle with an arrow inside pointing to the top.

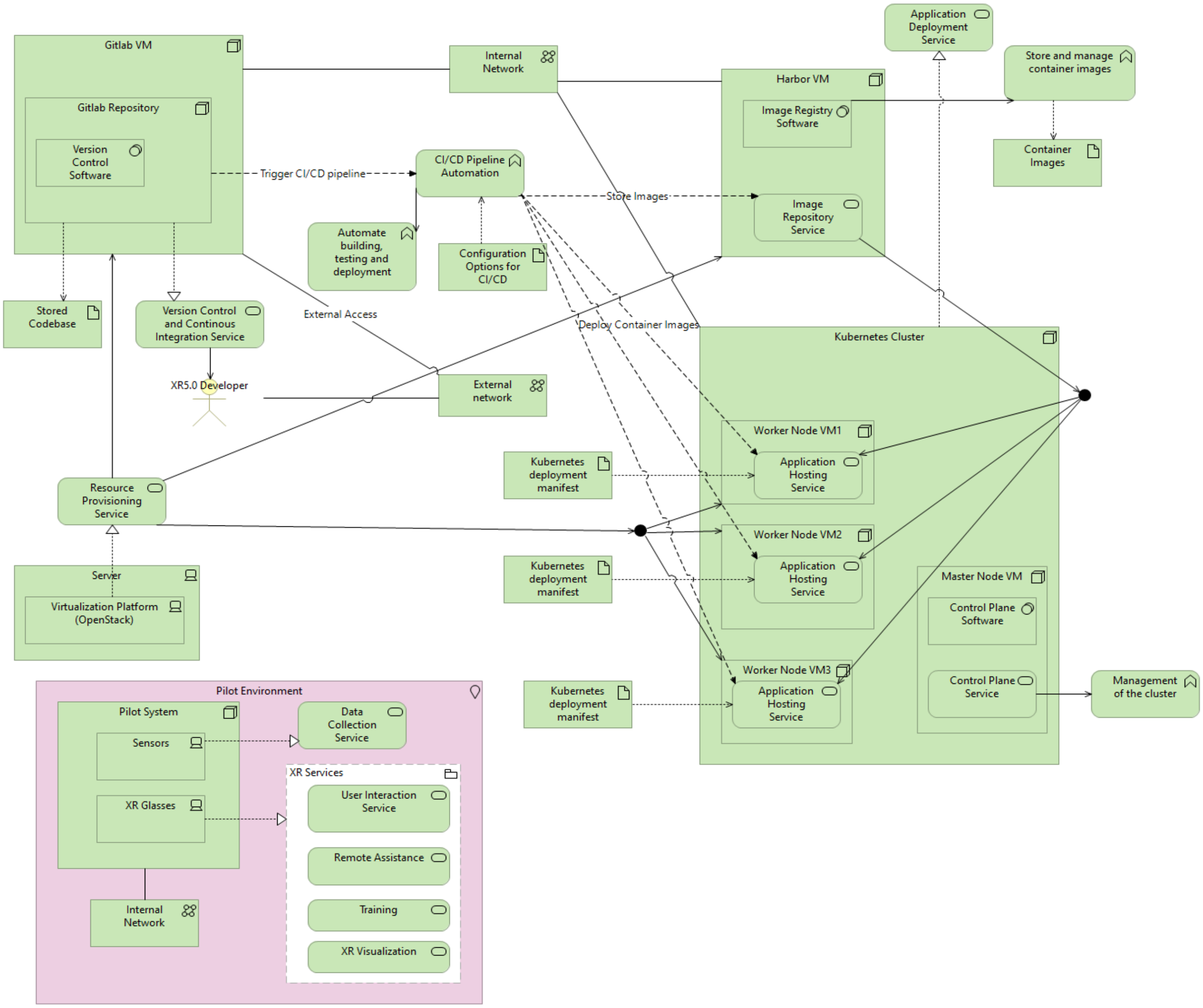


Figure 22: Technology Layer of the Architecture

The diagram depicted in Figure 22 models XR5.0 technical infrastructure for software development, artifact management and automated deployments using ArchiMate's Technology Layer concepts. It highlights the relationships between the physical hardware, virtualization layer, network services and the virtual machines (VMs) deployed for various purposes. The key components and their interactions are detailed below:

- **Physical Server and Virtualization Layer**: A physical server device has been provided in the project in order to host the project's resources. This server represents the underlying hardware. Moreover, the Virtualization Platform (system software) is realized on the server, providing the necessary Resource Provisioning Service to host and manage multiple VMs. The server and virtualization layer ensure resource efficiency and scalability while enabling isolation for different workloads.
- **Virtual Machines (VMs):** Several VMs are provisioned on the virtualization platform to support specific functions as follows:
  - **GitLab VM:** It hosts the Gitlab system software, which provides the shared repository for version control and continuous integration/continuous delivery (CI/CD) pipelines. Moreover, it enables the project partners to push and manage their codes collaboratively.

- **Harbor VM**: It acts as a container image registry to securely store and manage Docker images generated by the CI/CD pipelines.
- **Kubernetes**: It consists of a Master Node and multiple Worker Nodes, each realized as a VM. Moreover, it provides the platform for orchestrating and deploying project artifacts (containerized XR5.0 applications)

➢ **Communication Networks**: As shown in Figure 22, two types of networks exist in the XR5.0 system:
- **Internal Network**: There is the internal network that connects all VMs hosted on the server. It facilitates internal communication between the Gitlab VM and Harbor VM for artifact transfer. And it also allows workload orchestration between the Kubernetes master node and worker nodes. Moreover, there is the internal network in the pilot environment which ensures isolation of the industry systems and the operator devices (ERP, sensors, databases, machines, etc.). Access control is the most central aspect of the internal networks and also the privacy of internal processes and data flows plays a big role.
- **External Network**: It represents the external internet or network layer enabling partners from external organizations to connect to the Gitlab VM securely. It provides access for remote code submission and repository management.

➢ **Key Data Flows and Processes**:
- **External Access**: Project partners connect to the Gitlab VM through the external network to push their code to the shared repository.
- **Internal CI/CD Workflow**: Code from the repository is processed through Gitlab CI/CD pipelines, producing container images stored in the Harbor image registry.
- **Artifact Deployment**: The Kubernetes master node pulls images from Harbor and deploys them to the worker nodes, using the internal network for communication.
- **Pilot Application Use**: In the pilot settings, the operator will use both the deployed applications hosted in Kubernetes worker nodes but also their internal application and services which are internally deployed in order to perform their operations. These applications will enable the operator to perform operations aligned with the project's objectives, ensuring that the XR5.0 infrastructure meets the requirements identified in the Deliverable D2.1[2].

Thereafter, the Technology Layer ensures the following:

➢ **Scalability**: The virtualization platform allows for flexible resource allocation across VMs.
➢ **Security**: The separation of internal and external networks protects internal resources while allowing controlled access for external partners.
➢ **Automation**: The integration of Gitlab CI/CD, Harbor and Kubernetes streamlines the build, store and deploy cycle, reducing manual intervention.
➢ **Collaboration**: External access to the Gitlab VM supports seamless collaboration with partners across different organizations.

The Technology Layer for XR5.0 system effectively balances resource provisioning, secure networking and automation to meet the project's requirements for DevOps and artifact deployment. This architecture provides a robust foundation for the project's operations, ensuring efficiency, security and scalability.

6 Solution Architecture

This section transitions from the broader enterprise architecture explored earlier, to a more detailed methodology of solution architecture specifically focusing on visualizing software architecture. While the enterprise architecture provides an overview of interactions between the business, application, and technology layers enabling the identification of the XR5.0 system keys objectives, the solution architecture offers a detailed examination of the software components within these layers, including their structural configuration and operational characteristics.

In order to achieve this, the C4 model [1] is adopted for visualization of software architecture. The C4 model enables the decomposition of advanced software systems into four levels such as Context, Containers, Components and Code. This methodology will enable the alignment of the components of the system with both business goals and technical requirements, bridging the gap between the high-level enterprise architecture and the specific software design. As we proceed, the focus will shift to how software components function within the larger architecture and to their contribution to operational efficiency and scalability.

6.1 System Context

The **System Context Diagram** provides an overview of the XR5.0 platform and its interactions with external entities. The ***XR5.0 platform*** is defined as a central software hub that leverages XR and AI technologies to enhance safety, productivity, and user experience in Industry 5.0 operations. It facilitates external connections in order to utilize sensor measurements, enterprise resource planning data, operational manuals, maintenance procedures, and training content.

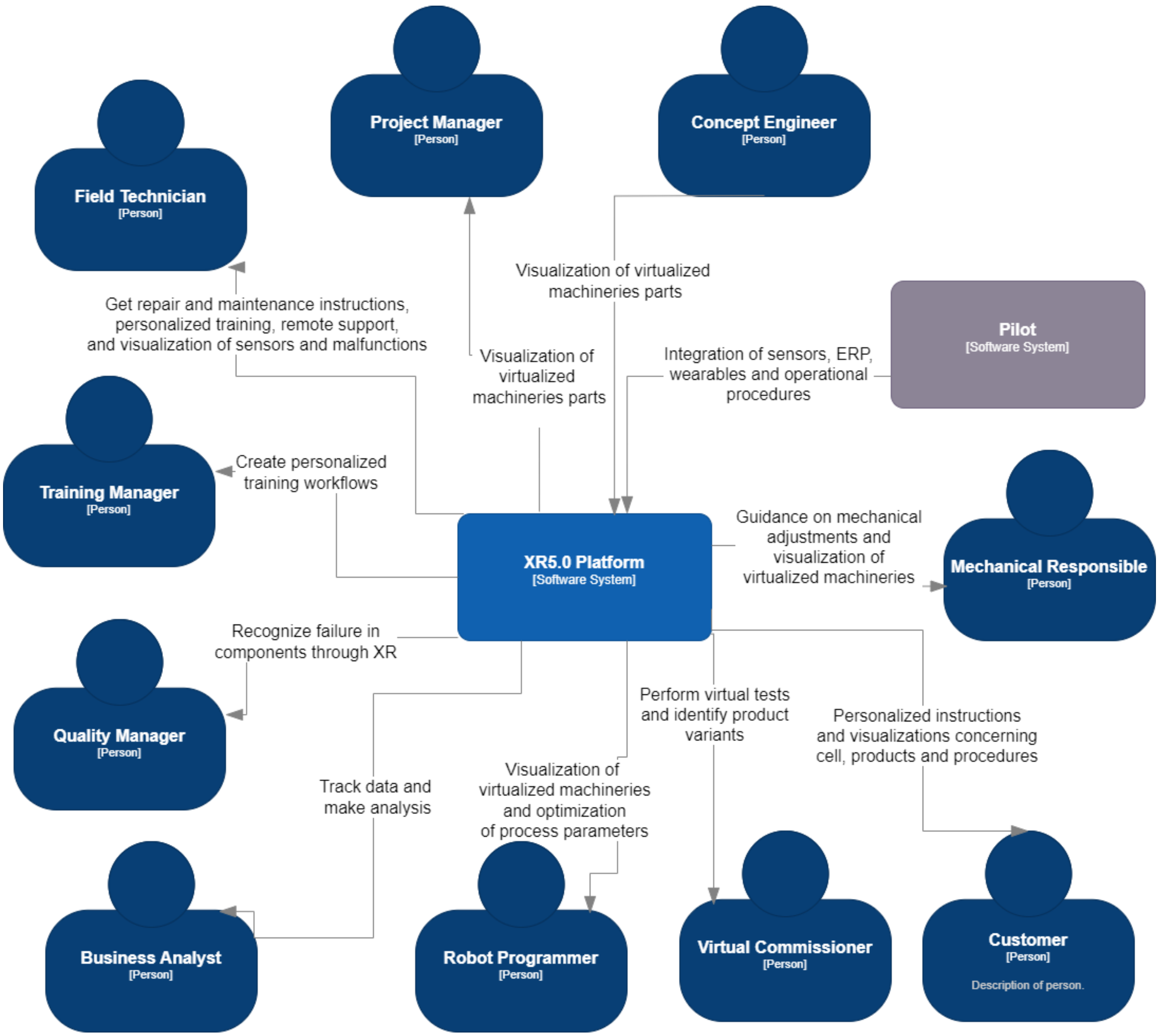


Figure 23: System context diagram of Solution Architecture

Figure 23 provides an overview of the high-level interactions and roles, offering clarity on the position of the system within the enterprise landscape and emphasizing its integrative functionality for Industry 5.0 initiatives.

This includes human roles, such as ***Field Technicians***, ***Training Managers***, and ***Quality Managers***, as well as third-party systems like external ***Pilots*** and external ***Data Sources***. This diagram illustrates the key external actors involved in the system, along with their primary interactions, as stated in the XR5.0 Deliverable D2.1 [2]:

- **Field Technician**: A skilled professional responsible for installing, maintaining, troubleshooting, and repairing equipment or systems directly on-site in industrial settings. This role is connected with the XR5.0 platform through an intuitive XR environment that provides: (i) digital assistance (e.g., chatbot), (ii) step-by-step instructions, (iii) personalized training, (iv) remote assistance support, (v) malfunction detection, (vi) monitoring of the production line and (vii) safety measures alerts. The integration allows the Field Technician to perform tasks efficiently, utilising advanced XR and AI functionalities to enhance productivity and ensure safety.

- **Training Manager**: A training manager is responsible for creating training programs that enhance employee skills and productivity across the organization. This role is connected with the XR5.0 platform through the ability to create training workflows personalized to individual technician skill levels. The integration enables Training Managers to devise targeted and efficient training programs that are aligned with both organisational goals and individual learning needs, utilising the advanced tools provided by the XR5.0 platform.
- **Quality Manager**: A Quality Manager ensures that products meet quality standards by conducting testing of raw materials, goods, and finished products. This role is connected with the XR5.0 platform through functionalities that allow them to (i) view information concerning testing, (ii) perform testing using a Digital Twin, (iii) recognize failure conditions (e.g., identifying leak conditions). The integration allows Quality Managers to maintain high standards of product reliability and safety while utilising sophisticated tools in the XR5.0 system for real-time testing and fault detection.
- **Business Analyst:** A Business Analyst plays a crucial role in analyzing system-generated data and aligning system performance with business objectives. This role is connected with the XR5.0 platform through functionalities that allow them to (i) track user actions and data generated by the system, (ii) analyze past maintenance activities to identify patterns, and (iii) flag recurring problems for predictive maintenance and improved efficiency. The integration allows Business Analysts to derive actionable insights from the system's data, thereby facilitating continuous improvement and alignment with organisational goals.
- **Robot Programmer:** A Robot Programmer is responsible for configuring and optimizing robotic systems used in industrial automation. This role is connected with the XR5.0 platform through functionalities that allow them to get a virtual presentation of the current state of machinery and their missing parts and receive instructions concerning the setting and optimization of process parameters for Programmable Logic Controller (PLC) programming. The integration facilitates the automation process for Robot Programmers, ensuring the seamless operation of robotic systems through the utilisation of XR5.0's advanced visualisation and instructional tools.
- **Mechanical Responsible:** Responsible for the mechanical aspects and systems, ensuring proper maintenance and optimization of mechanical components. This role is connected with the XR5.0 platform through functionalities that allow them to get instructions concerning the mechanical adjustments. The integration allows the mechanical responsible party to perform mechanical optimisations in an efficient manner and to guarantee seamless system functionality, making use of XR5.0's support for precision and operational effectiveness.
- **Virtual Commissioner:** The person who ensures that machinery, equipment, and systems are tested and validated before full-scale deployment. This role is connected with the XR5.0 platform through functionalities that allow them to (i) view information concerning the monitoring of the production line (e.g., cycle times, lot sizes, pictures of products as they are embedded in the production line), (ii) view highlighted identified product variants in AR glasses, and to (iii) view test results during campaigns. The integration allows the Virtual Commissioner to validate and optimize production processes, utilising the capabilities of XR5.0 to guarantee system readiness and performance prior to deployment.
- **Project Manager**: A Project Manager oversees the entire project lifecycle. He relies on reports from the technical team to monitor progress and ensure project success. In the context of XR5.0, the project manager needs to see the virtualized machineries parts, in order to have a better impression of the current state and the relation to the still upcoming installation work. Moreover, the visualization of information concerning the order in which parts need to be installed is a desired functionality that needs to be offered to this role.
- **Concept Engineer:** This role revolves around bridging technology, creativity and sustainability to design innovative solutions and systems that integrate advanced technologies with a human-centric and environmentally conscious approach. More specifically, key responsibilities of a Concept Engineer are the following: (i) to develop futuristic concepts for products, processes and systems by leveraging

emerging technologies, (ii) to design systems and processes and evaluate the lifecycle impact of proposed concepts, (iii) to work with software and hardware teams to prototype concepts and test their feasibility and (iv) to develop concepts that enhance resilience of supply chains and manufacturing processes. In the context of XR5.0, a Concept Engineer would like to view the virtualized machineries parts in order to get a better impression of the current state and the relation to the still upcoming work. Moreover, the visualization of the order in which the parts need to be installed is also important for this role.

- **Customer:** This role could represent either an operator or a dedicated maintenance department ensuring the continuous operation of the machines. According to feedback from pilot 6, a Customer is responsible for contacting the company in case of problems or preventive maintenance. He has access to relevant documentation and the technical support portal. The skill level of this role varies greatly, from deep technical knowledge to basic operation and maintenance abilities.
- **Pilot:** XR5.0 Pilots are used to drive the technical development, evaluate, and validate XR5.0 technology, and to experiment with diverse industry environments. In this diagram the pilot is recognized as a Software System and is connected with the XR5.0 platform through functionalities that allow them to (i) provide APIs for integrating ERP, sensors, and wearables, and (ii) provision information concerning operational procedures, historical data for training models, and manuals. This integration enables Pilots to serve as experimental and validation environments, ensuring XR5.0's adaptability to various industry scenarios and its alignment with enterprise systems. The pilot "box" in this diagram could represent any Industry 5.0 environment.

The System Context Diagram presented in this chapter aims at providing a high-level view of the XR5.0 system and shows how the system interacts with external entities, such as users, pilots, etc. Thereafter it focuses on:

- **The XR5.0 system as a whole:** Represented as a single box.
- **External interactions:** Highlighting relationships between the XR5.0 system and its external actors (e.g. users, pilots)
- **Purpose and boundaries:** Clarifying what the system does and where its responsibilities begin and end.

To this end, in this diagram all actors, as stated in Deliverable D2.1, have been presented in every small detail for focusing on their specific needs. In the other diagrams throughout this document, for reasons of simplicity all these actors have been merged into 2 different personas: (i) the Training Manager who creates the training workflows and (ii) the operator who makes use of XR5.0 technology in order to facilitate his operations in the Industry 5.0 environment.

6.2 Container View

Following the System Context Diagram, the Container Diagram divides the system into its principal structural components, or "containers," which represent applications, services, databases, or other operational elements. The diagram illustrates how these containers communicate, the technologies employed, and the pathways through which data flows within the system. The Container Diagram provides a detailed view of how the XR5.0 architecture is structured and how it interacts, establishing a deeper understanding of the system's technical foundation. Together with the System Context Diagram, it helps stakeholders grasp the system's architecture, paving the way for further investigation into the underlying components and code.

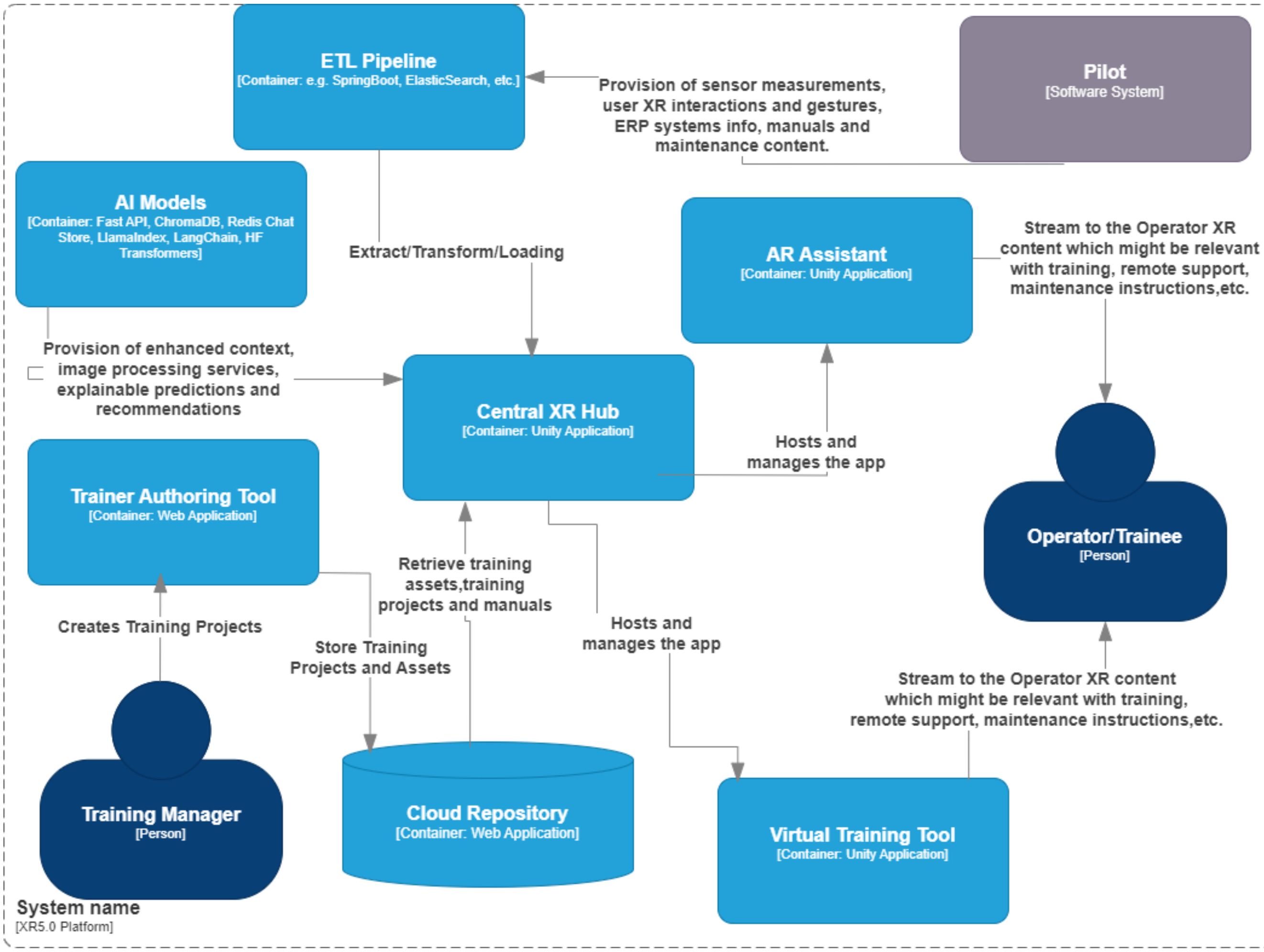


Figure 24: Container diagram of Solution Architecture

According to C4 Model specification [4] a container is a separately runnable/deployable unit (e.g. a separate process space) that executes code or stores data. Thereafter, every XR5.0 component that has been separately deployed in the project, has been identified in this diagram as a container. The Container diagram shows the high-level shape of the software architecture and how responsibilities are distributed across it. It also shows the major technology choices and how the containers communicate with one another. The containers. persons and software systems presented in the diagram in Figure 24 are the following:

- **The Pilot**: Each pilot is considered to be a **Software System** in the Container Diagram according to C4 specification. In a broader perspective, the grey box named "Pilot" could also represent any Industry 5.0 environment. The Pilot provides to the ETL Pipeline sensor measurements, user XR interactions and gestures, ERP information and manuals and maintenance content. In other words, every information that could be exploitable by the XR5.0 system is potentially provided to XR5.0 through the ETL Pipeline.
- **ETL Pipeline**: The Extract-Transform-Load (ETL) Pipeline is a Container. It is a core data integration component designed to facilitate the seamless transfer of data from pilot sites to the central hub. Its primary function is to ensure the efficient and reliable ingestion, processing and storage of data across distributed environments while maintaining data quality and integrity. It interfaces with heterogeneous data sources across pilot sites, including sensors, databases, APIs, etc. It supports diverse data formats and it implements secure and efficient data extraction mechanisms to minimize network latency and overhead. It standardizes data from diverse sources

into a unified format suitable for analysis and storage and it transfers processed data to the central hub for XR visualization, analysis or storage.

- **AI Models:** For simplicity reasons, all AI Models (XAI Model, Active Model, Generative AI, NeuroSymbolic Model) have been placed as a single container in the diagram. These models provide to the Central Hub (and more specifically to the AR applications) AI processing capabilities and other services, such as image recognition, human-AI collaboration, XR content generation, scenarios generation, operational optimization, explanations of AI decisions, etc.
- **Central XR Hub:** This Container is the orchestration platform that hosts and manages the various XR applications. Thereafter it is the underlying backbone technology of XR5.0 system and hence all XR applications that have been used within each pilot have been hosted on the hub. It provides centralized application management and secure access to 3D content from anywhere, on any device.
- **Cloud Repository:** This container is a cloud-based storage solution that hosts XR and conventional training modules. The storage solution is based on WebDAV and it is made available as RESTful service. The XR applications that are managed by the Central XR Hub can retrieve the content of the repository.
- **Training Manager**: The Training Manager plays a pivotal role in bridging human expertise and advanced technologies, ensuring a harmonious and productive collaboration between people and machines. He identifies skill gaps and provides training programs to keep employees updated with emerging technologies and processes in Industry 5.0. Moreover, he designs human-centric training projects tailored to individual workers' needs, considering their learning styles, roles and responsibilities. By leveraging XR and AI-driven platforms he paves the way for operators' adaptive learning and personalized skill development. In this way, he ensures operators are engaged, informed and motivated as they adapt to Industry 5.0 processes. He makes use of the Trainer Authoring Tool in order to create training projects.
- **Operator**: For simplicity reasons, in C4 Container Diagram, the Operator represents all personas that have been recognized through the pilot user stories, apart from the Training Manager. Thereafter, the Operator is the persona that makes use of XR5.0 technologies so as to: (i) oversee automated systems and machines, (ii) identify anomalies, (iii) troubleshoot errors (iv) analyze real-time data generated by IoT devices and sensors, (v) resolve technical issues (vi) adjust parameters as required for the production workflow and (vii) validate final outputs. To this end, XR5.0 streams XR content to the Operator in order to facilitate his operations. This XR content might be relevant with training, remote support, maintenance instructions, etc.
- **Trainer Authoring Tool**: The Trainer Authoring Tool is a tool used for creating training projects and programs. It is primarily used by Training Managers and it automatically stores all the training assets and programs into the Cloud Repository. Each training project is defined by many attributes such as: name, description, learning objectives, learning time, target audience, level, requirements, industrial domain and activities. Furthermore, each Training Program is associated with many XR-based materials which are defined by the attributes: name, description, type and configuration.
- **AR Assistant**: AR Assistant is a XR app managed through the Central XR Hub. This AR app is capable of the following: (i)visualizing the damage location, (ii) consuming AI services in order to analyze the damage, (iii) visualizing sensor data and (iv) providing checklists in the AR environment It offers text to speech and speech to text service, and it can visualize virtual multimedia content (3D models, images, metadata, videos, etc.). It is a Unity-based application and it has been integrated into the Central Hub. With the use of the Streaming plugin it can stream relevant XR content to the operator.
- **Virtual Training Tool**: The Maintenance Training Tool provides a virtual reality environment to be used in off-the-job settings providing a step-by-step procedure for handling devices. This VR app offers training in procedures that require following a predetermined sequence for the maintenance of equipment in industrial settings. It immerses technicians in interactive XR environments for virtual training on maintenance procedures. The app displays step-by-step instructions of selected maintenance procedures, allowing technicians to interact with a realistic 3D replica of the target

equipment using virtual projections of their hands. It has been integrated into the Central Hub and with the use of the streaming plugin, it can stream relevant XR content to the operator.

It has to be noted that in addition to the AR Assistant and the Virtual Training Tool, the Central Hub can accommodate even more XR apps according to the specific use case, so the aforementioned apps act as representatives in the C4 Container Diagram.

7 STANDARDS

7.1 Overview of Standards

Industry 4.0 standards

Industry 4.0 emphasizes the integration of cyber-physical systems, IoT, and data analytics to improve automation and manufacturing efficiency. Key frameworks and standards include:

7.1.1 RAMI 4.0 (Reference Architectural Model for Industry 4.0)

RAMI 4.0 [13] offers a structured framework for the implementation of Industry 4.0 principles. Developed by German organizations such as ZVEI, VDMA and BITKOM, RAMI 4.0 serves as a critical tool for navigating the complexities of industrial digital transformation. It provides a common language and methodology for implementing smart manufacturing practices and supports the adoption of emerging technologies such as the Industrial Internet of Things (IIoT) and Artificial Intelligence (AI) It organizes processes and technologies across a three-dimensional map comprising layers, life cycle/value stream, and hierarchy levels. This ensures a comprehensive approach to smart manufacturing and facilitates interoperability across systems. The three-dimensional relationship, which is guided by the RAMI 4.0 model, establishes connections between hierarchies, functions, and the product lifecycle.

As shown in Figure 25, RAMI 4.0 spans across 3 axis as follows [9]:

- **Vertical Axis: Functional Layers** RAMI 4.0 consists of six functional layers that describe the abstraction levels of an Industry 4.0 system. These layers facilitate the digital integration of physical and business processes:
  - **Asset Layer**: It represents the physical elements, such as equipment or products, that serve as the foundation for data sources in other layers and functions.
  - **Integration Layer**: It is used to obtain and digitise information, transforming data from physical phenomena into formats that can be quantified and utilised digitally.
  - **Communication Layer**: It is responsible for facilitating the exchange of information between different entities within the system. It defines the data standards and protocols that are required for the standardisation of Industry 4.0.
  - **Information Layer**: It encompasses all forms of information, including real-time data (e.g. production data) and the regulations or directives that govern operational procedures.
  - **Functional Layer**: It is responsible for defining the technical and logical functions necessary for the system's operations. It delineates the technical and logical functions that are indispensable for the system's operational efficacy.
  - **Business Layer**: It represents the operational and functional aspects of the enterprise, encompassing the organisational structure, business models, financial management and legal considerations. It encompasses the company's organisational structure, including business models, financial management, and legal considerations.
- **Horizontal Axis: Hierarchy Levels** Derived from the ISA-95 model, this axis defines levels of industrial operation, from physical devices to enterprise-level systems:
  - **Field Device Level**: Physical devices like actuators, sensors or edge nodes.
  - **Control Device Level**: PLCs and other controllers for real-time process management.
  - **Station Level**: Workstations or machine groups involved in production tasks.
  - **Work Center Level**: A collection of stations functioning as part of a production line.
  - **Enterprise level**: Strategic and resource planning systems, typically ERP solutions.
- **Third Axis: Life Cycle and Value Streams** Based on ISO 62890, this dimension represents the lifecycle stages of a product and the associated value streams. It ensures that all phases, from design to decommissioning, are accounted for:

- **Development**: It focuses on design, prototyping and engineering.
- **Production**: It covers manufacturing, assembly and quality assurance.
- **Service**: It includes operation, maintenance and eventual disposal.

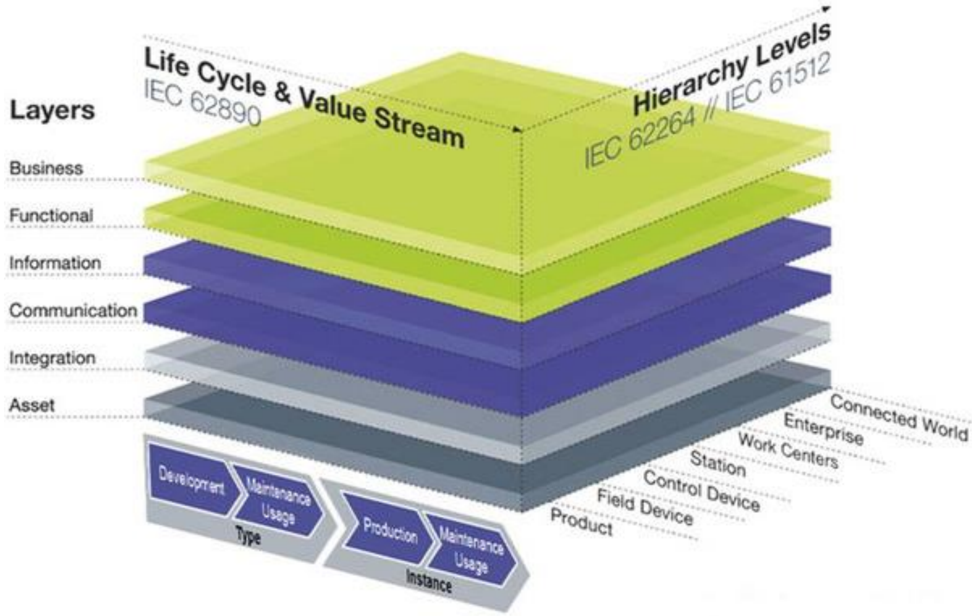


Figure 25: RAMI4.0 as three-dimensional Layer model

A central feature of RAMI 4.0 is the Asset Administration Shell (AAS), which acts as a digital interface for managing both physical and digital assets [10]. Each asset, whether a machine, product or software module is accompanied by an AAS that describes its properties, capabilities and interfaces. Key functionalities of the AAS include:

- **Digital Twin Integration**: It enables real-time synchronization between physical assets and their digital counterparts.
- **Interoperability**: It uses standardized semantic models to ensure compatibility across systems.
- **Data Management**: It facilitates data collection, analysis and decision making by exposing relevant information.

The adoption of RAMI 4.0 offers numerous advantages for industries seeking to modernize their operations:

- **Standardization**: It aligns with global standards like IEC 62264, ISO 62890 and ISA-95, ensuring consistency and interoperability
- **Modularity**: It provides a scalable architecture that industries can implement incrementally, reducing risk and cost.
- **Interoperability**: It encourages seamless communication between heterogeneous systems and technologies, fostering collaboration
- **Productivity Gains**: It optimizes manufacturing processes through automation, predictive maintenance and real-time insights.

Despite its benefits, implementing RAMI 4.0 comes with challenges:

- **Complexity**: Mapping existing processes to the RAMI 4.0 framework requires significant expertise and resources.

- ➢ **Legacy Systems**: Integrating outdated equipment with Industry 4.0 solutions can be technically challenging.
- ➢ **Skills Gap**: Organizations must train personnel in both operational technology and information technology
- ➢ **The abstract nature** of RAMI 4.0 hinders its applicability for real world use cases and thus also the implementation of the design principles [11].

RAMI 4.0 framework is applicable in diverse industrial contexts such as Smart Factories for automating production lines with IoT-enabled devices, **Predictive Maintenance** for using AAS and digital twins to anticipate and address equipment failures and **Supply Chain Optimization** for enhancing transparency and collaboration through real-time data sharing.

7.1.2 IIRA (Industrial Internet Reference Architecture)

The Industrial Internet Reference Architecture (IIRA) serves as a blueprint for designing and implementing Industrial Internet of Things (IIoT) systems [7]. Developed by the Industrial Internet Consortium (IIC), it aims to bridge the gap between operational technology and information technology, fostering interoperability and scalability while addressing the unique challenges of industrial applications. The objective of the IIRA is to enhance interoperability across different IoT systems, thereby providing a framework for leveraging various technologies in the development of IIoT solutions. The IIRA identifies the essential components of any such system, including sensing, connectivity, analytics and control, which are integral to its implementation. The IIRA is described based on the ISO/IEC/IEEE 42010:2011 standard [8], which has been adopted by the IIC to define its Industrial Internet Architecture Framework (IIAF).

IIRA is structured into four architectural layers:

- ➢ **Business Layer**: This defines the overall objectives of the system, focusing on value creation and aligning IIoT deployments with business goals such as cost reduction, productivity, improvements and new revenue streams [7].
- ➢ **Usage Layer**: It captures how users interact with the system, defining operational scenarios and functional requirements. This layer ensures that system design considers all user roles [12].
- ➢ **Functional Layer:** At this level, the system is broken into domains such as sensing, analytics and control. It specifies the interactions between these domains, ensuring seamless functionality.
- ➢ **Implementation Layer**: This layer outlines the technologies, protocols and standards required to realize the functional components. Examples include communication protocols like MQTT and edge computing techniques such as fog computing.

The functional domains, crosscutting functions and system characteristics framework, derived from RAMI 4.0, offers a structured approach to understanding the various operational layers and their interactions within an industrial system. Functional domains represent key operational areas such as business processes, manufacturing execution and control systems. These domains are underpinned by crosscutting functions, including interoperability, security and scalability which enable seamless integration across systems.

Additionally, system characteristics such as modularity, reusability and real-time responsiveness are critical to achieving the dynamic and adaptable architectures envisioned by both RAMI and IIRA. The interplay between these layers and characteristics ensures that industrial systems can scale, integrate new technologies and maintain robust operations across diverse use cases.

By visualizing these relationships, Figure 26 underscores the holistic nature of modern industrial reference architectures, which aim to bridge the gap between operational technology and information technology.

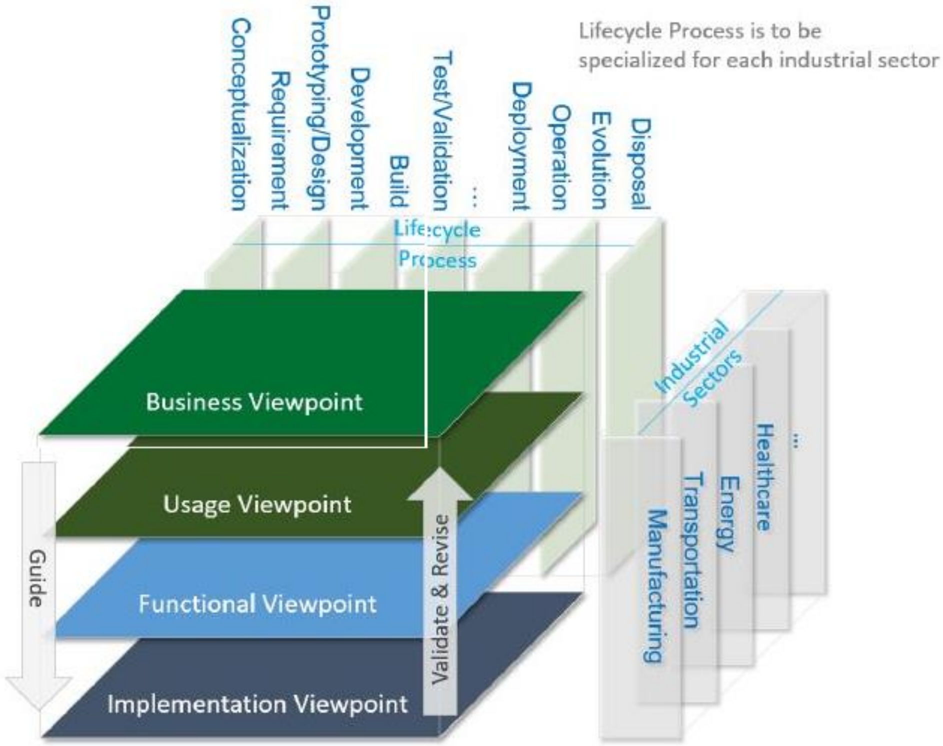


Figure 26: Relationship among IIRA Viewpoints, Application Scope and System Lifecycle Process

The IIRA framework emphasizes several critical characteristics to ensure the effective design, deployment and operation of IIoT systems. These characteristics address both technical and operational needs, ensuring alignment with industrial requirements.

Interoperability is a cornerstone of IIRA, ensuring seamless communication and data exchange between heterogeneous devices, platforms and systems [13]. The architecture facilitates integration across legacy systems, new technologies and multi-vendor environments through standardized communication protocols and shared data models. This characteristic is essential in environments where devices from multiple manufacturers must coexist and collaborate efficiently.

Scalability is another fundamental aspect of IIRA, enabling systems to expand from pilot projects to full-scale enterprise implementations without significant reengineering [7][12]. The modular design of the architecture supports both vertical scaling (e.g. increasing computational resources) and horizontal scaling (e.g. adding more devices or nodes to the network). This flexibility is critical in dynamic industries like manufacturing, where the scale of operations can change rapidly.

Security is integral to IIRA, given the sensitivity and criticality of industrial data [12]. The architecture incorporates security measures across all layers, from the physical devices to cloud services. This includes features such as encryption, authentication protocols, and intrusion detection systems. Security by design ensures the resilience of IIoT systems against cyber threats, protecting both data integrity and operational continuity.

Real-Time Processing and Low Latency are emphasized in the architecture to support applications requiring immediate responses, such as robotic control or autonomous vehicle systems. By leveraging edge computing technologies, IIRA reduces reliance on centralized cloud processing, enabling faster data analysis and decision-making closer to the source of data generation.

Manageability and Maintainability are also prioritized. The architecture supports remote monitoring and management of devices and systems, reducing downtime and maintenance costs. Features such as predictive maintenance, enabled by data analytics and machine learning, further enhance operational efficiency.

The flexibility and robustness of the IIRA framework make it applicable across a wide range of industrial sectors, addressing specific challenges and enabling innovative solutions.

In **smart manufacturing**, IIRA facilitates real-time monitoring of production lines, predictive maintenance of machinery, and optimization of supply chains [12]. By connecting equipment, sensors, and analytics platforms, the architecture supports adaptive manufacturing processes that can respond dynamically to changing demands and conditions.

The **energy and utilities** sector benefits significantly from IIRA, particularly in the management of smart grids and renewable energy systems. The architecture enables real-time monitoring and control of distributed energy resources, integration of renewable energy sources, and predictive analytics to forecast energy demand. These capabilities improve grid reliability, enhance energy efficiency, and reduce operational costs.

In **transportation and logistics**, IIRA underpins autonomous vehicle ecosystems, intelligent transportation systems, and smart logistics networks [13]. The architecture supports low-latency communication between vehicles and infrastructure, enabling features such as collision avoidance and traffic optimization. In logistics, it facilitates real-time tracking of goods, warehouse automation, and route optimization.

The **healthcare industry** leverages IIRA for applications such as remote patient monitoring, connected medical devices, and hospital automation. By integrating sensors, analytics, and secure communication protocols, the architecture supports timely and accurate medical interventions while protecting patient data.

In **agriculture**, the architecture enables precision farming practices. IoT-enabled sensors monitor soil conditions, weather, and crop health, while analytics platforms provide actionable insights for optimizing irrigation, fertilization, and pest control. These capabilities enhance productivity and sustainability.

7.1.3 ETSI Industry Specification

ETSI (European Telecommunications Standards Institute) plays a pivotal role in developing globally recognized standards for telecommunications and electronic systems, aligning with the growing demands of Industry 4.0 and IoT ecosystems. ETSI’s contributions address critical challenges, such as ensuring interoperability, securing communication systems, and enabling scalable industrial solutions through standardized frameworks. Below is a comprehensive exploration of ETSI's contributions to Industry 4.0, highlighting its key standards, applications, and the transformative role it plays in industrial settings.

ETSI’s Multi-access Edge Computing (MEC)

Multi-access Edge Computing (MEC) is one of ETSI's foundational contributions to Industry 4.0, enabling the decentralization of computing resources by bringing them closer to devices at the network edge [14]. MEC is instrumental in reducing latency and enhancing real-time analytics, crucial for applications like autonomous robotics, predictive maintenance, and augmented reality systems in manufacturing.

MEC operates through a structured framework that integrates edge devices with cloud platforms. This architecture supports data-intensive processes at the edge, minimizing the need for centralized processing and enabling quicker decision-making. The seamless connectivity between edge and cloud environments provided by MEC aligns with the dynamic requirements of modern industrial networks, where agility and rapid adaptation to operational changes are paramount.

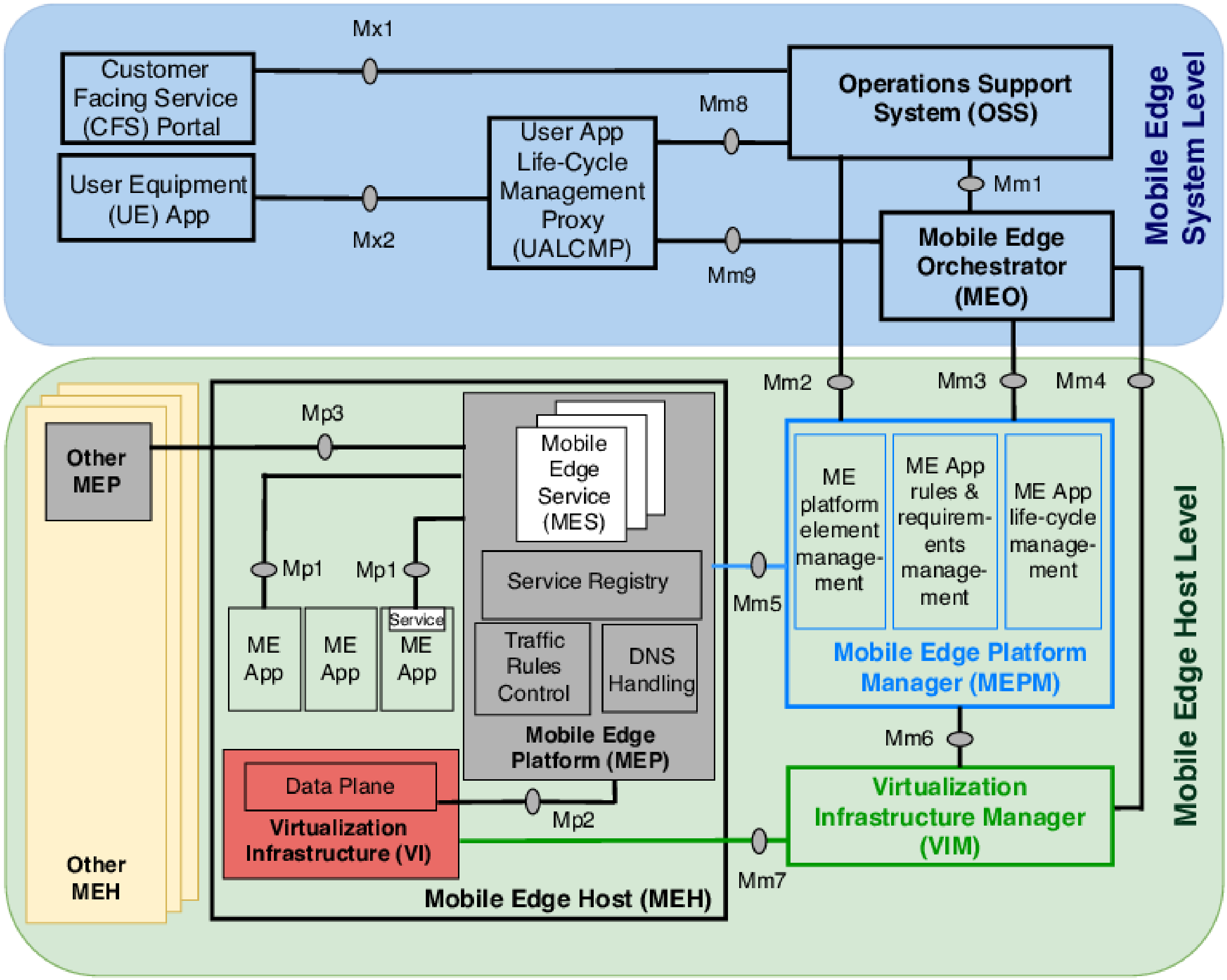


Figure 27: MEC Reference Architecture

Figure 27 depicts MEC ETSI Architecture. There are three distinct components, MEC Host, MEC Platform Manager, MEC Orchestrator and the Virtualization Infrastructure Manager (VIM).

The **Virtualization Infrastructure Manager** has the purpose to manage the virtual machines (VMs) on top of physical infrastructure (compute, storage and networking). It is responsible for allocating, maintaining and releasing virtual resources of the virtualization infrastructure. MEC Apps are the actual applications that are run in MEC on top of VMs. **MEC Service** is an important block in MEC. The network-related APIs are exposed by MEC service to MEC Apps through reference point Mp1, as shown in Figure 27. Also, the MEC platform can consume these services. MEC Apps are network-aware (so that MEC Apps can act based on that) and MEC Service can help by exposing the network information through APIs. According to ETSI, at least three types of following services must be exposed by MEC Service: (i) the radio network conditions, (ii) the location information and (iii) the bandwidth manager.

Traffic Rules Control is an important piece of MEC Platform. As Mec Platform is serving multiple applications, simultaneously, it should be able to assign priorities through **Traffic Rules Control**.

The mobile edge platform shall provide functionality that supports routing all DNS traffic received from any UE to a local DNS server/proxy. This is where **DNS Handling** comes into play since the benefit of the MEC is to process a lot of information locally in MEC instead of sending it to the internet. Thus, it should have a way to handle DNS redirection to a local DNS server so that traffic can be diverted for local processing instead of sending to the internet. Moreover, it should be noted that there could be other MEC hosts connected to the existing MEC host through the Mp3 interface.

Concerning **MEC Platform Manager,** it performs the following:

- ➢ It manages MEC Apps life cycle; therefore it instantiates, maintains and tears down MEC Apps on VMs.
- ➢ It is responsible for FCAPS (Fault, Configuration, Accounting, Performance, Security) management for the MEC platform.
- ➢ It manages the application rues, traffic rules and DNS configuration

The **Mobile Edge Platform Manager** assumes a central role in the architectural framework and it is responsible, among other things, for the following:

- ➢ It oversees the deployment, configuration, scaling, updating and termination of MEC applications on the MEC host.
- ➢ It configures MEC platforms, including platform services like DNS, service discovery and application enablement.
- ➢ It manages resource allocations for applications hosted on MEC servers.
- ➢ It implements resource policies, including CPU, memory and network bandwidth usage, for applications.
- ➢ It monitors the performance of MEC platform components and hosted applications
- ➢ It acts as the intermediary between the MEC Orchestrator and the MEC platform.

Regarding the **CFS Portal** (Customer Facing Service Portal), the mobile operators' customers can order new MEC applications or monitor the service SLAs.

Last but not least, the **User App LCM Proxy** is an optional feature in MEC system. This is applicable when the system supports a feature called "UserApps". When the mobile edge system supports the feature UserApps, the system shall allow the establishment of connectivity between a UE (that runs device application) and a specific instance of a mobile edge application. The user application lifecycle management proxy allows device applications to request on-boarding, instantiation and termination of user applications. In simple words, the user can now trigger specific applications in MEC system from his device if this feature is supported by MEC system.

Concerning **IoT Standards and Interoperability**, it has to be noted that **ETSI** has significantly advanced the IoT domain through its **oneM2M** standards, which focus on creating a common service layer for diverse IoT applications [15]. The oneM2M architecture fosters interoperability by enabling seamless communication and integration between devices from different manufacturers and across multiple industrial sectors. By employing semantic data models, the framework ensures consistent interpretation of data across heterogeneous systems, a critical factor in large-scale IoT deployments.

This approach promotes horizontal scalability, allowing systems to expand across different industries without the need for extensive reengineering. Additionally, oneM2M emphasizes secure data exchange and device lifecycle management, ensuring robustness and reliability in industrial operations. Figure 28 depicts how the employment of a oneM2M Service Layer boosts interoperability and facilitates seamless interaction between heterogeneous applications and devices.

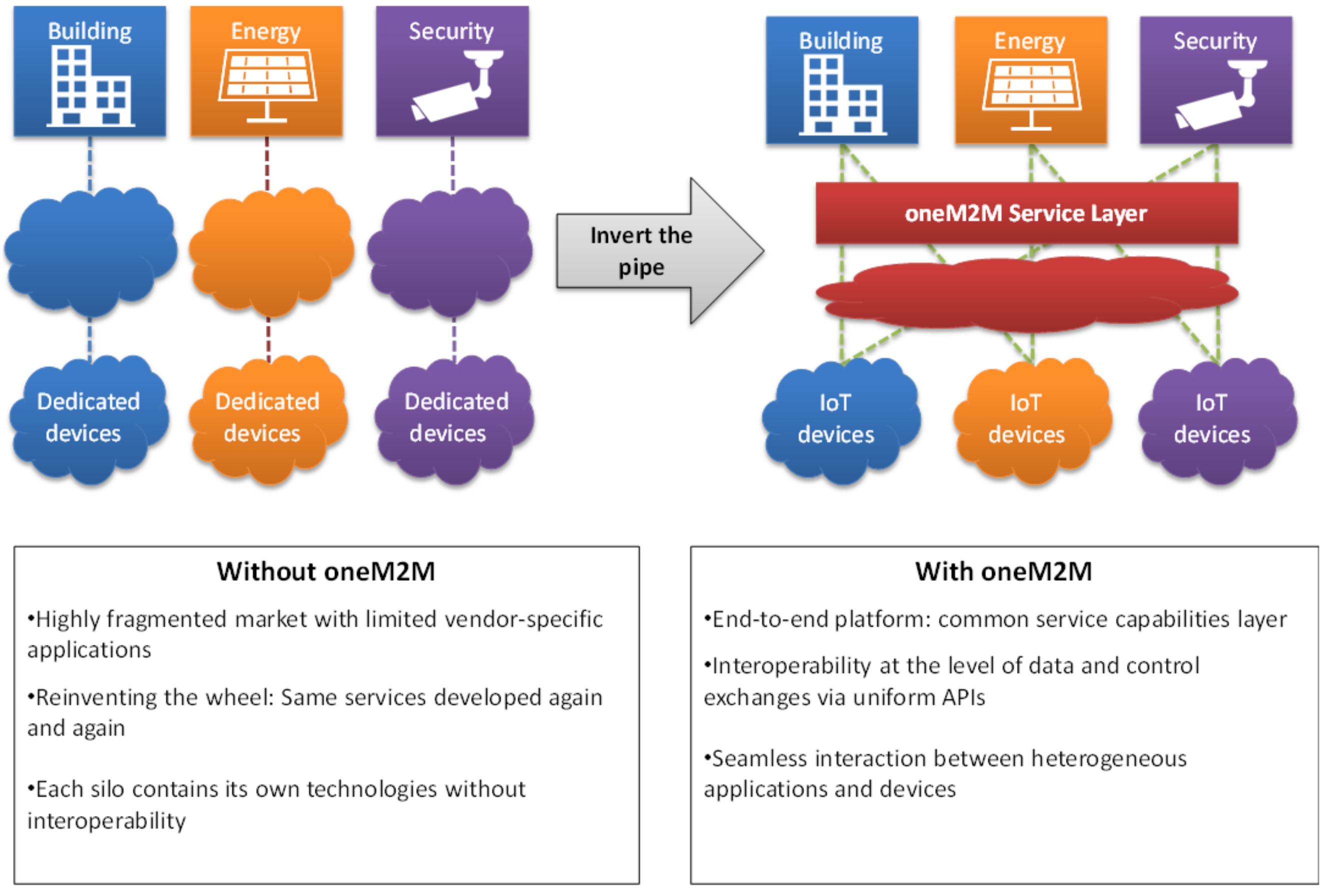


Figure 28: Benefits of using oneM2M standard

To this end, the oneM2M initiative can remove fragmentation of the IoT world. Because it is independent of the access or protocol technology that is used for transport, it is designed to be a long-term solution for IoT deployment.

Concerning ETSI's **cybersecurity standards**, they address the growing need for secure industrial communication networks in the industry 4.0 landscape [16]. These standards encompass a range of critical areas, including risk assessment frameworks, encryption techniques, and device identity management. By securing communication channels and ensuring robust access control, ETSI standards mitigate vulnerabilities inherent in legacy systems and emerging IoT environments.

A notable aspect of ETSI's cybersecurity efforts is the focus on end-to-end security solutions. These solutions cover everything from device onboarding and authentication to secure data transmission and system-wide intrusion detection mechanisms. This comprehensive approach ensures that industrial systems remain resilient against evolving cyber threats while maintaining operational efficiency.

Moreover, ETSI's **5G standards** are foundational for enabling advanced capabilities in industrial networks, such as ultra-reliable low-latency communication (URLLC), massive IoT connectivity, and network slicing [17]. These features support diverse Industry 4.0 applications, ranging from remote robotic surgery to automated logistics systems.

The integration of 5G within industrial environments allows for unprecedented levels of automation and coordination among devices. By leveraging URLLC, manufacturing systems can achieve real-time synchronization between robots and machinery, enhancing precision and productivity. Similarly, network slicing enables the creation of dedicated virtual networks tailored to specific industrial use cases, ensuring optimal resource allocation and performance.

Including a visual representation of ETSI's 5G network slicing or URLLC architecture can help readers understand how these technologies are structured and deployed in industrial contexts.

7.1.4 ISO/IEC Standards

- ***ISO 22400 (Expected to be replaced by ISO/DIS 22400-2)***

  ISO 22400 provides a standarised framework for defining and monitoring key performance indicators (KPIs) specifically for manufacturing operations, making it a cornerstone for Industry 4.0 implementations. The standard supports the integration of advanced technologies such as IoT, AI and Extended Reality (XR) by enabling consistent and effective tracking of performance metrics that are critical to operational efficiency and decision-making. In the context of Industry 4.0, ISO 22400 helps organisations align their processes with data-driven insights, facilitating real-time analysis and optimisation of production workflows. By ensuring interoperability and consistency in KPI definitions across systems and platforms, this standard promotes smarter, more connected manufacturing environments that drive innovation and competitiveness in the era of digital transformation.

- ***ISO 26262***

  ISO 26262 is an internationally recognised standard that provides a comprehensive framework for ensuring the functional safety of automotive systems. It addresses the unique challenges posed by increasing complexity and autonomy of modern vehicles and provides guidelines for the design, development and validation of systems critical to safety. In Industry 4.0, ISO 26262 is highly relevant to autonomous functions such as robotics, automated manufacturing and AI-driven processes. The standard emphasises risk assessment, hazard analysis and the implementation of safety mechanisms to mitigate potential system failures. By following ISO 26262, organisations can ensure the reliability and safety of autonomous operations, fostering trust and compliance in environments where advanced technologies are seamlessly integrated with human-centric workflows and Industry 4.0 principles.

7.1.5 Industry 5.0 standards

Industry 5.0 builds on Industry 4.0 by emphasizing human-centricity, sustainability and resilience. While standards are still emerging, existing frameworks and tools are being adapted:

1. Human-centric AI standards:

   Human-centric AI standards, such as those developed by ***ISO/IEC JTC 1/SC 42*** [18], are increasingly aligned with the objectives of Industry 5.0. These standards emphasise the importance of explainable and trustworthy AI, ensuring that artificial intelligence technologies are used ethically to enhance and support human workers in a transparent and reliable manner.

   The ***IEEE 7000-2021 standard*** [19] provides further guidance by outlining ethical concerns in system design, with a particular focus on integrating ethical AI concepts throughout the development lifecycle. This approach supports the development of human-centric and ethical AI systems, thereby reinforcing the principles of industry 5.0.

2. **XRSI (Extended Reality Safety Initiative)**:

   The **Extended Reality Safety Initiative (XRSI)** is a globally recognized non-profit organization committed to the advancement of safety, privacy, and ethical considerations in the evolving domains of extended reality (XR), including virtual reality (VR), augmented reality (AR), and mixed reality (MR). Headquartered in the San Francisco Bay Area, XRSI serves as a multidisciplinary platform for developing frameworks, fostering collaboration, and advocating for responsible innovation in immersive technologies [20].

   XRSI's mission revolves around addressing the privacy, security, and ethical challenges posed by immersive technologies. By uniting experts from diverse fields such as cybersecurity, law, healthcare, AI, and product design, XRSI aims to create global standards and best practices. Its initiatives focus on safeguarding vulnerable populations and ensuring inclusivity in XR applications, thereby reducing potential digital divides.

   One of XRSI's flagship projects is the **XRSI Privacy and Safety Framework**, a regulation-agnostic guide designed to address privacy and safety concerns in XR environments [25]. This framework emphasizes the protection of sensitive data, including biometrically inferred information, and aligns with global standards such as the GDPR and NIST guidelines. The framework introduces novel considerations like informed consent, data minimization, and anonymization to mitigate risks associated with immersive experiences. It also provides actionable insights into content moderation and proactive safety measures, making it adaptable to evolving technological landscapes.

   XRSI plays a pivotal role in exploring the potential of XR in transformative sectors such as healthcare and education. For instance, the **Medical XR Privacy and Safety Framework** targets the ethical use of XR in healthcare, ensuring that patient data is handled securely and equitably. XR's capability to create immersive training environments has also been highlighted in education, where it facilitates interactive learning and high-fidelity simulations for medical procedures, promoting accessibility and skill development across various demographics.

   Recognizing the impact of data biases in AI-driven XR systems, XRSI advocates for the inclusion of underrepresented groups in the development and governance of XR technologies [26]. This focus aims to prevent the perpetuation of gender, racial, or socioeconomic disparities in virtual spaces. XR platforms also benefit from accessibility features, such as voice guidance for visually impaired users, which align with XRSI's broader goals of fostering equity and diversity [27].

   XRSI has been instrumental in advising policymakers and industry stakeholders on the responsible adoption of XR technologies. Collaborations with academic institutions, such as the University of California San Diego, and participation in international forums highlight its dedication to shaping a safe and inclusive metaverse. By emphasizing cross-sector engagement, XRSI seeks to build a sustainable ecosystem that prioritizes user trust and safety [27].

   With the rapid advancement of XR and related fields like AI, 5G, and brain-computer interfaces, XRSI's efforts are increasingly vital. As immersive technologies become mainstream, the organization continues to refine its frameworks, expand its partnerships, and advocate for global standards that balance innovation with ethical accountability.

3. **OpenXR**:

OpenXR is an open-source and royalty-free standard for access to virtual reality (VR) and augmented reality (AR) platforms and devices. It simplifies the development and deployment of XR applications across various hardware platforms. By ensuring interoperability, OpenXR supports the seamless integration of XR technologies, which is vital for the creation of integrated and efficient ecosystems in the Industry 5.0 era. These standards provide a framework that facilitates the ethical, safe, and effective adoption of advanced technologies in a human-centric industrial landscape. It encompasses technologies like Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). As immersive environments become integral to industries such as healthcare, education, manufacturing, and entertainment, XRSI provides critical frameworks to address unique challenges related to data security, user safety, and ethical deployment.

The cornerstone of XRSI's contributions is its **Privacy and Safety Framework**, a comprehensive guideline that ensures the responsible development and use of XR technologies [20]. The framework aligns with global standards like the **General Data Protection Regulation (GDPR)**, the **NIST Privacy Framework**, and ISO standards, offering a robust reference for organizations across sectors. Key areas covered by the framework include:

- **Privacy and Data Governance:** The framework emphasizes privacy by design, urging developers to incorporate secure data-handling practices from the outset. This includes anonymization techniques, secure storage, and encryption to protect user identities and prevent misuse of behavioral data. Furthermore, XRSI promotes informed consent, ensuring users understand what data is collected and how it is used. XR systems collect vast amounts of personal and sensitive data, such as:
  - Biometric data (e.g., eye tracking, facial expressions, voice patterns)
  - Behavioral data (e.g., movement patterns, gaze duration)
  - Location-based data
- **Safety in Immersive Environments:** The physical and psychological risks of XR are unique and varied [21]. XRSI provides guidelines for minimizing these risks, including ergonomic hardware design, well-calibrated user interfaces, and clear policies against harassment in shared virtual environments. The risks fall into these categories:
  - **Physical Safety Risks**: Issues like motion sickness, spatial disorientation and repetitive strain injuries.
  - **Psychological Risks**: Cognitive overload, virtual harassment and addiction.
- **Ethical Considerations**: Ethical concerns are central to XR, as immersive technologies can influence user behavior and perceptions. XRSI advocates for transparency in algorithms, the prevention of misinformation, and inclusivity in XR content design to avoid bias or exclusion.

XRSI Guidelines apply to many sections such as the following:

- **Education**: In virtual classrooms, XRSI ensures that educational XR applications safeguard students' privacy and provide harassment-free environments. For example, the framework recommends encrypted communication for online lectures and secure user authentication for accessing XR educational content.
- **Healthcare**: In healthcare, XR technologies are transforming diagnosis, therapy, and training. XRSI frameworks guide organizations to secure sensitive medical data and ensure ethical use, such as in VR-based therapy for PTSD or AR-assisted surgeries. Figure 29 depicts an example of XR usage in biomedical applications and mainstream working principles [22].
- **Entertainment**: With the growing popularity of VR gaming and social XR platforms, XRSI focuses on mitigating risks related to addictive content, virtual harassment, and identity theft. The framework includes recommendations for parental controls and content moderation.

➢ **Industrial Applications:** XR is increasingly used in training simulations, remote collaboration, and product design in industrial contexts. XRSI frameworks guide the ethical deployment of these technologies, ensuring workplace safety and data protection.

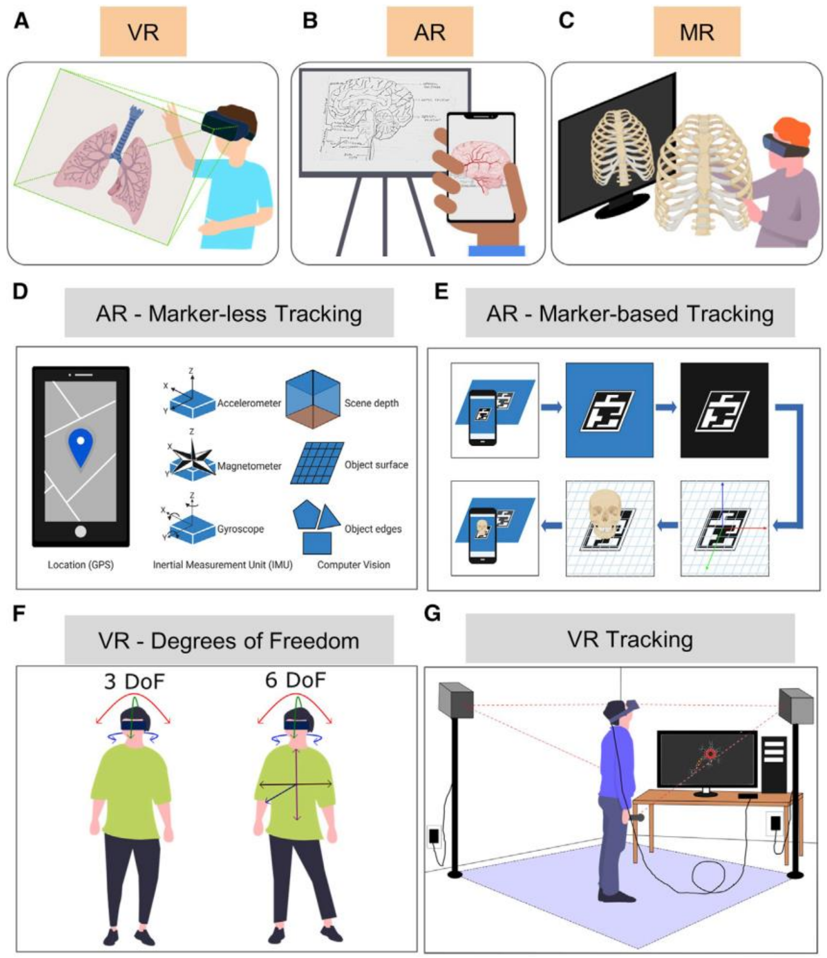


Figure 29: (A) Visualizing 3D image of a lung, (B) Smartphone based AR, (C) Visualization of a 3D image of the rib cage using MR glasses, (D) Marker-less tracking in AR, (E) Marker-based tracking in AR, (F) Degrees of freedom in VR, (G) Tracking VR principles.

Even if the rise of XR technologies introduces many opportunities, however it also comes with complex challenges that XRSI seeks to address, such as:

➢ **Interoperability**: XR systems often lack standardization, leading to fragmentation across platforms. XRSI promotes open standards to foster interoperability, enabling seamless communication between different XR applications and devices.
➢ **Cybersecurity Threats**: Immersive environments are vulnerable to hacking and data breaches. XRSI recommends multi-factor authentication, end-to-end encryption and robust cybersecurity protocols to mitigate these risks.
➢ **Behavioral Profiling and Privacy Invasion**: XR's ability to track detailed behavioral data raises concerns about profiling and surveillance. XRSI advocates for clear data minimization policies and strict regulatory compliance.
➢ **Digital Harassment and Safety**: The immersive nature of XR environments increases the risks of harassment and abuse. XRSI proposes real-time content moderation, robust reporting mechanisms, and safe interaction zones to protect users.

7.1.6 STAR-RA

The ***Reference Architecture for AI-Based Industry 5.0 Systems*** (STAR-RA) is a high-level framework designed to provide guidance for the development of human-centric, resilient, and sustainable AI-driven industrial systems that are aligned with the principles of Industry 5.0. It builds upon the concepts of Industry 4.0 reference architectures, such as ***IIRA and RAMI4.0***, but provides functionalities and structuring principles that are adapted to the requirements of Industry 5.0. The key features include:

1. **Human-Centricity**: A central tenet of Industry 5.0 is the collaboration between humans and machines. The STAR-RA integrates the concept **human-in-loop (HITL)**, allowing human operators to interact with AI systems (such as robots and digital twins) in real-time. This interaction aims to leverage the unique capabilities of both human intuition and machine intelligence. The architecture allows for **adaptive systems** that support human decision-making, increase productivity and improve safety in industrial environments [23]. The human-centric approach ensures that AI does not replace human workers but rather enhances their decision-making and operational capabilities [24].
2. **Sustainability:** In alignment with European initiatives such as the European Green Deal and the Circular Economy Action Plan, the STAR-RA framework prioritizes sustainability. By utilizing **AI for resource optimization,** the architecture supports efficient manufacturing processes that reduce waste, lower energy consumption, and promote environmentally friendly practices [23]. Moreover, AI can be used to develop **digital twins** (i.e. virtual representations of physical assets) which can simulate different scenarios to improve lifecycle management and predict the impact of various production strategies on sustainability [24].
3. **Trustworthiness:** The **trustworthiness** of AI systems is a core principle of STAR-RA. To build reliable, transparent, and accountable AI systems, the architecture incorporates **Explainable AI (XAI)**, ensuring that the decisions made by AI models are understandable and justifiable to human users. This feature is crucial in industrial environments, where regulatory compliance, data privacy, and operational safety are of utmost importance [23]. The architecture also includes **cybersecurity measures** to protect both data and the integrity of AI-driven systems. These systems are designed to comply with European standards such as the **General Data Protection Regulation (GDPR)** and the **EU Cybersecurity Act**, ensuring secure and ethical use of AI [23].
4. **Integration of Advanced Technologies:** STAR-RA enables the integration of various advanced AI technologies, such as **NeuroSymbolic AI**, **active learning**, and **multi-agent systems**. **NeuroSymbolic AI** combines the strengths of neural networks and symbolic reasoning to enhance the flexibility and interpretability of AI systems. This integration allows AI systems to process both structured and unstructured data, making them more adaptable to complex industrial environments [24]. Additionally, **active learning** enables AI models to continuously learn and improve over time by selecting the most relevant data for training. **Multi-agent systems** facilitate coordination between different AI agents, optimizing the entire production process across multiple systems, which is particularly valuable in large, complex manufacturing environments [23].
5. **Resilience:** The STAR-RA architecture also emphasizes the **resilience** of industrial systems by incorporating mechanisms for predictive maintenance and real-time **decision-making.** By analyzing data from IoT sensors and other sources, the system can predict equipment failures before they occur, ensuring higher operational uptime and minimizing costly disruptions. This feature is vital for industries that rely on continuous, high-efficiency operations [24]. Furthermore, STAR-RA's design allows it to be easily adapted to different industrial sectors, making a highly versatile and resilient framework for modern manufacturing [23].

To this end, the **STAR-RA** reference architecture provides a robust framework for the deployment of AI-based solutions in Industry 5.0 environments, focusing on human-centric, sustainable and resilient systems. By integrating advanced AI technologies with a focus on trust, transparency and human-machine collaboration, the architecture enables a shift from traditional industrial automation to a more collaborative, ethical and eco-friendly approach. This model not only supports operational efficiency but also ensures that AI applications are safe, compliant with regulations and aligned with sustainability goals.

7.2 Relevance of XR5.0 Reference Architecture with existing Standards

The XR5.0 architecture represents a cutting-edge approach to enabling Industry 5.0 principles, including human-centric operations, real-time decision-making and the integration of advanced XR and AI technologies. To ensure alignment with established practices and foster interoperability, XR5.0 draws upon a variety of existing standards and frameworks, including RAMI 4.0, IIRA, ISO/IEC specifications, ETSI standards, XRSI, OpenXR and the STAR Reference Architecture.

These standards provide foundational guidance for system structure, interoperability and functional layering, while XR5.0 extends their scope to address emerging requirements like immersive visualization and predictive analytics. This alignment ensures that XR5.0 is not only innovative but also adheres to established industry norms, facilitating its adoption and integration into diverse industrial ecosystems.

In the following subsections, we explore how XR5.0 aligns with each standard, emphasizing shared principles, functional similarities and key innovations that bridge Industry 4.0 and Industry 5.0 paradigms.

7.2.1 XR5.0 Reference Architecture and RAMI 4.0

RAMI 4.0 provides a structured reference architecture model for digitalizing industrial processes. It uses a three-dimensional model consisting of:

- **Hierarchy levels**: Covering all aspects of manufacturing from physical devices to business processes.
- **Life cycle & value stream**: Addressing the full lifecycle of assets and the value they generate.
- **Functional layers**: From physical assets to business processes.

The **similarities** between XR5.0 Architecture and RAMI 4.0 are the following:

- **Business Layer**:
    - XR5.0's **Personalized Training Service** aligns with RAMI's focus on lifecycle value. The service encompasses workflows for mechanical adjustments, production cell training and device handling, which directly reflect RAMI's functional emphasis on operator empowerment.
    - The Production Line Monitoring Service in XR5.0 supports real-time data integration, a hallmark of RAMI's emphasis on real-time operational intelligence.
- **Application Layer**:
    - XR5.0 integrates advanced AI models (e.g. Generative AI and NeuroSymbolic AI) to process data and generate insights. This complements RAMI's Information Layer which emphasizes digital representation and automation.
- **Technology Layer**:
    - IoT devices, digital twins and XR glasses within XR5.0 directly correlate with RAMI's Asset Layer, ensuring real-world systems are mapped to digital representations for seamless interaction.

However, there are some innovative additions of XR5.0. While RAMI 4.0 emphasizes structured data flow and interoperability, XR5.0 advances these principles by enabling **immersive XR visualization** and AI-driven analytics. For example, operators using XR glasses can view sensor data overlaid on digital twins, aligning physical and digital spaces dynamically.

7.2.2 XR5.0 Reference Architecture and Industrial Internet Reference Architecture (IIRA)

IIRA provides a comprehensive reference model for designing industrial IoT systems. Its key focus areas include:

- ➢ Functional domains (e.g. connectivity, control and operations)
- ➢ System characteristics (e.g. scalability, performance and interoperability)
- ➢ Architectural viewpoints for stakeholders to address concerns like security, safety and analytics.

XR5.0 has many similarities with IIRA such as the following:

- ➢ **Business Layer**:
    - ▪ XR5.0's maintenance workflows (e.g. **Predictive Maintenance Service** and **Troubleshooting Assistance Service**) align with IIRA's emphasis on operational efficiency.
    - ▪ Real-time XR-enhanced maintenance directly reflects IIRA's focus on real-time analytics and decision-making.
- ➢ **Application Layer**: The integration of AI-driven **Data, Image and Video Processing Services** in XR5.0 corresponds to IIRA's emphasis on advanced analytics and situational awareness.
- ➢ **Technology Layer**: XR5.0's IoT-enabled ecosystem, incorporating edge computing for reduced latency, mirrors IIRA's connectivity and operational responsiveness requirements.

Moreover, XR5.0 offers innovative additions to IIRA. While IIRA primarily focuses on IoT systems, XR5.0 enriches this with immersive XR environments and AI-augmented operator support. For instance, XR5.0 introduces the **real-time remote assistance**, enabling operators to communicate with experts while visualizing workflows in XR environments.

7.2.3 XR5.0 Reference Architecture and ISO/IEC JTC 1 Standards

ISO/IEC JTC 1 addresses IT standardization providing guidelines for data interoperability, cybersecurity and system quality. Relevant standards include:

- ➢ ISO/IEC 30134: Metrics for evaluating IoT-enabled systems.
- ➢ ISO/IEC 12207: Software lifecycle processes for quality assurance.
- ➢ ISO/IEC 42010: Architecture description standards.

XR5.0 bears many similarities with these standards in the various layers as follows:

- ➢ **Business Layer**:
    - ▪ XR5.0 adopts lifecycle management principles, ensuring **Training Workflows** and **Maintenance Assistance Services** align with ISO guidelines on quality and usability.
- ➢ **Application Layer**:
    - ▪ AI-driven components in XR5.0 adhere to **ISO's transparency and interpretability standards**, particularly the **XAI Model** for explainable insights.
- ➢ **Technology Layer**: XR5.0's IoT integration and secure cloud repositories align with ISO standards for data security and interoperability.

Moreover, XR5.0 Architecture provides some innovative additions. By embedding immersive interfaces and generative AI capabilities, XR5.0 enhances ISO's standards for usability and system design. For instance, operators can interact with manuals, digital twins and sensor data through XR glasses in real-time.

7.2.4 XR5.0 Reference Architecture and ETSI Industry Specifications

ETSI focuses on enabling real-time, high-performance industrial systems through its Multi-access Edge Computing (MEC) standards. MEC reduces latency and ensures efficient data processing at the network edge.

XR5.0 Architecture bears common characteristics in the various layers as follows:

- **Business Layer**:
  - XR5.0's **Production Line Monitoring Services** rely on real-time data processing, leveraging MEC-like principles to empower operators with immediate insights.
- **Application Layer**:
  - AI-powered analysis services (e.g. **Defect Recognition** and **Process Optimization**) benefit from low-latency data delivery, a core ETSI principle.
- **Technology Layer**:
  - Edge-enabled XR glasses and IoT devices in XR5.0 align with ETSI MEC standards for distributed data processing.

It has to be noted that in addition to the above similarities, XR5.0 provides some innovative additions to ETSI. By integrating AI and XR within MEC frameworks, XR5.0 creates **immersive**, **low-latency environments**, providing instant feedback during operations such as maintenance.

7.2.5 XR5.0 Reference Architecture and XRSI

XRSI is a non-profit initiative focusing on building safety, security, privacy, and ethics in XR environments. It provides guidelines to ensure that XR systems protect users' personal data, offer safe immersive experiences, and adhere to regulatory standards.

Key focus areas include:

- Data protection and privacy
- User safety
- Ethical AI in XR systems

XR5.0 Architecture incorporates several principles of XRSI, particularly in its **Business** and **Application Layers** as follows:

- Privacy and Security (**Application Layer**)
  - XR5.0 defines interfaces and application services such as the ETL Pipeline and Cloud Repository API, ensuring secure data handling and compliance with privacy requirements, aligning with XRSI's data protection guidelines.
- Ethical AI Integration **(Application Layer)**
  - XR5.0 leverages AI models (e.g. Generative AI, XAI) to process and explain data in ways that adhere to XRSI's guidelines for ethical AI, particularly in maintaining transparency through the **Explanation Service and supporting informed decision-making.**
- User Safety and Training **(Business Layer)**

- The Personalized Training Service and other XR5.0 training functionalities align with XRSI's emphasis on creating safe environments for immersive education, minimizing physical risks and ensuring that content is tailored to user needs.
- XR5.0's **Real-Time Remote Communication Service** ensures expert assistance for operators, enhancing safety during critical industrial operations.

Concerning XR5.0 innovations compared to XRSI, the following has to be noted:

- ➢ While XRSI provides guidelines, XR5.0 operationalizes these principles into specific components (e.g. **Remote Assistance Platform**) and services that directly contribute to user safety and privacy.
- ➢ XR5.0's inclusion of **AI-driven insights** in maintenance and training extends beyond XRSI's framework by ensuring proactive safety measures (e.g. damage predictions).

7.2.6 XR5.0 Reference Architecture and OpenXR

OpenXR is an open standard developed by the Khronos Group that provides a unified API for XR applications, enabling interoperability across various XR devices and platforms.

It has the following key principles:

- ➢ Cross-platform compatibility
- ➢ Device-agnostic development
- ➢ Enhanced performance through low-latency APIs

XR5.0 Architecture aligns with OpenXR's principles, particularly in its Application Layer, as follows:

- ➢ Device-Agnostic XR Applications
  - XR5.0's **XR Apps Group** incorporates diverse XR applications (e.g. AR Assistant, Maintenance Training Tool) while ensuring compatibility with external XR devices via interfaces like the **WebRTC Interface** and **Cloud Repository API,** resonating with OpenXR's cross-platform ethos.
- ➢ Streaming and Rendering (**Technology Layer**)
  - XR5.0 handles rendering on servers rather than XR glasses, aligning with OpenXR's goal to reduce device processing loads, ensuring low-latency performance for real-time XR interactions.
- ➢ Unified Development Framework (**Application Layer**)
  - The **Central XR Hub and Orchestration Platform** in XR5.0 offers a cohesive framework for managing XR applications, similar to OpenXR's approach to unifying XR development across hardware.

XR5.0 adds unique capabilities to OpenXR's framework, such as:

- ➢ AI-enhanced functionalities for **real-time decision-making** (e.g. **Reasoning Service**)
- ➢ Integration with **cloud-based training tools**, extending OpenXR's compatibility into industrial training contexts.

7.2.7 XR5.0 Reference Architecture and STAR-RA

The STAR Reference Architecture (STAR-RA) for AI-Based Industry 5.0 Applications focuses on creating a modular, scalable, and intelligent framework for integrating artificial intelligence, IoT, and human-centered technologies in industrial settings. STAR-RA emphasizes:

- ➢ Human-machine collaboration as a central design principle.
- ➢ AI-based decision-making to enhance operational efficiency and adaptability.
- ➢ IoT and digital twin integration for real-time data exchange.
- ➢ Scalability and modularity to support dynamic and evolving use cases in Industry 5.0

The architecture is organized into layers and domains, including **perception, data analysis, AI services, and interaction layers**, which ensure a seamless flow from data acquisition to actionable insights, enabling Industry 5.0 objectives like sustainability and customization.

Both XR5.0 and STAR-RA embrace a modular architecture with distinct layers to address complex industrial processes as follows:

- ➢ Modular and Layered Architecture:
  - The **Business Layer** in XR5.0 focuses on workflows like training, maintenance, and real-time assistance, mirroring STAR-RA's focus on human-centric interaction design.
  - The **Application Layer** in XR5.0, with its modular XR Apps Group and AI Models, aligns closely with STAR-RA's use of specialized AI services to enhance process optimization and human-machine interaction.
  - The **Technology Layer** in XR5.0, especially its reliance on IoT data pipelines and cloud repositories, reflects STAR-RA's emphasis on integrating digital twins and IoT data streams to drive intelligent applications.
- ➢ A common reliance on IoT and digital twins ensures both frameworks support proactive decision-making and system adaptability in complex industrial environments.
  - **IoT Data Streams** managed by the **ETL Pipeline**, enabling real-time insights.
  - The Digital Twin of Equipment, used in XR5.0's **Visualization of Augmented Information**, provides operators with real-time and predictive information about equipment status.
- ➢ STAR-RA's emphasis on integrating advanced AI techniques is mirrored in XR5.0's Application Layer, which features:
  - **AI Models** such as Generative AI, XAI and Active Learning, delivering services like defect recognition, optimization of parameters and reasoning for maintenance.
  - XR5.0's AI services directly map to STAR-RA's perception and decision-making layers, enabling automated reasoning and support for human operators.
- ➢ Concerning Human-Machine collaboration, STAR-RA prioritizes collaboration between humans and AI-driven systems, a principle embodied in XR5.0 through:
  - **Real-Time Remote Communication Service** via the **Remote Assistance Platform**, ensuring seamless operator-expert collaboration.
  - **XR Visualization Service** that integrates human feedback into augmented workflows, echoing STAR-RA's interactive and human-centered design principles.
- ➢ The STAR-RA framework emphasizes scalability, ensuring it can evolve with changing industrial needs. XR5.0 mirrors this flexibility through:
  - The modular **Central XR Hub and Orchestration Platform**, allowing for the addition of new XR applications without disrupting the existing system.
  - Dynamic **training workflows** that adapt based on operator skill levels, ensuring that human-centered processes remain relevant and effective.

Despite all those similarities, XR5.0 introduces several innovations. While STAR-RA provides a robust general framework, XR5.0 introduces innovations that cater specifically to XR and Industry 5.0, as follows:

- ➢ **Specialized XR Tools** for training and maintenance (e.g. Virtual Training Tool, AR Assistant) extend STAR-RA's capabilities into immersive learning environments.

- **Fusion of Data into XR Environments**, integrating AI services with real-time XR visualization, surpasses STAR-RA's existing interaction mechanisms to provide deeper contextual insights for operators.
- **Cloud-Integrated AI Models**, ensuring global accessibility and collaboration across industrial sites.

8 PLAN FOR BOOSTING COMPLIANCE AND INTEROPERABILITY WITH THE EU XR PLATFORM

As the XR5.0 Reference Architecture is designed with the goal of aligning seamlessly with European initiatives, a major focus of the project is ensuring interoperability with the EU XR platform being developed as part of the XR2Industry project of the Innovation Type II call. While, at the time of writing, detailed documentation about the EU XR platform is not yet publicly available, XR5.0 has developed a proactive strategy that will allow for smooth integration once the relevant specifications and architecture are released.

Interoperability Goals and Strategic Design Considerations

XR5.0 aims to serve as a foundational architecture for human-centric, AI-enhanced XR applications within the context of Industry 5.0. The following interoperability goals have been identified to ensure XR5.0's alignment with the EU XR platform:

- **Flexible Integration through Standardized Interfaces**: The architecture of XR5.0 emphasizes modularity and flexibility, enabling straightforward integration with external platforms. XR5.0 employes standardized interfaces (e.g. RESTful APIs, WebSockets) for communication between the system's components. This allows for smooth connection with third-party platforms like the EU XR platform, ensuring compatibility with future data structures and communication protocols that may be specified by the EU project.
- **Data Interoperability and Semantic Alignment**: XR5.0 is committed to semantic interoperability, ensuring that data flows seamlessly between the two systems, regardless of the underlying technologies or platforms. By leveraging industry standards like RAMI 4.0 and OpenXR, XR5.0 guarantees that the data format and terminology used within its architecture can easily map to those in the EU XR platform. A key aspect of this is ensuring that business-level processes and application-level interactions in XR5.0 follow common ontologies that will likely be adopted by the EU XR platform.
- **Cross-Platform Accessibility:** Given the varied nature of devices and hardware in both XR and industry 5.0 environments, XR5.0 adopts cross-platform compatibility principles. The application layer of XR5.0 is built with frameworks that are not only flexible but also hardware-agnostic. For instance, XR5.0 has the capability to stream high quality XR content from cloud-based infrastructure to XR glasses and smartphones. Thereafter, the rendering process shifts from the low-performance XR device to the high-performance server and the XR app does not need to be installed on an end device. This feature characterizes XR5.0 as hardware-agnostic which ensures that the platform can operate across a range of devices and integrate easily with emerging XR hardware being developed for the EU XR platform.

Planned Actions for Integration

Although, at the time of writing, detailed information regarding the EU XR platform is not yet available, XR5.0 has developed a detailed roadmap for ensuring alignment as more information emerges as follows:

- **Engagement with the EU XR Platform Consortium:**
  - The XR5.0 team will actively seek to establish communication channels with the EU XR platform stakeholders. This will involve setting up initial meetings and exploring their vision for interoperability. The goal is to discuss and analyze the platform's architecture, expected use cases and alignment opportunities with XR5.0.
  - Collaborative workshops will be held to map out integration points, addressing challenges such as data flow, platform-specific requirements and user interface compatibility.
- **Revisiting and Extending the Architecture**: Once detailed specifications for the EU XR platform is available, XR5.0 will undergo an evaluation phase to determine which parts of its current

architecture need to be adapted. Key areas of focus include:

- **Business Layer:** User stories and personas in XR5.0 will be examined to ensure alignment with the EU XR platform's business processes. Potential changes in workflows, resource management, and human-centered application design will be incorporated to ensure that the two platforms complement each other seamlessly.
- **Application Layer:** Integration points such as AI models XR interfaces and modular application containers will be assessed. XR5.0 is designed with flexibility in mind, allowing for the introduction of new application containers that integrate external systems from the EU XR platform with minimal disruption to existing workflows.
- **Technology Layer:** The technical components of XR5.0, including its data storage, networking protocols and hardware abstractions will be analyzed for compatibility with the EU XR platform. New cross-platform tools and technologies may be incorporated to ensure that XR5.0 works across a broad range of hardware, from edge devices to cloud-based resources.

➢ **Proactive alignment with Industry 5.0 Standards**: XR5.0 aligns with leading standards in Industry 5.0, XR and AI. By utilizing frameworks such as RAMI 4.0, IIRA and XRSI, XR5.0 ensures that its architecture will comply with emerging standards set by the EU XR platform, particularly in terms of:

- **Security and Privacy:** By adopting security and privacy standards, XR5.0 will align with the EU's data protection and privacy requirements, ensuring that it meets regulatory guidelines likely to be set by the EU XR platform.
- **AI and Automation:** The incorporation of AI-based decision-making systems within the XR5.0 architecture (e.g. malfunction detection, process optimization, equipment recognition) positions XR5.0 as a natural complement to any AI-enhanced functionalities the EU XR platform may employ.

➢ **Validation:** Continuous validation with end-users from the XR5.0 will ensure that the integration does not impact the user experience while adding value through enhanced interoperability with the EU XR platform.

By following the aforementioned strategic plan, XR5.0 aims to achieve the following outcomes:

➢ **Enhanced Interoperability**: With a focus on standardized interfaces and data formats, XR5.0 ensures that both systems can exchange information effortlessly.

➢ **Scalability**: XR5.0's modular and scalable architecture is well-positioned to adapt to the evolving needs of the EU XR platform

➢ **Wider Adoption and Collaboration**: By aligning with EU standards and initiatives, XR5.0 ensures compatibility with broader Industry 5.0 frameworks. This positions the architecture as a practical and adaptable reference point, facilitating its use across diverse industrial applications and encouraging collaborative efforts in the XR domain.

9 CONCLUSIONS

The document has outlined a comprehensive Reference Architecture Model and the technical specifications of the tools required to implement it. This deliverable represents a key milestone in the XR5.0 project by establishing a robust, flexible, and interoperable framework capable of addressing a diverse set of Industry 5.0 use cases, such as rapid product design, remote maintenance, simulation of production processes, and XR-enabled training.

Designed collaboratively with project partners and based on the findings of Deliverable D2.1, the architecture reflects the real-world requirements of six diverse pilot scenarios, ensuring that it remains grounded in practical industry needs. At the same time, the architecture avoids narrowing its scope to specific industrial settings; instead, it proposes a generalized, interoperable solution that can be adapted to a wide range of Industry 5.0 environments.

A significant strength of this deliverable lies in its adherence to widely accepted standards—such as TOGAF, ArchiMate, and C4—and its alignment with key Industry 4.0 and XR frameworks. This alignment guarantees compliance, promotes integration, and positions the XR5.0 system as a forward-looking reference for future Industry 5.0 initiatives.

The XR5.0 Reference Architecture is presented through two complementary perspectives:

- ➢ The Enterprise Architecture provides a high-level, holistic view that ensures alignment between business processes, technology, and strategic objectives. It outlines the delivery of value to stakeholders, core business processes, functions, applications, and the technology stack.
- ➢ The Solution Architecture focuses on operational design, presenting the system's position within the ecosystem, the role of external actors, and a breakdown of logical components (containers) along with their relationships, dependencies, and interactions.

In addition, the document dives into the internal workings of each XR5.0 tool—covering functionalities, interfaces, and dependencies—offering a detailed understanding of how these components integrate within the overall system.

A key aspect of the XR5.0 project is its forward-looking strategy to ensure compliance and interoperability with the EU XR platform, a parallel initiative aimed at developing a unifying framework for XR technologies in Europe. Chapter 8 of this deliverable outlined preliminary efforts and planned actions to foster seamless integration with this platform, ensuring XR5.0 aligns with the evolving standards and technical specifications emerging from the EU XR initiative. This collaboration will enhance the applicability and adoption of XR5.0 as a reference model in Industry 5.0 scenarios.

This deliverable marks the first iteration of the XR5.0 Reference Architecture, serving as both a reference point for developers and a blueprint for development and integration activities throughout the project. As the work progresses, refinements and updates will be systematically documented, ensuring the architecture continues to evolve and align with emerging needs and feedback.

References

[1] Vázquez-Ingelmo, A., García-Holgado, A., & García-Peñalvo, F. J. (2020, April). C4 model in a Software Engineering subject to ease the comprehension of UML and the software. In 2020 IEEE Global Engineering Education Conference (EDUCON) (pp. 919-924). IEEE.

[2] XR5.0, D2.1 - Requirements and Reference Scenarios Analysis, 2024.

[3] The Open Group, ArchiMate 3.2 Specification. The Open Group, 2023. [Online]. Available: https://pubs.opengroup.org/architecture/archimate3-doc/

[4] S. Brown, "C4 Model for Software Architecture," [Online]. Available: https://c4model.com/. [Accessed: 28-Nov-2024]

[5] Adolphs, P., Bedenbender, H., Dirzus, D., Ehlich, M., Epple, U., Hankel, M., Wollschlaeger, M. (2015) "Reference Architecture Model Industrie 4.0 (RAMI 4.0)". VDI/VDE and ZVEI. Retrieved from https://www.zvei.org/en/subjects/industry-4-0/the-reference-architectural-model-rami- 40-and-the-industrie-40-component/ [last accessed 21/05/2021]

[6] The Open Group, *TOGAF® Standard, 10th Edition: A Pocket Guide*. The Open Group, 2022.

[7] Industrial Internet Consortium.: The Industrial Internet Reference Architecture v 1.9. Available at: https://www.iiconsortium.org/IIRA.htm. Last accessed 26 June 2023

[8] ISO/IEC/IEEE.: ISO/IEC/IEEE 42010:2011 Systems and software engineering – Architecture description. http://www.iso.org/iso/catalogue_detail.htm?csnumber=50508 (2011). Last accessed 26 June 2023

[9] A. Buchner, M. Höchtl, T. Kramler, and E. Veith, "Modeling of Customer-Oriented Applications in Product Lifecycle Using RAMI 4.0," *International Journal of Modeling and Optimization*, vol. 9, no. 1, pp. 1–7, Feb. 2019. DOI: 10.7763/IJMO.2019.V9.676.

[10] F. Figueroa, W. Pavon, H. Calvopiña, D. Mideros, and F. Castro De la Cruz, "Integration of the Asset Administration Shell (AAS) for Smart Manufacturing: State-of-Art and Future Opportunities," *Sciety*, Jun. 2024. [Online]. Available: https://sciety.org/articles/activity/10.20944/preprints202406.1271.v1.

[11] Binder, M., Müller, G., & Schmidt, S. (2024). Ensuring the application of Industry 4.0 design principles by using reference architectures. *Sensors & Transducers*, 265(2), 97–105. Available: https://sensorsportal.com/HTML/DIGEST/may_2024/Vol_265/p_3338.pdf

[12] F. Bonomi, R. Milito, P. Natarajan, and J. Zhu, "Fog Computing: A Platform for Internet of Things and Analytics," in *Big Data and Internet of Things: A Roadmap for Smart Environments*, Springer, 2020, pp. 169–186. [Online]. Available: https://www.researchgate.net/publication/264589945_Research_Directions_for_the_Internet_of_Things .

[13] J. A. Stankovic, "Research Directions for the Internet of Things," *IEEE Internet of Things Journal*, vol. 1, no. 1, pp. 3–9, 2020. [Online]. Available: https://www.researchgate.net/publication/264589945_Research_Directions_for_the_Internet_of_Things

[14] ETSI, "ETSI Multi-access Edge Computing (MEC)," [Online]. Available: https://www.etsi.org/technologies/multi-access-edge-computing. [Accessed: Dec. 7, 2024].

[15] ETSI, "IoT and oneM2M Standards," [Online]. Available: https://www.etsi.org/technologies/internet-of-things. [Accessed: Dec. 7, 2024].

[16] ETSI, "Cyber Security for IoT Standards," [Online]. Available: https://www.etsi.org/technologies/cyber-security. [Accessed: Dec. 7, 2024].

[17] ETSI, "5G and Industrial Networks," [Online]. Available: https://www.etsi.org/technologies/5g. [Accessed: Dec. 7, 2024].

[18] Chang, W. (2022). ISO/IEC JTC 1/SC 42 (AI)/WG 2 (data) data quality for analytics and machine learning (ML). *Information Technology Laboratory*.

[19] Spiekermann, S. (2021). What to expect from IEEE 7000: The first standard for building ethical systems. *IEEE Technology and Society Magazine*, *40*(3), 99-100.

[20] XRSI, "XRSI Privacy and Safety Framework," [Online]. Available: https://xrsi.org/. [Accessed: Dec. 7, 2024].

[21] M. Slater and M. V. Sanchez-Vives, "Enhancing Our Lives With Immersive Virtual Reality," *Frontiers in*

Robotics and AI, vol. 3, no. 74, 2016, [Online]. Available: https://www.frontiersin.org/. [Accessed: Dec. 7, 2024].

[22] M. Venkatesan, H. Mohan, J. R. Ryan, C. M. Schürch, G. P. Nolan, D. H. Frakes, and A. F. Coskun, "Virtual and augmented reality for biomedical applications," *Cell Reports Medicine*, vol. 2, no. 7, Jul. 2021, Art no. 100348, doi: 10.1016/j.xcrm.2021.100348.

[23] STAR-AI EU Funded Project, "Human-Centric Artificial Intelligence Architecture for Industry 5.0 Applications," *STAR-AI*, 2024. [Online]. Available: https://star-ai.eu/new-publication-human-centric-artificial-intelligence-architecture-industry-50-applications

[24] I. Papanikolaou, et al., "Reference Architecture for AI-Based Industry 5.0 Applications," *ResearchGate*, 2024. [Online]. Available: https://www.researchgate.net/publication/378099277_Reference_Architecture_for_AI-Based_Industry_50_Applications

[25] XRSI, "Medical XR Privacy & Safety Framework," Medical XR Council, 2021. [Online]. Available: https://xrsi.org/medical-xr-privacy-safety-framework. [Accessed: Dec. 10, 2024].

[26] XRSI, "Ethics in Immersive Technologies," XR Safety Initiative, 2021. Available: https://xrsi.org/ethics. [Accessed: Dec. 10, 2024].

[27] XRSI, "Collaborating for a Safer Metaverse," XR Safety Initiative, 2021. Available: https://xrsi.org/metaverse-collaboration. [Accessed: Dec. 10, 2024].

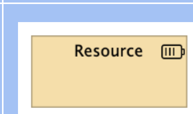
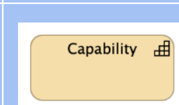
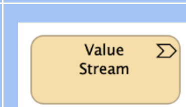
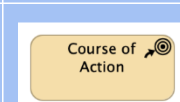
ANNEX I.

In this annex, a brief explanation of the various ArchiMate elements that were leveraged to design the various layers of the XR5.0 (Human-Centric AI-Enabled Extended Reality Applications for the Industry 5.0 Era) will be presented. For a more thorough review, the reader may consult the thorough online tutorial provided by the Open Group located at:

https://pubs.opengroup.org/architecture/archimate3-doc/

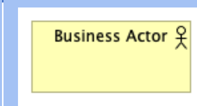
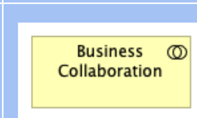
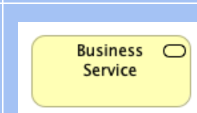
The descriptions of the elements used are taken from the online tutorial. Table 7 lists the main motivation and strategy elements used for the strategy layer. Motivations are used for modelling the reasons that guide the design of the architecture, while strategy elements model the directions and choices of the enterprise that have a direct impact on how the architecture is designed. Business elements that are used to model the operational and organizational aspects of the enterprise are depicted in Table 8. The application elements of an architecture model, the structure, behavior and interaction of the applications that compose the solution are depicted in Table 9. Finally, the structure and behavior of the technology infrastructure is described by the technology elements in the ArchiMate approach; these elements are depicted in Table 10.

Table 7 Strategy and motivation elements used

Element	Description	Notation
Goal	Represents a high-level statement of intent, direction, or desired end state for an organization and its stakeholders.	
Resource	Represents an asset owned or controlled by an individual or organization.	
Capability	Represents an ability that an active structure element, such as an organization, person, or system, possesses.	
Value Stream	Represents a sequence of activities that create an overall result for a customer, stakeholder, or end user	
Course of action	Represents an approach or plan for configuring some capabilities	

	and resources of the enterprise, undertaken to achieve a goal.	

Table 8 Business elements used

Element	Description	Notation
Business Actor	Represents a business entity that is capable of performing behavior.	
Business Role	Represents the responsibility for performing specific behavior, to which an actor can be assigned, or the part an actor plays in a particular action or event.	
Business Collaboration	Represents an aggregate of two or more business internal active structure elements that work together to perform collective behavior.	
Business interaction	Represents a unit of collective business behavior performed by (a collaboration of) two or more business actors, business roles, or business collaborations.	
Business service	Represents explicitly defined behavior that a business role, business actor, or business collaboration exposes to its environment.	
Contract	Represents a formal or informal specification of an agreement between a provider and a consumer that specifies the rights and obligations associated with a product and establishes functional and non-functional parameters for interaction.	

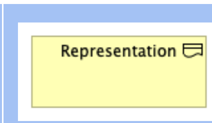
Representation	Represents a perceptible form of the information carried by a business object.	
Product	Represents a coherent collection of services and/or passive structure elements, accompanied by a contract/set of agreements, which is offered as a whole to (internal or external) customers.	

Table 9 Application elements used

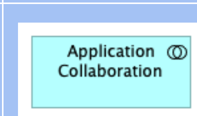
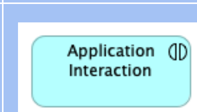
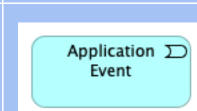
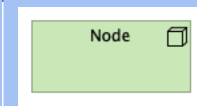
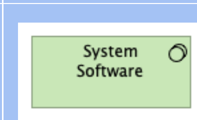
Element	Description	Notation
Application Component	Represents an encapsulation of application functionality aligned to implementation structure, which is modular and replaceable.	
Application Collaboration	Represents an aggregate of two or more application internal active structure elements that work together to perform collective application behavior.	
Application function	Represents automated behavior that can be performed by an application component.	
Application Interaction	Represents a unit of collective application behavior performed by (a collaboration of) two or more application components.	
Application event	Represents an application state change.	
Application Service	Represents an explicitly defined exposed application behavior.	
Data Object	Represents data structured for automated processing.	

Table 10 Technology elements used

Element	Description	Notation
Node	Represents a computational or physical resource that hosts, manipulates, or interacts with other computational or physical resources.	
System Software	Represents software that provides or contributes to an environment for storing, executing, and using software or data deployed within it	
Technology Process	Represents a sequence of technology behaviors that achieves a specific result.	
Facility	Represents a unit of collective application behavior performed by (a collaboration of) two or more application components.