

Framework Requirements and Technological Tools Review

Deliverable 2.2 Work Package 2

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Table of Contents

Table of Contents.....	3
Glossary of terms and abbreviations used	5
Executive Summary	7
1 Introduction	9
1.1 Mapping 6G-DALI outputs	9
1.2 Deliverable overview and report structure	9
2 6G-DALI Project Overview.....	11
2.1 6G-DALI Reference Architecture.....	11
2.2 6G-DALI Thematic Areas (Organization/Decomposition).....	12
3 6G-DALI Framework Requirements Analysis	14
3.1 MLOps Thematic Area Requirements	14
3.1.1 General Functional Requirements.....	14
3.1.2 General Non-Functional Requirements	15
3.1.3 MLOps Orchestration Technical Dimension	15
3.1.4 Experiment as a Service and Hyper Parameter Optimization Technical Dimension.....	18
3.1.5 Meta-Orchestration of ML Pipelines Technical Dimension.....	18
3.1.6 Trustworthy AI and societal acceptance Technical Dimension	19
3.2 DataOps Thematic Area Requirements.....	20
3.2.1 General Functional Requirements.....	21
3.2.2 General Non-Functional Requirements	21
3.2.3 Data Transformation (ELT Pipelines) Technical Dimension.....	22
3.2.4 Data Augmentation Technical Dimension	23
3.2.5 Intent-Driven DataOps Technical Dimension.....	23
3.3 Data Spaces and Data Connectors Requirements Area.....	24
3.3.1 General Functional Requirements.....	25
3.3.2 General Non-Functional Requirements	26
3.4 Digital Twin Thematic Area Requirements	27
3.4.1 General Functional Requirements.....	27
3.4.2 General Non-Functional Requirements	28
3.4.3 6G Digital Twin Library Technical Dimension.....	28
3.4.4 AI-as-a-Service (AIaaS) and HPO for RLOps Technical Dimension	29
3.4.5 Collaborative RLOps Technical Dimension	30
3.4.6 Federated Learning with NWDAF Technical Dimension	30
3.5 Adaptation Layer Area.....	31
3.5.1 General Functional Requirements.....	31
3.5.2 General Non-Functional Requirements	32
4 Technological Tools Analysis	33
4.1 MLOps.....	33
4.1.1 MLOps Orchestration.....	33
4.1.2 Experimentation-as-a-service & HPO for MLOps.....	35
4.1.3 Meta-Orchestration of ML Pipelines.....	36
4.1.4 Trustworthy AI and societal acceptance	37
4.2 DataOps.....	39
4.2.1 Data Transformation (ELT Pipelines).....	39
4.2.2 Data Augmentation	40
4.2.3 Intent-driven DataOps via Generative AI.....	40
4.3 Data Spaces & Connectors.....	43
4.3.1 Data Spaces.....	43
4.3.2 Data Lake.....	45
4.3.3 Connectors.....	47
4.4 Digital Twin	48
4.4.1 Digital Twin Components.....	48
4.4.2 AIaaS and HPO for RLOps.....	49
4.4.3 Collaborative RLOps through Digital Twin	49

4.4.4	Federated learning for NWDAF	50
4.5	Adaptation Layer.....	50
4.5.1	Adaptation Layer tools	50
5	Gap Analysis and Proposed Tools Extensions	52
6	Conclusions	56
7	References	57

List of Figures

Figure 1.	6G-DALI Framework Reference Architecture	11
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List of Tables

Table 1.	Adherence to 6G-DALI GA Deliverable & Tasks Descriptions.....	9
Table 2.	6G-DALI Objectives.....	12
Table 3.	6G-DALI Thematic Areas Organization	12
Table 4.	Summary of the technological tools	52

Glossary of terms and abbreviations used

Abbreviation / Term	Description
AI	Artificial Intelligence
AlaaS	AI-as-a-Service
ADO	Accelerated Discovery Orchestrator
APIs	Application Programming Interfaces
AWS S3	Amazon Web Services Simple Storage Service
AI-RSG	AI RAN Scenario Generator
AnLF	Analytics Logical Function
CN	Core Network
CU	Centralized Units
DataOps	Data Operations
DT	Digital Twin
DTT	Digital Twin Testbed
DCAT-AP	Data Catalog Vocabulary — Application Profile
DUs	Distributed Units
E2E	End To End
ELT	Extract Load Transform
ETL	Extract Transform Load
ETHAI	Ethics of AI
ETSI	European Telecommunications Standards Institute
Eclipse-EDC	Eclipse — Energy Data Connector
FAIR	Findable-Accessible-Interoperable-Reusable
FLOps	Federated Learning Operations
GDPR	General Data Protection Regulation
GUI	Graphical User Interface
GA	Grant Agreement
HPO	Hyperparameter Optimization
IDC	International Data Corporation
IDSA	International Data Spaces Association
IoT	Internet of Things
ITU	International Telecommunication Union
KPI	Key Performance Indicator
KSI	Key Sustainability Indicators
KV	Key Values
KVI	Key Value Indicator
LLM	Large Language Model
LIME	Local Interpretable Model-agnostic Explanations
ML	Machine Learning
MLOps	Machine Learning Operations
MTLF	Model Training Logical Function
MAPIE	Model Agnostic Prediction Interval Estimator
NWDAF	Network Data Analytics Function
near-RT RIC	near-real-time RAN Intelligent Controller
PUNCC	Predictive Uncertainty Calibration and Conformalization
PHY	Physical Layer

QoE	Quality of Experience
ONNX	Open Neural Network Exchange
RIS	Reconfigurable Intelligent Surfaces
RAG	Retrieval-Augmented Generation
RPC	Remote Procedure Call
RDF	Resource Description Framework
RDS	RDF Data at Scale
RLOps	Reinforcement Learning Operations
RAN	Radio Access Networks
SLA	Service Level Agreement
SNS JU	Smart Networks and Services Joint Undertaking
SHAP	SHapley Additive exPlanations
SPARQL	SPARQL Protocol and RDF Query Language
UE	User Equipment
3GPP	3rd Generation Partnership Project

Executive Summary

This Deliverable 2.2, “Framework Requirements and Technological Tools Review,” represents the collective efforts of Work Package 2 (Framework requirements and technological tools) within the 6G-DALI project (6G Data and ML Operations Automation via an End-to-End Artificial Intelligence (AI) Framework). Funded under the Horizon Europe Research and Innovation Action program, 6G-DALI aims to advance 6G data usage and machine learning automation through a comprehensive AI-driven framework. This deliverable pursues two principal objectives: first, to systematically review the functional and non-functional requirements of the 6G-DALI framework, using a modular approach that comprehensively addresses both Data Operations (DataOps) and Machine Learning Operations (MLOps); and secondly, to analyze existing state-of-the-art tools to identify opportunities for leveraging proven technologies while addressing identified gaps through targeted enhancements.

The 6G-DALI project addresses the critical need for an end-to-end AI framework to support the evolution of 6G networks. At its core, the project introduces a novel architecture built upon two synergistic pillars: AI experimentation as a service via MLOps and data collection and storage via DataOps. This framework is designed to automate MLOps and DataOps workflows, fostering a robust 6G data economy by enabling secure, trusted, and sovereign data exchange among diverse stakeholders. The architecture aligns with International Data Spaces (IDS) and Gaia-X principles, positioning 6G-DALI as a complementary and synergistic initiative that creates an active environment for AI deployment and on-demand data generation within the broader European data governance ecosystem.

Given the inherent complexity of the 6G-DALI framework, which integrates both DataOps and MLOps capabilities within a unified architecture, this deliverable adopts a bottom-up approach. The framework is systematically decomposed into distinct thematic areas, each addressing specific functional domains of 6G-DALI. For instance, the DataOps thematic area focuses exclusively on data-related requirements and tool analyses, while the MLOps thematic area concentrates on MLOps tools and workflows. Additional thematic areas cover Data Spaces and Data Connectors, Digital Twin and Reinforcement Learning capabilities, and the Adaptation Layer. This modular decomposition facilitates comprehensive requirements elicitation and tool assessment while maintaining awareness of the overall integration strategy that merges all thematic areas into a unified, coherent architecture.

This deliverable is meticulously structured to provide a systematic, comprehensive, and deeply analytical exposition of the 6G-DALI framework, encompassing both its conceptual foundations and technological landscape. The document unfolds across a sequence of well-defined sections, each contributing to a coherent and progressive narrative.

Section 1 serves as an introduction, situating this deliverable within the broader context of the 6G-DALI project outcomes. It delineates the purpose, scope, and relevance of the document while mapping its internal organization and logical progression. Section 2 offers a holistic description of 6G-DALI, presenting the project’s initial architectural vision alongside its organizational configuration. Within this section, Subsection 2.1 elaborates on the Initial Architecture, identifying and characterizing the principal architectural components and explicating their interconnections and functional synergies. Subsection 2.2, in turn, articulates the organization of the 6G-DALI thematic areas, detailing the conceptual underpinnings that define each area and the intricate interdependencies that bind them together into an integrated research and development framework.

Section 3 advances into a comprehensive requirements analysis of the 6G-DALI framework, organized in alignment with its thematic domains. Subsection 3.1 concentrates on DataOps requirements, encompassing data transformation pipelines, data augmentation mechanisms, and the integration of intent-driven DataOps functionalities. Subsection 3.2 focuses on MLOps requirements, discussing orchestration, experimentation-as-a-service paradigms, meta-orchestration capabilities, and the critical aspects of trustworthiness, specifically uncertainty quantification and explainability. Subsection 3.3 examines the requirements concerning Data Spaces and Data Connectors, which are pivotal for realizing the envisioned 6G data economy. Subsection 3.4 explores the Digital Twin and Reinforcement Learning requirements, elaborating on the conception of the 6G Digital Twin Library, AI-as-a-Service for RLOps, collaborative reinforcement learning operations, and the integration of federated learning with the Network Data Analytics Function (NWDAF). Finally, Subsection 3.5 delineates the Adaptation Layer

requirements, emphasizing their role as the critical interface ensuring seamless interaction between the framework and its diverse use cases.

Building upon this foundation, Section 4 undertakes an exhaustive Technological Tools Analysis, systematically reviewing state-of-the-art platforms and tools across the domains of MLOps, DataOps, Data Spaces, and Digital Twin technologies. The section identifies mature solutions that demonstrate potential for direct adoption, customization, or integration within the evolving 6G-DALI framework.

Section 5 proceeds to a detailed Gap Analysis, juxtaposing the established framework requirements with the surveyed technological landscape. It delineates existing discrepancies, formulates targeted tool extensions, and articulates the additional enhancements necessary to fully realize the ambitious vision of the 6G-DALI ecosystem.

Finally, Section 6 presents the concluding synthesis, distilling insights from the preceding analyses and outlining a strategic pathway for the framework's continued development and implementation. The deliverable, through this rigorous and methodical structure, ensures that the 6G-DALI framework is firmly anchored in well-defined requirements, while simultaneously leveraging mature technological innovations. This methodological approach positions 6G-DALI to achieve a transformative yet pragmatic realization of automated data and machine learning operations for next-generation 6G systems.

1 Introduction

The goal of this section is to provide a brief outline of the objectives of the specific 6G-DALI Deliverable, how those are aligned and relevant with the overall project, and what was the approach followed in order to achieve them.

1.1 Mapping 6G-DALI outputs

The purpose of this section is to map 6G-DALI Grant Agreement commitments, both within the formal Deliverable and Task description, against the project’s respective outputs and work performed (see Table 1).

Table 1. Adherence to 6G-DALI GA Deliverable & Tasks Descriptions

Deliverable description			
D2.2 ‘ Framework requirements and technological tools review ’ - ‘ Report on the functional and non-functional requirements of the 6G-DALI framework as well as a review of the existing technological tools that can be employed to support and develop the components of the 6G-DALI framework. ’			
6G-DALI Task No. and Title	6G-DALI GA Task Description	Respective document chapter(s)	Justification
Task 2.2 Framework requirements and technological tools	The task defines the functional and non-functional requirements for the 6G-DALI framework, focusing on DataOps, MLOps, and testbed integration with 6G data spaces. It includes a comparative study of suitable technologies aligned with IDS, Gaia-X, and modern MLOps to ensure compatibility and prevent integration issues.	Section 2 – 6G-DALI Overall Architecture	Section 2 offers an Overall Description of 6G-DALI, presenting the project’s initial architecture and organizational structure.
		Section 3 – 6G-DALI Framework Requirements Analysis	Section 3 provides a detailed analysis of the 6G-DALI framework’s requirements, organized by thematic areas (DataOps, MLOps, Data Spaces, Digital Twin, and Adaptation Layer). It systematically defines both functional and non-functional requirements essential for framework development, directly addressing the GA task objectives.
		Section 4 – Technological Tools Analysis	Section 4 thoroughly reviews state-of-the-art technological tools across the identified thematic areas. It evaluates the suitability of these tools for integration into the 6G-DALI architecture, ensuring alignment with Gaia-X and IDS principles while identifying proven technologies for adoption.
		Section 5– Gap Analysis and Tool Extensions	Section 4 performs a comparative assessment between framework requirements and existing technological capabilities. It identifies the necessary extensions and enhancements required to bridge identified gaps, fulfilling the GA task goal of refining and aligning technological tools to 6G-DALI’s needs.

1.2 Deliverable overview and report structure

This deliverable is structured to provide a systematic and comprehensive treatment of the 6G-DALI framework requirements and technological landscape:

- **Section 1** provides an introduction to the deliverable, establishing the context within the broader 6G-DALI project outputs and outlining the document structure.
- **Section 2** presents the comprehensive 6G-DALI Framework Requirements Analysis, organized by thematic areas. Section 2.1 addresses DataOps requirements, covering data transformation pipelines, data augmentation, and intent-driven DataOps capabilities. Section 2.2 focuses on MLOps requirements, including orchestration, experimentation as a service, meta-orchestration, and trustworthiness through uncertainty quantification and explainability. Section 2.3 examines Data Spaces and Data Connectors requirements, essential for enabling the envisioned 6G data economy. Section 2.4 details Digital Twin and Reinforcement Learning requirements, including the 6G Digital Twin Library, AI-as-a-Service for RLOps, collaborative RLOps, and federated learning integration with NWDAF. Section 2.5 describes the Adaptation Layer requirements, which provide the crucial interface between the framework and diverse use cases.
- **Section 3** conducts a comprehensive Technological Tools Analysis, systematically reviewing existing state-of-the-art solutions across MLOps platforms, DataOps tools, Data Spaces implementations, and Digital Twin technologies. This analysis identifies mature technologies suitable for adoption or integration within the 6G-DALI framework.
- **Section 4** performs a Gap Analysis and proposes specific tool extensions, comparing the identified requirements against available technological solutions. This section articulates the necessary enhancements and developments required to bridge identified gaps and achieve the full vision of the 6G-DALI framework.
- **Section 5** presents conclusions, synthesizing the findings from the requirements analysis, tool review, and gap assessment, while outlining the path forward for framework development and implementation.

2 6G-DALI Project Overview

The 6G-DALI project represents a cutting-edge European initiative that aims to create a comprehensive end-to-end framework for DataOps and MLOps in 6G networks. It bridges the domains of AI, data management, and telecommunications to enable automated, intelligent, and trustworthy 6G infrastructures. Through its innovative architecture and structured organization, 6G-DALI enables experimentation, data analytics, and digital twin integration to accelerate the evolution of AI-driven 6G systems.

The project aligns with other large-scale initiatives and research efforts in Europe, ensuring consistency with the principles of Gaia-X [1] and the International Data Spaces Association (IDSA) [2]. This alignment guarantees data sovereignty, interoperability, and secure data exchange while contributing to global standards and open innovation ecosystems [3].

2.1 6G-DALI Reference Architecture

The high-level architecture of 6G-DALI establishes a comprehensive end-to-end AI framework designed to revolutionize 6G network operations and service delivery. As depicted in Figure 1, the architecture is structured around two foundational pillars that work in concert to enable intelligent, automated network management. The first pillar focuses on AI Experimentation as a Service via MLOps, encompassing complete machine learning lifecycle management including model training, validation, deployment automation, performance benchmarking and optimization, and integration with 6G testbeds and Digital Twin environments. The second pillar addresses Data and Analytics Collection and Storage via DataOps, providing automated data pipeline orchestration, real-time and historical data management, data quality assurance and governance, and intent-driven DataOps.

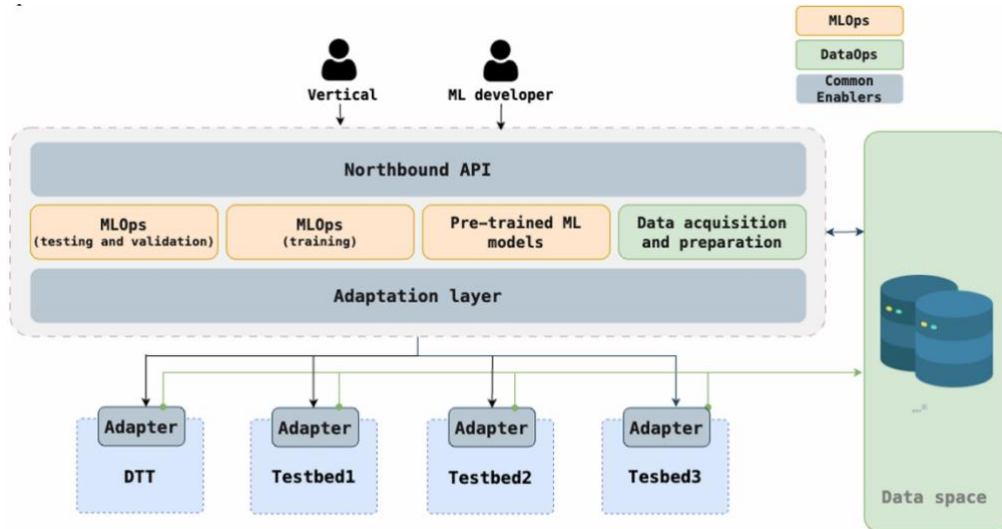


Figure 1. 6G-DALI Framework Reference Architecture.

Both pillars support comprehensive workflow automation, enabling seamless MLOps and DataOps operations while serving two primary user communities. Namely, ML developers that focus on optimizing 6G infrastructure performance and enabling closed-loop, zero-touch network management [4], and vertical industry users, who concentrate on developing ML models to enhance their 6G-enabled services and applications.

The framework interfaces with diverse 6G infrastructure components spanning the entire telecommunications ecosystem. These include Radio Access Networks (RAN) providing next-generation wireless access infrastructure, Core Networks (CN) delivering 6G network core functionality and services, and distributed computing infrastructure extending from extreme-edge devices through edge computing to cloud platforms. Additionally, the framework incorporates a high-fidelity Digital Twin Testbed that provides virtual environments for large-scale testing and validation scenarios.

6G-DALI defines seven measurable objectives, each contributing to the realization of its two main pillars detailed in Table 2:

Table 2. 6G-DALI Objectives.

Objective	Description
1. End-to-End AI Framework	Develop a user-friendly AI framework for DataOps and MLOps with graphical and API-based interfaces for AI experimentation, data discovery, and interaction with LLMs.
2. Gaia-X and ELT for DataOps	Deliver Gaia-X-compliant ELT pipelines for handling both historical (cold) and real-time (hot) data, ensuring high-quality datasets for ML training.
3. Trustworthy AI/ML via MLOps	Support the complete AI model lifecycle using MLOps, RLOps, and FLOps for validation, benchmarking, and deployment with a meta-orchestration layer.
4. Plug-and-Play Testbed Integration	Provide adaptable adapters and standardized APIs for integrating current and future 6G testbeds into the AI framework.
5. Digital Twin Testbed (DTT)	Build a high-fidelity Digital Twin to simulate large-scale scenarios, generate realistic datasets, and complement physical testbeds.
6. Ethical and Legal Compliance	Ensure ethical data practices aligned with GDPR, the AI Act, and the Data Governance Act to maintain trust and compliance.
7. Dissemination and Standardization	Promote impact through scientific dissemination, contributions to standardization bodies (3GPP, ETSI, ITU), and engagement with open-source communities.

2.2 6G-DALI Thematic Areas (Organization/Decomposition)

6G-DALI employs a systematic bottom-up organizational methodology to comprehensively address the framework's architectural requirements. This strategic approach ensures that each thematic area is developed through a rigorous, structured process consisting of three interconnected phases. The **Requirements Analysis Phase** involves the detailed identification of technical and functional requirements for each thematic area, ensuring alignment with overall architectural objectives while assessing stakeholder needs from ML developers, vertical industries, and operators. Gap analysis with existing technologies and frameworks informs the development priorities.

The **Technological Tool Assessment Phase** involving evaluation of state-of-the-art technologies and methodologies to select optimal tools and frameworks for each technical area. This phase carefully considers interoperability and integration requirements alongside scalability and performance demands. Finally, the **Targeted Implementation Phase** develops specialized components that address specific architectural demands while ensuring seamless integration into the overall 6G-DALI framework. This phase maintains flexibility for future enhancements and extensions through continuous validation against architectural principles.

This bottom-up approach ensures that foundational technical components are built on a solid basis before higher-level integration, resulting in a robust, scalable, and maintainable architecture that effectively addresses the complex requirements of 6G AI frameworks.

The 6G-DALI organizational structure is built around five thematic areas as presented in Table 3, each addressing a critical technological domain required to realize the project's architecture. Within each thematic area, there are dedicated technical sub-areas that focus on specific components and enablers.

Table 3. 6G-DALI Thematic Areas Organization

Thematic Area	Technical Dimension	Description
MLOps	MLOps Orchestration	Development of orchestration layers for managing ML workflows and lifecycle automation.

	Experimentation-as-a-Service & HPO for MLOps	Provision of on-demand AI experimentation services and hyperparameter optimization tools.
	Meta-Orchestration of ML Pipelines	Integration of multiple MLOps and RLOps stacks into a unified meta-orchestration layer.
	Trustworthy AI and societal acceptance.	Ensuring trustworthy AI by incorporating explainability and uncertainty estimation mechanisms.
DataOps	Data Transformation (ELT Pipelines)	Implementation of advanced Extract-Load-Transform processes for data preparation and management.
	Data Augmentation	Enhancement of dataset diversity and robustness using synthetic data generation and enrichment techniques.
	Intent-driven DataOps via GenAI	Enabling intent-based data management powered by Generative AI for context-aware operations.
Data Spaces	Data Spaces & Connectors	Establishing secure connectors for cross-domain and multi-actor data collaboration.
Digital Twin	Digital Twin Library	Building a high-fidelity virtualized environment mirroring real 6G testbeds.
	AIaaS and HPO for RLOps	Scalable AI services with automated hyperparameter tuning for RL workflows.
	Collaborative RLOps through Digital Twin	Supporting reinforcement learning experimentation and optimization in simulated 6G conditions.
	Federated learning for NWDAF	Privacy-preserving distributed training for adaptive network analytics.
Adaptation Layer	Adaptation layer	Interfacing 6G-DALI framework and testbeds for seamless model and data integration.

The four thematic areas are designed to operate as an integrated ecosystem where each area both provides capabilities to and consumes capabilities from other areas. This synergistic approach ensures that 6G-DALI operates as a cohesive, integrated framework rather than isolated components, maximizing efficiency and enabling comprehensive AI-driven 6G innovation across the entire ecosystem.

3 6G-DALI Framework Requirements Analysis

3.1 MLOps Thematic Area Requirements

The MLOps Thematic Area focuses on establishing a robust foundation for AI-driven automation within the 6G-DALI vision. In this context, MLOps is envisioned as the central enabler for AI experimentation, model lifecycle management, and continuous intelligence deployment across the 6G ecosystem. It provides the technological and operational backbone required to integrate data-driven intelligence into the network fabric, ensuring adaptability, scalability, and trustworthiness. From the perspective of 6G-DALI, MLOps embodies a unified framework that supports the design, deployment, and maintenance of AI and ML models throughout their complete lifecycle. It facilitates automated workflows for model training, validation, fine-tuning, and optimization, leveraging advanced mechanisms such as AutoML and AutoRL. These workflows enable efficient experimentation and rapid iteration, while maintaining alignment with the performance and energy-efficiency objectives of the 6G-DALI architecture.

A core aspect of the 6G-DALI MLOps vision is its support for diverse AI paradigms, including federated learning, reinforcement learning, and time-series analytics. Each paradigm contributes to different dimensions of the 6G intelligent network, from distributed data privacy and learning at the edge to dynamic resource orchestration and network optimization. The MLOps infrastructure ensures that these models can be continuously evaluated and improved through interconnected testbeds, with automated feedback loops for detecting drift and maintaining model reliability.

Knowledge sharing and reusability are integral to the framework. Through pre-trained models and transfer learning capabilities, 6G-DALI reduces computational overhead, accelerates experimentation, and minimizes energy consumption. This approach enhances sustainability while fostering collaboration across AI-driven services. Furthermore, the MLOps framework integrates explainable AI (XAI) and trust management mechanisms, ensuring that learning agents and decision-making processes remain interpretable, accountable, and aligned with network safety requirements. Reinforcement learning agents, for example, are validated in controlled digital twin environments before deployment, guaranteeing safe and trustworthy operation.

In summary, the MLOps Thematic Area defines the foundational capabilities that enable AI experimentation as a service within the 6G-DALI architecture. It specifies the functional and non-functional requirements necessary to operationalize large-scale, automated, and trustworthy AI experimentation across distributed 6G infrastructures.

This section defines the general functional and non-functional requirements for MLOps, enabling AI experimentation as a service within the 6G-DALI architecture.

3.1.1 General Functional Requirements

General Functional Requirements of the MLOps	
FR-ID	FR-Description
FR-MLOPS-1	The system shall support the end-to-end management of ML model lifecycles across multiple tools and environments.
FR-MLOPS-2	The system shall enable framework-agnostic integration of MLOps components, including experiment tracking, artifact storage, and model serving.
FR-MLOPS-3	The system shall allow secure and policy-driven access to models and orchestration resources.
FR-MLOPS-4	The system shall enable reproducibility, observability, and auditability of all ML operations.
FR-MLOPS-5	The system shall seamlessly integrate with the DataOps/Dataspace 6G-DALI components.

3.1.2 General Non-Functional Requirements

General Non-Functional Requirements of the MLOps	
NFR-ID	NFR-Description
NFR-MLOPS-1	The MLOps system shall enforce access control, ensuring only authenticated and authorized users can access models, functionalities, and execution environments.
NFR-MLOPS-2	The system shall provide job scheduling and resource orchestration mechanisms to support concurrent task execution and scalability.
NFR-MLOPS-3	The system shall support interoperability with third-party MLOps tools and pipelines through standard APIs (e.g., REST, OpenAPI, gRPC).
NFR-MLOPS-4	In case of failures, the system shall notify users and offer diagnostic information.

3.1.3 MLOps Orchestration Technical Dimension

3.1.3.1 Functional Requirements

Functional Requirements of the MLOps Orchestration Technical Dimension	
FR-ID	FR-Description
FR-MO-1	The system shall allow users to select a model for training, either one they own, or one retrieved from the 6G-DALI catalogue.
FR-MO-2	The system shall allow users to select a dataset sourced from the 6G-DALI data space, or generated on demand.
FR-MO-3	The system shall allow users to configure the type of training operation, such as initial training, fine-tuning, or model pruning.
FR-MO-4	The system shall allow users to define the result of sharing policy, including public sharing, restricted sharing with testbeds, or keeping the results private.
FR-MO-5	The system shall allow users to select multiple models for creating an ensemble, either from models they own or from the 6G-DALI model catalogue.
FR-MO-6	The system shall allow users to configure the ensemble strategy, including methods like bagging, boosting, stacking, or voting.
FR-MO-7	The system shall allow users to define the model combination policy, such as using equal weights, performance-based weighting, or learned aggregation.
FR-MO-8	The system shall allow users to define a diversity metric, which can be selected from a catalogue, custom-defined, or automatically determined.
FR-MO-9	The system shall allow users to define the evaluation protocol, including cross-validation, hold-out, or task-specific schemes.
FR-MO-10	The system shall allow users to select a model from the 6G-DALI catalogue or upload their own to perform a compression task.
FR-MO-11	The system shall allow users to choose a compression technique, including pruning, quantization, knowledge distillation, or a predefined combination.

FR-MO-12	The system shall allow users to define the compression level manually, based on target accuracy, or through automatic optimization.
FR-MO-13	The system shall allow users to select a validation strategy, either from the catalogue, user-defined, or auto-selected based on model/task.
FR-MO-14	The system shall allow users to define an evaluation metric to assess the compressed model.
FR-MO-15	The system shall allow users to define the result sharing policy, such as keeping results private or sharing only with some testbeds.
FR-MO-16	The system shall allow users to select an attack method and test scenario (black-white-gray box) to test the model's robustness.
FR-MO-17	The system shall allow users to define a robustness metric, which may be selected from a catalogue, custom-defined, or auto-selected.
FR-MO-18	The system shall allow users to configure a defense strategy, choosing a catalogue, including none.
FR-MO-19	The system shall allow users to define the drift metric to be evaluated during drift detection.
FR-MO-20	The system shall allow users to define the validation dataset to be evaluated during drift detection.
FR-MO-21	The system shall allow users to define the detection frequency to be used for drift detection.
FR-MO-22	The system shall allow users to define the trigger policy for re-training upon drift detection.
FR-MO-23	The system shall allow users to define the re-training strategy upon drift detection.
FR-MO-24	The system shall allow users to search for pre-trained models in the model registry.
FR-MO-25	The system shall allow users to express data requests and trigger data generation procedures.
FR-MO-26	The system shall allow users to benchmark available models in the 6G-DALI framework using pipelines for model evaluation and comparison.
FR-MO-27	The system shall include an interface for verticals to define tasks and review results.
FR-MO-28	The system shall allow verticals to express requests for continuous monitoring of machine learning models.
FR-MO-29	The system shall allow verticals to configure model monitoring metrics and thresholds.
FR-MO-30	The system shall include the essential infrastructure for model monitoring and re-training
FR-MO-31	The system shall allow users to select a base LLM model from the 6G-DALI catalogue or sourced online.
FR-MO-32	The system shall allow users to provide custom context or context that is available in a shared space.
FR-MO-33	The system shall allow users to configure the adaptation strategy, such as prompt engineering, fine-tuning, RAG, or adapter-based tuning.
FR-MO-34	The system shall allow users to select a task type, including classification, generation, summarization, reasoning, or a custom-defined type.

FR-MO-35	The system shall inform users about the pipeline execution and make the adapted model and evaluation outputs available.
FR-MO-36	The system shall allow providers/ML developers to publish models to the ML catalogue.
FR-MO-37	The system shall allow providers/ML developers to annotate models with metadata attributes.
FR-MO-38	The system shall allow providers/ML developers to configure the access control policy of their model.
FR-MO-39	The system shall allow providers/ML developers to configure the lifecycle rules of their model.
FR-MO-40	The system shall allow experimenters/ML developers to search for available pipelines.
FR-MO-41	The system shall allow experimenters/ML developers to privately store or share the results of pipelines executions.
FR-MO-42	The system shall allow experimenters/ML developers to run experiments in the 6G-DALI facility or in the testbed that allows experiment execution.
FR-MO-43	The system shall allow experimenters/ML developers to search for available pipeline components to compose new pipelines.
FR-MO-44	The system shall allow providers/ML developers to privately store the version and share the composed pipeline.

3.1.3.2 Non-Functional Requirements

Non-Functional Requirements of the MLOps Orchestration Technical Dimension	
NFR-ID	NFR-Description
NFR-MO-1	The system shall ensure that MLOps tasks are reproducible by storing all relevant metadata, parameters, and runtime environment details.
NFR-MO-2	Sharing policies shall be enforced via the underlying access control layer and support fine-grained scoping by user role, project, or organization.
NFR-MO-3	The system shall inform users about the status and outcome of the training job, including access to outputs or logs.
NFR-MO-4	The system shall inform users about the execution status and provide access to ensemble performance results.
NFR-MO-5	The system shall inform users about the compression of job execution and provide access to the resulting compressed model and evaluation reports.
NFR-MO-6	The system shall inform the user of the information about the detected drift and the triggered re-training.
NFR-MO-7	The system shall include a notification/ alerting system.
NFR-MO-8	The system shall include a dashboard so that verticals can review/control the monitoring.
NFR-MO-9	The system shall allow providers/ML developers to monitor usage statistics or their models.

3.1.4 Experiment as a Service and Hyper Parameter Optimization Technical Dimension

3.1.4.1 Functional Requirements

Functional Requirements of the EaaS & HPO Domain	
FR-ID	FR-Description
FR-EH-1	The system shall allow the user to provide an experiment specification using the schema adopted by the consortium
FR-EH-2	The system shall allow users to specify the HyperParameter Optimization experiments in terms of a base model and a dataset
FR-EH-3	The system shall ensure that at least one model and one dataset is provided for hyperparameter optimization experiment
FR-EH-4	The system shall allow the user to have a choice of the model, whether it is provided by themselves, or referenced to a catalogue.
FR-EH-5	The system shall allow users to select a dataset, whether it is owned by the user, sourced from the 6G-DALI data space, or generated on demand.
FR-EH-6	The system must be able to trigger a child job for the generation of the dataset to be used for the HPO job if requested by the user.
FR-EH-7	The system shall allow users to configure the type of optimization task to run. In the specific users shall be able to at least set optimization strategy, search space and search budget.
FR-EH-8	The system shall allow users to define the result of sharing policy, including public sharing, restricted sharing with testbeds, or keeping the results private.

3.1.4.2 Non-Functional Requirements

Non-Functional Requirements of the EaaS & HPO Technical Dimension	
NFR-ID	NFR-Description
NFR-EH-1	The system shall inform users about the status and outcome of the optimization job, including access to outputs or logs.
NFR-EH-2	The system shall allow the users to monitor ongoing experiments and access previously executed ones.
NFR-EH-3	The system shall aim to optimize the amount of computing resources used for the experiments.
NFR-EH-4	The system shall aim to accommodate as many users as possible by balancing competing job resource requirements.
NFR-EH-5	The system shall implement job scheduling policies to avoid starvation of resources.

3.1.5 Meta-Orchestration of ML Pipelines Technical Dimension

3.1.5.1 Functional Requirements

Functional Requirements of the Meta-Orchestration Technical Dimension	
FR-ID	FR-Description

FR-MEO-1	The MLOps meta-orchestration solution shall support the execution of pipelines across multiple orchestrators (e.g. Kubeflow, Airflow, Prefect, etc.).
FR-MEO-2	The MLOps meta-orchestration component shall support the registration and configuration of heterogeneous MLOps stack components (e.g., MLFlow for tracking, S3 for artifact storage, BentoML for serving).
FR-MEO-3	The MLOps meta-orchestration component shall expose a meta-orchestration API that abstracts over the underlying orchestration backends.
FR-MEO-4	The MLOps meta-orchestration shall allow users to search, register, update, share, and run custom pipelines.
FR-MEO-5	The MLOps meta-orchestration component shall integrate with experiment tracking systems (e.g., MLFlow, Weights & Biases) to track runs, metrics, and artifacts.
FR-MEO-6	The system shall allow users to choose the user-owned MLOps stack on which model training or fine-tuning will be executed.
FR-MEO-7	The system shall allow users to select the MLOps stack where model compression will be executed, including user-owned stacks, specific testbed stack, or the 6G-DALI MLOps stack.
FR-MEO-8	The system shall allow users to select the MLOps stack where model inference and evaluation will run, including user-owned stacks, specific testbed stack, or the 6G-DALI MLOps stack.

3.1.5.2 Non-Functional Requirements

Non-Functional Requirements of the Meta-Orchestration Technical Dimension	
NFR-ID	NFR-Description
NFR-MEO-1	The MLOps meta-orchestrator shall support a number of MLOps stacks ≥ 2 .
NFR-MEO-2	The MLOps meta-orchestrator shall guarantee consistency and synchronization of MLOps stacks metadata.
NFR-MEO-3	MLOps stack registration, updates, and MLOps tasks execution shall be auditable with logs.
NFR-MEO-4	The MLOs meta-orchestrator shall provide monitoring to track pipeline executions across different MLOps stacks through a dashboard.

3.1.6 Trustworthy AI and societal acceptance Technical Dimension

3.1.6.1 Functional Requirements

Functional Requirements of the Trustworthy AI Technical Dimension	
FR-ID	FR-Description
FR-TAI-1	Trustworthy AI (in terms of Uncertainty Quantification (UQ)) shall be integrated within the MLOps pipeline to provide probabilistic predictions with specific confidence intervals to ensure trust for deployed models.
FR-TAI-2	Trustworthy AI shall have direct access to the models and/or to the data (training, validation, calibration datasets), as they are required by most UQ methods.
FR-TAI-3	Trustworthy AI shall provide specific uncertainty metrics (Expected Calibration Error, prediction interval coverage).

FR-TAI-4	Trustworthy AI shall manage multiple model instances or hyperparameters, to select the version with the most trustworthy predictions on the input data.
FR-TAI-5	Trustworthy AI shall monitor distributions of uncertainty over time (logs) to detect performance degradation or model drift.
FR-TAI-6	Trustworthy AI shall define specific actions based on the level of uncertainty: reject low confidence predictions, request more data for calibration, trigger model retraining.
FR-TAI-7	UQ shall be supported for different types of models written in different frameworks (Scikit-Learn, TensorFlow, PyTorch).

3.1.6.2 Non-Functional Requirements

Functional Requirements of the Trustworthy AI Technical Dimension	
NFR-ID	NFR-Description
NFR-TAI-1	Trustworthy AI solutions shall be computationally efficient or optimized through GPU use or batch inference, to not introduce significant latency overhead in the overall pipeline.
NFR-TAI-2	Trustworthy AI solutions shall be scalable with model and data size.
NFR-TAI-3	Trustworthy AI shall be flexible and able to switch between UQ methods or tune parameters and also provide reproducible results.
NFR-TAI-4	Trustworthy AI shall be interpretable and provide explanations of why the predictions are uncertain or why there is model drift.
NFR-TAI-5	Trustworthy AI shall detect 80% of non-efficient ML models compared to SotA solutions.
NFR-TAI-6	Trustworthy AI shall improve the reliability of end users of AI models (i.e., verticals) via >20% reduction in vertical SLA violations due to model drift.

3.2 DataOps Thematic Area Requirements

The DataOps Thematic Area establishes foundational mechanisms for managing, processing, and optimizing data workflows within the 6G-DALI vision. It enables the seamless orchestration of data collection, transformation, and provisioning processes that underpin AI experimentation and analytics across distributed 6G environments. In this context, DataOps is conceived as a core component of the 6G-DALI architecture, ensuring that data-driven intelligence can be efficiently accessed, refined, and utilized for model development and validation.

Within 6G-DALI, DataOps is realized through an intent-driven framework designed to simplify and automate the full data lifecycle. The framework allows users to discover, request, and generate datasets tailored to specific AI and ML training needs. It integrates data quality management, augmentation, and transformation pipelines to ensure that the data used for experimentation maintains high fidelity and relevance. The DataOps workflow follows an Extract-Load-Transform (ELT) paradigm adapted for 6G experimentation. The "Extract" phase begins with user-defined data intents formulated through natural language, which are translated into actionable data queries across the 6G Dataspace. When suitable datasets are unavailable, the framework automatically triggers new experiments across connected testbeds to generate the required data. These experiments are executed on optimal platforms, ensuring that the resulting data meets the desired experimental and contextual requirements.

The "Load" phase occurs concurrently across the testbeds conducting data collection activities. Each testbed is connected to the 6G Dataspace through dedicated 6G-DALI connectors that implement the IDS and Gaia-X interoperability principles. This ensures secure, standardized, and transparent data exchange between components of the broader 6G ecosystem.

The "Transform" phase encompasses the processing and preparation of collected datasets before they are exposed to end users or ML pipelines. This includes data cleaning, normalization, augmentation, and validation, with a strong emphasis on maintaining consistency, reliability, and traceability. Advanced AI-assisted data discovery and cleaning techniques are integrated to enhance data quality and availability, directly supporting the development of accurate and robust AI models.

DataOps within 6G-DALI also emphasizes the distinction between cold data, historical datasets stored in the 6G Dataspace, and hot data, which are dynamically generated through ongoing experiments. This duality allows flexible data management strategies that balance reuse of existing information with the generation of new, context-specific datasets.

Overall, the DataOps Thematic Area defines the key functional and non-functional requirements for data management, curation, and accessibility across 6G-DALI. It ensures that AI experimentation services operate on high-quality, contextually relevant, and interoperable datasets, enabling a continuous and scalable data-driven intelligence cycle.

This section outlines the functional and non-functional general requirements for DataOps, enabling seamless data orchestration and accessibility as envisioned in the architecture proposed by 6G-DALI.

3.2.1 General Functional Requirements

General Functional Requirements of the DataOps	
FR-ID	FR-Description
FR-DATAOPS-1	DataOps shall allow experimenters to express data requests to the 6G-DALI user interface written in human language.
FR-DATAOPS-2	DataOps shall use an LLM-based mechanism to translate human-language user requests (intents) into service catalogue requests for the 6G dataspace.
FR-DATAOPS-3	DataOps shall be able to use the Gaia-X service (federated) catalogue along with trust and security procedures to search and extract datasets that match the experimenter's intent.
FR-DATAOPS-4	DataOps shall use an LLM-based mechanism to translate dataset requests to experiment requests interpretable by testbeds, in case the requested dataset is not found.
FR-DATAOPS-5	DataOps shall be able to run an algorithm that selects the most appropriate testbed for executing the data generation experiment.
FR-DATAOPS-6	DataOps shall support integration with the 6G Dataspace via an IDS- and Gaia-X-compliant connector.
FR-DATAOPS-7	DataOps shall demonstrate an end-to-end generation of dataset on all testbeds and successfully generate at least three datasets.
FR-DATAOPS-8	DataOps shall include logging capabilities for data access.

3.2.2 General Non-Functional Requirements

General Non-Functional Requirements of the DataOps	
NFR-ID	NFR-Description
NFR-DATAOPS-1	DataOps shall ensure seamless communication between the 6G-DALI AI framework and the 6G dataspace using Gaia-X and 6G-DALI standard interfaces and APIs.
NFR-DATAOPS-2	DataOps shall align experiments' results with users' objectives and priorities.

NFR-DATAOPS-3	DataOps shall allow flexible execution of experiments based on the computational and storage capability of testbeds.
NFR-DATAOPS-4	DataOps pipelines shall satisfy users from intent-based data requests up to 90%.
NFR-DATAOPS-5	DataOps shall provide a user-friendly interface to support natural language interaction.
NFR-DATAOPS-6	DataOps shall execute DataOps workflows reliably and provide meaningful error messages in case of failure.

3.2.3 Data Transformation (ELT Pipelines) Technical Dimension

3.2.3.1 Functional Requirements

Functional Requirements of the Data Transformation Technical Dimension	
FR-ID	FR-Description
FR-ELT-1	ELT pipelines shall be able to trigger on-demand experiments on testbeds and digital twin testbed for data generation.
FR-ELT-2	ELT pipelines shall be able to extract datasets generated from the experiments in a format tailored to the testbeds.
FR-ELT-3	ELT pipelines shall use machine learning algorithms to clean, enrich and transform the generated datasets to improve their quality.
FR-ELT-4	ELT pipelines shall allow experimenters to search for available data transformation (e.g., data imputation, outlier detection algorithms, etc.) and augmentation algorithms in the federated catalogue.
FR-ELT-5	ELT pipelines shall be able to perform data transformation and augmentation services upon request to improve the quality of datasets.
FR-ELT-6	ELT pipelines shall allow users to customize a data transformation pipeline based on their choices.
FR-ELT-7	ELT pipelines shall include data validation and integrity check mechanisms.
FR-ELT-8	ELT pipelines shall allow versioning of pre-processed/final datasets.
FR-ELT-9	ELT pipelines shall be able to register the metadata of the processed generated datasets on the 6G Dataspace catalogue for future similar requests.

3.2.3.2 Non-Functional Requirements

Non-Functional Requirements of the Data Transformation Technical Dimension	
NFR-ID	NFR-Description
NFR-ELT-1	ELT pipelines shall ensure that data seamlessly flows from the testbeds to the 6G dataspace.
NFR-ELT-2	ELT pipelines shall satisfy users up to 90%, validated through surveys.
NFR-ELT-3	ELT pipelines shall align experiments results with user objectives and priorities.
NFR-ELT-4	ELT pipelines shall ensure that datasets meet high quality standards.
NFR-ELT-5	ELT pipelines shall be resilient to failures and ensure uninterrupted data processing.

NFR-ELT-6	ELT pipelines shall ensure 100% compliance with Gaia-X principles and standards.
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3.2.4 Data Augmentation Technical Dimension

3.2.4.1 Functional Requirements

Functional Requirements of the Data Augmentation Technical Dimension	
FR-ID	FR-Description
FR-DA-1	Data augmentation tools/algorithms shall support a wide range of data types, such as tabular or structured, and time-series data.
FR-DA-2	Data augmentation shall ensure that augmentations hold valuable information and do not merely add noise to the data.
FR-DA-3	Data augmentation shall ensure that no initial data is lost in the process.
FR-DA-4	Data augmentation shall support selecting proper augmentation techniques for the data at hand.
FR-DA-5	Data augmentation shall support augmenting data according to user's instructions.
FR-DA-6	Data augmentation shall add a reasonable amount of augmented data to the dataset.
FR-DA-7	Data augmentation shall support randomization control for reproducibility.
FR-DA-8	Data augmentation shall be easily integrated into the proposed architecture of the 6G-DALI data space.

3.2.4.2 Non-Functional Requirements

Non-Functional Requirements of the Data Augmentation Technical Dimension	
FR-ID	FR-Description
NFR-DA-1	Data augmentation shall efficiently handle large datasets.
NFR-DA-2	Data augmentation shall ensure seamless integration with ELT pipelines.
NFR-DA-3	Data augmentation shall ensure that augmented datasets meet high quality standards for ML model training.
NFR-DA-4	Data augmentation shall allow for an easy addition of new augmentation techniques.
NFR-DA-5	Data augmentation shall provide comprehensive documentation of implemented data augmentation techniques.
NFR-DA-6	Data augmentation shall adhere to all legal requirements established in T2.4.

3.2.5 Intent-Driven DataOps Technical Dimension

3.2.5.1 Functional Requirements

Functional Requirements of the Intent-Driven DataOps Technical Dimension	
FR-ID	FR-Description

FR-IDD-1	Intent-Driven DataOps framework shall support natural language prompting for on-demand dataset search and retrieval.
FR-IDD-2	Intent-Driven DataOps shall use LLMs to automatically generate ELT pipelines from natural language prompts.
FR-IDD-3	The system shall include a chat interface for iterative interaction until correct ELT formulation is finalized.
FR-IDD-4	The framework shall support retrieval and generation using the RAG paradigm.
FR-IDD-5	Intent-Driven DataOps shall translate natural language intents into ELT pipelines using LLMs and semantic techniques.
FR-IDD-6	The system shall validate user intent using Semantic Role Labeling (SRL) and Knowledge Graph (KG) techniques.
FR-IDD-7	Intent-Driven DataOps shall allow users to search datasets in the Gaia-X Data Space using translated intents.
FR-IDD-8	The framework shall trigger dataset search requests via a Northbound API connected to the Gaia-X catalogue and display dataset search results to users.
FR-IDD-9	The system shall demonstrate cleaning and augmentation algorithms for the retrieved data.

3.2.5.2 Non-Functional Requirements

Non-Functional Requirements of the Intent-Driven DataOps Technical Dimension	
FR-ID	FR-Description
NFR-IDD-1	Intent-Driven DataOps shall reduce dataset fetch time by 50% compared to a non-6G Data Space baseline.
NFR-IDD-2	Intent-Driven DataOps system shall demonstrate 100% compliance with Gaia-X framework and legal requirements.
NFR-IDD-3	The framework shall generate at least 3 datasets as output of the intent-based pipeline system.
NFR-IDD-4	DataOps shall achieve over 90% user satisfaction with intent-based data requests, validated via user surveys.

3.3 Data Spaces and Data Connectors Requirements Area

The Data Spaces and Data Connectors Requirements Area defines the foundational principles and mechanisms for establishing a secure, interoperable, and sovereign data-sharing ecosystem within the 6G-DALI architecture. This thematic area focuses on enabling seamless integration of data sources, testbeds, and services while ensuring compliance with European standards for data governance, security, and interoperability.

Building upon the efforts of leading European initiatives such as the International Data Spaces (IDS) Association, Data Space Support Centre (DSSC), and Gaia-X, 6G-DALI extends these frameworks to create a federated data ecosystem supporting AI experimentation and intelligent automation. The 6G-DALI Data Space enables participants to share, access, and utilize data while maintaining full control and sovereignty over their assets. This aligns with the broader vision of open, trustworthy, and sovereign data infrastructures across Europe.

The 6G-DALI Data Space incorporates the principles of transparency, interoperability, and trust defined by Gaia-X and IDS. Each participating testbed, whether physical or virtual, contributes datasets that are aggregated and catalogued within the Data Space. This shared environment allows datasets to be securely uploaded, registered, and accessed by authorized entities, ensuring consistent governance across distributed infrastructures. The Data Space ensures that all data exchanges adhere to defined usage policies, licensing terms, and access permissions negotiated through a policy enforcement engine and smart contract mechanisms.

A comprehensive suite of core components supports the operation of the 6G-DALI Data Space. These include a Data Catalogue for dataset discovery and classification, an Identity Provider for secure authentication and access control, a Metadata Broker for query management and dataset retrieval, and a Clearing House for transaction logging and compliance auditing. Together, these components form the operational backbone that guarantees secure and accountable data sharing within the ecosystem.

The Data Connector serves as the pivotal interface between the testbeds and the Data Space, adhering to IDS Data Connector specifications. It manages secure data transfer, dataset registration, and enforcement of data usage policies. By incorporating cybersecurity and trust management mechanisms, the connector ensures compliance with the Gaia-X Trust Framework and supports interoperability across heterogeneous environments. These connectors act as the operational enablers for distributed experimentation, allowing real-time data exchange between testbeds, digital twins, and AI frameworks. Furthermore, 6G-DALI remains aligned with ongoing developments from initiatives such as SIMPL, DOME, FiWare, and iShare. Continuous monitoring and integration of these technologies ensure that the 6G-DALI Data Space evolves in concert with the European Data Space landscape, maintaining compatibility with emerging standards and tools for federated data management.

Overall, the Data Spaces and Data Connectors Requirements Area defines the essential functional and non-functional requirements that enable secure, interoperable, and sovereign data sharing within 6G-DALI. It ensures that all testbeds and services are seamlessly interconnected, supporting efficient data-driven experimentation and collaboration across the 6G-DALI architecture.

This section provides the functional and non-functional general requirements for the Data Spaces as well as the interconnection required with the testbeds.

3.3.1 General Functional Requirements

Functional Requirements of the Data Spaces, Data Lake & Data connectors	
FR-ID	FR-Description
FR-DS 1	The system shall allow users to search for existing data sets in the Data Space and Data Lake
FR-DS 2	The system shall allow users to search for data manipulation services in the Data Space and Data Lake
FR-DS 3	The system shall allow users to search for existing ML models in the Data Space and Data Lake
FR-DS 4	The system shall include rich metadata annotation for all data sets, ML models and services in the Data Space
FR-DS 5	The system shall allow storing of new data sets, ML models and data manipulation services in the Data Space and Data Lake
FR-DS 6	The system shall allow storing of new data set versions after the application of a DataOps pipelines to the Data Space and Data Lake
FR-DS 7	The system shall ensure metadata for all available datasets is registered and searchable in the Data Space Catalogue
FR-DS 8	The system shall authenticate clients before granting access to the Data Space and Data Lake

FR-DS 9	The system shall verify that clients have necessary permissions to discover and retrieve data sets
FR-DS 10	The system shall enforce identity, trust, and security policies based on predefined user roles and data set classifications
FR-DS 11	The system shall allow secure and policy-compliant data set retrieval
FR-DS 12	The system shall require explicit acceptance of presented policies before allowing data set retrieval
FR-DS 13	The system shall allow Gaia-X compatibility for catalogue interoperability and trust enforcement
FR-DS 14	The system shall include Gaia-X compliant rich metadata annotation for all data sets
FR-DS 15	The system shall include backend components to support metadata matching and access decisioning

3.3.2 General Non-Functional Requirements

Non-Functional Requirements of the Data Space, Data Lake & Data connectors	
NFR-ID	NFR-Description
NFR-DS 1	The system shall scale to support concurrent users performing search and retrieval queries
NFR-DS 2	The system shall respond to support concurrent users performing search and retrieval queries with minimal latency
NFR-DS 3	The system shall comply with applicable data protection, trust, and security regulations (e.g., GDPR, Gaia-X policies)
NFR-DS 4	The system shall use backup mechanisms and disaster recovery plans to maintain data integrity and availability in case of system failures
NFR-DS 5	The system shall encrypt sensitive data both in transit (e.g., via TLS) and at rest
NFR-DS 6	The system shall use strong authentication and authorization mechanisms (e.g., multi-factor authentication, OAuth)
NFR-DS 7	The system shall use audit logs and activity tracking for monitoring user actions and ensuring data security
NFR-DS 8	The system shall be adaptable to accommodate future advances in 6G technology, including new data sources, formats, and processing requirements
NFR-DS 9	The system shall support evolving standards and protocols in the 6G ecosystem
NFR-DS 10	The system shall offer training materials and documentation to ensure ease of use
NFR-DS 11	The system shall be capable of handling large volumes of high-frequency data generated by 6G testbeds
NFR-DS 12	The system shall be designed to operate continuously with minimal downtime
NFR-DS 13	The system shall be able to recover gracefully from network failures, device errors, or any other disruptions in data flow
NFR-DS 14	The system shall have a modular and extensible architecture, allowing for easy updates and future additions, such as new protocols or data processing capabilities

NFR-DS 15	The system shall provide comprehensive logging and monitoring capabilities to track its health, performance, and data transfer activities
NFR-DS 16	The system shall ensure that data privacy and ethical standards are upheld, particularly when dealing with personally identifiable information or sensitive data collected from testbed environments

3.4 Digital Twin Thematic Area Requirements

The Digital Twin Thematic Area defines the functional and operational requirements for creating and using a large-scale Digital Twin within the 6G-DALI framework. The Digital Twin provides a virtual test environment for experiments, model testing, and data generation, complementing physical testbeds and supporting 6G system development. The 6G-DALI Digital Twin Testbed addresses the limits of traditional testbeds, which often support only a small number of users and network cells. The DTT allows large-scale simulations with many mobile devices, multiple network cells, and various network configurations, enabling experiments that better reflect realistic network conditions.

The DTT uses the OpenAirInterface 5G software and VIA RAN testing tools. OAI provides software implementations of both the 5G Radio Access Network and Core Network. The RAN is divided into Radio, Distributed, and Centralized Units, which can be monitored and controlled through the OAI FlexRIC software. This software allows applications to manage network settings and collect performance data in real time. The system collects performance metrics, such as signal strength, throughput, and resource usage, which are used to create datasets for AI and machine learning models. It also allows network configurations to be changed dynamically, supporting testing of models that control or optimize network behavior. The 5G Core Network runs in a cloud environment and includes all major network functions. It collects information about user sessions, handovers, and other network events. This data is combined with RAN metrics to create comprehensive datasets that support model training and evaluation.

Within 6G-DALI, the Digital Twin supports AI model testing, reinforcement learning experiments, and federated learning workflows. It provides a safe virtual environment for models to be tested before deployment, helping improve performance and reliability. The Digital Twin also reduces reliance on physical infrastructure, saving resources and accelerating innovation. It contributes to making 6G-DALI more efficient, scalable, and reliable.

This section outlines the general functional and non-functional requirements for the Digital Twin, as proposed in the 6G-DALI architecture.

3.4.1 General Functional Requirements

Functional Requirements of the Digital Twin & RL	
FR-ID	FR-Description
FR-DT-1	6G-DALI shall define a Northbound API accessible via the enablers to configure and manage experiments, generate datasets, and deploy ML models and RL agents for MLOps and RLOps processes.
FR-DT-2	6G-DALI shall define a consistent data model that the Digital Twin will adhere to and ensure compliance with the requisite Data Spaces and Catalogues.
FR-DT-3	6G-DALI shall provide a common set of API tools that ensure interoperability across different technical domains.
FR-DT-4	6G-DALI shall provide a way to translate natural language requests into an intent that can be understood by the Digital Twin such that it can generate the experiment requested

FR-DT-5	6G-DALI shall provide a data space where previous Digital Twin simulation results can be stored for future use.
FR-DT-6	The Digital Twin shall connect with the relevant ELT pipelines for Data Augmentation purposes
FR-DT-7	The Digital Twin shall generate data that is compatible with a flexible format such as YAML or other similar formats suited for multiple purposes and machine readability.

3.4.2 General Non-Functional Requirements

Non-Functional Requirements of the Digital Twin & RL	
NFR-ID	NFR-Description
NFR-DT-1	6G-DALI shall provide extensive documentation on usage of the Digital Twin aspects of the 6G-DALI project
NFR-DT-2	6G-DALI shall take into consideration computational Resource Requirements

3.4.3 6G Digital Twin Library Technical Dimension

3.4.3.1 Functional Requirements

Functional Requirements of the Digital Twin Library Technical Dimension	
FR-ID	FR-Description
FR-DTL-1	6G-DALI shall deliver a Digital Twin that is O-RAN compliant.
FR-DTL-2	6G-DALI shall deliver a Digital Twin that supports the capability of network performance monitoring and optimization.
FR-DTL-3	6G-DALI shall deliver a Digital Twin that supports the capability of Radio resource management and allocation.
FR-DTL-4	6G-DALI shall deliver a Digital Twin that supports the capability of Radio environment mapping.
FR-DTL-5	6G-DALI shall deliver a Digital Twin that supports the capability of data set generation for ML model training and validation.
FR-DTL-6	6G-DALI shall enable saving of the datasets that are generated by novel experiments to the Data Space.
FR-DTL-7	The 6G-DALI Data Space shall meet required Data Security standards while ensuring minimal friction in sharing generated datasets among users of the Data Space

3.4.3.2 Non-Functional Requirements

Functional Requirements of the Digital Twin Library Technical Dimension	
NFR-ID	NFR-Description
NFR-DTL-1	6G DALI shall ensure Network Latency requirements are met at all levels of the Radio network, with special attention given to edge nodes and the impact of AI/ML models on latency.

3.4.4 AI-as-a-Service (AIaaS) and HPO for RLOps Technical Dimension

3.4.4.1 Functional Requirements

Functional Requirements of the AIaaS & RLOps Technical Dimension	
FR-ID	FR-Description
FR-AR-1	6G-DALI framework shall deliver an AIaaS framework built on top of MLOps to automate ML task execution with minimal user intervention.
FR-AR-2	6G-DALI shall provide monitoring and observability of ML task status and performance through dashboards.
FR-AR-3	The framework shall expose its services through Open APIs and AutoML to reduce the learning curve for 6G experimentation.
FR-AR-4	6G-DALI shall offer unified support for searching, serving, optimizing, finetuning, and testing ML models.
FR-AR-5	6G-DALI shall include an Automated Hyperparameter Optimization (HPO) component for resource-aware model placement across the Cloud-Edge-Continuum.
FR-AR-6	6G-DALI shall support continuous model testing and validation across the 6G stack, adapting to latency and resource constraints.
FR-AR-7	The system shall intelligently prioritize experiments based on their data generation and model validation value to optimize testbed usage.
FR-AR-8	6G-DALI shall use novel HPO techniques that leverage prior tuning/validation history to reduce the hyperparameter search space
FR-AR-9	6G-DALI shall enable Cooperative Transfer Learning, Finetuning, and Quantization for distributed model management across domains.
FR-AR-10	6G-DALI shall orchestrate dynamic provisioning and sharing of ML models across administrative domains.
FR-AR-11	6G-DALI shall support adaptive and context-aware knowledge distillation and reuse across multiple tasks and domains.
FR-AR-12	6G-DALI shall offer RLOps automation with support for policy libraries (Policy Gradient, Q-Learning) and AutoRL for agent/environment optimization.
FR-AR-13	6G-DALI shall compress and organize contextual information to dynamically customize RL agent environments.
FR-AR-14	6G-DALI shall adapt RL experiments at runtime based on fresh data without static reconfiguration.
FR-AR-15	6G-DALI shall enable saving of trained RL models in the AI/ML Model Catalogue upon achieving performance thresholds.
FR-AR-16	6G-DALI shall support redeployment of trained models in both emulated and real environments to reduce DRL exploration time.

3.4.4.2 Non-Functional Requirements

Functional Requirements of the AIaaS & RLOps Technical Dimension	
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NFR-ID	NFR-Description
NFR-AR-1	6G-DALI shall minimize resource usage (especially in Edge/Deep Edge domains) while maintaining ML task performance.
NFR-AR-2	6G-DALI shall ensure adaptive tuning of hyperparameters and model training based on objective changes without full retraining.
NFR-AR-3	6G-DALI shall provide scalable HPO and AutoRL solutions that avoid intractable global searches.
NFR-AR-4	6G-DALI shall track KPIs, including reward metrics and model drift, during RL training.

3.4.5 Collaborative RLOps Technical Dimension

3.4.5.1 Functional Requirements

Functional Requirements of the Collaborative RLOps Technical Dimension	
FR-ID	FR-Description
FR-CR-1	6G-DALI shall be able to transfer knowledge to different scenarios in simulation.
FR-CR-2	6G-DALI shall track how assertive the transfer of that model was in the simulation or real testbed.
FR-CR-3	6G-DALI shall generate a new policy for user scenarios that are not in the catalogue.

3.4.5.2 Non-Functional Requirements

Functional Requirements of the Collaborative RLOps Technical Dimension	
NFR-ID	NFR-Description
NFR-CR-1	6G-DALI shall guarantee RL model generalization in multiple environments, with a Low Generalization Error.
NFR-CR-2	6G-DALI shall be able to reduce the learning process time by the transferable knowledge approach.
NFR-CR-3	6G-DALI shall ensure system scalability, allowing support for at least 5 simultaneous simulation evaluations without significant performance degradation.

3.4.6 Federated Learning with NWDAF Technical Dimension

3.4.6.1 Functional Requirements

Non-Functional Requirements of the FL with NWDAF Technical Dimension	
FR-ID	FR-Description
FR-FL-1	6G-DALI shall support automatic training and deployment of FL models via integrated MLOps with NWDAF.
FR-FL-2	6G-DALI shall allow experimenters to initiate analytics requests from NWDAF in 3GPP-compliant formats.
FR-FL-3	6G-DALI shall support on-demand model validation and benchmarking via NWDAF-based analytics.
FR-FL-4	6G-DALI shall leverage the NWDAF FL framework to validate federated learning (FL) algorithms for privacy and efficiency.

FR-FL-5	6G-DALI shall facilitate cross-domain collaboration by enabling model sharing through a common model registry.
FR-FL-6	6G-DALI shall train novel FL models using real-world 6G time-series data accessed through NWDAF.
FR-FL-7	6G-DALI shall use NWDAF for deployment and evaluation of FL models in real network environments.

3.4.6.2 Non-Functional Requirements

Non-Functional Requirements of the FL with NWDAF Technical Dimension	
NFR-ID	NFR-Description
NFR-FL-1	6G-DALI shall reduce the time required to validate FL models by 2x compared to cases without NWDAF integration.
NFR-FL-2	6G-DALI shall rely on NWDAF Release 18 architecture to access Core Network data via the Analytics Data Repository Function (ADRF).

3.5 Adaptation Layer Area

The Adaptation Layer Area defines the functional and operational requirements for the Adaptation Layer and its associated adapters within the 6G-DALI architecture. This layer enables seamless integration of new testbeds and Digital Twins into the AI framework while supporting standardized communication and data collection. The Adaptation Layer manages requests from the AI framework to the adapters on connected testbeds. These requests define test scenarios, including the resources to use, traffic models, and data to generate. The requests are expressed in a machine-readable format such as JSON or YAML. Adapters translate these requests into the local APIs provided by each testbed, ensuring compatibility and interoperability.

Each adapter is specific to its corresponding testbed. When a testbed introduces a new 6G feature, such as Terahertz communication, only the adapter requires development to map Adaptation Layer messages to the local testbed API. Adapters also include the data space connector, which allows collected data to be stored in the 6G Dataspace. This ensures the data is accessible to end users following the data collection and generation pipeline. Initial testbeds connected to the project are those participating in the SUNRISE-6G SNS C flagship projects. These testbeds already provide experimentation models, including APIs, and can generate datasets. For large-scale experiments, 6G-DALI will use a Digital Twin Testbed for RAN and CN, addressing scalability limitations such as a restricted number of User Equipment in traditional testbeds.

This section outlines the general functional and non-functional requirements for the Adaptation Layer and adapters, as proposed in the 6G-DALI architecture.

3.5.1 General Functional Requirements

Functional Requirements of the Adaptation Layer	
FR-ID	FR-Description
FR-AL-1	The adaptation layer shall interact with adapters deployed on various testbeds to request experiment execution and collect datasets.
FR-AL-2	The adaptation layer shall provide a common set of APIs to connect different 6G testbeds, including Digital Twin (DT).
FR-AL-3	The adaptation layer shall define test scenarios, including resource allocation, traffic models, and data generation.

FR-AL-4	The adaptation layer shall support APIs dedicated to defining experiments and parameters, allowing automation without human intervention.
FR-AL-5	The adaptation layer shall send requests in a machine-readable language (e.g., JSON or YAML) for execution on testbeds.
FR-AL-6	The adaptation layer shall facilitate storing collected data into the 6G data space through the adapters.
FR-AL-7	The adaptation layer shall support large-scale experimentation via DTT for RAN and CN.
FR-AL-8	The adaptation layer shall be agnostic to testbed-specific APIs, relying on adapters to translate requests into local APIs.
FR-AL-9	The adaptation layer shall interact with adapters built using a standardized template that exposes a unified Northbound API.
FR-AL-10	The adaptation layer shall integrate the IDS and trust framework of Gaia-X for ELT (Load and Transform) to upload datasets.

3.5.2 General Non-Functional Requirements

Non-Functional Requirements of the Adaptation Layer	
NFR-ID	NFR-Description
NFR-AL-1	The adaptation layer shall follow a modular design to allow easy integration of new testbeds.
NFR-AL-2	The adaptation layer shall ensure seamless communication between different testbeds and existing APIs.
NFR-AL-3	The adaptation layer shall support large-scale experiments and adapt to future 6G testbed expansions.
NFR-AL-4	The adaptation layer shall interact with a standardized adapter template for consistent API translation.

4 Technological Tools Analysis

6G-DALI aims to build an end-to-end AI framework that supports AI experimentation through MLOps and data analytics and storage through DataOps. This framework serves both expert ML developers and vertical users, integrating with various 6G testbeds, including RAN, CN, edge/cloud platforms, and Digital Twins. It also establishes a sovereign Dataspace based on IDS and Gaia-X to enable secure and trusted data sharing across stakeholders.

To build this ambitious framework, 6G-DALI will leverage a wide range of technological tools across the MLOps and DataOps domains. This includes solutions for model training, orchestration, deployment, monitoring, and lifecycle management, as well as platforms for secure data ingestion, metadata management, cataloging, and sharing. The analysis presented in this section evaluates these tools based on their alignment with the functional requirements of 6G-DALI, compatibility with IDS and Gaia-X specifications, scalability across federated environments, and ability to support automation, observability, and interoperability. The goal is to identify a cohesive set of technologies that will form the backbone of the AI framework while ensuring long-term sustainability and ease of integration.

4.1 MLOps

4.1.1 MLOps Orchestration

4.1.1.1 Prefect

Description. Prefect¹ is an open-source orchestration engine that turns Python functions into production-grade pipelines with minimal effort. It enables users to define complex flows (pipelines) comprising several tasks (steps) and execute them in either a local environment or cloud infrastructures. Prefect provides powerful monitoring capabilities, offering a CLI/GUI for monitoring as well as automated handling of retries and failures. Prefect is fully open-source under the Apache 2.0 license and it is built and maintained by an active community² of over 25000 contributors. Prefect has been adopted by a variety of organisations, including Cisco³, which uses it for infrastructure automation and observation at scale, orchestrating over 10,000 workflows daily.

Main Features. The main features of Prefect relevant to the 6G-DALI project are:

- Pipeline abstraction: flows are defined as python functions composed of sub-functions (tasks) that can run independently or dependently. Moreover, Prefect supports dynamic DAGs, meaning that the tasks graph change at runtime.
- Run parametrization: flows can accept runtime parameters that can model a particular execution behaviour.
- Pipeline run deployment: flows can be run locally or on-premise infrastructures by using the abstractions of prefect workers and workpools.

Mapping to 6G-DALI Requirements. Flow and task abstractions allow flows to be described in terms of metadata and enable the possibility of dynamically assembling flows from pre-existing flows and tasks, as described by requirements FR-MO-40, FR-MO-43 and FR-MO-44. Furthermore, the ability to add runtime input parameters and run pipelines in different environments fulfils the requirements FR-MO-41 and FR-MO-42.

4.1.1.2 MLFlow

Description. MLFlow⁴ is an open-source platform that manages the entire machine learning lifecycle by enabling users to seamlessly track model training, register model versions, and compare them. Its unified interface for experimentation, reproducibility, and governance of models makes it especially suited to collaborative and modular AI workflows. MLFlow is fully open-source under the Apache 2.0 license and is actively maintained by Databricks⁵ and a community of contributors. Organisations

¹ <https://www.prefect.io>

² <https://www.prefect.io/community>

³ <https://www.cisco.com>

⁴ <https://mlflow.org>

⁵ <https://www.databricks.com>

including Databricks, Microsoft⁶, and Meta⁷ leverage MLFlow to support large-scale model experimentation and tracking.

Main Features. The main features of MLFlow relevant to the 6G-DALI project are:

- Experiment tracking: users can track parameters, metrics, datasets, and artifacts associated with model training runs and compare them across multiple runs.
- Model registry: models can be registered with version control, annotated with metadata, and shared according to access policies.
- Metric logging and evaluation: training and validation metrics are logged real-time and can be used to compare different model versions to detect regressions or behavioural changes over time.

Mapping to 6G-DALI Requirements. Models can be described in terms of metadata thanks to tracking and registry abstractions, which also enable the reuse and lifecycle management of models and training runs. This is in line with requirements FR-MO-24, FR-MO-35, FR-MO-36, FR-MO-37, FR-MO-38 and FR-MO-39. Furthermore, logging training metadata supports FR-MO-1, FR-MO-2, FR-MO-3, FR-MO-13 and FR-MO-14. Support for metric monitoring and tagging enables FR-MO-26, FR-MO-28, FR-MO-29 and FR-MO-30.

4.1.1.3 MinIO

Description. MinIO is an open-source high-performance object storage system compatible with the Amazon S3 API⁸ and designed to support large-scale data workloads such as AI/ML data and artifacts. It is fully open-source under the GNU AGPL v3 license and is supported by an active developed and enterprise community. It has been adopted by several organizations including NVIDIA⁹ and Intel¹⁰, particularly in context where private, high-performance storage for unstructured data is required.

Main Features. The main features of MinIO that are relevant to the 6G-DALI project are:

- S3-compatible format: allows MLOps artifacts to be stored in a cloud-native and portable way.
- Scalability and Performance: optimized for high-throughput workloads, supporting petabyte-scale data management.

Mapping to 6G-DALI Requirements. MinIO enables reproducible and framework-agnostic storage of datasets and ML artifacts, aligning with requirements FR-MLOPS-1, FR-MLOPS-2, and FR-MLOPS-5. Its access control features support FR-MLOPS-3 and NFR-MLOPS-1, while the ability to scale and interoperate through S3 APIs fulfils NFR-MLOPS-2 and NFR-MLOPS-3. In addition, support for model storage directly supports orchestration requirements FR-MO-1, FR-MO-2, FR-MO-25, and FR-MO-41.

4.1.1.4 ONNX

Description. The Open Neural Network Exchange (ONNX) is an open-source standard for representing AI/ML models in an interoperable way. It provides a common format to enable interoperability between several frameworks (e.g. Pytorch, Tensorflow, etc.) and execution environments. ONNX is fully open-source under the Apache 2.0 license and is actively maintained by the Linux Foundation AI&Data initiative and supported by major companies as Meta and Microsoft. It is considered the de facto interchange standard for portable and framework-agnostic model-representation.

Main features. The main features of ONNX relevant to the 6G-DALI project are:

- Model Portability: models trained in a framework can be exported to ONNX and executed in a different runtime environment.
- Graph-based representation: models are internally represented as computational graphs, improving explainability, visualization, and facilitating optimization.

⁶ <https://www.microsoft.com>

⁷ <https://www.meta.com>

⁸ https://docs.aws.amazon.com/AmazonS3/latest/API/Type_API_Reference.html

⁹ <https://www.nvidia.com>

¹⁰ <https://www.intel.com>

Mapping to 6G-DALI Requirements. Models can be represented in a standardized format and enriched ensuring interoperability and lifecycle management across frameworks, in line with requirements FR-MO-24, FR-MO-36, FR-MO-37, FR-MO-38 and FR-MO-39. The ability to export/import models support reuse and portability, addressing FR-MO-1, FR-MO-10 and FR-MO-31. Graph-based representations enhance explainability, directly supporting FR-MO-27. Furthermore, the interoperability and observability features contribute to reproducibility (FR-MLOPS-4, NFR-MO-1) and seamless integration with heterogeneous environments (FR-MLOPS-2, FR-MLOPS-5).

4.1.1.5 MLServer

Description. MLServer is an open-source model serving framework, part of the Seldon ecosystem, designed to provide a standardized and interoperable lightweight inference server for AI/ML models. It supports multiple model formats and exposes REST and gRPC APIs compatible with the V2 inference protocol¹¹. MLServer is open-source under the Apache2.0 license and actively maintained by Seldon¹², while it is used in productions by organizations such as Red Hat¹³ and IBM¹⁴ for large-scale AI deployments.

Main Features. The main features of MLServer relevant to the 6G-DALI project are:

- Multi-framework support: allows serving of heterogeneous models in a single runtime.
- Protocol standardization: exposes models via standardized inference APIs compatible with V2 Inference Protocol.
- Extensibility: customizable inference pipelines with inference pre/post-processing.
- Containerized deployment: models can be packaged and deployed as Docker containers, enabling portability across cloud, edge, and on-premise infrastructures.

Mapping to 6G-DALI Requirements. Models can be served in a framework-agnostic and standardized manner, supporting interoperability across environments, in line with requirements FR-MLOPS-1, FR-MLOPS-2, and FR-MLOPS-5. Standardized inference APIs and multi-framework support fulfil FR-MO-26 and FR-MO-30, while enabling continuous monitoring and comparison of models at runtime, covering FR-MO-28 and FR-MO-29. Containerized deployment capabilities support reproducibility and portability across heterogeneous infrastructures, addressing FR-MO-42 and NFR-MO-1. Furthermore, scalability and request management features directly address NFR-MLOPS-2, and the secure API exposure aligns with FR-MLOPS-3 and NFR-MLOPS-1.

4.1.2 Experimentation-as-a-service & HPO for MLOps

4.1.2.1 ADO (Accelerated Discovery Orchestrator)

Description. The Accelerated Discovery Orchestrator (ADO) is a framework developed by IBM to support scalable and reproducible computational experiments. Its primary goal is to help researchers and engineers collaborate more effectively by automating and organizing complex workflows. It provides a command-line interface for managing experiments, integrates with Ray for distributed execution, and includes tools for optimization, benchmarking, and analysis. The system tracks data provenance and reuses previous results to avoid redundant computation. It is designed to be extensible, allowing users to add custom plugins for new experiment types or analysis methods, making it particularly useful for tasks like, but not limited to, AI model development and performance evaluation.

Main Features. The main features of ADO relevant to the 6G-DALI framework are:

- Enables scalable execution and analysis of computational experiments.
- Easily integrates new experiments, optimizers, and analysis tools.
- Supports distributed teams with shared projects and data access.
- Offers a command-line interface designed with usability and best practices in mind.
- Leverages Ray for distributed computing across multiple nodes.
- Prevents redundant computations by reusing existing results when applicable.

¹¹ https://kserve.github.io/archive/0.8/model-serving/inference_api

¹² <https://www.seldon.io>

¹³ <https://www.redhat.com>

¹⁴ <https://www.ibm.com>

- Maintains clear lineage between data and operations for reproducibility.
- Includes native optimizers and supports RayTune for advanced tuning.
- Provides tools for fine-tuning and inference benchmarking, including vLLM support.

Works with Python 3.10+, with optional infrastructure for advanced features like remote databases and GPU support.

Mapping to 6G-DALI Requirements. For FR-EH-1, it supports flexible experiment specification via CLI, adaptable to consortium schemas. FR-EH-2 and FR-EH-3 are met through built-in support for hyperparameter optimization requiring a base model and dataset. FR-EH-4 and FR-EH-5 are addressed by allowing model and dataset selection from user inputs, external catalogues, or generated sources. FR-EH-6 is fulfilled by its ability to trigger child jobs for dataset generation. FR-EH-7 is supported through RayTune integration, enabling configuration of strategy, search space, and budget. FR-EH-8 is met via project-based collaboration with customizable result sharing policies.

ADO addresses several of the specified non-functional requirements. It provides mechanisms for tracking experiment status and outcomes, including access to logs and outputs, thereby fulfilling NFR-EH-1. Through its CLI and project-based collaboration features, users can monitor ongoing experiments and revisit previously executed ones, satisfying NFR-EH-2. ADO's integration with Ray enables distributed execution and resource-aware scheduling, which contributes to optimizing computing resource usage (NFR-EH-3). However, while ADO supports scalable execution, there is no explicit mention of features that actively balance competing job resource demands across multiple users (NFR-EH-4), nor is there clear evidence of implemented job scheduling policies designed to prevent resource starvation (NFR-EH-5).

4.1.3 Meta-Orchestration of ML Pipelines

4.1.3.1 ZenML Tool

Description. ZenML¹⁵ is a unified MLOps framework, available in both open-source and Pro editions, designed to simplify the transition from experimentation to production for machine learning and AI systems. It enables teams of data scientists, ML engineers, and developers to build, deploy, track and manage pipelines in a reproducible and scalable way. ZenML provides a single framework capable of orchestrating multiple ML stacks, emphasizing flexibility through its tool-agnostic and infrastructure-agnostic design. With well-defined abstractions such as steps, pipelines, stacks, and artifacts, ZenML allows workflows developed locally to be seamlessly scaled to full enterprise deployments without requiring extensive rewrites.

Main Features. The main features of ZenML relevant to the 6G-DALI project are:

- Stack-based architecture: ZenML introduces the concept of “stacks” where components such as orchestrators, artifact stores, and model deployers can be swapped or combined, making it highly flexible and tool-agnostic.
- Model management: Models are treated as first-class citizens, with built-in supporting for versioning, metadata tracking, and lineage tracking to guarantee reproducibility and traceability.
- Pipeline abstraction: Pipelines are composed of modular steps that produce and consume artifacts, enabling reusability, reproducibility, and clear lineage tracking.
- Plug-and-play with popular tools & Framework agnostic: ZenML supports integrations with tools like Mlflow, Kubeflow, Airflow, MinIO, and others, and works across ML frameworks such as TensorFlow, PyTorch, or scikit-learn.
- Reproducibility: Automatically tracks code, data, experiments, and model artifacts for each pipeline run, ensuring experiments are easy to reproduce and validate.

Mapping to 6G-DALI Requirements. ZenML shows strong alignment with the functional and non-functional requirements of the meta-orchestration component. Its stack-based architecture supports the registration and configuration of heterogeneous MLOps components (FR-MEO-2), while enabling execution across multiple orchestrators (FR-MEO-1) and integration with experiment tracking systems

¹⁵ <https://www.zenml.io/>

(FR-MEO-5). Through its well-defined abstraction layers (pipelines, stacks, artifacts), ZenML exposes a meta-orchestration API that abstracts over different backends (FR-MEO-3), allowing users to register, update and share pipeline templates (FR-MEO-4). Furthermore, ZenML offers the flexibility for users to select the stack on which specific tasks such as model training, fine-tuning, inference, evaluation, or compression are executed (NFR-MEO-1, FR-MEO-6, FR-MEO-7, FR-MEO-8), thereby meeting requirements for resource and stack selection. On the non-functional side, ZenML ensures consistency and synchronization of metadata across stacks through artifact and model versioning (NFR-MEO-2), while providing detailed logging, caching, and lineage tracking (NFR-MEO-3). Finally, ZenML supports monitoring and observability of pipelines' executions through its dashboard (NFR-MEO-4), making it a suitable candidate to meet both the functional and non-functional requirements of the 6G-DALI meta-orchestration solution.

4.1.4 Trustworthy AI and societal acceptance

4.1.4.1 *Tensorflow Probability*

Description. TensorFlow Probability¹⁶ is an open-source library for probabilistic reasoning and statistical analysis, built on top of TensorFlow. The library is widely supported with extensive documentation and a strong user base in both academia and industry. TensorFlow Probability is highly compatible with MLFlow and ZenML, as these MLOps platforms are designed to work with TensorFlow and Keras.

Main Features. Its main features relevant to the 6G-DALI project are:

- Probabilistic programming library built on TensorFlow: Allows for tracking and managing the uncertainty of TensorFlow models within the MLOps pipelines of 6G-DALI.
- Supports Bayesian Neural Networks and Monte Carlo Dropout methods, which are central to the 6G-DALI project's UQ strategy.

Mapping to 6G-DALI Requirements. This tool provides probabilistic predictions with confidence intervals and enables the calculation of various uncertainty metrics, thus being in line with FR-TAI-1 and FR-TAI-3. It also supports models that follow the TensorFlow framework, relevant to FR-TAI-7, as well as different UQ methods, in line with NFR-TAI-3.

4.1.4.2 *Fortuna AWS*

Description. Fortuna AWS¹⁷ is a toolkit that supports a wide range of UQ methods, including Bayesian, Ensemble, Monte Carlo Dropout, and Conformal Prediction. It is designed to work across different frameworks, including Scikit-Learn, TensorFlow, and PyTorch. This wide range of integrations makes it a highly flexible solution for the 6G-DALI project. While the community is still growing, its direct support for multiple UQ methods and broad framework compatibility make it a valuable tool for assessing the trustworthiness of models across different AI applications.

Main Features. Its main features relevant to the 6G-DALI project are:

- Supports a wide range of UQ methods, including Bayesian, Ensemble, MC Dropout, and Conformal Prediction.
- Integrates with multiple frameworks (Scikit-Learn, TensorFlow, and PyTorch), offering flexibility in the project's diverse MLOps pipeline.
- Designed to easily calibrate model outputs and obtain reliable uncertainty estimates, promoting the effortless estimation of uncertainty in production systems.

Mapping to 6G-DALI Requirements. This tool also provides probabilistic predictions and provides various uncertainty metrics, thus being in line with FR-TAI-1 and FR-TAI-3. It also supports multiple AI frameworks, relevant to FR-TAI-7, as well as different UQ methods, in line with NFR-TAI-3.

¹⁶ <https://github.com/tensorflow/probability>

¹⁷ <https://github.com/awsmlabs/fortuna>

4.1.4.3 PyTorch Pyro

Description. PyTorch Pyro¹⁸ is a deep probabilistic programming library, integrated with the PyTorch ecosystem. Its main functionality is to enable the development of complex probabilistic models, including those that incorporate neural networks. It is particularly well-suited for Bayesian, Ensemble, and Monte Carlo Dropout methods in a PyTorch environment. Because it is built on PyTorch, it can be seamlessly integrated into MLOps platforms like MLFlow and ZenML.

Main Features. Its main features relevant to the 6G-DALI project are:

- UQ library built on PyTorch: Enables tracking the uncertainty of PyTorch models within the 6G-DALI MLOps pipeline.
- Supports Bayesian and Monte Carlo Dropout methods.

Mapping to 6G-DALI Requirements. PyTorch Pyro supports probabilistic predictions and different UQ algorithms for PyTorch models, making it relevant to FR-TAI-1, FR-TAI-3, FR-TAI-7 and NFR-TAI-3.

4.1.4.4 MAPIE and PUNCC

Description. Model Agnostic Prediction Interval Estimator (MAPIE)¹⁹ and Predictive Uncertainty Calibration and Conformalization (PUNCC)²⁰ are Python libraries that specialize in Conformal Prediction. They are designed to work with frameworks like Scikit-Learn, TensorFlow, and PyTorch. The framework-agnostic nature of these tools makes them suitable for use with MLOps pipelines like MLFlow and ZenML, which can easily log and monitor the prediction intervals they generate.

Main Features. The main features of MAPIE and PUNCC relevant to the 6G-DALI project are:

- Used for Conformal Prediction, a method that provides prediction intervals with a guaranteed coverage probability.
- Model-agnostic, meaning they can be applied to any pre-trained model regardless of its underlying framework.

Mapping to 6G-DALI Requirements. These tools support Conformal Prediction, mainly for Scikit-Learn models (also with indirect support for TensorFlow and PyTorch), and similarly to previous tools, extend the feasibility of FR-TAI-1, FR-TAI-3, and FR-TAI-7.

4.1.4.5 SHAP and LIME

Description. The 6G-DALI framework will also incorporate XAI methods like SHapley Additive exPlanations (SHAP)²¹ and Local Interpretable Model-agnostic Explanations (LIME)²². These tools are critical for enhancing the overall trustworthiness by explaining instances where high uncertainty is detected.

Main Features. The main features of these tools relevant to the 6G-DALI framework are:

- Model-Agnostic Explanations: Both SHAP and LIME can be applied to any machine learning model, regardless of its underlying architecture.
- Local Interpretability: They focus on explaining individual predictions rather than the entire model, which is crucial for understanding specific cases of high uncertainty.
- Feature Importance: They identify which input features are most influential in a single prediction, providing a clear and transparent reason for the model's output.

Mapping to 6G-DALI Requirements. These tools can be used for specific actions like providing explanations for low-confidence predictions, which are relevant to FR-TAI-6 and NFR-TAI-4.

¹⁸ <https://pyro.ai/>

¹⁹ <https://mapie.readthedocs.io/en/stable/>

²⁰ <https://github.com/deel-ai/puncc>

²¹ <https://github.com/shap/shap>

²² <https://github.com/marcotcr/lime>

4.2 DataOps

4.2.1 Data Transformation (ELT Pipelines)

4.2.1.1 Apache Beam

Description. Apache Beam²³ is an open-source, unified programming model for defining both batch and streaming data-parallel processing pipelines. Beam enables users to design, create and test their pipelines, which can be used for Extract, Transform, and Load (ETL and/or ELT) tasks and pure data integration. Currently, it supports multiple language-specific SDKs, i.e., Java, Python, and Go, for writing pipelines. It also supports executing programs on multiple distributed backends through PipelineRunner, including local machine, cloud environment, and possible clusters.

Main Features. The main features of Apache Beam relevant to the 6G-DALI project are:

- Support Extract, Transform, and Load tasks and enable design, create, and test data pipelines for data processing.
- support AI/ML pipelines, and a variety of transform patterns, many of which are documented in its Transform Catalog.

Mapping to 6G-DALI Requirements. This tool can be used for specific actions like data preprocessing operations, such as filtering, aggregation, de-duplication, and enrichment, etc. These functionalities are relevant to FR-ELT-3, FR-ELT-5, and FR-ELT-6. The data pipelines can be expressed with generic transforms, hence they are flexible, understandable, and maintainable, which contributing to fulfilling non-functional requirements such as NFR-ELT-3 and NFR-ELT-4.

4.2.1.2 Apache Airflow

Description. Apache Airflow²⁴ is an open-source platform for programmatically authoring, scheduling, and monitoring data workflows. It enables users to define workflows as Directed Acyclic Graphs (DAGs) using Python code, making it easy to orchestrate complex data pipelines across multiple systems. Airflow provides a rich user interface for visualizing pipelines, monitoring their execution, and troubleshooting issues. It supports distributed task execution through various executors (Local, Sequential, Celery, Kubernetes, etc.) and integrates with numerous data sources and services through its extensive library of operators and hooks, making it ideal for ETL/ELT processes, data engineering workflows, and task automation.

Main Features. The main features of Apache Airflow relevant to our project are:

- Support Extract, Transform, and Load tasks and enable design, schedule, and monitor data pipelines through code-based workflow orchestration.
- Support dynamic pipeline generation, complex dependencies, and parallel execution of tasks across distributed systems.
- Provide extensive integration with cloud platforms, databases, and data processing frameworks through a rich ecosystem of operators and hooks.
- Enable workflow visualization, execution monitoring, and automatic retry mechanisms with detailed logging and alerting capabilities.

Mapping to 6G-DALI Requirements. This tool can be used for specific actions like data preprocessing operations, such as filtering, aggregation, de-duplication, and enrichment, etc. These functionalities are relevant to FR-ELT-3, FR-ELT-5, and FR-ELT-6. Non-functional requirements such as NFR-ELT-1, NFR-ELT-5, and NFR-ELT-6 are fulfilled.

²³ <https://github.com/apache/beam>

²⁴ <https://github.com/apache/airflow>

4.2.2 Data Augmentation

4.2.2.1 AutoFeat

Description. AutoFeat²⁵ is an open-source approach for feature discovery on tabular datasets. Given a base table with a target variable and a repository of tabular datasets in a data-lake setting, AutoFeat helps discover relevant features for augmentation among tables from the data repository. The resulting augmented table will be a better training dataset for decision tree-based machine learning algorithms.

Main Features. The main features of AutoFeat relevant to the 6G-DALI project are:

- Support tabular data augmentation. Tabular data is one of the most common and practical data types in the 6G-DALI project.
- Support visualization of discovered datasets. This tool uses Valentine²⁶ to discover joinable tables and uses Neo4J²⁷ to visualize the discovered datasets.
- Support flexible deployment. This tool is able to be deployed and integrated with the data lake of the 6G-DALI framework, via Docker container services.

Mapping to 6G-DALI Requirements. This tool can be used for specific actions of data augmentation and find relationships among tabular datasets, which is relevant to FR-DA-1, FR-DA-2, FR-DA-3, FR-DA-6, FR-DA-7. It enables to customize the augmentation strategies and evaluation process with downstream applications. It contributes to fulfilling non-functional requirements such as NFR-DA-3 and NFR-DA-4.

4.2.3 Intent-driven DataOps via Generative AI

4.2.3.1 Agent Orchestration

Agent orchestration is the coordination layer that ensures that multiple LLM-powered agents and tools can work together coherently to achieve user-specified goals. In the context of intent-driven DataOps, this means translating a single high-level user request into a set of atomic tasks, assigning them to specialized agents. Effective orchestration reduces human intervention, handles error recovery automatically, and allows dynamic adaptation of pipelines when data sources or requirements change.

4.2.3.1.1 LangChain

Description. LangChain²⁸ is a widely used open-source framework for building applications that integrate LLMs with external data sources and tools. It has a strong developer community and is used in both research and production environments for retrieval-augmented generation, tool orchestration, and building conversational agents.

Main Features. The main features relevant to the 6G-DALI project are:

- Composable abstractions for prompt templates, LLM calls, and tool execution.
- Built-in support for RAG pipelines with vector databases.
- Multi-agent orchestration where LLMs can call external APIs and tools dynamically.
- Large ecosystem of integrations with databases, APIs, and machine learning libraries.

Mapping to the 6G-DALI requirements. FR-IDD-1, FR-IDD-3, FR-IDD-4, FR-IDD-5, FR-IDD-8.

4.2.3.1.2 CrewAI

Description. CrewAI²⁹ is an emerging open-source framework designed for multi-agent orchestration, where different AI agents act in specialized roles to complete tasks collaboratively. It emphasizes reproducibility, transparency, and human-like workflows.

²⁵ <https://github.com/delftdata/autofeat>

²⁶ <https://github.com/delftdata/valentine>

²⁷ <https://neo4j.com/>

²⁸ <https://www.langchain.com/>

²⁹ <https://www.crewai.com/autogen>

Main Features. The main features relevant to the 6G-DALI project are:

- Supports defining agents with specific roles (planner, executor, reviewer).
- Enables task decomposition for complex workflows.
- Provides collaboration protocols among agents to reduce failure rates.
- Useful for scenarios where ELT pipelines must be broken down into sequential steps.

Mapping to the 6G-DALI requirements. FR-IDD-2, FR-IDD-3, FR-IDD-5.

4.2.3.1.3 *AutoGen*

Description. AutoGen³⁰ (developed by Microsoft Research) is an open-source framework enabling conversation-driven collaboration between multiple LLM-based agents and humans. It is used in scenarios where multiple agents negotiate, refine, or validate task execution.

Main Features. The main features relevant to the 6G-DALI project are:

- Multi-agent conversation paradigm for coordination.
- Flexible function calling for connecting agents to external APIs and tools.
- Human-in-the-loop support to iteratively refine workflows.
- Particularly suited for refining ELT pipelines based on user input.

Mapping to the 6G-DALI requirements. FR-IDD-3, FR-IDD-5, FR-IDD-8.

4.2.3.2 *LLM Providers*

LLM providers form the intelligence layer of the intent-driven DataOps stack. They supply the reasoning capability required to parse user input, generate data transformation code, and interact with APIs. By selecting the right model and deployment method, organizations can optimize for latency, cost, and privacy. Local LLM deployment is particularly attractive in regulated environments where sensitive data cannot leave the premises.

4.2.3.2.1 *Ollama*

Description. Ollama³¹ is an open-source framework for running large language models locally, designed to simplify the deployment and management of LLMs on local infrastructure. Developed by the Ollama team, it has gained significant adoption in the developer community for its ease of use and comprehensive model support, enabling organizations to deploy LLMs without relying on external API services.

Main Features. The main features relevant to the 6G-DALI project are:

Ollama provides simplified local LLM deployment with support for popular open-source models including Llama, Mistral, and Llama. The framework includes model quantization capabilities, GPU acceleration support, and REST API interfaces for integration with applications. Ollama offers automatic model downloading, version management, and resource optimization for efficient local inference. The platform supports custom model fine-tuning and deployment workflows. Open source language models including Mistral AI's models, Meta's Llama series, and DeepSeek represent the cutting edge of democratized AI technology. These models have gained widespread adoption in research and enterprise environments due to their competitive performance, transparency, and cost-effectiveness compared to proprietary alternatives.

Mapping to 6G-DALI Requirements. The main mapping to the 6G-DALI requirements are:

- FR-IDD-1: Superior natural language understanding enables highly accurate dataset search and retrieval operations
- FR-IDD-2: Advanced code generation capabilities ensure high-quality ELT pipeline creation from natural language descriptions
- FR-IDD-3: Sophisticated conversational abilities support complex iterative chat interfaces for pipeline refinement

³⁰ <https://microsoft.github.io/autogen/stable//index.html>

³¹ <https://ollama.com/>

FR-IDD-5: State-of-the-art reasoning enables robust intent translation and semantic understanding.

4.2.3.3 Retrieval-Augmented Generation (RAG)

RAG is the memory subsystem that enhances the capabilities of LLMs by grounding their outputs in factual, context-relevant data. Instead of relying purely on parametric memory (the model's internal weights), RAG allows queries to retrieve up-to-date information from vector databases before generating responses. In DataOps workflows, this is crucial for ensuring that generated pipelines use the correct dataset schemas, column names, and metadata from distributed data spaces.

4.2.3.3.1 Qdrant

Description. Qdrant³² is an open-source vector database designed for high-performance similarity search and recommendation systems. It is widely used in LLM-powered applications for retrieval and contextual augmentation.

Main Features. The main features relevant to the 6G-DALI project are:

- Optimized for billion-scale vector search with sub-second latency.
- Hybrid search capabilities (dense + sparse retrieval).
- Provides APIs for filtering and metadata search.
- Actively maintained with strong integration with LangChain, CrewAI.

Mapping to the 6G-DALI requirements. FR-IDD-4, FR-IDD-6, FR-IDD-7.

4.2.3.3.2 ChromaDB

Description. ChromaDB³³ is a lightweight open-source embedding database built for LLM prototyping. It is simple to deploy and is increasingly popular for smaller-scale projects.

Main Features. The main features relevant to the 6G-DALI project are:

- Local-first design suitable for quick development cycles.
- Easy-to-use Python API for storing and retrieving embeddings.
- Tight integration with LangChain for RAG pipelines.
- Minimal configuration compared to enterprise vector DBs.

Mapping to the 6G-DALI requirements. FR-IDD-4, FR-IDD-7.

4.2.3.3.3 Weaviate

Description. Weaviate³⁴ is an open-source vector database with advanced semantic search capabilities, including support for knowledge graphs. It has an enterprise-ready ecosystem and is widely deployed in AI-driven search engines.

Main Features. The main features relevant to the 6G-DALI project are:

- Schema-based design supporting hybrid vector + symbolic search.
- Knowledge graph support to encode semantic relationships.
- Multi-modal data support (text, images, video).
- Strong cloud-native scalability.

Mapping with the 6G-DALI requirements. FR-IDD-4, FR-IDD-6, FR-IDD-7.

³² <https://qdrant.tech/>

³³ <https://www.trychroma.com/>

³⁴ <https://weaviate.io/>

4.3 Data Spaces & Connectors

4.3.1 Data Spaces

4.3.1.1 Piveau Hub

Description. Piveau Hub³⁵ is an open-source platform tailored for managing large-scale open data ecosystems. It simplifies data ingestion, management, and publication processes while ensuring interoperability through adherence to metadata standards like DCAT-AP. Actively maintained by the Piveau community and adopted by governments and research organizations, it provides a modular infrastructure for building reliable and scalable open data portals. Its API-driven architecture supports automation and seamless integration with external tools and services.

Main Features. The main features relevant to the 6G-DALI project are:

- Automated data harvesting from multiple sources and APIs.
- Metadata management and cataloging based on DCAT-AP standards.
- Standard-compliant data publishing and discovery services.
- Integrated visualization tools and RESTful APIs for accessibility.

Mapping to 6G-DALI Requirements. Piveau Hub supports dataset discovery and standards-based publication within 6G-DALI. It ensures that data from diverse testbeds can be ingested, cataloged, and shared consistently. It contributes to fulfilling FR-DS 1 FR-DS 2 FR-DS 3 FR-DS 4 FR-DS 5 FR-DS 6 by handling different data types, formats, and protocols, and supporting collaboration among researchers. Non-functional requirements such as scalability (NFR-DS 1 NFR-DS 2) and adaptability to future advances (NFR-DS 8 NFR-DS 9) are also addressed by its modular design.

4.3.1.2 Piveau Metrics

Description. Piveau Metrics³⁶ is an open-source module within the Piveau ecosystem that evaluates dataset quality and completeness. It generates detailed quality metrics that help organizations ensure that their open data assets meet standards for usability and reliability. Actively used in large-scale open data portals, it integrates seamlessly with Piveau Hub to provide automated quality monitoring and reporting.

Main Features. The main features relevant to the 6G-DALI project are:

- Calculation of dataset quality and completeness scores.
- Metadata analysis and reporting tools.
- RESTful API for integration with external applications.
- Automated quality assessments during data ingestion.

Mapping to 6G-DALI Requirements. Piveau Metrics provides advanced analytics and monitoring for open data platforms, supporting performance evaluation of data spaces. It contributes to fulfilling FR-DS 4, FR-DS 7 by ensuring rich metadata and catalog monitoring capabilities, enabling better management of datasets and services. It supports non-functional requirements such as monitoring and logging (NFR-DS 15), scalability (NFR-DS 1), and adaptability (NFR-DS 8, NFR-DS 14) through its flexible reporting architecture.

4.3.1.3 Virtuoso

Description. Virtuoso³⁷ is a multi-model data server designed for managing graph, relational, and RDF data at scale. It is widely used for linked data publishing and knowledge graph applications, providing

³⁵ <https://www.piveau.de/en/>

³⁶ <https://github.com/piveau/piveau-metrics>

³⁷ <https://virtuoso.openlinksw.com/>

high-performance query capabilities. Maintained by OpenLink Software and supported by a large user community, Virtuoso is a proven solution for organizations needing semantic data integration and advanced query features.

Main Features. The main features relevant to the 6G-DALI project are:

- RDF triple store with SPARQL query support.
- Multi-model capabilities for relational and graph data.
- Scalable federation of heterogeneous data sources.
- High-performance querying and data management.

Mapping to 6G-DALI Requirements. Virtuoso provides a high-performance RDF store and SPARQL endpoint for semantic data integration within data spaces. It fulfills FR-DS 1, FR-DS 4, FR-DS 7, FR-DS 14 by enabling semantic search, rich metadata annotation, and Gaia-X-compliant data representation. Non-functional requirements like scalability for large RDF graphs (NFR-DS 1), security (NFR-DS 3, NFR-DS 5), and adaptability to new ontologies (NFR-DS 8, NFR-DS 9) are also addressed through its extensible SPARQL-based architecture.

4.3.1.4 *Elasticsearch*

Description. Elasticsearch³⁸ is an open-source, distributed search and analytics engine that enables organizations to store, index, and analyze large volumes of data in near real time. Widely adopted across industries, Elasticsearch is part of the Elastic Stack and is actively maintained with a large developer and enterprise user base.

Main Features. The main features relevant to the 6G-DALI project are:

- Full-text search and real-time data indexing.
- Distributed architecture for horizontal scalability.
- REST API and rich query language for flexible analytics.
- Advanced data visualization through Kibana integration.

Mapping to 6G-DALI Requirements. Elasticsearch supports fast and scalable search for datasets and metadata within the data space. It meets FR-DS 1, FR-DS 4, FR-DS 7 by enabling efficient dataset discovery with rich metadata indexing and retrieval capabilities. Non-functional requirements such as high scalability (NFR-DS 1, NFR-DS 2), security (NFR-DS 3, NFR-DS 5, NFR-DS 6), and robustness with fault tolerance (NFR-DS 4, NFR-DS 13) are supported through its distributed architecture.

4.3.1.5 *Data Space Ontology*

Description. The Data Space Ontology³⁹ defines a shared conceptual model for semantic interoperability within federated data spaces. Developed under the GAIA-X initiative, it provides a standardized vocabulary for representing data space entities and relationships, ensuring consistent interpretation of data across organizations and domains.

Main Features. The main features relevant to the 6G-DALI project are:

- RDF/OWL-based ontology for federated data spaces.
- Common vocabulary for participants, datasets, and connectors.
- Semantic alignment for cross-domain interoperability.
- Openly maintained by GAIA-X and its contributors.

Mapping to 6G-DALI Requirements. The Data Space Ontology enables semantic interoperability and standardized metadata models within data spaces. It contributes to FR-DS 4, FR-DS 7, FR-DS 13, FR-DS

³⁸ <https://github.com/elastic/elasticsearch>

³⁹ <https://gitlab.com/gaia-x/lab/ontologies/dataspace>

14 by ensuring Gaia-X-compliant metadata annotation and catalog interoperability. Non-functional requirements such as adaptability to evolving standards (NFR-DS 8, NFR-DS 9, NFR-DS 14) and support for modular integration into future systems are also fulfilled.

4.3.1.6 IDS AppStore

Description. The IDS AppStore⁴⁰ is a trusted marketplace for distributing certified IDS applications, enabling participants of data spaces to extend their capabilities with prebuilt, standard-compliant components. Managed by the International Data Spaces Association, the AppStore ensures that applications adhere to IDS principles for secure and interoperable data sharing.

Main Features. The main features relevant to the 6G-DALI project are:

- Repository of certified IDS applications.
- Verified interoperability and security compliance.
- Modular extensions for data space functionalities.
- Community-driven contributions and updates.

Mapping to 6G-DALI Requirements. The IDS AppStore supports the discovery and provisioning of data-related services within the IDS-based data space ecosystem. It fulfills FR-DS 2, FR-DS 5, FR-DS 6 by enabling service search and storage of data manipulation services and new versions after pipeline processing. Non-functional requirements like scalability (NFR-DS 1), compliance with trust and security policies (NFR-DS 3, NFR-DS 5, NFR-DS 6, NFR-DS 7), and adaptability to new service offerings (NFR-DS 8, NFR-DS 9) are addressed.

4.3.1.7 IDS Clearing House Service

Description. The IDS Clearing House Service⁴¹ is a trusted transaction logging and auditing component within IDS-based data spaces. It acts as a neutral authority that records and verifies all data transactions, ensuring transparency and accountability in data exchanges between participants.

Main Features. The main features relevant to the 6G-DALI project are:

- Immutable transaction logging and verification.
- Auditing capabilities for compliance monitoring.
- Neutral trust service for participants.
- Open-source implementation maintained by IDSA.

Mapping to 6G-DALI Requirements. The IDS Clearing House Service enables accountability and transaction logging for all data exchanges, ensuring transparency and compliance. It supports FR-DS 8, FR-DS 9, FR-DS 10, FR-DS 12 by authenticating clients, verifying permissions, enforcing trust policies, and logging data transactions. Non-functional requirements such as security (NFR-DS 3, NFR-DS 5, NFR-DS 6, NFR-DS 7), auditing (NFR-DS 7, NFR-DS 15), and system robustness (NFR-DS 13) are fulfilled.

4.3.2 Data Lake

Data Lakes are centralized repositories designed to store vast amounts of structured and unstructured data at scale. They enable organizations to retain raw data in its native format while allowing advanced analytics and machine learning workflows to extract value from it. Within 6G-DALI, the data lake concept supports the accumulation of diverse data sources needed for developing, training, and validating machine learning models. It underpins flexible and cost-effective data storage and processing, crucial for large scale AI development.

⁴⁰ <https://github.com/International-Data-Spaces-Association/IDS-AppStore>

⁴¹ <https://github.com/International-Data-Spaces-Association/ids-clearing-house-service>

4.3.2.1 OpenMetadata

Description. OpenMetadata⁴² is an open-source metadata management solution that provides a unified interface for data discovery, governance, and observability. It is used to catalog datasets, track lineage, and ensure data compliance, making it suitable for complex, distributed data ecosystems.

Main Features. The main features relevant to the 6G-DALI project are:

- Dataset cataloging and metadata search.
- Lineage tracking and impact analysis.
- Access control and governance tools.
- Integration with modern data pipelines and tools.

Mapping to 6G-DALI Requirements. OpenMetadata provides centralized metadata management, discovery, and governance for datasets and ML models. It meets FR-DS 1, FR-DS 3, FR-DS 4, FR-DS 5, FR-DS 7 by supporting search and cataloging of datasets, ML models, and services with rich metadata. Non-functional requirements like scalability (NFR-DS 1, NFR-DS 2), security compliance (NFR-DS 3, NFR-DS 4, NFR-DS 5), and adaptability to new metadata standards (NFR-DS 8, NFR-DS 9) are supported.

4.3.2.2 MinIO

Description. MinIO⁴³ is an open-source, high-performance object storage platform fully compatible with Amazon S3 APIs. It is designed for large-scale data storage across hybrid cloud environments, providing reliability and speed for big data and AI applications.

Main Features. The main features relevant to the 6G-DALI project are:

- Scalable object storage with S3 compatibility.
- High-performance architecture for large datasets.
- Deployment flexibility (cloud, on-premises).
- Integrated security with encryption and access controls.

Mapping to 6G-DALI Requirements. MinIO is an object storage solution enabling efficient and secure storage of datasets in the data lake. It addresses FR-DS 5, FR-DS 6, FR-DS 11 by allowing secure storage of datasets and their versions while enabling policy-compliant retrieval. Non-functional requirements like encryption (NFR-DS 5), scalability for high-volume data (NFR-DS 1), and fault tolerance with recovery (NFR-DS 4, NFR-DS 13) are also fulfilled.

4.3.2.3 AWS S3

Description. AWS S3⁴⁴ (Simple Storage Service) is a widely adopted cloud-based object storage service by Amazon. It provides scalable, durable, and secure storage for any data type, integrating seamlessly with analytics and AI services in the AWS ecosystem.

Main Features. The main features relevant to the 6G-DALI project are:

- Virtually unlimited object storage capacity.
- Data lifecycle management and tiered storage.
- Strong encryption and fine-grained access controls.
- Native integration with AWS analytics and ML tools.

Mapping to 6G-DALI Requirements. AWS S3 provides scalable and reliable object storage for datasets and model artifacts in the data lake. It satisfies FR-DS 5, FR-DS 6, FR-DS 11 by enabling secure storage

⁴² <https://open-metadata.org/>

⁴³ <https://min.io/>

⁴⁴ <https://aws.amazon.com/s3/>

and retrieval of data sets and versions. Non-functional requirements such as elasticity (NFR-DS 1), strong security (NFR-DS 3, NFR-DS 5, NFR-DS 6), and continuous availability (NFR-DS 12, NFR-DS 13) are met through its cloud-native architecture.

4.3.3 Connectors

4.3.3.1 Eclipse-EDC Connector

Description. The Eclipse-EDC⁴⁵ Connector is an open-source implementation facilitating sovereign data exchange between organizations. Developed under Eclipse Foundation governance, it adheres to IDS and GAIA-X principles, ensuring standardized and secure data transfer in federated ecosystems.

Main Features. The main features relevant to the 6G-DALI project are:

- Policy-based data sharing and enforcement.
- Authentication and participant verification.
- Flexible deployment and protocol support.
- Open-source community maintenance and updates.

Mapping to 6G-DALI Requirements. The Eclipse EDC Connector enables secure, policy-driven data exchange across federated data spaces. It fulfills FR-DS 8, FR-DS 9, FR-DS 10, FR-DS 11, FR-DS 12 by ensuring authentication, authorization, trust enforcement, and secure data transfer. Non-functional requirements like security compliance (NFR-DS 3, NFR-DS 5, NFR-DS 6, NFR-DS 7), modularity (NFR-DS 14), and adaptability to future standards (NFR-DS 8, NFR-DS 9) are addressed by its extensible architecture.

4.3.3.2 IDS DataspaceConnector

Description. The IDS DataspaceConnector⁴⁶ is an open-source reference implementation enabling participants to operate within IDS-compliant data spaces. Maintained by the IDSA, it supports secure connector-to-connector communication and enforces usage policies during data exchanges.

Main Features. The main features relevant to the 6G-DALI project are:

- Identity and access management.
- Secure, policy-governed data transfer.
- Connector-to-connector communication protocols.
- Open-source community support and updates.

Mapping to 6G-DALI Requirements. The IDS Dataspace Connector provides trusted connectivity between participants in an IDS-compliant data space. It meets FR-DS 8, FR-DS 9, FR-DS 10, FR-DS 11 by enforcing identity, trust, and policy-based secure data exchange. Non-functional requirements like compliance with data protection regulations (NFR-DS 3), encryption in transit and at rest (NFR-DS 5) and adaptability (NFR-DS 8, NFR-DS 9) are fulfilled.

4.3.3.3 Sovity Connector

Description. The Sovity Connector⁴⁷ is a community driven implementation of the Eclipse Dataspace Connector, offering simplified deployment and preconfigured modules. It provides the same core functionalities as Eclipse-EDC but with additional enhancements for faster adoption and usability.

Main Features. The main features relevant to the 6G-DALI project are:

⁴⁵ <https://projects.eclipse.org/projects/technology.edc>

⁴⁶ <https://github.com/International-Data-Spaces-Association/DataspaceConnector>

⁴⁷ <https://github.com/sovity/edc-ce>

- Preconfigured modules for quick setup.
- Policy-based secure data exchange.
- Support for IDS and GAIA-X principles.
- Open source with community enhancements.

Mapping to 6G-DALI Requirements. The Sovity Connector extends EDC capabilities to provide Gaia-X-compliant data exchange features. It addresses FR-DS 8, FR-DS 9, FR-DS 10, FR-DS 13 by authenticating clients, enforcing trust, and enabling Gaia-X interoperability. Non-functional requirements such as security (NFR-DS 3, NFR-DS 5, NFR-DS 6), modularity for future updates (NFR-DS 14), and resilience to network failures (NFR-DS 13) are also supported.

4.4 Digital Twin

4.4.1 Digital Twin Components

The Digital Twin is composed of multiple components:

4.4.1.1 AI-RSG

Description. The AI RAN Scenario Generator (AI-RSG)⁴⁸ creates realistic, high-fidelity RAN scenarios for AI/ML model training and validation. It enables operators and vendors to simulate diverse network conditions, accelerating the development and deployment of AI-driven RAN solutions.

Features. The main features relevant to the 6G-DALI project are:

- Hybrid data generation (real + synthetic KPIs)
- Scenario simulation for urban, rural, and custom environments
- Cloud-native and containerized (supports Docker, Kubernetes)
- Integration with Open RAN for near-RT and non-RT RIC validation
- Scalability: Handles large-scale UE and cell modeling for complex scenarios.
- Digital Twin Capability: Creates a virtual replica of the RAN for testing and optimization.
- An ADK used to control the AI-RSG using python.

Mapping to 6G-DALI Requirements. AI-RSG provides the digital twin foundation for 6G-DALI. It is able to simulate the different E2 Nodes: Users, Base Stations, Distributed Units (DUs) and (CUs), etc.(FR-DTL-1, FR-DTL-2, FR-DTL-3, FR-DTL-4, FR-DTL-5, FR-DTL-6, NFR-DTL-1).

4.4.1.2 Flex-RIC

Description. FlexRIC⁴⁹ is an open-source SDK developed by EURECOM / OpenAirInterface (Mosaic5G project) that implements a near-real-time RAN Intelligent Controller (near-RT RIC) with E2 Node Agent emulators, enabling the development of xApps

Features. The main features relevant to the 6G-DALI project are:

- Modular architecture for service models, encoding schemes, and RIC vs Agent components. The architecture is lean, with minimal footprint, enabling specialization for different RAN scenarios (flow-based control, slicing, multi-RAT etc.).
- SDK for xApps (C/C++ and Python) allowing developers to plug in application logic, using standardized service models (e.g. KPM, RC) and metric reporting.
- Support for E2 interface: FlexRIC supports multiple versions of E2AP and multiple E2 Service Models. It also includes E2 Node Agent emulators to simulate RAN nodes.
- Lightweight and performance-oriented: Designed to have low latency, low overhead in CPU and memory compared to some alternatives.
- Encoding flexibility: multiple encoding schemes supported (ASN.1, flatbuffer, etc.) depending on the service model and configuration.
- Test / emulation support: with agent emulators, example xApps, etc., for offline / laboratory

⁴⁸ <https://www.viavisolutions.com/en-us/products/teravm-ai-rsg>

⁴⁹ <https://gitlab.eurecom.fr/mosaic5g/flexric>

testing.

Mapping to 6G-DALI Requirements. Flex-RIC acts as the control and orchestration layer in the digital twin, enabling adaptive and intelligent RAN management aligned with 6G-DALI's closed-loop automation goals (FR-DTL-1, FR-DTL-2, FR-DTL-3, FR-DTL-4, FR-DTL-5, NFR-DTL-1).

4.4.1.3 Docker

Description. Docker⁵⁰ is a containerization platform that packages applications and their dependencies into portable containers, ensuring consistent deployment across environments.

Features. The main features relevant to the 6G-DALI project are:

- Lightweight, portable containers
- Supports microservices and modular architectures
- Integration with CI/CD pipelines
- Works with Kubernetes for orchestration
- Enables reproducible environments for AI/ML workflows

Mapping to 6G-DALI Requirements. Docker ensures modular, scalable deployment of digital twin components (AI-RSG, Flex-RIC, xApps, RL training environments), supporting agile development and RLOps in 6G-DALI (FR-DTL-1, FR-DTL-2, FR-DTL-3, FR-DTL-4, FR-DTL-5, FR-DTL-6, FR-DTL-7, NFR-DTL-1).

4.4.2 AlaaS and HPO for RLOps

4.4.2.1 Ray: Ray Tune

Description: Ray⁵¹ is a distributed computing framework that makes it easy to scale Python workloads from a laptop to a cluster. While RLlib is specific to reinforcement learning, Ray Agile or Ray's agile libraries refer to the flexible, distributed workflow and orchestration tools in the Ray ecosystem, often including Ray Core, Ray Tune, and Ray Serve. Therefore, only Ray Tune will be utilized in the RLOps for enhancing the tuning of the policies.

Main Features. The main features relevant to the 6G-DALI project are:

- Distributed Computing Made Easy: Parallelize Python functions or classes across multiple nodes without managing low-level concurrency.
- Hyperparameter Tuning: Ray Tune enables efficient, distributed hyperparameter optimization.

Mapping to 6G-DALI Requirements. Ray Tune allows distributed optimization of RL models (FR-AR-4, and 5), essential for rapid RLOps cycles (NFR-AR-2). As an AlaaS component, it facilitates continuous training and deployment pipelines in the 6G-DALI ecosystem.

4.4.3 Collaborative RLOps through Digital Twin

4.4.3.1 RLlib

Description: RLlib⁵² is a high-level library for Reinforcement Learning (RL) built on Ray, designed for both research and production. It provides scalable, distributed RL training for a variety of algorithms while simplifying complex RL workflows.

Main Features. The main features relevant to the 6G-DALI project are:

- Scalable & Distributed: Can train RL models across multiple CPUs, GPUs, or clusters without rewriting code.
- Algorithm Support: Includes built-in support for a wide range of RL algorithms, both policy gradient (e.g., PPO, A3C) and value-based (e.g., DQN) methods.

⁵⁰ <https://www.docker.com/>

⁵¹ <https://docs.ray.io/en/latest/tune/index.html>

⁵² <https://docs.ray.io/en/latest/rllib/index.html>

- Flexible APIs: Supports both high-level training abstractions and custom RL environments, policies, and models.
- Integration with Gym: Works seamlessly with OpenAI Gym and other RL environments.
- Multi-Agent Support: Can handle multi-agent RL environments for complex simulations.
- Production-Ready: Offers checkpointing, evaluation, and rollout management, making deployment easier.
- TensorFlow & PyTorch: Supports both major deep learning frameworks interchangeably.

Mapping to 6G-DALI Requirements. RLlib aligns with the **collaborative RLOps** paradigm by enabling multi-agent reinforcement learning and scalable simulation of Digital Twin environments. Its distributed nature enhances learning efficiency (FR-CR-1, NFR-CR-2), and also involves multi-agent RL, and supports **multi-objective and multi-domain** goals typical of 6G-Networks (NFR-CR-3).

4.4.4 Federated learning for NWDAF

Description. OpenAirInterface (OAI) NWDAF⁵³ is an open-source implementation of the 3GPP-defined NWDAF designed to enable network data collection, analytics, and AI-driven insights for 5G networks. It serves as a foundational analytics component within the 5G Core (5GC) ecosystem and provides standardized interfaces for data exposure and model management.

Main Features. The main features relevant to the 6G-DALI project are:

- Open-source framework supporting 3GPP Rel 15 specifications for NWDAF functions.
- Modular architecture allowing integration of custom analytics logic.
- REST-based APIs for data collection and analytics result dissemination.
- Extensible design compatible with external data sources and machine learning components.

Mapping to the 6G-DALI requirements. FR-IDD-4, FR-IDD-7.

4.5 Adaptation Layer

4.5.1 Adaptation Layer tools

4.5.1.1 API & Integration Layer

The API and integration layer is what operationalizes the intelligence generated by LLMs and orchestrators. It acts as the glue between intent interpretation, data retrieval, and actual experiment execution. Well-designed APIs enable modularity, making it possible to plug in new models, swap vector databases, or connect to additional testbeds with minimal changes to the higher-level logic.

4.5.1.1.1 Flask / FastAPI

Description. Flask⁵⁴ and FastAPI⁵⁵ are open-source Python frameworks for developing web APIs. Flask is a mature, lightweight framework, while FastAPI offers asynchronous execution and higher performance for modern workloads. Both are extensively used in research and industry.

Main Features. The main features relevant to the 6G-DALI project are:

- REST API development for exposing LLM-agent workflows.
- Lightweight integration with RAG systems and orchestration tools.
- Supports async and real-time interaction (FastAPI).
- Easy deployment in microservice-oriented architectures.

Mapping to the 6G-DALI requirements. FR-IDD-8, FR-IDD-9.

4.5.1.1.2 SUNRISE-6G Library

⁵³ <https://gitlab.eurecom.fr/oai/cn5g/oai-cn5g-nwdaf>

⁵⁴ <https://flask.palletsprojects.com/en/stable/>

⁵⁵ <https://fastapi.tiangolo.com/>

Description. SUNRISE-6G library [5] provides a standardized interaction with testbeds, allowing experiments to be configured, started, and monitored in a uniform manner. They abstract away heterogeneity across different infrastructures.

Main Features. The main features relevant to the 6G-DALI project are:

- Functions for starting, stopping, and monitoring experiments.
- Unified schema for experiment configuration across testbeds.
- Allows integration with higher-level orchestration agents.
- Key enabler for automating experiment-driven dataset collection.

Mapping to the 6G-DALI requirements. FR-IDD-7, FR-IDD-8, FR-IDD-9.

4.5.1.1.3 *FastMCP*

Description. FastMCP⁵⁶ is a high-performance middleware platform designed for managing and orchestrating massive connectivity points in next-generation networks. It provides efficient mechanisms for controlling and monitoring large numbers of network nodes and supports real-time data streaming and analytics.

Main Features. The main features relevant to the 6G-DALI project are:

- Real-time monitoring and control of distributed network nodes.
- Scalable orchestration for large-scale multi-connectivity experiments.
- APIs for data collection, logging, and event notification.
- Support for integration with experiment automation frameworks.
- Optimized for low-latency communication in high-density 6G testbeds.

Mapping to the 6G-DALI requirements. FR-IDD-3, FR-IDD-5, FR-IDD-8.

⁵⁶ <https://gofastmcp.com/getting-started/welcome>

5 Gap Analysis and Proposed Tools Extensions

After examining the existing tools for each thematic area in the previous sections, in accordance with the initial architecture of the 6G-DALI framework, this section focuses on identifying the current gaps in tooling. These gaps summarized in Table 4 highlight the areas where 6G-DALI will implement new solutions to advance the state of the art.

Table 4. Summary of the technological tools

Thematic Area	Architectural Dimension	Available technological tools
MLOps	MLOps Orchestration	<ul style="list-style-type: none"> - Model Registry: <ul style="list-style-type: none"> o MLflow - Artifact Storage: <ul style="list-style-type: none"> o MinIO - Model Representation: <ul style="list-style-type: none"> o ONNX - Model Deployment: <ul style="list-style-type: none"> o ONNX Runtime o MLServer - Pipeline Orchestration: <ul style="list-style-type: none"> o Prefect - Gaps: <ul style="list-style-type: none"> o Lack of integration across components o Lack of unified interfaces and APIs o Limited interoperability across heterogeneous frameworks o Absence of centralized security and governance layer o Fragmented monitoring and observability - 6G-DALI Contributions: A framework-agnostic MLOps solution will be designed and developed. It will define core MLOps functionalities (e.g., model training, deployment, cataloguing, monitoring) independently of any specific tool, while providing unified management and monitoring. The concrete implementation of these functionalities will rely on tool-specific plugins that interact with an open-source MLOps stack. To guarantee interoperability across AI/ML frameworks and runtimes, the solution will adopt ONNX as the standard model representation format.
	Experimentation-as-a-service & HPO for MLOps	<ul style="list-style-type: none"> - Experiments orchestration: <ul style="list-style-type: none"> o ADO - Gaps: <ul style="list-style-type: none"> o Even though ADO enables the execution scalable and reproducible computational experiments, it does not directly support experiments like hyper parameter optimization, discovery of data gaps for model building and intelligent utilization of testing hardware. - 6G-DALI Contributions: In 6G-Dali we will use ADO to create a framework for automated testing at scale applied to 6G-applications. In the specific we will focus on enabling HPO experiments, data generation for model building where training datasets are partially available or not available at all. The consortium will also explore optimization techniques to be integrated in ADO for efficient utilization of the testbed resources while conducting experimental campaigns.
	Meta-Orchestration of ML Pipelines	<ul style="list-style-type: none"> - Meta-orchestrator: <ul style="list-style-type: none"> o ZenML - Gaps: <ul style="list-style-type: none"> o Although ZenML integrates with a variety of orchestrators, it does not natively support Prefect. While ZenML is designed to be orchestrator-agnostic and exposes an abstraction layer for orchestrator integration, Prefect is not listed among the officially supported orchestrators.

		<p>6G-DALI Contributions: 6G-DALI will extend the ZenML orchestrator abstraction by developing a Prefect integration. Using ZenML’s support for custom orchestrators, we will implement a Prefect-based orchestrator capable of handling pipeline submission, scheduling, and execution through Prefect’s execution model. This extension will allow ZenML pipelines to run seamlessly on Prefect, ensuring interoperability with the ADROIT-6G stack and enabling cross-testbed meta-orchestration.</p>
	Trustworthy AI and societal acceptance	<p>Uncertainty Quantification:</p> <ul style="list-style-type: none"> ○ TensorFlow Probability and PyTorch Pyro are used to support UQ methods like Monte Carlo Dropout for deep learning AI models. ○ MAPIE and Fortuna AWS offer multi-framework compatibility and are used to apply Conformal Prediction. <p>Explainable AI:</p> <ul style="list-style-type: none"> ○ SHAP and LIME will be used to provide model-agnostic explanations for predictions of high uncertainty. <p>Gaps:</p> <ul style="list-style-type: none"> ○ The lack of a trustworthy AI framework that fully incorporates both UQ and XAI within a functional MLOps pipeline, especially in the context of 6G systems. <p>6G-DALI Contributions: We will extend the above tools by integrating the novel Trustworthy AI framework with the 6G-DALI MLOps pipeline to ensure trustworthy outputs for various models running on the facility's platform, addressing a currently non-existent solution for 6G. The primary targeted extension is the development of a functional Trustworthy MLOps solution that utilizes the output of the UQ tools (high uncertainty) as a trigger for the XAI tools. This approach will provide both uncertainty measures and relevant explanations for the various models trained on 6G datasets, running on the facility's platform.</p>
DATAOps	Data Augmentation	<p>Join path-based dataset augmentation:</p> <ul style="list-style-type: none"> ○ AutoFeat is a method for augmenting relational datasets through join paths and evaluated by publicly available datasets sourced from OpenML, Kaggle, and UC Irvine, as well as ML models using AutoGluon framework. <p>Gaps:</p> <ul style="list-style-type: none"> ○ The method has not yet been tested on 6G datasets. ○ The current method uses Valentine for matching DataFrame pair. However, the exact calculation for each possible pair of columns in a data lake will be costly. ○ This method has not yet integrated to the 6G-DALI DataOps pipeline. <p>6G-DALI Contributions: We will extend the above method with an automated data augmentation approach for 6G datasets, involving: enumerating join paths of various lengths, given a base table, ranking the join paths using filter methods for the feature selection, and finding efficient methods to deal with the problem of costly computation. The goal is to improve prediction accuracy for common 6G experimentation tasks and reduce the runtime of ML models. Note that data augmentation usually goes after the cleaned datasets. If you augment problematic data, it will enlarge the issue of data quality. In terms of the data cleaning tasks in DataOps, we will contribute to algorithm design and tool implementation, for example, AI-based data imputation methods, for DataOps.</p>
	Data Transformation	<p>ELT Pipelines:</p> <ul style="list-style-type: none"> ○ Apache Airflow is a tool for orchestrating data processing pipelines ○ Apache Beam is a tool for applying data transformations to datasets and data streams. <p>Gaps:</p>

		<ul style="list-style-type: none"> ○ Both tools are not designed to work with data sets originating from Data Spaces or Data Lakes. <p>6G-DALI Contributions: We will extend the above mentioned tools to integrate them with the 6G DALI Data Space and Data Lake. Apache Airflow will be integrated with Data Connectors in order to retrieve existing and publish processed data sets to the Data Space.</p>
	<p>Intent-driven DataOps via GenAI</p>	<ul style="list-style-type: none"> - Agent Orchestration: <ul style="list-style-type: none"> ○ LangChain, CrewAI, AutoGen, etc. - LLM Providers: <ul style="list-style-type: none"> ○ Ollama, OpenAI, Anthropic, etc. - RAG: <ul style="list-style-type: none"> ○ Qdrant, ChromaDB, Weaviate, etc. - Gaps: <ul style="list-style-type: none"> ○ Current tools provide isolated capabilities. ○ No unified orchestration across heterogeneous testbeds. ○ Lack of schema-aware dataset discovery and dynamic pipeline adaptation. ○ No closed feedback loop between pipeline execution and refinement. - 6G-DALI Contributions: Integrated agentic system combining orchestration with LLM inference capabilities and schema-aware RAG. Automated dataset discovery, pipeline generation, and testbed orchestration via unified API layer. Feedback-driven, self-healing workflows ensuring reproducibility and adaptive experimentation for 6G-DALI use cases.
<p>Data space & Connectors</p>	<p>Dataspaces & Connectors</p>	<ul style="list-style-type: none"> - Catalogue & Metadata Management: <ul style="list-style-type: none"> ○ Piveau Hub ○ OpenMetadata ○ Elasticsearch - Storage: <ul style="list-style-type: none"> ○ MinIO ○ AWS S3 - Connectors: <ul style="list-style-type: none"> ○ Eclipse EDC Connector ○ IDS Dataspace Connector ○ Sovity Connector - Gaps: <ul style="list-style-type: none"> ○ Lack of a unified catalogue supporting datasets, ML models, and data services. ○ Absence of seamless integration between connectors and metadata registries when including datasets, ML models, and data services. - 6G-DALI Contributions: We will extend catalogue services to also include ML models, and data services in a single repository to enable unified search and discovery across datasets, models, and data services. We will extend connectors' capabilities to enable advanced data retrieval and processing capabilities. We will extend metadata frameworks with Gaia-X compliance to ensure interoperability with existing standards.
<p>Digital Twin</p>	<p>6G Digital Twin Library</p>	<ul style="list-style-type: none"> - Digital Twin: <ul style="list-style-type: none"> ○ Flex RIC and VIAVI's ○ AI-RSG Integration - Gaps: <ul style="list-style-type: none"> ○ Not able to operate together - 6G-DALI Contributions: The goal is to apply the necessary modifications so they can be interoperable. The FlexRIC communicates with the AI-RSG over the E2 interface. This means the interface on both sides should be correctly implemented using the same versions of E2AP, E2SM-KPM, and E2SM-RC on each. nd

	<p>AlaaS & HPO for RLOps</p>	<ul style="list-style-type: none"> - RL Library & Model registry: <ul style="list-style-type: none"> o Ray Tune o MLflow - Gaps: <ul style="list-style-type: none"> o Lack of RL model registries integrated to support full RLOps workflows. o No seamless HPO and policy storage linked to DT-based RL experiments. - 6G-DALI Contributions: Enabled MLflow to store RL policies and run HPO with Ray-Tune by adding XX and YY. This enables AlaaS & HPO.
	<p>Collaborative RLOps</p>	<ul style="list-style-type: none"> - RL Library & Model registry: <ul style="list-style-type: none"> o Rrlib o MLflow - Gaps: <ul style="list-style-type: none"> o No integration with Rrlib and mlflow for implementing collaborative RL. - 6G-DALI Contributions: Integration of RLlib with MLflow enables 6G-DALI DT experiments to automatically store RL policies, checkpoints, and metrics in a shared model registry. Enabling RL agents inside 6G-DALI DT nodes to retrieve, reuse, and jointly evaluate policies supports collaborative knowledge transfer across nodes. Enabling MLflow-based HPO orchestration with RLlib allows 6G-DALI to jointly tune and compare RL agents across heterogeneous DT deployments.
	<p>FL with NWDAF</p>	<ul style="list-style-type: none"> - NWDAF: <ul style="list-style-type: none"> o OAI NWDAF Implementation - Gaps: <ul style="list-style-type: none"> o Current OAI NWDAF is Rel 15 compliant. Hence, no support for AnLF, MTLF which are key enablers for FL. - 6GDALI Contributions: Upgrade OAI NWDAF current implementation to make it REL18 Compliant. Implement 3GPP Compliant MTLF, AnLF. Apply federated learning techniques Leveraging MTLF, AnLF.
<p>Adaptation Layer (EUR)</p>	<p>Adaptation Layer</p>	<ul style="list-style-type: none"> - API & Integration Frameworks: <ul style="list-style-type: none"> o Flask o FastAPI o FastMCP - 6G Experimentation Libraries: <ul style="list-style-type: none"> o SUNRISE-6G APIs - Gaps: <ul style="list-style-type: none"> o Lack of integration for 6G-native orchestration. o Limited interoperability between SUNRISE-6G APIs and AI-driven agents. o Absence of unified semantic interfaces across testbeds. o Limited real-time feedback and adaptive control mechanisms. - 6G-DALI Contributions: 6G-DALI will leverage assets from SUNRISE-6G to build an AI-driven adaptation layer integrating APIs, libraries, and middleware. Development of a new unified semantic API framework for experiment orchestration and automation. Integration of FastMCP monitoring and control functions with LLM-based adaptive agents. Enable modular and interoperable connections across heterogeneous 6G testbeds and orchestration tools.

6 Conclusions

This deliverable has presented the framework requirements and technological tools review for the 6G-DALI project, which aims to develop an end-to-end AI framework that supports the automation of Data and MLOps in 6G networks. Building upon the project's two fundamental pillars, namely Data and Analytics collection and storage through DataOps and AI Experimentation as a Service through MLOps, this document systematically defined the requirements and analysed the technological foundations necessary for their realization.

The work conducted within this deliverable focused on two main objectives. First, it identified and structured the functional and non-functional requirements of the 6G-DALI framework by adopting a modular and thematic approach. Second, it performed a comprehensive review of existing technological tools across the DataOps and MLOps domains, as well as in the areas of Data Spaces, Digital Twin, and Reinforcement Learning. This process enabled the identification of mature technologies suitable for reuse, as well as areas where innovation and extension are required to meet the specific needs of the project.

The analysis revealed that while several advanced tools exist across the data and AI operations ecosystem, none fully address the integrated vision of 6G-DALI. The gap analysis therefore provided a clear roadmap for targeted development, focusing on key aspects such as interoperability, cross-domain orchestration, trust and explainability in AI models, and data sovereignty. These findings will directly inform the design and implementation of the 6G-DALI framework in the following work packages.

By aligning with the principles of Gaia-X and International Data Spaces, the 6G-DALI framework ensures compliance with European data governance values, fostering trust, transparency, and secure data sharing across stakeholders. This alignment not only reinforces the technical robustness of the proposed architecture but also enhances its relevance and potential impact on the emerging European 6G data economy.

In summary, Deliverable 2.2 provides the foundation for the subsequent design and development phases of 6G-DALI. The identified requirements, reviewed tools, and analyzed gaps form the basis for creating an innovative, interoperable, and scalable framework that will advance automation in data and AI operations for next-generation 6G networks. Through this work, 6G-DALI is well-positioned to contribute significantly to the evolution of the European digital ecosystem and to strengthen Europe's leadership in AI-driven network technologies.

7 References

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