D4.1

CLUSTERS AND UC PREPARATION & INTEGRATION - INTERMEDIATE

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D4.1: CLUSTERS AND UC PREPARATION & INTEGRATION - INTERMEDIATE

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Abstract	This deliverable presents the intermediate status of cluster preparation and use case integration activities carried out under WP4 of COP-PILOT. It describes the progressive integration methodology applied across the project's piloting clusters, covering infrastructure readiness, use case development, deployment of COP-PILOT platform components, cross-domain workflows, and closed-loop services. The document provides a consolidated view of the current integration baseline, highlights the main technical and operational constraints identified across the clusters, and outlines the actions required to advance towards final end-to-end integration and validation. The results reported in D4.1 provide the operational foundation for the next WP4 integration cycle and for the pilot validation activities conducted under WP5.
Keywords	COP-PILOT; Work Package 4; cluster preparation; use case integration; multi-domain orchestration; edge-to-cloud continuum; closed-loop services; interoperability; large-scale pilots

Document Revision History

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* R: Document, report (excluding the periodic and final reports)

DEM: Demonstrator, pilot, prototype, plan designs

DEC: Websites, patents filing, press & media actions, videos, etc.

DATA: Data sets, microdata, etc.

DMP: Data management plan

ETHICS: Deliverables related to ethics issues.

SECURITY: Deliverables related to security issues

OTHER: Software, technical diagram, algorithms, models, etc.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

This deliverable presents the intermediate status of cluster preparation and use case integration activities carried out under WP4 of COP-PILOT. It documents the progress made in moving from clusters and use-case blueprints towards deployable, interoperable piloting environments. It also provides a structured overview of the current integration status across the clusters and identifies the main actions required to progress towards final integration.

The WP4 integration methodology is based on successive integration cycles, through which cluster infrastructures, use-case components, platform services, data management functions, and secure interconnection mechanisms are progressively consolidated. During the current reporting period, covering the first integration cycle and the ongoing consolidation of the second, the focus has been on strengthening this baseline through broader deployment, technical alignment, and cluster-level integration activities. For these activities, COP-PILOT follows a federated and multi-domain approach. The central platform connects, orchestrates, and exposes partner infrastructures without replacing them, while each cluster retains control over its own domains, assets, and operational environment. Each cluster therefore aligns its compute environments, data sources, domain services, workflows, and security boundaries with common platform capabilities such as End-to-End and Domain Orchestration, Data Management, and service cataloguing.

Across the clusters, several operational platform anchors are already in place, including domain orchestrators, Kubernetes or equivalent runtime environments, FIWARE-based data-management components, secure interconnection mechanisms, and initial service deployment paths. In parallel, use case applications are progressing towards containerised, orchestrated, and cross-domain deployments, creating the technical basis for more advanced end-to-end cluster capabilities. Common integration aspects requiring further consolidation before final integration have also been identified. These include infrastructure heterogeneity, seasonal or site-specific operational conditions, data availability, legacy-system integration, secure cross-domain data sharing, alignment between management and data planes, and the stabilisation of orchestration interfaces and deployment artefacts. These aspects are inherent to a federated project of this scale and are being progressively addressed through all the WP4 integration activities.

Hence, D4.1 confirms that WP4 has established the foundations required for the next phase of integration. The priority now is to consolidate the current baseline into repeatable and demonstrable end-to-end cluster capabilities, complete the remaining platform alignments, and continue to provide the technical basis for the pilot validation activities to be carried out under WP5. The results reported here will serve as the operational reference for the next WP4 activities and for the final integration deliverable, D4.2.

LIST OF FIGURES

LIST OF TABLES

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ABBREVIATIONS

Term	Description
3GPP	3rd Generation Partnership Project
5G	Fifth-generation mobile network
AEMET	Spanish State Meteorological Agency (Agencia Estatal de Meteorología)
AGA	AgroApps
AI	Artificial Intelligence
AIS	Automatic Identification System
ALM	Ajuntament d'Almussafes
API	Application Programming Interface
ATSI	AgriTech Transformation and Sustainability Initiative
AUA	Agricultural University of Athens
BAR	Barba Stathis
BM-L	Business Management Layer
BPO	Preveza Biogas One
BSS	Business Support System
CAT-M	LTE Category M
CB	Context Broker
CB-LD	Linked Data Context Broker
CCaaS	Chaincode as a Service
CHP	Combined Heat and Power
CI/CD	Continuous Integration and Continuous Deployment
CIM	Context Information Management
CL3A	Cluster 3A
CL3E	Cluster 3E
CNCF	Cloud Native Computing Foundation
COP-PILOT	Collaborative Open Platform for PILOTing services across emerging smart IoT and edge-computing environments
CPU	Central Processing Unit
DDO-L	Distributed Domain Orchestration Layer
DER	Distributed Energy Resource
DIS-L	Distributed Infrastructure Services Layer
DM	Data Management
DO	Domain Orchestration / Domain Orchestrator
E2E	End-to-End
ECDSA	Elliptic Curve Digital Signature Algorithm
eMBB	Enhanced Mobile Broadband
ENIK	Enakronik, project partner short name
ERP	Enterprise Resource Planning
ESO	End-to-End Service Orchestration / End-to-End Service Orchestrator
ESO-L	End-to-End Service Orchestration Layer
ETSI	European Telecommunications Standards Institute
EU	European Union
EV	Electric Vehicle
FIVE	5G Communications for Future Industry Verticals
FMIS	Farm Management Information System
FVP	Fundación Valenciaport
GDPR	General Data Protection Regulation

Term	Description
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
gRPC	gRPC Remote Procedure Calls
HAT	Hardware Attached on Top
HPA	Horizontal Pod Autoscaler
HTTP	Hypertext Transfer Protocol
HTTPS	Hypertext Transfer Protocol Secure
HypO	Hyper Orchestrator
IAM	Identity and Access Management
ICCS	Institute of Communication and Computer Systems
ICT	Information and Communication Technology
IEC	International Electrotechnical Commission
IETF	Internet Engineering Task Force
IIoT	Industrial Internet of Things
INFRA-L	Infrastructure Layer
IoT	Internet of Things
ISG	Industry Specification Group
JIG	J.I.G. Internet Consulting
JIT	Just in Time
JSON	JavaScript Object Notation
JSON-LD	JavaScript Object Notation for Linked Data
JWT	JSON Web Token
K8s	Kubernetes
KPI	Key Performance Indicator
LiDAR	Light Detection and Ranging
LoRaWAN	Long Range Wide Area Network
LSP	Large-Scale Pilot
LTE	Long-Term Evolution
LTU	Luleå University of Technology
ML	Machine Learning
MPN	Mobile Private Network
MQTT	MQ Telemetry Transport
MS	Microservice; milestone when used in milestone identifiers (e.g., MS4.1)
mTLS	Mutual Transport Layer Security
NaC	Network as Code
NBI	Northbound Interface
NB-IoT	Narrowband Internet of Things
NDVI	Normalized Difference Vegetation Index
NES	Nespra
NETC	Netcompany-Intrasoft
NFC	Near-Field Communication
NGSI-LD	Next Generation Service Interfaces – Linked Data
NMEA	National Marine Electronics Association
NR	New Radio
NRM	Network Resource Model
OC	Open Call
OCI	Open Container Initiative
OCPP	Open Charge Point Protocol
OEE	Overall Equipment Effectiveness
ONE	OneSource

Term	Description
OPC-UA	Open Platform Communications Unified Architecture
OSS	Operations Support System
OT	Operational Technology
OTE	Hellenic Telecommunications Organization
PNET	P-NET Emerging Networks and Next Generation Applications
PPC	Public Power Corporation
PV	Photovoltaic
QR	Quick Response
RaaS	Routing as a Service
RAN	Radio Access Network
RBAC	Role-Based Access Control
REST	Representational State Transfer
RFC	Request for Comments
RGB	Red, Green and Blue
RISE	Research Institutes of Sweden
RPi	Raspberry Pi
RTK	Real-Time Kinematic
RTSP	Real-Time Streaming Protocol
SCADA	Supervisory Control and Data Acquisition
SDG	Software Development Group
SERI	Swiss State Secretariat for Education, Research and Innovation
SIF	Secure Integration Fabric
SIF-L	Secure Integration Fabric Layer
SLA	Service-Level Agreement
SQL	Structured Query Language
TAB	ThingWave AB
TBD	To Be Determined
TID	Telefónica Innovación Digital
TLS	Transport Layer Security
TMF	TM Forum
ToC	Table of Contents
TOR	University of Rome Tor Vergata
TRL	Technology Readiness Level
UAV	Unmanned Aerial Vehicle
UBI	UBITECH
UC	Use Case
UGV	Unmanned Ground Vehicle
UI	User Interface
UoP	University of Patras
UPF	User Plane Function
UPS	Uninterruptible Power Supply
UPV	Universitat Politècnica de València
URLLC	Ultra-Reliable Low-Latency Communications
VCH	Valencia Innovation Capital
W3C	World Wide Web Consortium
WMS	Warehouse Management System
WP	Work Package
X.509	Standard for public-key digital certificates

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1 INTRODUCTION

1.1 SCOPE, MOTIVATION AND OBJECTIVES

This deliverable reports the intermediate status of cluster preparation and use case integration within COP-PILOT across the first and second integration cycles, covering progress up to M19 and the work carried out under Tasks 4.1 to 4.4. It addresses the managerial and technical activities required to move from cluster blueprints to deployable piloting environments, where COP-PILOT services, partner-domain assets, and use case components operate together in a coherent and verifiable manner. In this context, integration encompasses the coordination of distributed infrastructures, domain-specific services, and cross-domain workflows across multiple organisational boundaries.

The motivation for this deliverable is twofold. First, D4.1 provides a common, up-to-date view of WP4 progress across the piloting clusters and demonstrates that cluster preparation, use case development, and integration activities are advancing in a controlled manner and in line with the plan. Second, the deliverable provides a reliable basis for assessing current readiness, identifying remaining constraints, and preparing the transition towards the final integration phase.

Accordingly, this deliverable:

- present the WP4 integration methodology and its relation to the project work plan;
- explain the alignment with the COP-PILOT architecture and the operationalisation at cluster level;
- report the preparation and integration status of each cluster;
- describe how platform components (e.g. orchestration, data management, and secure interconnection) are being deployed and integrated; and
- identify key dependencies, constraints, and next steps for WP4.

As an intermediate deliverable, D4.1 does not aim to demonstrate full integration across all clusters. Rather, it establishes a shared view of the current integration cycles and identifies areas where uneven maturity may affect progression and operational readiness.

1.2 STRUCTURE OF THE DOCUMENT

The document is structured to reflect both the methodological logic of WP4 and the operational reality of cluster implementation within the COP-PILOT federated, multi-domain environment.

Section 2 explains the alignment between WP4 activities and the final COP-PILOT architecture, clarifying the respective roles of the cluster infrastructures, use case applications, platform components, and shared integration mechanisms.

Section 3 presents the integration methodology underpinning WP4's execution, including the integration cycles, milestones, and management checkpoints that guide progress. It also introduces the COP-PILOT multi-layered, multi-domain integration approach, showing how distributed infrastructures, domain-specific services, and common platform capabilities are progressively integrated.

Section 4 presents the closed-loop platform services identified in COP-PILOT, including their design logic, application areas, interfaces with the clusters, and relation to open-source activities and standards.

Sections 5 to 9 constitute the cluster-specific core of the deliverable. Each cluster section describes the implementation environment, including infrastructure and domain boundaries, key workflows and data paths, integration challenges, COP-PILOT capabilities in scope, development planning, use case maturity, and deployment status. Together, these sections provide the intermediate evidence base for assessing cluster readiness and identifying the actions required for the next integration cycle.

Section 10 presents the main conclusions of the deliverable and outlines the plan towards final integration, including the main cross-cluster priorities for the next phase.

2 ALIGNMENT WITH THE FINAL COP-PILOT ARCHITECTURE

This section demonstrates the alignment of WP4 activities with the final COP-PILOT architecture, which is introduced in D2.2 [1]. To facilitate the mapping, Figure 2-1 visualises the final COP-PILOT architecture annotated with green and purple boxes. Green boxes indicate parts of the architecture related to WP4, while purple boxes indicate aspects of the architecture related to WP3. From this mapping, the COP-PILOT platform is entirely managed by WP3, while all aspects related to the Clusters' testbeds, piloting activities, and use cases are the responsibility of WP4. Grey boxes in Figure 2-1 highlight areas in the architecture where WP3 and WP4 jointly tackle. This is mostly integration work that is an activity that is not assigned to a particular Work Package or Task; thus, it is managed across all tasks of both technical Work Packages.

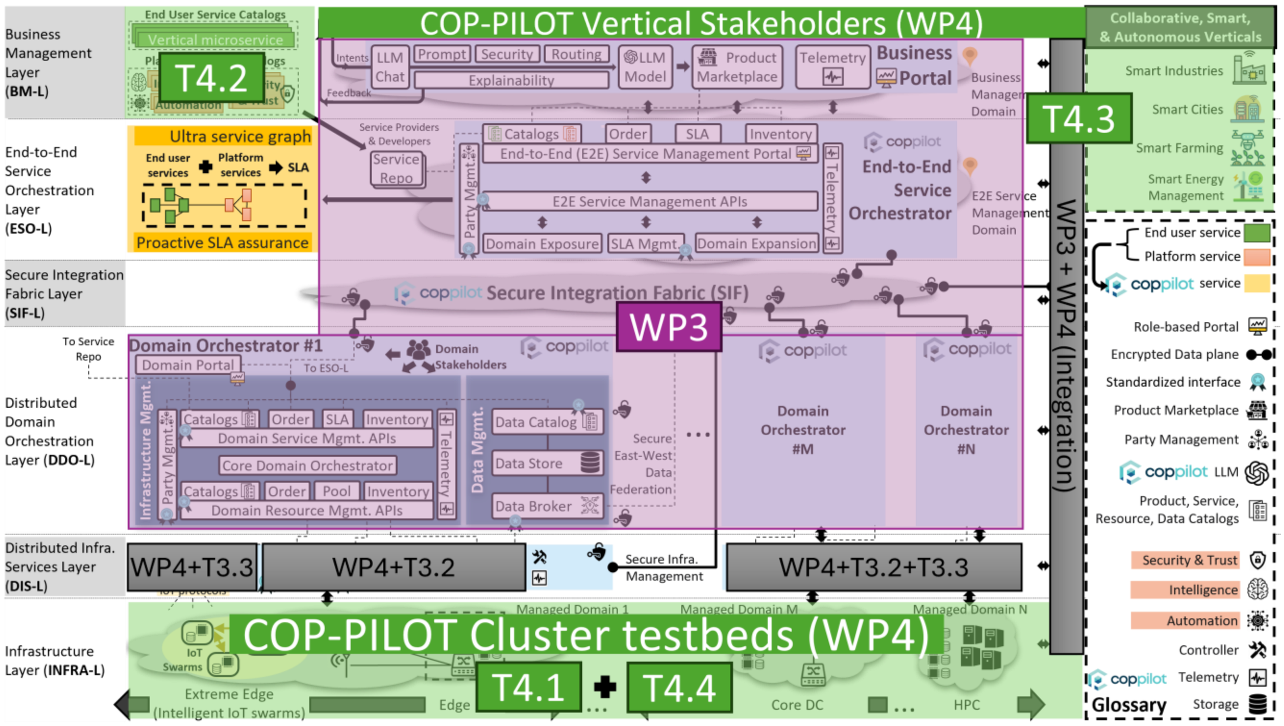

Figure 2-1: Mapping of WP4 activities to the final version of the COP-PILOT architecture.

The role of the WP4 tasks in the COP-PILOT ecosystem is outlined below on a per-task basis:

Task 4.1 is responsible for ensuring the early readiness of the COP-PILOT Clusters' infrastructures to host platform and UC components for the Large-Scale Pilots (LSPs). The task should ensure proper integration of the COP-PILOT platform (WP3) with the infrastructure (INFRA-L) and infrastructure services (DIS-L) across all COP-PILOT clusters, as well as effective synchronisation with the UC development activities under T4.2 and their integration onto the testbeds under T4.3.
Task 4.2 undertakes the development of all piloting use cases through application components, their packaging, and delivery to the COP-PILOT platform. Early testing of the developed components on the testbeds should be conducted jointly by WP5 and T4.1.

Task 4.3 is responsible for ensuring the integration of the COP-PILOT use case applications with the COP-PILOT platform via the NBIs offered by the ESO (T3.1), DO (T3.2), and DM (T3.3) components as well as the Business Management Portal (T3.4).
Task 4.4 is responsible for ensuring the integration of the COP-PILOT architecture with the infrastructure (INFRA-L), infrastructure services (DIS-L), and vertical applications that correspond to the COP-PILOT Open Call projects. Inputs stemming from WP6 must be translated into actual infrastructures and services so that the OC partners fit into the COP-PILOT ecosystem through integration.

The COP-PILOT CI/CD platform is a cross-WP3 and WP4 activity that ensures end-to-end integration across the entire COP-PILOT ecosystem. This component of the architecture constitutes a dedicated task force managed under WP3 and by the COP-PILOT Scrum Master.

3 INTEGRATION METHODOLOGY

3.1 INTEGRATION PHASES AND MILESTONES

In line with the WP4 execution plan, integration in COP-PILOT is organised as a structured, progressive process that progresses from cluster preparation to use case onboarding, integration, and validation. WP4 is implemented through successive integration cycles. Each cycle expands the scope of integration and increases the maturity of the clusters, use cases, and cross-domain workflows (Figure 3-1).

This approach reflects a central principle of the project: piloting readiness depends on the coordinated progress of cluster infrastructure, use case maturity, and platform integration capabilities. For this reason, WP4 progress is assessed not only through individual deployments but also by the extent to which domains, components, and workflows can be brought together into a stable and reusable integration baseline.

The WP4 work plan is structured around three main integration cycles, each linked to specific milestones and deliverables. Integration Cycle 1, completed at M12 and associated with milestone MS4.1, focused on establishing the initial integration conditions, including cluster preparation, early onboarding of use cases, and first deployment of platform components. Integration Cycle 2, at M20, focuses on consolidating that baseline through broader service deployment, initial cross-domain workflows, and intermediate validation of cluster capabilities. Integration Cycle 3, to be documented in D4.2 at M33, will complete the integration process through expanded onboarding, including open-call participants, and final cross-cluster validation.

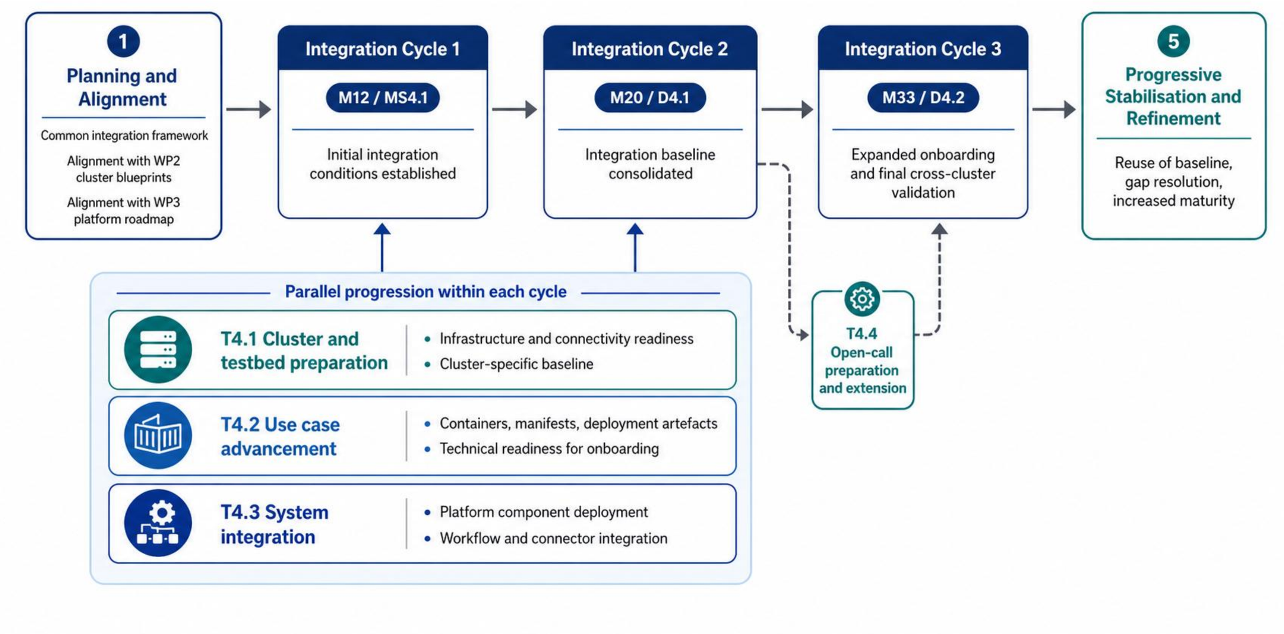

Figure 3-1 WP4 integration methodology based on successive integration cycles

The methodology begins with planning and alignment. In this phase, the project establishes the common integration framework, aligns WP4 activities with the cluster blueprints delivered in WP2 and the platform roadmap developed in WP3, and identifies the relevant clusters, domains, testbeds, scenarios and dependencies. This considers that cluster and testbed preparation under T4.1, use case advancement under T4.2, and system integration under T4.3 are carried out in parallel and remain tightly coupled. T4.1 establishes the infrastructure conditions required for piloting, including compute environments, connectivity assumptions, domain boundaries, and hosting contexts for COP-PILOT components. T4.2 advances use cases from the blueprint level towards deployable assets, with an emphasis on containers, manifests, packaging artefacts, and other technical prerequisites required for deployment in target environments. T4.3 brings together platform components, domain services, and use case applications into coherent cross-domain workflows through deployment, configuration, and connector onboarding.

Integration does not wait for full readiness of all elements. Progress is made incrementally within each cycle as components and use cases reach sufficient levels of maturity. WP4 progress is therefore measured through the ability to demonstrate working end-to-end cluster capabilities.

After each cycle, the integration baseline is consolidated and extended through iterative refinement, integration of updated platform components, broader onboarding of use cases, and preparation of open-call extensions under T4.4. This process allows the consortium to stabilise results, address remaining technical and organisational constraints, and move towards more complete and robust integration across all clusters.

3.2 COP-PILOT PLATFORM MULTI-LAYERED & MULTI-DOMAIN INTEGRATION APPROACH

COP-PILOT follows a multi-layered, multi-domain integration approach, as it brings together heterogeneous infrastructures, platform services, and vertical applications across several clusters. In practice, integration must be addressed from two complementary angles.

The first angle is **system-level integration**. From this perspective, the COP-PILOT platform must interoperate with the cluster testbeds and provide the technical means to onboard, expose, and manage their resources and services. This includes integrating platform components developed in WP3 with the cluster environments prepared in T4.1, so that use cases developed in T4.2 can be integrated and deployed through the mechanisms addressed in T4.3.

The second angle is **business integration**. From this perspective, the main concern is not the platform's internal complexity but the ability of cluster stakeholders to integrate their infrastructures, services, and use cases into the COP-PILOT ecosystem in a practical, usable way. The focus is therefore on enabling adoption at cluster level and supporting the operational needs of the vertical domains.

For this reason, COP-PILOT breaks down integration responsibilities between WP3 and WP4 (see Section 4 in D3.1[2]). WP3 addresses the system-level integration of the COP-PILOT platform. Whereas WP4 addresses the business integration perspective, focusing on the onboarding, preparation, and operational integration of cluster environments, services, and use cases.

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4 CLOSED-LOOP PLATFORM SERVICES

This section introduces the methodology for designing closed-loop services for COP-PILOT. Section 4.1 proposes a generic design for any COP-PILOT closed-loop service. Section 4.2 provides an overview of the available closed-loop services during the first period of the project (i.e., up to M18). Section 4.3 lists a short description of all available closed-loop services. Sections 4.4 and 4.5 outline the relationship between these closed-loop services and open-source communities and implemented standards, respectively.

4.1 GENERAL DESIGN OF A COP-PILOT CLOSED-LOOP SERVICE

A COP-PILOT closed-loop service is developed by Service Developers and guided by the business goals of the Vertical End User. Service Providers design relevant standardised service specifications on top of the COP-PILOT orchestrators and then onboard their service in a relevant Service Catalogue of a COP-PILOT Orchestrator. Each closed-loop service is designed in a modular manner. It receives inputs from (any) underlying infrastructure, covering data, network, and compute resources. Based on these inputs, it analyses the current situation and applies specific business logic (depending on the objective of each closed-loop service), ultimately producing the appropriate outputs. Part of these outputs may be tangible actuations towards the COP-PILOT Platform, which are in turn translated into orchestration actions towards vertical services and/or infrastructure services, effectively closing the loop. Figure 4-1 introduces a generic design of a COP-PILOT Closed-loop service bound to the reasoning explained above.

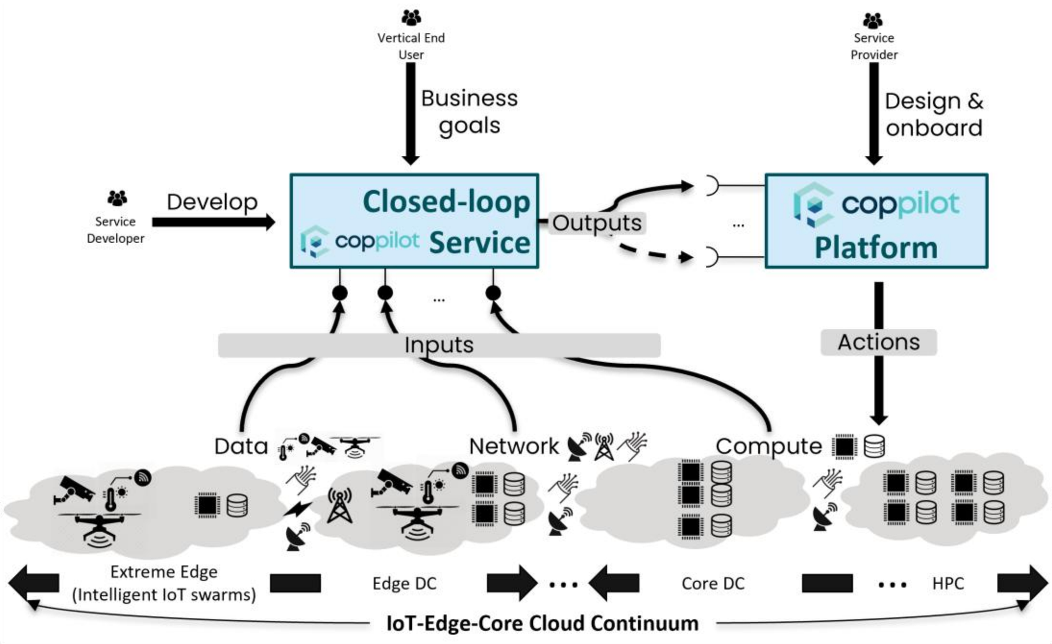


Figure 4-1: General design of a COP-PILOT Closed-loop service.

4.2 OVERVIEW OF ALL COP-PILOT CLOSED-LOOP SERVICES

This section provides an overview of all COP-PILOT Closed-loop services, identified during the first phase of the project (i.e., up to M18). In the context of the project, a closed-loop service refers to a service that collects data from the underlying infrastructure, applications, or domain systems, analyses this information against predefined policies, and produces recommendations or automated actions through the COP-PILOT platform when specific conditions are met. Table 1 summarises the COP-PILOT Closed-loop services, providing a name, a short description, an owner, and the target application area for each service.

Table 1: Summary of all COP-PILOT Closed-loop services.

Closed loop Service Name	Closed loop Service Description	Closed loop Service Owner	Closed loop Service Application Area
EdgeCloud Autoscaling with Priority Decay	Allows data processing, e.g. seismic processing to effectively handle peak-load scenarios, such as when a large seismic event happens, without over-provisioning compute resources. Achieve near-real time performance while maintaining resource efficiency.	LTU,	Cluster 1 – UC1.4
Seismic and displacement, Location-based Alert system	Seismic events, smart bolt data and analysis of those data sources are associated with coordinates (location) in the underground mine. With the open data/API architecture of RockSigma BEMIS, this enables ThingWave location-aware services (e.g., seismic-aware geofencing).	TAB, ROC	Cluster 1 – UC1.2
Dynamic Maritime Resource Provisioning	Automates maritime infrastructure management by using vessel detection (AIS/radars) to dynamically deploy 5G slices and berthing assistance.	FVP, FIVE	Cluster 2 – UC2.3
AI-driven Traffic Validation Loop	Uses traffic radars to trigger YOLO-based computer vision, analysing real-time camera feeds to verify and confirm congestion before notification.	VCH, FIVE	Cluster 2 – UC 2.1A
Adaptive Flood Monitoring Loop	Monitors weather alerts to autonomously increase the sampling frequency of water level radars, providing high-resolution data during flood risks.	VCH, FIVE	Cluster 2 – UC2.1B
Multi-modal Environmental Alerter	Monitors thresholds for diverse metrics to autonomously dispatch alerts when environmental anomalies are detected.	UPV, VCH, FIVE, NES	Cluster 2 – UC2.1B, 2.2A, 2.4A, 2.4B
HPA+: Predictive AI-based Kubernetes Autoscaler	HPA+ extends Kubernetes HPA native autoscaler with predictive scaling, using historical CPU metrics and ML models to adjust pod replicas ahead of demand.	ICCS	Cluster 2
Blockchain SLA-Triggered Logistics Reconfiguration	Monitors on-chain SLA events from a permissioned Hyperledger Fabric ledger and autonomously triggers logistics reconfiguration actions (vehicle reassignment, route changes, alerts) through the COP-PILOT orchestrators when supply-chain SLAs are breached, with corrective decisions committed back to the ledger for auditability.	iLINK	Cluster 3A – UC3A.3
PowerFleet Freshness-Aware JIT Rerouting Loop	Continuously evaluates GNSS and temperature telematics from refrigerated vehicles against freshness/SLA constraints and dynamically reroutes the fleet via PowerFleet RaaS through the COP-PILOT orchestrators to minimise product loss	iLINK	Cluster 3A – UC3A.4

	before freshness thresholds are violated, with deviations logged to the blockchain for auditability.		
Adaptive DER Flexibility Optimization Loop	Continuously aggregates DER and flexible load data to autonomously optimize and dispatch operational signals, enabling real-time flexibility delivery to the grid.	UoP, ENIK	Cluster 3.E – UC3.1
EV Charger Fault Detection Loop	Continuously monitors EV charging infrastructure measurements and autonomously detects and reports electrical anomalies to the admin for rapid diagnosis and resolution.	ENIK, PPC	Cluster 3.E – UC3.2
Biogas Digestion Monitoring Loop	Continuously monitors facility process parameters via a digital twin and autonomously alerts the administrator upon detection of any rule-configured violations.	ENIK, BPO	Cluster 3.E – UC3.3
AI Driven Green Energy Vineyard Management: Virtual Soil Stations for Vinyards	Some Terraview & Nokia soil sensors are deployed on several vineyards. Then virtual Stations located in other vineyards are available to new sites with IA forecast algorithms.	Nokia,	Cluster 4 – UC4.4A
AI Driven Green Energy Vineyard Management: Virtual Soil Stations for Vinyards with 5G connectivity	Extension of UC4.4A with provisioning of 5G connectivity with several QoS profiles by using Nokia Network-as-Code	Nokia, Terraview, Onesource	Cluster 4 – UC4.4B
AI Driven Green Energy Vineyard Management: 5G rural vineyards connectivity with programmed energy savings actions	5G Rural site provides connectivity with only solar energy. Some energy saving actions are programmed when available battery energy is below some limits.	Nokia, Terraview, Onesource	Cluster 4 – UC4.4C
AI Driven Green Energy Vineyard Management: 5G rural vineyards connectivity with energy AI guided savings actions	5G Rural site provides connectivity with only solar energy. Some energy saving actions are guided by AI training algorithms when energy below some limits.	Nokia, Terraview, Onesource	Cluster 4 – UC4.4D

Table 2 delves into more details per closed-loop service, providing a mapping of inputs and outputs associated with each one.

Table 2: COP-PILOT Closed-loop service details.

Closed loop Service Name	Closed-loop Service Input(s) – Interfaces with the COP-PILOT Clusters (Infrastructure)	Closed-loop Service Output(s) – Interfaces with the COP-PILOT Platform
EdgeCloud Autoscaling with Priority Decay	The service consumes monitoring data via the Colonies server API and the Kubernetes control plane: queue state (waiting/running processes, priorities, age), executor state (registered executors, capabilities, liveness), and cluster resource telemetry (CPU, memory, node availability).	The service outputs scaling decisions as ColonyOS blueprints, reconciled against the infrastructure by adding or removing workers in response to load.

Seismic and displacement, Location-based Alert system	Asset location data from IoT devices sent via 5G or similar into edge or cloud processing. The same is true for seismic data and rock bolt elongation data.	Geofencing outputs to send alarm to staff and underground visual alert systems. Underground orchestration is performed via Arrowhead services.
Dynamic Maritime Resource Provisioning	Vessel entry telemetry from Valencia port via entrance radars; AIS NMEA data streams via FVP Portcalls API; distance/proximity and vessel arrival/docking metadata via berthing assistance radars	COP-PILOT ESO/DO orchestration actions (trigger dispatched by Smart City Stack for executing 5G network management service and provisioning a dedicated network slice for radar connectivity)
AI-driven Traffic Validation Loop	Congestion detection telemetry from 5G traffic radars; real time video feeds from open city cameras ingested via RTSP streams	COP-PILOT ESO/DO orchestration actions (triggers dispatched by Smart City Stack for deploying the YOLO-based validator service for visual verification, and Alert Notification Service for dispatching confirmed traffic jam alerts to External Users)
Adaptive Flood Monitoring Loop	Real-time water-level telemetry streams from WIOTRAD radars; External weather forecast data polled from AEMET & Ajuntament d'Almussafes	COP-PILOT ESO/DO orchestration actions (triggers dispatched by Smart City Stack for deploying the Frequency Modifier Service and Alert Notification Service for dispatching confirmed flood alerts to External Users)
Multi-modal Environmental Alerter	Filling-level, air quality, and room occupancy telemetry streams	COP-PILOT ESO/DO orchestration actions (triggers dispatched by Smart City Stack for deploying the Alert Notification Service for dispatching environmental anomaly alerts to External Users)
HPA+: Predictive AI-based Kubernetes Autoscaler	COP-PILOT compute infrastructure / Kubernetes Metrics Server for CPU usage and pod replica metrics, COP-PILOT DO/OpenSlice for autoscaling policy restrictions.	COP-PILOT DO / OpenSlice for enforcing horizontal pod scaling decisions.
Blockchain SLA-Triggered Logistics Reconfiguration	Hyperledger Fabric chaincode events recording supply-chain milestones (harvest, packaging, transport, delivery); ledger queries for current batch state via gRPC; cross-validating telemetry from logistics platforms (e.g., PowerFleet).	COP-PILOT ESO/DO orchestration actions (e.g., trigger PowerFleet reroute, vehicle reassignment); operator notifications via web/mobile portals; new blockchain transactions recording the reconfiguration decision.
PowerFleet Freshness-Aware JIT Rerouting Loop	GNSS and temperature telemetry from edge nodes (Raspberry Pi 5 + Ubuntu Server + k3s) on refrigerated vehicles via 5G/LTE; production/harvest readiness events from	Dynamic route updates pushed to vehicles via PowerFleet RaaS (web/mobile driver interfaces); operator notifications; blockchain

	upstream FMIS via FIWARE Orion-LD; ERP/WMS fulfilment status.	transactions logging route deviations and reroute decisions.
Adaptive DER Flexibility Optimization Loop	Real-time DER (biogas plant generated power, EV-charger consumed power) and simulated (wind turbines and PVs power generation) data streams	Flexibility requests to the relevant DER and triggered alerts
EV Charger Fault Detection Loop	Voltage, current, frequency, power and power factor measurements of EV-charging stations	Triggered alerts
Biogas Digestion Monitoring Loop	Real-time telemetry during anaerobic digestion operation: pH — Process acidity/alkalinity, CHP unit 1 and 2 electrical output, Primary / Secondary stream methane concentration. Primary / secondary stream carbon dioxide concentration. Hydrogen sulphide concentration in the primary / secondary biogas stream	Triggered alerts
AI Driven Green Energy Vineyard Management UC4.4A Virtual Sensors Stations	Information from vineyards Soil sensors are the input through the COP-PILOT FIWARE broker. The soil sensors with humidity and temperature is used with AI algorithm to create virtual soil stations in vineyards without real sensors stations,	COP-PILOT DO / OpenSlice for deploying new virtual stations with AI prediction algorithms.
AI Driven Green Energy Vineyard Management UC4.4B 5G network provissioning	Extension of UC4.4A with 5G Radio sensors and 5G Modems monitoring which are the input through the COP-PILOT FIWARE broker. This information is used to monitor the current state of the sensors connectivity on the vineyards, and to prioritize the connectivity of some sensors or devices.	COP-PILOT DO / OpenSlice for configuring or prioritize the 5G connectivity of the sensors or devices deployed in the area..
AI Driven Green Energy Vineyard Management UC4.4C Saving Energy	Extension of UC4.4B with Energy sensors which are the input through the COP-PILOT FIWARE broker. This information is used to understand the current balance of energy required to provide 5G connectivity in the area. Depending of the consumption and of the generation of energy some actions can be implemented to optimize the use of energy.	COP-PILOT DO / OpenSlice for switching on or off some network capabilities like radiation power, radio layers use, backend servers swithing off/on.
AI Driven Green Energy Vineyard Management UC4.4D AI guided Saving Energy	Extension of UC4.4C with AI automatic algorithms using OpenSlice for switching on and off electronic devices or changing configurations. The information it used for training these AI algorithms.	COP-PILOT DO / OpenSlice for switching on and off electronic devices or changing energy levels by configurations of infrastructure to save energy

4.3 CLOSED-LOOP SERVICES' DESCRIPTION

This section provides short descriptions of the closed-loop services currently identified in COP-PILOT. The services are presented at an abstract level, highlighting their main objective, operational logic, and potential application across clusters and use cases.

4.3.1 Closed-loop service #1: EdgeCloud Autoscaling with Priority Decay (LTU, RockSigma)

Data processing demand is rarely constant, it swings between steady-state and sudden peaks. This service makes compute capacity elastically follow actual demand: it monitors system load and automatically scales workers up or down across the edge-to-cloud continuum, while priority decay ensures fair resource sharing between tenants. Built on ColonyOS meta-orchestration, it keeps lightweight tasks at the edge and absorbs peak workloads with elastic cloud capacity, delivering robust, cost-efficient processing under highly variable demand. Demonstrated in seismic monitoring, applicable to any bursty, shared-infrastructure scenario.

4.3.2 Closed-loop service #2: Seismic and displacement, Location-based Alert system (TAB, RockSigma)

The location based alert system is an underground alert system to that combines ThingWave's asset tracking and Digital Ground Support system with RockSigma's seismic analysis to provide warnings to staffers in dangerous areas. If an area that is monitored experience large movements, the system can process that information using an Edge node and generate an alarm directly to the worker.

4.3.3 Closed-loop service #3: Dynamic Maritime Resource Provisioning (FPV, FIVE)

Dynamic Maritime Resource Provisioning is an automated infrastructure management service for port operations. By integrating data from AIS, radars, and port-call applications, the system identifies approaching vessels and predicts docking needs. Upon detection, the loop automatically triggers the deployment of a private 5G network slice (UPF2) and activates a radar-based berthing assistance application. This event-driven approach ensures that high-bandwidth connectivity and guidance tools are provisioned exactly when needed, reducing resource waste and enhancing maritime safety. Overall, this service provides an intelligent, automated orchestration loop for responsive maritime resource management.

4.3.4 Closed-loop service #4: AI-driven Traffic Validation Loop (VCH, FIVE)

The AI-driven Traffic Validation Loop is an intelligent mobility verification service designed for urban environments. When traffic radars detect potential congestion, the loop automatically triggers a YOLO-based computer vision service to analyze real-time feeds from city cameras. This process confirms the presence of a traffic jam through visual analysis before any notifications are issued. This multi-layered verification ensures high data accuracy and reduces false alarms, creating a more reliable and efficient traffic management system.

4.3.5 Closed-loop service #5: Adaptive Flood Monitoring Loop (VCH, FIVE)

The Adaptive Flood Monitoring Loop is a data-driven control system designed for environmental safety and early warning. It continuously monitors AEMET open data for weather alerts to identify potential hazards. When a flood risk is detected, the loop autonomously increases the sampling frequency of water level radars to capture high-resolution data during the critical period. This dynamic adjustment ensures granular monitoring and better situational awareness when it is most needed, establishing an intelligent and responsive framework for proactive flood risk management.

4.3.6 Closed-loop service #6: Multi-modal Environmental Alerter (UPV, VCH, FIVE, NES)

The Multi-modal Environmental Alerter is an event-based closed-loop service built to enhance smart city resilience. The system continuously monitors diverse environmental parameters, including water levels, waste container capacity, room occupancy, and air quality. When an anomaly is detected or a threshold is breached, the loop manages the autonomous dispatch of alerts. This integrated monitoring approach enables a rapid, cross-domain response to urban challenges, ensuring a more robust and responsive framework for city-wide safety and maintenance.

Co-funded by the European Union

4.3.7 Closed-loop service #7: HPA+: Predictive AI-based Kubernetes Autoscaler (ICCS)

HPA+ is a predictive autoscaling service for Kubernetes workloads. It extends the standard Horizontal Pod Autoscaler with proactive scaling capabilities. Instead of reacting only to current CPU usage, it uses historical metrics to forecast future demand. The service includes a configurable suite of machine-learning models for workload prediction. Users can select the model that best fits the behaviour of their application. The model suite is designed to be extensible and continuously enriched with new forecasting models. Based on the selected model, HPA+ estimates upcoming traffic patterns and adjusts pod replicas in advance. This helps applications handle traffic spikes before they affect performance. It also reduces the risk of under-provisioning and unnecessary resource waste. Overall, HPA+ provides a Kubernetes-native, intelligent, and adaptable autoscaling loop for COP-PILOT services.

4.3.8 Closed-loop-service #8: Blockchain SLA-Triggered Logistics Reconfiguration (iLINK)

The Blockchain SLA-Triggered Logistics Reconfiguration loop is an event-driven orchestration service for supply-chain operations that require provenance assurance and SLA-bound delivery. It continuously monitors on-chain events from a permissioned Hyperledger Fabric ledger that records harvest, processing, transport, and delivery milestones across a tracked supply chain. When a chaincode event signals an SLA breach — for example, a temperature excursion, a freshness-threshold deviation, or a forecast late arrival — the loop autonomously triggers a logistics reconfiguration action through the COP-PILOT End-to-End and Domain Orchestrators (vehicle reassignment, dispatch of a substitute route, escalation alerts). Reconfiguration decisions are themselves committed back to the ledger, providing a tamper-proof audit trail of the corrective response. By coupling immutable ledger events with orchestratable platform actions, the service enables autonomous, regulation-aligned recovery from supply-chain disruptions in any vertical with traceability and SLA requirements.

4.3.9 Closed-loop-service #9: PowerfFleet Freshness-Aware JIT Rerouting Loop (iLINK)

The PowerFleet Freshness-Aware JIT Rerouting Loop is a real-time logistics optimisation service for perishable-goods transport. It continuously ingests GNSS telematics and temperature readings from on-board edge nodes installed in refrigerated transport vehicles, alongside readiness signals from upstream production or harvest systems exposed through the COP-PILOT data fabric. PowerFleet's meta-heuristic routing engine inspired by the Jsprit library re-evaluates the optimal route under freshness, distance, and SLA constraints on every telemetry update. When the projected delivery time risks violating the cargo's freshness threshold, the loop autonomously issues a dynamic rerouting action through the COP-PILOT orchestrators, updates driver mobile interfaces with the new route, and records the deviation event to the Hyperledger Fabric ledger for traceability. This event-driven, freshness-aware feedback loop minimises product loss, supports just-in-time delivery, and ensures auditable supply-chain compliance for any vertical that handles perishable or time-sensitive cargo.

4.3.10 Closed-loop-service #10: Adaptive DER Flexibility Optimization Loop (UoP, ENIK)

A data-driven control loop that continuously aggregates operational data from DERs and flexible loads across the monitored energy system. The system autonomously executes a flexibility optimization algorithm to compute optimal dispatch signals, which are then sent back to the DERs and flexible loads to adjust their behaviour in real time, ensuring consistent, accurate, and timely flexibility delivery to the grid operator.

4.3.11 Closed-loop-service #11: EV Charger Fault Detection Loop (ENIK, PPC)

A data-driven control loop that continuously monitors voltage, current, and power measurements across the full EV charging infrastructure. Upon detecting anomalies or unexpected deviations in the electrical readings, the system autonomously identifies the affected charger and immediately notifies the administrator, enabling rapid diagnosis and resolution of underlying hardware or grid-side faults before they escalate.

4.3.12 Closed-loop-service #12: Biogas Digestion Monitoring Loop (ENIK, BPO)

A data-driven control loop that continuously ingests pH, temperature, and other critical process sensor readings from an anaerobic digestion facility. Leveraging a digital twin model of the facility, the system continuously evaluates incoming measurements against admin-configured operational rules and thresholds, and upon detecting any parameter violation, autonomously triggers an alert to notify the administrator for immediate corrective action and process stabilization.

4.3.13 Closed-loop service #13: AI Driven Green Energy Vineyard Management – Virtual Sensor Stations (Nokia, Terraview, ONE)

The AI-Driven Green Energy Vineyard Management – Virtual Soil Stations loop is a closed-loop optimisation service that extends vineyard monitoring to areas without direct physical instrumentation. The loop ingests soil and environmental data from physical sensors deployed across the vineyard and makes this information available to AI-based forecasting algorithms. These algorithms generate predicted values for virtual soil stations in vineyard zones where no real sensor station is deployed. Through the COP-PILOT orchestration layer and OpenSlice, the prediction components can be deployed and managed as part of the operational vineyard monitoring service, improving field visibility without requiring dense physical sensor deployment.

4.3.14 Closed-loop service #14: AI Driven Green Energy Vineyard Management – Virtual Sensor Stations with 5G Connectivity (Nokia, Terraview, ONE)

The AI-Driven Green Energy Vineyard Management – Virtual Soil Stations with 5G Connectivity loop is a closed-loop optimisation service that combines vineyard monitoring with connectivity-aware service assurance. The loop ingests data from physical and virtual soil stations together with telemetry from 5G-connected sensors, radio equipment, modems, and connectivity infrastructure. When degraded connectivity or the need to prioritise specific devices is detected, the loop can trigger recommended or automated actions through the COP-PILOT orchestration layer, OpenSlice, and Nokia 5G-enabled management APIs. This supports reliable data collection and monitoring continuity across the vineyard environment.

4.3.15 Closed-loop service #15: AI Driven Green Energy Vineyard Management – 5G Rural Vineyard Connectivity with Programmed Energy-Saving Actions (Nokia, Terraview, ONE)

The AI-Driven Green Energy Vineyard Management – 5G Rural Vineyard Connectivity with Programmed Energy-Saving Actions loop is a closed-loop optimisation service for energy-aware operation of rural vineyard connectivity infrastructure. The loop ingests data from energy-production systems, battery storage, energy-consumption monitoring, 5G infrastructure components, and operational telemetry. When available battery energy or renewable generation falls below predefined thresholds, the loop can trigger programmed energy-saving actions through the COP-PILOT orchestration layer and OpenSlice, such as adapting radio transmission power, enabling or disabling radio layers, or switching selected infrastructure components on or off.

4.3.16 Closed-loop service #16: AI Driven Green Energy Vineyard Management – 5G Rural Vineyard Connectivity with AI-Guided Energy-Saving Actions (Nokia, Terraview, ONE)

The AI-Driven Green Energy Vineyard Management – 5G Rural Vineyard Connectivity with AI-Guided Energy-Saving Actions loop is a closed-loop optimisation service that extends programmed energy management with AI-based decision-making. The loop ingests historical and real-time data from vineyard sensors, energy systems, battery storage, 5G infrastructure, and operational telemetry. AI models use this information to forecast energy availability, expected demand, connectivity requirements, and potential service-impact conditions. When an optimisation opportunity is detected, the loop can trigger recommended or automated actions through COP-PILOT, OpenSlice, and Nokia 5G-enabled management APIs, supporting autonomous energy optimisation while preserving vineyard connectivity and service continuity

4.4 RELATION TO OPEN-SOURCE COMMUNITIES

This section outlines the relation between the COP-PILOT closed-loop services with existing open-source communities, summarized in Table 3.

Table 3: Relation of COP-PILOT Closed-loop services with open-source activities.

Closed loop Service Name	Closed loop Service Application Area	Relation with open-source activities
EdgeCloud Autoscaling with Priority Decay	Cluster 1 – UC1.1	The solution is built on ColonyOS (open source, MIT-licensed), which provides the meta-orchestration layer, distributed job queue, and executor framework used across the edge-to-cloud continuum. ColonyOS in turn relies on PostgreSQL for state management, and the deployment uses S3-compatible open-source object storage (e.g., MinIO) for data handling. The infrastructure is deployed on Kubernetes (CNCF) clusters, through which workers are dynamically provisioned and reconciled.
Seismic and displacement, Location-based Alert system	Cluster 1 – UC1.2	The solution is built with Arrowhead support (open source, Eclipse license), which provides features for service orchestration, system management and data distribution. The solution relies heavily on the use of MQTT via Mosquitto broker. The processing supports AI, using TensorFlow.
Dynamic Maritime Resource Provisioning	Cluster 2 – UC2.3	The application relies on the FIWARE Orion-LD (FIWARE Foundation Generic Enabler) context broker and the Smart City Stack (using FIWARE Scorpio for context data management and FIWARE Perseo for real-time event rules) to detect vessel arrival metadata via APIs. It integrates with OpenSlice to dynamically orchestrate and provision 5G network slices. The infrastructure is deployed on an Ubuntu Server-based Kubernetes (CNCF) cluster.
AI-driven Traffic Validation Loop	Cluster 2 – UC 2.1A	The application relies on the FIWARE Orion-LD context broker and the Smart City Stack (leveraging FIWARE Scorpio and FIWARE Perseo for rule detection and complex condition triggering) to identify initial congestion alerts. Visual verification is processed over RTSP streams

		using the open-source YOLOv8s (small) computer vision model, which is licensed under the GNU Affero General Public License v3.0 (AGPL-3.0). Microservices are deployed on Ubuntu Server using a standard Kubernetes (CNCF) cluster.
Adaptive Flood Monitoring Loop	Cluster 2 – UC2.1B	The application relies on the FIWARE Orion-LD context broker to collect real-time water-level telemetry and external weather forecasts. The Smart City Stack uses its core context components (FIWARE Scorpio) and event rules engine (FIWARE Perseo) to autonomously analyse the data and trigger both radar sampling frequency modifications and notification orders. The execution infrastructure runs on Ubuntu Server managed by a standard Kubernetes (CNCF) cluster.
Multi-modal Environmental Alerter	Cluster 2 – UC2.1B, 2.2A, 2.4A, 2.4B	The application integrates with the FIWARE Orion-LD context broker to aggregate filling-level, air quality, and room occupancy data from edge sensors. The Smart City Stack leverages FIWARE Scorpio for data persistence and context management alongside FIWARE Perseo to evaluate predefined environmental thresholds and dispatch automated operator notifications. The solution is hosted entirely on an Ubuntu Server-based Kubernetes (CNCF) cluster infrastructure.
HPA+: Predictive AI-based Kubernetes Autoscaler	Cluster 2	HPA+ as an open-source Kubernetes-native predictive autoscaling service. https://github.com/cslab-ntua/HPA-Plus
Blockchain SLA-Triggered Logistics Reconfiguration	Cluster 3A – UC3A.3	Built on Hyperledger Fabric (Apache 2.0, Linux Foundation Decentralized Trust, formerly Hyperledger Foundation), with chaincode developed in Go using fabric-contract-api-go/v2 and deployed under the Chaincode-as-a-Service (CCaaS) pattern. The ledger receives signed events from authorised writer services (e.g., PowerFleet) over gRPC.
PowerFleet Freshness-Aware JIT Rerouting Loop	Cluster 3A – UC3A.4	Routing engine inspired by the open-source Jsprit library (Apache 2.0). The telemetry ingestion layer integrates with FIWARE Orion-LD (FIWARE Foundation Generic Enabler) for cross-domain data exchange. Edge node stack runs on Ubuntu Server with k3s (CNCF).
Adaptive DER Flexibility Optimization Loop	Cluster 3.E – UC3.1	The application relies on FIWARE Orion-LD as the context broker for collecting measurements from both actual and simulated DERs and flexible loads. The operating environment of the application is specified using the GEISSA (Linux Foundation) stack, while OpenLEADR (Linux Foundation) enables the Demand Response control signal exchange between the Aggregator (UoP) and the DERs and flexible loads. Edge nodes are deployed on Ubuntu Server with k3s (CNCF) as the lightweight Kubernetes distribution.
EV Charger Fault Detection Loop	Cluster 3.E – UC3.2	The application relies on FIWARE Orion-LD as the context broker for collecting voltage, current, and power measurements from the EV charging infrastructure. OpenLEADR (Linux Foundation) enables the reception of Demand Response control signals at the edge. Edge nodes are deployed on Ubuntu Server with k3s (CNCF) as the lightweight Kubernetes distribution.
Biogas Digestion Monitoring Loop	Cluster 3.E – UC3.3	The application relies on FIWARE Orion-LD as the context broker for collecting pH, temperature, and other process sensor measurements from the biogas plant facility. OpenLEADR (Linux Foundation) enables the reception of Demand Response control signals at the edge. Edge nodes are deployed on Ubuntu Server with k3s (CNCF) as the lightweight Kubernetes distribution.
AI Driven Green Energy Vineyard Management – Virtual Sensor Stations	Cluster 4 – UC4.4A	The service relies on the COP-PILOT FIWARE broker for data ingestion and on OpenSlice/COP-PILOT orchestration mechanisms for deployment and lifecycle management. Nokia Network as Code (NaC) is aligned with open network API ecosystems such as CAMARA and GSMA Open Gateway, while COP-PILOT provides the integration context for validating these capabilities in the vineyard domain.

AI Driven Green Energy Vineyard Management – Virtual Sensor Stations with 5G Connectivity	Cluster 4 – UC4.4B	The service relies on the COP-PILOT FIWARE broker for data ingestion and on OpenSlice/COP-PILOT orchestration mechanisms for deployment and lifecycle management. Nokia Network as Code (NaC) is aligned with open network API ecosystems such as CAMARA and GSMA Open Gateway, while COP-PILOT provides the integration context for validating these capabilities in the vineyard domain.
AI Driven Green Energy Vineyard Management – 5G Rural Vineyard Connectivity with Programmed Energy-Saving Actions	Cluster 4 – UC4.4C	The service relies on the COP-PILOT FIWARE broker for data ingestion and on OpenSlice/COP-PILOT orchestration mechanisms for deployment and lifecycle management. Nokia Network as Code (NaC) is aligned with open network API ecosystems such as CAMARA and GSMA Open Gateway, while COP-PILOT provides the integration context for validating these capabilities in the vineyard domain.
AI Driven Green Energy Vineyard Management – 5G Rural Vineyard Connectivity with AI-Guided Energy-Saving Actions	Cluster 4 – UC4.4D	The service relies on the COP-PILOT FIWARE broker for data ingestion and on OpenSlice/COP-PILOT orchestration mechanisms for deployment and lifecycle management. Nokia Network as Code (NaC) is aligned with open network API ecosystems such as CAMARA and GSMA Open Gateway, while COP-PILOT provides the integration context for validating these capabilities in the vineyard domain.

4.5 RELATION TO STANDARDS

This section outlines the relation between the COP-PILOT closed-loop services and relevant standards. This information is summarized in Table 4.

Table 4: Relation of COP-PILOT Closed-loop services with standards.

Closed loop Service Name	Closed loop Service Application Area	Relation with standards
EdgeCloud Autoscaling with Priority Decay	Cluster 1 – UC1.1	HTTP/REST and WebSocket APIs; zero-trust security via ECDSA signatures over TLS; CNCF Kubernetes deployment with OCI containers; PostgreSQL (SQL) and S3-compatible object storage.
Seismic and displacement, Location-based Alert system	Cluster 1 – UC1.2	HTTP/REST and WebSocket APIs; JWT for user access control; X509 certificates for device authentication; JSON for data export
Dynamic Maritime Resource Provisioning	Cluster 2 – UC2.3	ETSI ISG CIM NGSI-LD for modelling and managing port context data; NMEA 0183 / NMEA 2000 (IEC 61162) standards for maritime AIS telemetry stream ingestion; OpenAPI 3.0 for the FVP Portcalls API; Aligned with TM Forum (TMF) Open APIs via the Smart City Stack to orchestrate network management services in OpenSlice.
AI-driven Traffic Validation Loop	Cluster 2 – UC 2.1A	ETSI ISG CIM NGSI-LD for cross-domain traffic and radar telemetry data models; RTSP (Real-Time Streaming Protocol - IETF RFC 2326) for open city camera video feed ingestion; OpenAPI 3.0 for service endpoints; Aligned with TM Forum (TMF) Open APIs via the

		Smart City Event Manager to trigger validation and notification workflows.
Adaptive Flood Monitoring Loop	Cluster 2 – UC2.1B	ETSI ISG CIM NGSI-LD for environmental and water-level context data streams; OpenAPI 3.0 for consuming meteorologic data from external weather forecast providers; Aligned with TM Forum (TMF) Open APIs via the Smart City Stack to issue automated frequency modification service orders.
Multi-modal Environmental Alerter	Cluster 2 – UC2.1B, 2.2A, 2.4A, 2.4B	ETSI ISG CIM NGSI-LD and W3C JSON-LD for cross-device telemetry structuring; OpenAPI 3.0 for sensor metadata ingestion; Aligned with TM Forum (TMF) Open APIs via the Smart City Event Manager to evaluate thresholds and dispatch alert notifications.
HPA+: Predictive AI-based Kubernetes Autoscaler	Cluster 2	Aligned with TMF-based COP-PILOT interfaces: /tmf-api/serviceActivationManagement/v4/ for service configuration, /tmf-api/resourceOrderingManagement/v4/ for scaling requests, and /tmf-api/resourceInventoryManagement/v4/ for active resource state.
Blockchain SLA-Triggered Logistics Reconfiguration	Cluster 3A – UC3A.3	Apache 2.0 license framework for Hyperledger Fabric components; OpenAPI 2.0 (Swagger) for service interfaces; W3C JSON-LD for chaincode payload structuring.
PowerFleet Freshness-Aware JIT Rerouting Loop	Cluster 3A – UC3A.4	ETSI ISG CIM NGSI-LD for vehicle and cargo telemetry data models (e.g., VehicleEmission entity); OpenAPI 2.0 (Swagger) for service interfaces.
Adaptive DER Flexibility Optimization Loop	Cluster 3.E – UC3.1	ETSI NGSI-LD, OpenADR 3.0, OpenAPI 3.0
EV Charger Fault Detection Loop	Cluster 3.E – UC3.2	ETSI NGSI-LD, OpenADR 3.0, OpenAPI 3.0
Biogas Digestion Monitoring Loop	Cluster 3.E – UC3.3	ETSI NGSI-LD, OpenADR 3.0, OpenAPI 3.0
AI Driven Green Energy Vineyard Management – Virtual Sensor Stations	Cluster 4 – UC4.4A	Aligned with CAMARA network APIs, GSMA Open Gateway, GSMA Operator Platform concepts, TM Forum Open APIs for operational processes and API lifecycle management, and 3GPP NEF-based exposure of 5G network capabilities.
AI Driven Green Energy Vineyard Management – Virtual Sensor Stations with 5G Connectivity	Cluster 4 – UC4.4B	Aligned with CAMARA network APIs, GSMA Open Gateway, GSMA Operator Platform concepts, TM Forum Open APIs for operational processes and API lifecycle management, and 3GPP NEF-based exposure of 5G network capabilities.
AI Driven Green Energy Vineyard Management – 5G Rural Vineyard Connectivity with Programmed Energy-Saving Actions	Cluster 4 – UC4.4C	Aligned with CAMARA network APIs, GSMA Open Gateway, GSMA Operator Platform concepts, TM Forum Open APIs for operational processes and API lifecycle management, and 3GPP NEF-based exposure of 5G network capabilities.
AI Driven Green Energy Vineyard Management – 5G Rural Vineyard Connectivity with AI-Guided Energy-Saving Actions	Cluster 4 – UC4.4D	Aligned with CAMARA network APIs, GSMA Open Gateway, GSMA Operator Platform concepts, TM Forum Open APIs for operational processes and API lifecycle management, and 3GPP NEF-based exposure of 5G network capabilities.

5 CLUSTER 1 — BUSINESS INTEGRATION IN MINING (SWEDEN)

5.1 CLUSTER INFRASTRUCTURE & DOMAINS

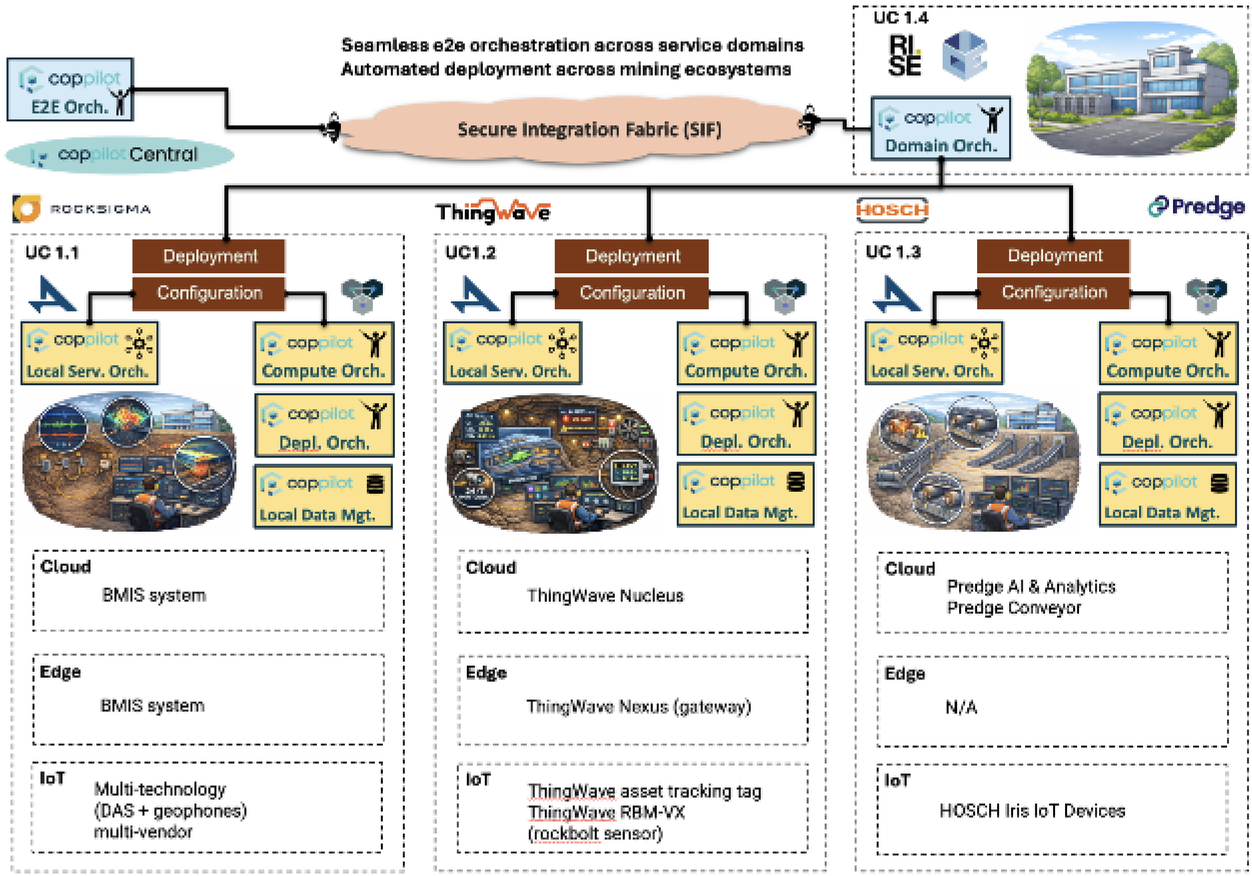


Figure 5-1 - Cluster 1 Architecture

The cluster infrastructure is organised as a multi-domain, distributed edge–cloud continuum, where each industrial stakeholder operates within a local domain while being securely interconnected through the COP-PILOT platform.

Table 5: Cluster 1 infrastructure

Site	Domain / Operator	Hardware	Connectivity
RISE ICE Mining pre-production environment	Academic domain	Cloud and Edge compute infrastructure.	Public Internet and OpenZiti secure tunnel to SIF.

5.1.1 Cluster Structure

The cluster consists of one COP-PILOT domain in which three use cases, UC1.1, UC1.2, and UC1.3 represent different but connected services provided in a mine infrastructure. In addition, UC1.4 provides the testbed environment that provides the infrastructure as such, i.e., representing the infrastructure of a mining company. The different use cases are deployed in separate local domains within the cluster 1 COP-PILOT domain. The following service offerings are covered by UC1.1-1.3:

HOSCH/Predge (UC 1.3) – Industrial OT environment focused on conveyor systems and condition monitoring (HOSCH), and advanced analytics and AI-driven processing environment (PREDGE).

ThingWave (UC1.2) – Edge IoT platform managing sensor ingestion, preprocessing, and local analytics.

RockSigma (UC1.1) – Data analytics, visualization, and decision-support services.

The local domain is logically isolated and operated independently, consistent with the Distributed Domain Orchestration Layer (DDO-L) defined in COP-PILOT, ensuring sovereignty over local compute, data, and services.

5.1.2 Compute and Functional Tiers

Within the Cluster 1 domain, the infrastructure is structured into four main tiers:

1. **Local Data Management (Local Data Mgt.)**
   Handles ingestion, storage, and governance of IoT/OT data streams.

2. **Deployment Orchestration (Depl. Orch.)**
   Manages lifecycle of applications and services deployed within the domain.

3. **Compute Orchestration (Compute Orch.)**
   Controls compute resources across edge nodes, enabling scalable analytics and processing.

4. **Local Service Orchestration (Local Serv. Orch.)**
   Coordinates domain-specific services and workflows.

5.1.3 Connectivity and Integration

Only UC 1.4 (hosted by RISE) is interconnected via the Secure Integration Fabric (SIF), which provides:

- Secure, programmable connectivity between domains
- Policy-driven data exchange
- Interoperability across heterogeneous systems

This aligns with the COP-PILOT SIF-L layer, enabling cross-domain workflows while preserving security and autonomy. See also Figure 4.

5.1.4 Summary

The cluster represents a federated architecture, where:

- The Cluster 1 domain is autonomous but interoperable.

- External data flows are governed through SIF.
- Compute can be distributed across edge and cloud.

5.2 KEY WORKFLOWS AND DATA PATHS

The cluster enables several cross-domain workflows driven by industrial data exchange and analytics pipelines.

5.2.1 HOSCH → Predge

Within the HOSCH-to-Predge data flow, operational technology (OT) systems and sensors in the HOSCH domain act as the primary data sources. Data is collected and pre-processed locally before being transmitted from the UC1.4 piloting environment's internal network to the cloud and subsequently to Predge. Once received, the data is processed using AI and machine learning techniques to support predictive maintenance, pattern detection, and anomaly identification. The resulting outputs include maintenance insights, alerts, and recommendations aimed at optimizing operations and reducing downtime.

5.2.2 ThingWave → RockSigma

In the ThingWave-to-RockSigma data flow, IoT sensor data is aggregated and pre-processed by ThingWave at the edge. Seismogram data collected from ThingWave geophones is stored in ColonyFS, which triggers a ColonyOS compute workflow. This workflow integrates with RockSigma seismic processors as part of the UC4 piloting infrastructure. The processed data is then used for analytics, visualization, KPI generation, and dashboarding, providing operational dashboards and decision-support insights for users.

5.2.3 Cross-cutting Characteristics

Data exchange within each cluster is managed locally inside the respective piloting environment. The overall architecture supports both near real-time and batch processing modes, allowing flexibility in handling different operational and analytical requirements.

5.3 CHALLENGES AND CONSTRAINTS

The cluster faces several technical and operational challenges, including:

Table 6: Cluster 1 challenges and constraints

#	Challenge	Detail
1	**Access to operational mine sites, real-world data, and field events**	Several indicators depend on data, events, and conditions that can only be obtained inside operating mines, where access to equipment and personnel is restricted and partner-supplied data streams can be delayed or of poor quality. This is the dominant constraint and affects vendor integration (KPI-VSS-CL1-1.1, 1.2), rock-bolt installation and end-user feedback (KPI-VSS-CL1-2.1, 2.2), collaborative data streams (KPI-VSS-CL1-2.4), automatic tunnel-inspection report volume (KPI-VSS-CL1-2.5), and edge-processing validation (KPI-VSS-CL1-2.12). Mitigation: emulate installations internally; generate and inject synthetic sensor and event data; retain synthetic waveform datasets as a fallback where real multi-vendor recordings of the same event are unavailable; and engage several mines in parallel to secure feedback and real data.

#	Challenge	Detail
2	**Hardware and infrastructure availability for testing at scale**	Scale- and performance-oriented indicators cannot be exercised at target levels with the hardware currently available, and acquisition-hardware development can slip. This affects sensor-infrastructure scale (KPI-VSS-CL1-2.3), data-reception performance (KPI-VSS-CL1-2.8), data sample rate (KPI-VSS-CL1-3.3), device scalability (KPI-VSS-CL1-3.4), and heterogeneous compute-platform coverage (KPI-VSS-CL1-4.2). Mitigation: use simulated sensors and devices to reach the required packet and device counts; use virtualised compute platforms where physical ones are unavailable; add backend load balancing and cluster processing; obtain more powerful servers through RISE and external partners; and replan hardware-dependent assessments where development is delayed.
3	**Distributed compute orchestration and dynamic autoscaling**	Distributing seismic and analytics workloads across the edge-to-cloud continuum, and scaling them dynamically for SLA compliance, carries technical risk in job orchestration, autoscaler decision logic, and the suitability and cost of moving workloads between edge and cloud. This affects distributed compute (KPI-VSS-CL1-1.3), dynamic autoscaling for SLA compliance (KPI-VSS-CL1-1.4), and automated workload placement (KPI-VSS-CL1-4.5). Mitigation: reuse the existing ColonyOS orchestration platform rather than building bespoke mechanisms; adopt an early, iterative approach starting from basic algorithms; combine distributed-compute trials with simpler demonstrations to limit overhead; and use the simulator to assess offloading benefits before migrating a workload, avoiding migration where the overhead is too large.
4	**Resilience, recovery, and continuous availability of the testbed**	Maintaining service continuity and high availability under failure is required across the orchestration layer and the UC1.4 testbed, with risks from stateful workloads that have external side effects, high observability data volumes, and physical failures (hardware, power, and connectivity). This affects state reconciliation (KPI-VSS-CL1-4.4), fault recovery and task preservation (KPI-VSS-CL1-4.6), observability and auditability coverage (KPI-VSS-CL1-4.7), system availability (KPI-VSS-CL1-2.9), and UC1.4 testbed availability (KPI-VSS-CL1-4.9). Mitigation: apply rollback, retry, and application-level consistency handling for stateful workloads; use a scalable monitoring architecture with optimised log and metrics retention; rely on high availability provided by the underlying Kubernetes platform and ColonyOS; back the testbed with UPS and local energy storage rated for more than two hours; and provide two independent internet connections to the testbed.
5	**Secure service interoperability across heterogeneous platforms**	Enforcing secure service discovery, authentication, authorization, and encryption across the heterogeneous systems present in the mining environment may introduce compatibility and performance limitations. This affects secure service interoperability (KPI-VSS-CL1-4.8) and underpins observability and auditability coverage (KPI-VSS-CL1-4.7). Mitigation: apply lightweight, platform-compatible cryptographic mechanisms where appropriate, so that secure communication can be extended across the defined critical interactions without prohibitive overhead on constrained platforms.

From a general point of view, cross-domain industrial data-sharing solutions face several challenges related to technology, data management, operations, and security. Industrial environments typically consist of a heterogeneous mix of IoT devices, operational technology (OT), edge platforms, and cloud services, making integration and interoperability difficult. Vendor-specific solutions, latency requirements for real-time applications, and the need to scale data pipelines across multiple domains further increase complexity.

Data-related challenges include managing data ownership and sovereignty, addressing inconsistencies in data formats and semantics, and enabling secure data sharing across organizational boundaries. Operationally, limited computing resources at edge sites, deployment complexity in distributed environments, and strict availability requirements must be considered. In the mining industry, additional constraints often restrict the sharing of IT infrastructure and operational data with external parties.

Security remains a key concern, requiring secure cross-domain communication, effective access control mechanisms, and integration across heterogeneous systems. Compliance with relevant data governance regulations must also be addressed where applicable, although many mining operations are not directly subject to EU data governance requirements.

5.4 INTEGRATION OF COP-PILOT CAPABILITIES, COMPONENTS AND SERVICES

The cluster integrates several COP-PILOT platform capabilities:

Table 7: Cluster 1 COP-PILOT platform capabilities integration

COP-PILOT Capability	Scope (UCs)	Cluster Must Expose / Consume
End-to-End Service Orchestration (ESO / Maestro)	All four UCs. Deploy and lifecycle-manage containerised ColonyOS and Arrowhead services.	**Expose:** endpoint metadata, resource requirements per service, and service blueprints for: • ColonyOS blueprint reconciliation service. **Consume:** Kubernetes Custom Resources.
Domain Orchestration (DO / OpenSlice)	All four UCs. Manage compute service provisioning and lifecycle at RISE ICE datacenter.	**Expose:** Kubernetes cluster endpoints at RISE. **Consume:** K8s-as-a-Service APIs; dynamic resource allocation and scaling interfaces per domain.
Data Management (ColonyFS/ Eclipse Arrowhead, RabtitMQ/MQTT)	In all four UCs, ingest, store, route, and manage heterogeneous OT/IoT data streams across the edge-to-cloud continuum, with RabitMQ / MQTT, ColonyFS for distributed storage and event-triggered execution, ColonyOS for compute-workflow orchestration, and in UC1.2 use Eclipse Arrowhead for secure service discovery. .	**Expose:** sensor data streams ingested via RabbitMQ / MQTT twith data persisted in ColonyFS triggering ColonyOS compute workflows, and services registered in the Eclipse Arrowhead local cloud. **Consume:** ColonyFS for distributed storage and event-driven triggering; ColonyOS for cross-tier data routing and processing; Eclipse Arrowhead for service discovery.
Secure Integration Fabric (SIF / OpenZiti)	UC 1.4. Ensure end-to-end encrypted, authenticated communication within Cluster 1 domain and the COP-PILOT Central layer functions (HypO).	**Expose:** domain credentials and access policies for Cluster 1 **Consume:** mTLS-secured inter-domain tunnels; zero-trust network access enforcement.

5.4.1 In-Scope Components

- **Distributed Domain Orchestration (DDO-L)**
  → Local orchestration within each domain
- **Secure Integration Fabric (SIF-L)**
  → Cross-domain connectivity and data exchange
- **End-to-End Service Orchestration (ESO-L)**
  → Coordination of multi-domain workflows
- **Business Management Layer (BM-L)**
  → Service catalogues, monitoring, and user interfaces

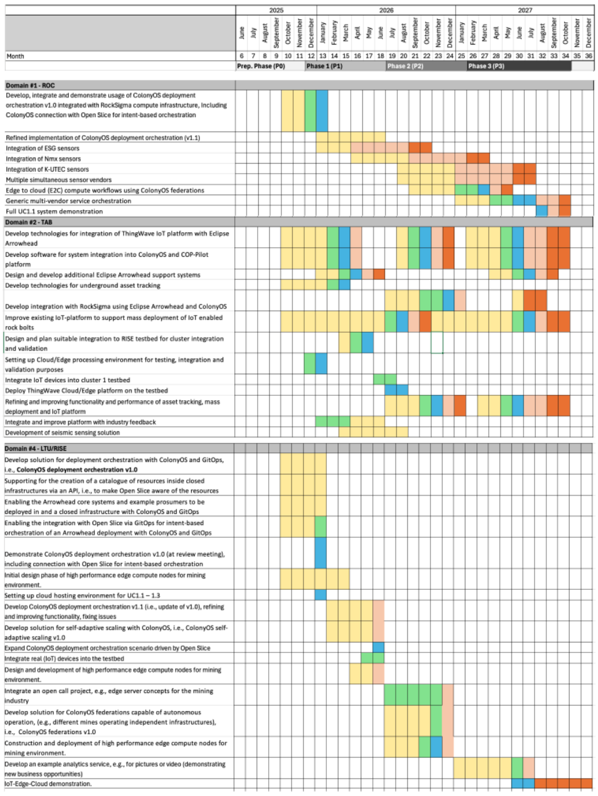
These layers are defined in the COP-PILOT architecture.

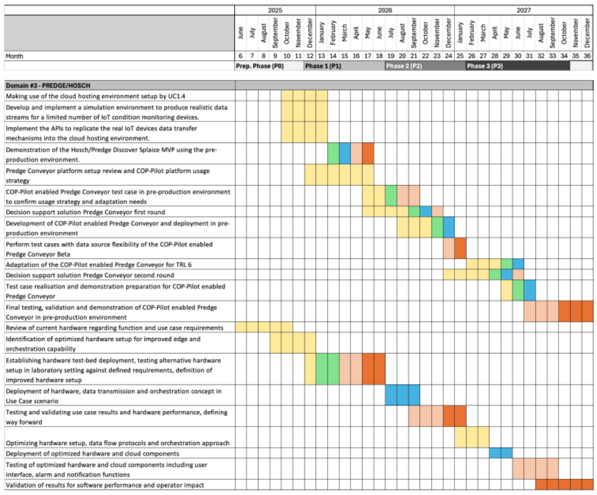
5.4.2 Integration Scope

- Deployment orchestration through ColonyOS.
- Data management via ColonyOS.
- Service orchestration using the Arrowhead framework and/or ColonyOS.

5.5 INTEGRATION & DEVELOPMENT PLAN

The Development & Integration Planning Gantt figure below provides an overview of the key activities, milestones, and dependencies required to deliver the pilot scope. The timeline supports progress tracking and ensures alignment across development, integration, testing, and deployment phases.





5.5.1 Development Plan

Cluster 1's development plan is organised around the partner use cases for seismic monitoring, asset tracking and condition monitoring, with the RISE test and demonstration environment acting as the common target for edge-to-cloud integration. The immediate development path is to move from local partner implementations and pre-production components towards a shared piloting environment in which the use cases can use the COP-PILOT orchestration and compute-continuum capabilities in a controlled way.

UC 1.1 - RockSigma seismic monitoring. Development continues around RockSigma BEMIS as the seismic monitoring and processing environment. The integration of relevant ColonyOS releases into the existing BEMIS software remains an ongoing activity through the pilot period, while the first version of the auto-scaling feature, its test case and demonstration scenario have already been completed and used for project review. The next development steps focus on broadening seismic vendor interoperability, preparing simultaneous multi-vendor sensing tests, and progressing from local demonstrations towards integration in the RISE test and demonstration environment with an edge-to-cloud architecture.

UC 1.2 - ThingWave asset tracking. ThingWave has completed the integration of Arrowhead services into the Nucleus platform and is now developing the asset-tracking and smart rock-bolt capabilities needed for larger-scale pilot operation. The plan includes continued testing of underground asset-tracking technologies, preparation for a larger field trial, work towards mass deployment of smart rock bolts, development of the seismic sensing solution, and scalability improvements for both the IoT platform and the visual demonstration tools. Data integration to RockSigma and to external stakeholders is being prepared, while the software integration into the RISE test environment is ongoing and the move of hardware is under planning.

UC 1.3 - HOSCH / Predge condition monitoring. The condition-monitoring use case is structured around the SplAIce and Predge Conveyor pilots. For SplAIce, the current hardware has been reviewed against use-case requirements, the optimised hardware setup has been selected, and the hardware test-bed has been established and qualified in laboratory testing. The next steps are deployment of hardware, data transmission and orchestration concepts in the use-case scenario, followed by testing, optimisation, deployment of cloud components, user-interface and alarm testing, and final validation of software performance and operator impact. For Predge Conveyor, the platform setup review and COP-PILOT usage strategy are ongoing, the first pre-production test case has started through a ColonyOS usage investigation, and a first draft of the decision-support solution has been created. The next step is to connect the solution to the RISE test environment and deploy the sensor and customer data-provider models in the test bed.

UC 1.4 - LTU/RISE Testbed and Integration Platform. The UC1.4 activities focus on establishing and operating the Cluster 1 computing continuum testbed that provides the infrastructure foundation for the pilot use cases. Development continues around the integration of ColonyOS, Arrowhead, Kolony CRDs, OpenSlice and COP-PILOT orchestration components to create a unified edge-to-cloud environment spanning edge devices, the RISE ICE datacentre and public cloud resources. The initial integration architecture and service interfaces have been defined, while work is ongoing to expand heterogeneous compute coverage through the introduction of new edge hardware and automated provisioning capabilities. The next development steps focus on implementing declarative infrastructure provisioning, automated workload placement, observability and fault-recovery mechanisms, and validating the end-to-end orchestration of UC1.1–UC1.3 workloads across the computing continuum. The testbed will progressively evolve towards a fully integrated demonstration environment supporting secure service interoperability, autonomous operation, and large-scale pilot validation against the Cluster 1 KPIs.

5.5.2 Key Milestones

The current Cluster 1 milestone baseline shows that several partner components have already moved beyond definition and into implementation or validation. RockSigma has completed the first auto-scaling version and demonstrated it locally. ThingWave has completed Arrowhead integration into Nucleus and has initial asset-tracking technologies under test. HOSCH has completed the requirements review, hardware-selection work and laboratory qualification for the SplAIce hardware setup, while Predge has selected technologies for the decision-support interface and created an initial preview of the Predge Conveyor solution.

The next milestones are the consolidation of multi-vendor interoperability for UC 1.1, the larger-field and RISE-environment integration steps for UC 1.2, and the progressive deployment and validation of UC 1.3 hardware, data-transmission, orchestration and decision-support components. During 2026, the emphasis is on moving partner solutions into the RISE test and demonstration environment and preparing the edge-to-cloud integration path. During 2027, the emphasis shifts towards optimisation, pre-production demonstration, final testing and validation across the use-case feature sets.

5.6 USE CASE DEVELOPMENT STATUS

At cluster level, development is progressing unevenly but coherently across the three partner use cases. Some technical building blocks are already completed or advanced, while the main remaining work concerns integration into the RISE test environment, broader partner interoperability, field validation and final pre-production demonstration.

5.6.1 Completed / Advanced

RockSigma has completed the first version of the BEMIS auto-scaling feature, including the associated test case and demonstration scenario, and this result has already been used for project review. In the ThingWave use case, Arrowhead services have been integrated into the Nucleus platform, and initial underground asset-tracking technologies have been tested. In the HOSCH / Predge use case, the SplAIce pilot is advanced in its hardware preparation: the hardware review has been completed, the optimised setup has been defined, and the laboratory test-bed has qualified the final hardware setup. The SplAIce setup has also been live in the test bed since December 2025, where the architecture is being stress-tested with multiple data sources. Predge has completed preparatory steps for the Predge Conveyor work, including technology selection and a draft preview of the decision-support solution. In UC1.4, the core computing continuum architecture has been established, including the integration of ColonyOS, Arrowhead and the Kolony orchestration framework as the foundation for the Cluster 1 testbed. Initial edge-to-cloud orchestration capabilities have been demonstrated, and development is now focused on expanding heterogeneous infrastructure support, automated provisioning, observability, and workload placement to enable large-scale integration and validation of the Cluster 1 use cases.

5.6.2 In Progress

RockSigma is continuing the integration of relevant ColonyOS releases into BEMIS and is actively expanding seismic vendor interoperability. ESG integration has been completed, while K-UTEC implementation is ongoing and ThingWave/TAB and Nmx integrations are being prepared. RockSigma is also preparing local testing and demonstration of simultaneous multi-vendor seismic sensing, including an ESG and IMS case based on actual customer data and a synthetic-data simulation. ThingWave is progressing the mass-deployment capability for smart rock bolts, the seismic sensing solution, scalability of the IoT platform and visual demonstration tools, and data integration towards RockSigma and other stakeholders. For UC 1.3, hardware installation, data transmission and orchestration in the test bed are ready for deployment for the SplAIce pilot, while Predge Conveyor is progressing its platform usage strategy, ColonyOS investigation, sensor and customer data-provider models, and connection of the decision-support solution to the test bed. UC1.4 is progressing the expansion of the Cluster 1 computing continuum testbed through the integration of edge, on-premise and cloud infrastructure resources. Development is focused on automated infrastructure provisioning, workload placement, observability and fault-recovery capabilities, while preparing the testbed for large-scale integration and validation of the UC1.1–UC1.3 workloads within the RISE test environment.

5.6.3 Planned / Upcoming

The main upcoming work for UC 1.1 is to integrate the COP-PILOT-enabled BEMIS solution into the RISE test and demonstration environment with an edge-to-cloud architecture, complete the full UC 1.1 feature set, and carry out final testing, validation and demonstration in a pre-production environment. For UC 1.2, the next steps include the larger field trial for underground asset tracking, continuation of smart rock-bolt deployment and IoT-platform scalability work, finalisation of data-integration paths to partners and stakeholders, and completion of the RISE test-environment integration including the planned hardware move. For UC 1.3, the 2026-2027 plan includes testing and validation of use-case results and hardware performance, optimisation of hardware setup, data-flow protocols and orchestration approach, deployment of optimised hardware and cloud components, testing of user-interface, alarm and notification functions, and validation of both software performance and operator impact. The Predge Conveyor track will proceed through beta test cases with flexible data sources, adaptation towards TRL 6, a second decision-support iteration, demonstration preparation, and final validation in the pre-production environment. For UC1.4, the main upcoming activities focus on completing the integration of the Cluster 1 computing continuum testbed with the COP-PILOT infrastructure and the RISE test environment. Planned work includes deployment of new edge-computing resources, implementation of automated infrastructure provisioning and workload-placement capabilities, validation of observability and fault-recovery mechanisms, and final end-to-end demonstrations of UC1.1–UC1.3 workloads operating across the edge-to-cloud continuum in a pre-production environment.

5.7 INTEGRATION & DEPLOYMENT STATUS

An OpenSlice server instance has been successfully deployed and is now operating as the domain orchestrator for Cluster 1 at the RISE ICE data center. The OpenSlice instance has been connected to the SIF layer and validated against the COP-Pilot integration pipelines using Netcompany's comprehensive test routines, ensuring full compliance.

ColonyOS services have been exposed through OpenSlice to the Hyper Orchestrator (HypO). ColonyOS has been integrated via Kubernetes using the new Kubernetes operator Kolony, enabling it to be registered and offered as an OpenSlice service and made available through the COP-Pilot Hyper Orchestrator.

As a result, Use Case 1.4 has reached a maturity level that enables a live demonstration of how Cluster 1 integrates into the COP-Pilot platform. Building on this milestone, work is ongoing to demonstrate how Use Cases 1.1–1.3 can leverage these capabilities.

In parallel, the Hosch-to-Predge initial data pipeline has been successfully deployed at the RISE ICE data center.

6 CLUSTER 2 — SMART SUSTAINABLE IOT SOLUTIONS IN VALENCIA (SPAIN)

6.1 CLUSTER INFRASTRUCTURE & DOMAINS

The COP-PILOT Cluster 2 infrastructure is a geographically distributed environment spanning four key domains in the Valencia region. The architecture, as seen in Figure 6-1, is designed to support a heterogeneous mix of IoT/OT sensing and high-performance compute. The architecture distinguishes between Compute Domains, breakdown in Table 8, which host the platform's intelligence and data management stacks, and Sensing Domains, which act as data collection points.

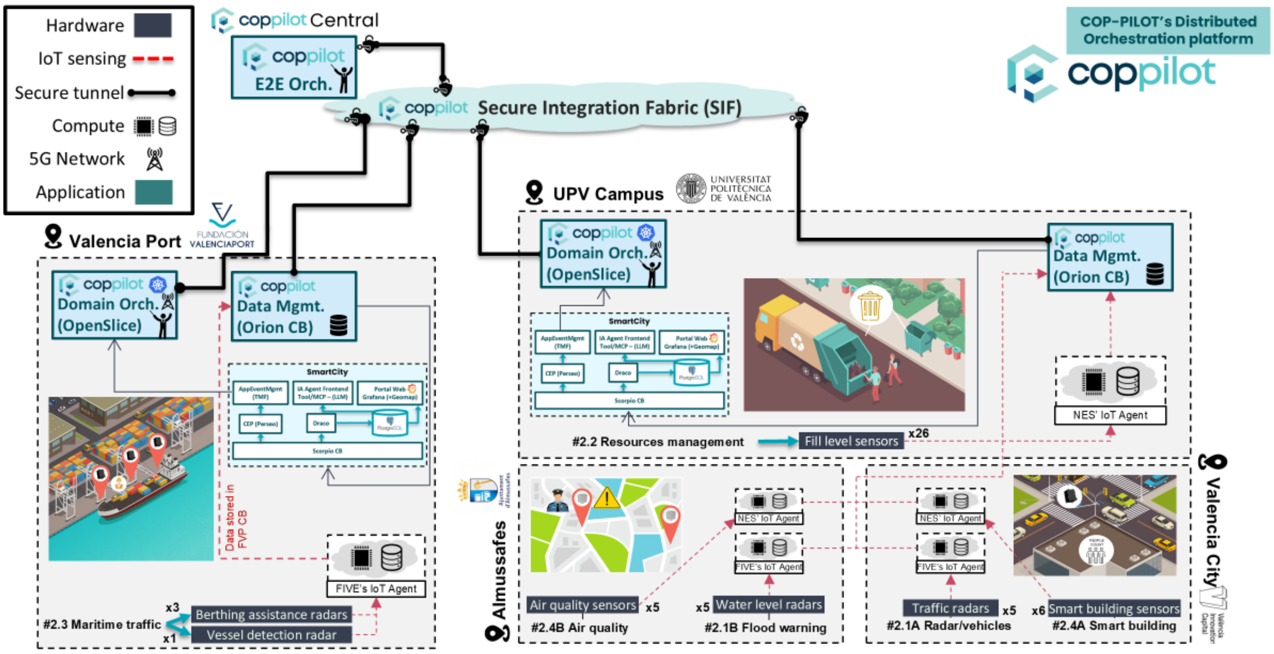


Figure 6-1: Cluster2 Architecture Diagram

Table 8: Cluster 2 breakdown by locations, domains, hardware, and connectivity.

Site	Domain / Operator	Hardware	Connectivity
Valencia Port Port testbed	Port domain / Fundación Valenciaport (FVP)	5G berthing assistance radars, 5G vessel detection radar. Compute infrastructure.	FVP 5G private network, 5G-NR for radar data streams; radar sensing over private 5G uplink. OpenSlice API for dynamic slice management. OpenZiti secure tunnel to SIF
UPV Campus Academic facility, controlled "small city"	Academic Domain / Universitat Politècnica de València (UPV)	Fill-level container sensors. Compute infrastructure.	UPV 5G private network + public network. NB-IoT for sensor data streams; IoT sensing and actuation over public and private 5G uplink. OpenZiti secure tunnel to SIF

Valencia City Urban environment	**Urban Domain / Valencia Innovation Capital (VCH)**	**5G traffic radars, Smart building sensors**	**5G NR and LoRaWAN for sensor data streams and backhaul from VCH to UPV**
Almussafes Industrial environment	**Industrial environment / Ajuntament d'Almussafes (ALM)**	**Air quality sensors, water-level radars**	**NB-IoT/CAT-M (LTE) and LoRaWAN for sensor data streams and backhaul from VCH to UPV**

Compute tiers

Cluster 2 operates across three primary compute tiers.

1. Central cloud: Hosts the COP-PILOT Central end-to-end orchestrator, which communicates with the local clusters via the SIF for lifecycle management.
2. Near-edge (Compute Domains): The Port and UPV sites host the local intelligence. Virtual Machines are used for Domain Orchestration (OpenSlice) and the Orion Context Broker. Kubernetes clusters in each site host scalable microservices, including data persistence and event processing. This enables service execution close to domain boundaries while maintaining orchestration connectivity to the COP-PILOT platform.
3. Field level (Sensing Domains): IoT Agents at the sensing sites act as protocol translators, capturing data from the field for transmission to the compute hubs.

IoT/OT categories. The cluster integrates four categories of assets.

- Maritime OT: Valencia Port site uses 5G-NR radars, including berthing assistance and vessel detection systems. These assets stream real-time maritime traffic data to the data management platform located in the port.
- Urban Traffic OT: High-resolution traffic radars are deployed within the Valencia City sensing domain to monitor vehicle flow and congestion. These units communicate via 5G-NR connectivity.
- Environmental IoT: This category includes air quality sensors and water level radars located in the Almussafes municipality.
    - Air quality sensors: use LoRaWAN for energy-efficient transmission of environmental pollutants.
    - Water level radars: use commercial NB-IoT/CAT-M connectivity to provide critical data for the site's flood warning system.
- Resource Management IoT: A network of fill-level sensors is deployed across the UPV Campus for smart waste management. These devices use NB-IoT to transmit container capacity data, enabling optimized collection routes.
- Facility IoT: Smart building sensors are integrated into the Valencia City domain. These sensors capture occupancy and environmental data within municipal buildings using LoRaWAN, providing a baseline for facility energy optimization.

All field-resident services and applications are deployed as Kubernetes containerized microservices managed through the COP-PILOT orchestration platform.

6.2 KEY WORKFLOWS AND DATA PATHS

Cluster 2 implements a series of active workflows that cross the full technology stack, from field-level sensing and OT assets to near-edge intelligence and centralized orchestration. These workflows follow a consistent architectural pattern: Field Assets (Radars/Sensors/IoT Agents) → Data Management (Orion Context Brokers) → Intelligence/Validation (Smart City Stack/Microservices) → Orchestration (Domain Orchestrator/OpenSlice) → Dynamic Response/Alerting.

Connectivity between local resources and the COP-PILOT Central layer is secured via the Secure Integration Fabric (SIF) using OpenZiti tunnels to ensure encrypted and authenticated communication for orchestration and lifecycle management.

Four primary workflows defined the operational logic of the cluster:

Workflow 1: Multi-modal Environmental Alerting (UC2.2, UC2.4A & UC2.4B)
This workflow integrates diverse environmental data to provide real-time situational awareness for municipal and campus management. The process begins with the continuous collection of air quality data in Almussafes and Valencia City (via Open Data), room occupancy in buildings in Valencia City, and waste fill-level information across the UPV Campus, all of which are transmitted through IoT Agents to the local Orion Context Broker located in UPV compute domain. The entities received in the Orion Context Broker are forwarded to the Smart City Stack, which serves as the intelligence layer, monitoring these incoming data streams against predefined environmental and operational thresholds. When a threshold is reached, the stack triggers the Domain Orchestrator (OpenSlice) to dynamically deploy an Alert Notification Service. This service ensures that critical events, such as high pollutant levels or overflowing waste containers, are immediately communicated to the relevant external users or municipal operators through alerts and the platform dashboard.

Workflow 2: AI-driven Urban Traffic Validation (UC2.1A)
This workflow leverages 5G connectivity and computer vision to validate traffic congestion events within the Valencia City domain. High resolution 5G Traffic Radars continuously monitor vehicle flow and report potential congestion anomalies to the Orion Context Broker. To minimize false positives, the Smart City Stack does not alert immediately; instead, it initiates a verification loop by requesting the deployment of a YOLO-based Validator service. The Domain Orchestrator provisions this AI microservice onto the local compute infrastructure in UPV, where it captures and processes RSTP video streams from the city's traffic camera network. Only after the AI model visually confirms the traffic jam does the platform trigger a Notification Service to alert external users and municipal traffic management authorities, providing a high-confidence operational baseline.

Workflow 3: Dynamic Maritime Resource Provisioning (UC2.3)
Focusing on the Valencia Port testbed, this workflow coordinates 5G network resources with real-time maritime traffic arrivals. The cycle is initiated when Ship Detection Radars at the port identify an approaching vessel and forward the detection data to the Orion Context Broker. The platform then performs a cross-data fusion, checking the radar signals against external port data, such as AIS NMEA and FVP Portcalls APIs, to confirm if the vessel is scheduled for a monitored dock. Upon confirmation of a docking maneuver, the Smart City Stack issues a request for specialized resources, leading the Domain Orchestrator to interact with the 5G Controller to provision a dedicated, low-latency network slice. Simultaneously, the orchestrator deploys Berthing Assistance Radars that use the new 5G slice to provide the vessel and port pilots with high-precision, real-time telemetry for safe docking.

Workflow 4: Adaptive Flood Monitoring (UC2.1B)
This workflow provides predictive environmental protection by adjusting sensor behaviour based on external weather forecasts. The system polls External Weather Data from AEMET to monitor for flood risks or heavy precipitation alerts in the Almussafes region. If a significant meteorological risk is identified, the Smart City Stack initiates a proactive optimization by triggering a Frequency Modifier Service Order. The Domain Orchestrator then deploys a specialized service that reconfigures the local Water-level Radars, increasing their sampling and transmission frequency over the backhaul

to provide near-continuous monitoring. If the water levels exceed safety thresholds during this heightened monitoring phase, the system automatically escalates the event by deploying a Notification Service to trigger emergency response protocols.

6.3 CHALLENGES AND CONSTRAINTS

The integration of Cluster 2 with the general platform presents specific technical and organizational challenges, primarily driven by the diversity of its administrative domains and the variety of its IoT/OT assets. The following table summarizes the primary challenges and the corresponding mitigation strategies implemented within the cluster.

Table 9: Cluster 2 breakdown of potential challenges and constraints

#	Challenge	Detail
1	**Multi-stakeholder Jurisdictional Governance**	Cluster 2 operates across four distinct administrative entities: Fundación Valenciaport (FVP), Universitat Politècnica de València (UPV), Valencia City (VCH), and the Almussafes Municiapality (ALM). Each domain maintains its own data ownership policies, security protocols, and legal frameworks for public-space monitoring. To mitigate this, role-based access control (RBAC) and specific data-sharing agreements have been stablished. The platform ensures that while orchestration is centralized, the actual data ownership and governance remain decentralized within each domain's local Orion Context Broker.
2	**Data Standardization and Semantic Mapping**	The cluster integrates high-resolution maritime radars, urban traffic sensors, and environmental devices using different data formats and proprietary protocols, as well as External Open Data. Harmonizing these into a unified NGSI-LD data fabric requires complex semantic mapping to ensure interoperability within the Orion Context Broker. Mitigation involves the deployment of IoT Agents that act as protocol translators, normalizing diverse telemetry into standardized entities before they reach the data management layer.
3	**Architectural Alignment of Management and Data Planes**	As identified during initial integration, a clear distinction must be maintained between the management plane (centralized orchestration) and the data plane (local cluster traffic). The Secure Integration Fabric is used as the management link between the End-to-End Orchestrator and the local Domain Orchestrators, while intra-cluster data flows rely on local 5G, LTE, and LoRaWAN infrastructure. This alignment ensures that heavy data streams do not congest management tunnels.
4	**Heterogeneous Connectivity and Hybrid Backhaul**	The cluster relies on a mix of Private 5G networks (Port and UPV), Public 5G/LTE, and LoRaWAN/NB-IoT. Ensuring consistent end-to-end latency for real-time workflows (such as maritime berthing or flood alerts) across these heterogeneous networks is a significant constraint. Mitigation includes the use of local compute nodes to process critical logic at the edge, reducing the reliance on long backhaul and providing local data buffering during temporary connectivity loss.
5	**AI Model Training and Cold-start Reliability**	Workflows involving YOLO-based traffic validation and AEMET-driven flood monitoring require high precision models that often face a "cold-start" problem due to limited initial training data for specific local anomalies. To mitigate potential inaccuracies, the cluster employs human-in-the-loop protocols, where AI-generated alerts (such as a detected traffic jam or flood risk) are verified against external data sources (RTSP streams or manual operator confirmation) before triggering high-impact municipal notifications.
6	**Integration with Legacy and**	The cluster must synchronize with several external and legacy systems, including AIS NMEA maritime data, the FVP Portcalls API, and the AEMET weather service.

	External Data Systems	Differences in update frequencies and API structures between these external providers and the internal platform can lead to data staleness. The Smart City Stack addresses this implementing adaptive polling mechanisms and data fusion logic to reconcile real-time-sensor data with asynchronous external updates.

6.4 INTEGRATION OF COP-PILOT CAPABILITIES, COMPONENTS AND SERVICES

Cluster 2 incorporates a wide array of COP-PILOT platform features to manage its geographically dispersed sensing and computing sites. The integration strategy prioritizes a clear separation between the central orchestration logic and the local execution of containerized services. The architecture is anchored by the FIWARE Orion Context Broker for multi-domain data management, while Secure Integration Fabric (SIF) serves exclusively as the secure bridge for management and lifecycle traffic between the central End-to-End Orchestrator and the local Domain Orchestrators.

The following table details the specific platform capabilities in scope and the requirements for cluster-level exposure and consumption:

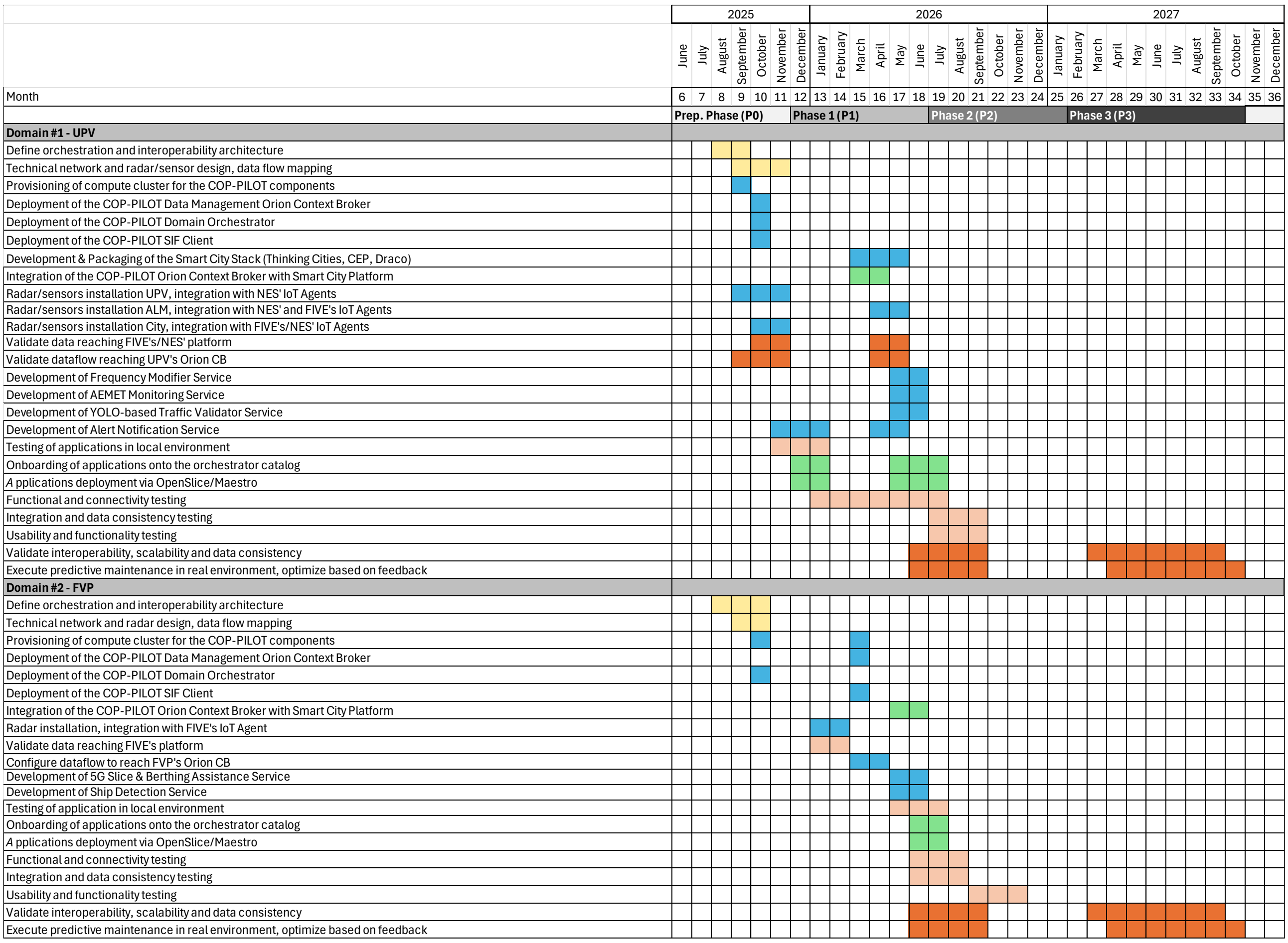
Table 10: Cluster 2 breakdown of COP-PILOT capabilities and their scope

COP-PILOT Capability	Scope (UCs)	Cluster Must Expose / Consume
End-to-End Service Orchestration (ESO / Maestro)	All six UCs. Deploy and lifecycle-manage containerised microservices across all Cluster 2 domains, coordinating cross-domain workflows sensing to execution.	**Expose:** endpoint metadata, resource requirements per service, and service blueprints (Helm charts) for: • Smart City Stack service • Alert Notification service • AEMET monitoring service • Frequency Modifier service • Ship Detection service • 5G Slice & Berthing Assistance service • YOLO-based Verification service **Consume:** multi-domain Helm-as-a-Service deployment API; service registry; cross-domain SLA monitoring.
Domain Orchestration (DO / OpenSlice)	All six UCs. Manage compute service provisioning and lifecycle at each near-edge Kubernetes domain (Universitat Politècnica de València and Fundación Valenciaport)	**Expose:** Kubernetes cluster endpoints at UPV and FVP. **Consume:** K8s-as-a-Service and single-domain Helm-as-a-Service APIs; dynamic resource allocation and scaling interfaces per domain.
5G Network Slice Management (DO / OpenSlice + 5G Controller)	UC2.3. Enable low-latency, high-reliability 5G connectivity for 5G Berthing Assistance Radars at FVP domain.	**Expose:** FVP 5G Slice Manager interface; Open5GS 5G Core configuration. **Consume:** dynamic 5G slice selection and configuration API via OpenSlice.
Data Management (FIWARE / Orion-LD)	All six UCs. Ingest, route, and manage heterogeneous data streams from sensors/radars,	**Expose:** structured NGSI-LD data streams from traffic radars, water level radars, maritime traffic and berthing assistance radars, waste container

	through a unified NGSI-LD interoperability fabric.	sensors, building occupancy sensors and environmental monitoring sensors. **Consume:** FIWARE Orion-LD context broker for data routing and subscription; federated data ingestion pipelines; data access APIs for cross-domain service consumption.
Secure Integration Fabric (SIF / OpenZiti)	All six UCs. Ensure end-to-end encrypted, authenticated communication between all Cluster 2 domains and the COP-PILOT Central layer, with network isolation enforced across domain boundaries.	**Expose:** domain credentials and access policies per Cluster **Consume:** TLS-secured inter-domain tunnels; zero-trust network access enforcement.

6.5 INTEGRATION & DEVELOPMENT PLAN

The integration and development roadmap for Cluster 2 is structured to ensure a progressive transition from local infrastructure readiness to centralized, multi-domain orchestration.



The Gantt chart is partitioned into two primary operational streams: Domain #1 (UPV) and Domain #2 (FVP), to reflect the geographical and administrative separation of the testbeds. Each stream follows a layered maturity model:

- Infrastructure baseline: Rows covering the provisioning of Kubernetes clusters and the deployment of COP-PILOT core components (Orion CB, Domain Orchestrator, and SIF Client).
- Software stack & service development: Specific rows for the packaging of the Smart City Observability Stack and the coding of domain-specific intelligence.
- Integration & testing: Tasks dedicated to mapping data flows to NGSI-LD and validating the management plane links between local and central orchestrators.
- Validation: Performance testing, KPI measurement, and predictive maintenance optimization.

6.6 USE CASE DEVELOPMENT STATUS

Table 11: Breakdown of use cases in Cluster 2 and their development status up to M20

Functional Capability	Development Status at M20	Outstanding Items
5G Connected Radars for Traffic Classification and Vehicle Counting (UC2.1A)	Traffic radars deployed in the planned locations. Measurements collected and forwarded to the Orion-CB on UPV domain. Development of traffic jam detection solution integrating video from traffic camera has started.	Revision of disconnected radar. Final traffic-jam detection solution container for deployment by the orchestrator.
Flood Warning and Mitigation via Radar Sensing (UC2.1B)	Sensors deployed on strategic locations coordinated with Almussafes's personnel. Collection of measurements validated and example of flood event captured. Initial solution of integration of meteorological data for more accurate measurement period being developed.	Improvement on variability of measurements through firmware upgrade of devices. Integration of meteorological data for dynamic sensing periods configuration.
Smart Resource Management at UPV Campus (UC2.2)	Sensors have been deployed on grey waste containers selected by the UPV's Environmental Unit. To optimize installation and measurement accuracy, a custom support system was developed. Data is collected periodically and integrated with the Orion Context Broker within the UPV domain.	Final validation of fill-level measurement consistency. Integration with the project's alert and notification system. Long-term assessment of sensor connectivity and battery performance.
Maritime Traffic Monitoring and Berthing Assistance (UC2.3)	Development of the maritime data enrichment module based on the AIS system and the port call API from the Valenciaport Foundation. Deployment of OpenSlice, Orion CB-LD, and SIF. Installation of ship detection radars and integration of messages through Orion CB-LD. Q&A testing of the applications and initial functional testing.	Refactoring based on the bugs identified and deployment of the applications on Kubernetes (K8s). Initial tests with OpenSlice to manage the network and create new slices in the private 5G network. End-to-end system testing and network performance testing of the system connected to port radars.
IoT-Driven Smart Building	Installation of people-counting sensors at "La Harinera" building to complement legacy	Full validation of occupancy data accuracy. Development and

Functional Capability	Development Status at M20	Outstanding Items
Management (UC2.4A)	environmental sensors. Occupancy data successfully integrated and forwarded to the Orion Context Broker. Initial data acquisition and installation validation phase ongoing.	integration of the automated alert system. Cross-analysis of occupancy levels with existing environmental parameters.
IoT-Based Environmental Quality Monitoring System (UC2.4B)	Ongoing installation of formaldehyde (gas) sensors at Almussafes Industrial Park for early incident detection. Initial configuration of data transmission towards the project's central architecture.	Completion of hardware deployment and connectivity verification. Integration with the project's alert system for early warning notifications. Calibration of sensors within the industrial environment.

6.7 INTEGRATION & DEPLOYMENT STATUS

Cluster 2 has achieved an advanced level of functional integration, with the foundational orchestration and data management layers now active across the UPV Campus and Valencia Port compute domains. The Secure Integration Fabric (SIF) provides the management link to the central platform while local Kubernetes clusters host the primary intelligence and service logic.

While the core infrastructure is operational and receiving initial data streams, several domain-specific services are currently in the development and configuration phase.

Table 12: Deployment status of components and development of services within cluster 2

Component / Interface	Status at M20	Evidence / Remarks
Domain Orchestrators (OpenSlice)	Deployed & operational	Active in both domains; the UPV instance has been successfully used for service tests, while the Port instance is currently being linked to the central End-to-End Orchestrator.
Orion Context Broker (FIWARE)	Deployed & operational	Both instances are installed, the UPV broker is actively receiving telemetry, while the Port broker is undergoing final configuration to receive maritime data.
SIF Client (OpenZiti)	Deployed	Installed in both domains, configuration for the Port domain is currently being finalized to ensure full management.
Compute Infrastructure (K8s)	Deployed & operational	Kubernetes clusters are fully operational across both primary compute domains to support containerized microservices.
Smart City Stack (1) (Core Logic)	Operational	The core logic is usable and active; currently undergoing upgrades and refinements to support additional cross-domain features.
Notification Service	Deployed & operational	Service is functional; however, iterative changes are expected as the alerting workflows are consolidated.
YOLO-based Verification Service	In progress	AI model and containerized service are under development for the traffic validation loop.

Co-funded by the European Union

Component / Interface	Status at M20	Evidence / Remarks
5G Slice & Berthing Assistance	In progress	Interface logic for the 5G Controller and berthing telemetry is under development.
Ship Detection Service	In progress	Currently being configured to process radar data and integrate with the Orion Context Broker.
Frequency Modifier Service	In progress	Logic for adaptive sensor sampling is being implemented for the flood monitoring loop.
AEMET Monitoring Service	In progress	Ingestion pipeline for external weather forecasts is currently being integrated into the data fabric.

TID has developed a completely new stack from the ground up to replace the Thinking City product. This new solution is called SmartCity.

Please find below a brief description.

SmartCity –The SmartCity Stack provides a comprehensive, end-to-end platform for Smart City deployments, integrating core services, real-time event management, advanced visualisation, open data capabilities, and AI-driven functionalities. It is designed to support scalable, interoperable, and data-driven urban services.

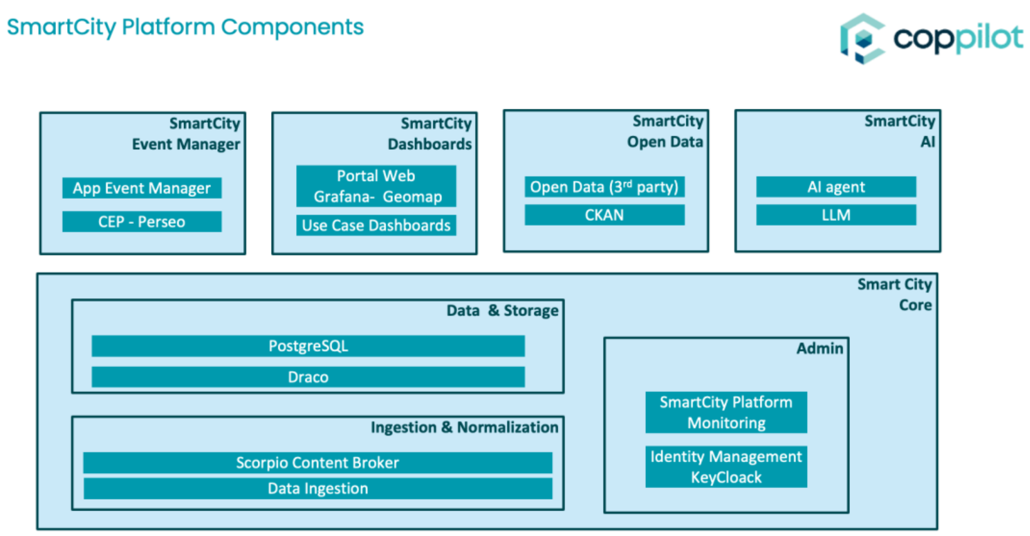


Figure 6-2: SmartCity Platform Components Diagram

SmartCity Platform components are:

SmartCity Core – The SmartCity Core constitutes the foundational layer of the platform, enabling robust data ingestion, context management, and persistent storage leveraging PostgreSQL. It further incorporates identity and access management (IAM) mechanisms, as well as platform monitoring capabilities to ensure operational reliability and governance.

SmartCity Event Manager – The SmartCity Event Manager delivers real-time event processing and orchestration. It supports the definition of complex rules, detection of multi-condition events, and the automated triggering of external actions, including seamless integration with external systems via TMF-compliant APIs.

SmartCity Dashboards – The SmartCity Dashboards component provides the visualisation layer of the platform. Through direct integration with PostgreSQL, it leverages Grafana to deliver real-time monitoring, analytics, and interactive visualisations, including charts, geospatial maps, and operational dashboards.

SmartCity Open Data – The SmartCity Open Data module facilitates the publication, sharing, and consumption of open datasets through CKAN-based extensions, promoting transparency, interoperability, and data reuse across stakeholders.

SmartCity AI – The SmartCity AI module introduces AI-driven interaction capabilities via a chatbot-based portal. It enables users to query the platform using natural language, supporting advanced data interpretation and access to insights derived from stored datasets.

7 CLUSTER 3A — AGRITECH TRANSFORMATION AND SUSTAINABILITY INITIATIVE (ATSI) (GREECE)

7.1 CLUSTER INFRASTRUCTURE & DOMAINS

Cluster 3A, the AgriTech Transformation and Sustainability Initiative (ATSI) is a distributed, multi-domain piloting environment spanning seven operational domains across Greece. The cluster is anchored in the Kilkis region of Central Macedonia, where Barba Stathis (BAR) contractual spinach cultivation fields serve as the primary testbed. Domain boundaries extend to Thessaloniki, Athens, and a set of moving logistics domains covering the farm-to-industry and industry-to-market transport legs. The overall architecture is illustrated in Figure 7-1, which maps the physical sites, domain boundaries, compute nodes, connectivity infrastructure, and COP-PILOT platform components deployed across the cluster.

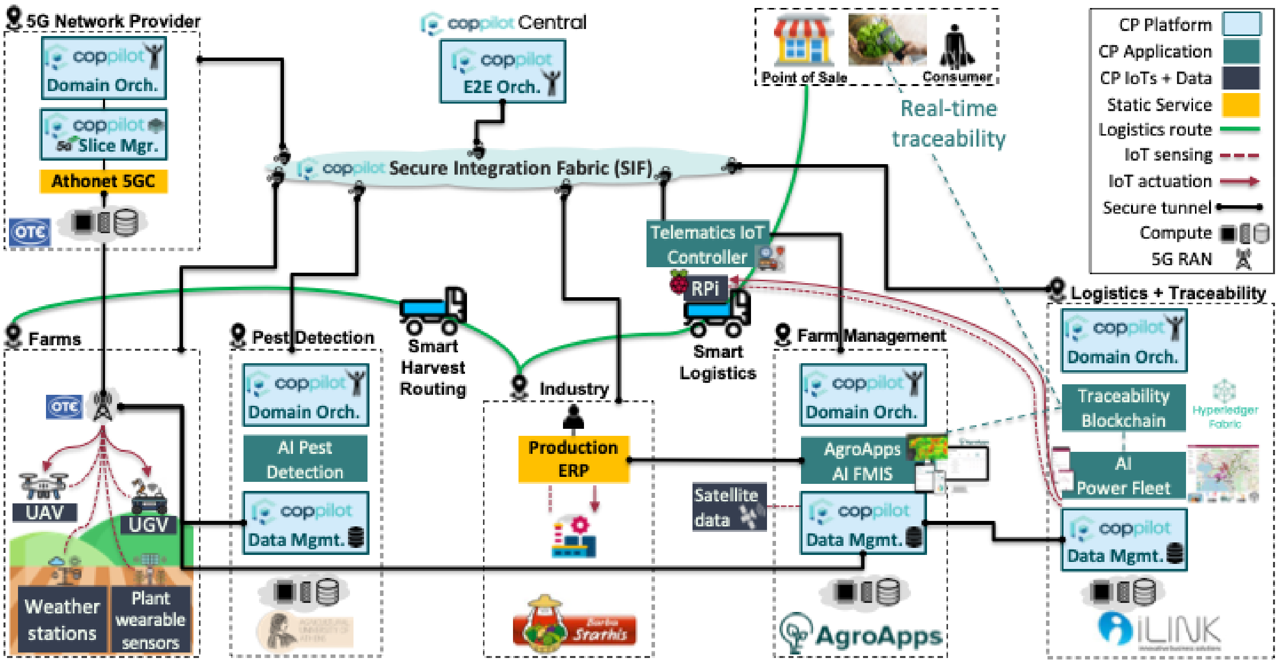


Figure 7-1 Cluster3A Architecture Diagram

In the following table we summarise the seven domains, their physical locations, roles, deployed hardware, and connectivity arrangements.

Site	Domain / Operator	Hardware	Connectivity
Kilkis, Central Macedonia Farm testbed	Farm Domain / Barba Stathis (BAR) contractual farms	Spinach plots; network of weather stations; DJI Matrice 350 RTK UAV with MicaSense RedEdge multispectral camera; UGV (SFT Group) for precision spraying; electrochemical plant wearable sensors	OTE public 5G (Phase 1); OTE 5G MPN via Ericsson RAN on-site (Phase 2 target) HTTPS for sensor data streams; IoT sensing and actuation over 5G uplink

Sindos, Thessaloniki Processing facility	Industry Domain / Barba Stathis (BAR)	Production ERP system managing batch intake, processing, and packaging operations	REST APIs for ERP integration; FIWARE Orion-LD for data exchange with AgroApps and iLink
Thessaloniki FMIS & analytics	Farm Management Domain / AgroApps (AGA)	Kubernetes compute cluster (near-edge); AgroApps 360 AI FMIS; COP-PILOT Data Management Platform (FIWARE/Orion-LD); Domain Orchestrator (OpenSlice); Copernicus Sentinel-2 satellite data integration	Public internet; HTTPS/REST APIs; OpenZiti secure tunnel to SIF
Athens AI robotics	Pest Detection Domain / Agricultural University of Athens (AUA)	Kubernetes compute cluster (near-edge); AI pest detection and weed segmentation service; COP-PILOT Data Management Platform (FIWARE/Orion-LD); Domain Orchestrator	Public internet; FIWARE Orion-LD southbound from farm UAV/UGV data streams; OpenZiti secure tunnel to SIF
Athens Blockchain & logistics	Logistics & Traceability Domain / iLink	Kubernetes compute cluster; Hyperledger Fabric blockchain nodes (permissioned ledger); PowerFleet JIT routing platform (Routing-as-a-Service); COP-PILOT Data Management Platform; Domain Orchestrator	Public internet; GNSS/HTTPS for vehicle telematics ingestion; OpenZiti secure tunnel to SIF; REST/OpenAPI 2.0 for ERP and FMIS integration
Athens (core) & Kilkis (RAN) 5G infrastructure	5G Network Provider Domain / OTE	Athonet 5G Core Network; 5G Slice Manager (integrated with OpenSlice); Ericsson RAN base station at farm site; OpenStack cloud infrastructure	5G NR radio backhaul from farm to OTE core; OpenSlice & OTE Slice Manager API for dynamic slice management (Phase 2 target); secure tunnel to COP-PILOT Central
Mobile domains Kilkis ↔ Sindos & Sindos ↔ Points of Sale	Moving Domains / iLink	Refrigerated transport vehicles equipped with Raspberry Pi 5 edge nodes (Ubuntu Server + k3s), GNSS modules, and a temperature sensor; Telematics IoT Controller	5G/LTE public connectivity for telemetry uplink; MQTT/HTTPS to PowerFleet, which forwards relevant events (load, unload, threshold deviations) to the Hyperledger Fabric ledger

Compute tiers

Cluster 3A operates across four compute tiers.

1. Central cloud: the COP-PILOT Central end-to-end orchestrator and the OTE OpenStack infrastructure provide the top-level service management and 5G core functions.
2. Near-edge: Kubernetes clusters at AgroApps (Domain 3), AUA (Domain 4), and iLink (Domain 5) host containerised microservices, the FMIS, AI pest detection, PowerFleet routing engine, and Hyperledger Fabric nodes, enabling service execution close to domain boundaries while maintaining orchestration connectivity to the COP-PILOT platform.

3. Far-edge: RPi 5 nodes on logistics vehicles (Domain 7) act as onboard data acquisition and forwarding units, buffering telematics data locally during transit and forwarding timestamped temperature and GNSS readings to PowerFleet over the public 5G/LTE network.
4. Field level: the UAV onboard computer performs initial image capture and telemetry packaging; the UGV runs edge AI inference (weed classification, dosage optimisation) directly on its onboard processor, enabling autonomous decision-making in low-connectivity conditions.

IoT/OT categories. The cluster integrates five categories of IoT and OT assets.

- Environmental IoT: weather stations at the Kilkis farm site continuously stream microclimate data (air temperature, humidity, rainfall, solar radiation, wind speed, soil moisture) to the FIWARE Orion-LD broker.
- Plant IoT: TOR Vergata electrochemical wearable sensors attached to representative spinach plants transmit biochemical readings, including oxalate (antinutrient) concentration and stress indicators, at defined sampling intervals.
- Aerial IoT/OT: the DJI Matrice 350 RTK UAV captures high-resolution multispectral and RGB imagery over the spinach plots; image sets are transferred to the FMIS and the AI pest detection service via FIWARE.
- Ground robotics OT: the AUA UGV, equipped with onboard cameras, LiDAR, and GPS, performs semi-autonomous field navigation and precision spot-spraying; it receives tasking commands via FIWARE and returns execution reports and imagery to the platform.
- Logistics IoT: GNSS modules and a temperature sensor on transport vehicles continuously report cargo location and temperature to the PowerFleet platform, which acts as the blockchain writer and commits relevant events (load, unload, threshold deviations) to the Hyperledger Fabric ledger, supporting end-to-end supply chain visibility from harvest to point of sale.

All field-resident services and applications are deployed as Docker/Kubernetes containerised microservices managed through the COP-PILOT orchestration platform.

7.2 KEY WORKFLOWS AND DATA PATHS

Three primary workflows operate across Cluster 3A, each traversing the full technology stack from field-level sensing through edge AI processing, platform orchestration, and supply chain execution. Together, they follow a common architectural pattern: field assets (sensors, UAV, UGV) to FIWARE Orion-LD data fabric to near-edge domain services (FMIS, AI pest detection, PowerFleet) to COP-PILOT orchestration layer and to operator dashboard / downstream supply chain actors. A cross-cutting secure data management and blockchain traceability layer underpins all three, ensuring data integrity and auditability at every stage of the agricultural value chain.

Workflow 1: Integrated Crop Monitoring and Precision Intervention (UC3A.1 & UC3A.2)
The workflow begins at the start of each spinach cultivation cycle, when BAR agronomists register the contracted farm parcels in AgroApps 360. Farmers then indicate the start of the cultivation season through the platform, activating the continuous monitoring pipeline for their registered parcels. Throughout the cultivation cycle, farmers log every field activity they perform, irrigation events, fertilisation doses, crop protection applications, and other cultivation operations, directly into AgroApps 360. The platform aggregates these activity records with sensor and satellite data to continuously calculate the environmental footprint of each parcel, tracking metrics such as water use, chemical input load, and carbon-related indicators per unit of production. BAR agronomists, operating remotely from Thessaloniki, monitor all contracted parcels through AgroApps 360, gaining

continuous visibility over crop conditions, input use, and field-level events across the Kilkis testbed without the need for frequent physical site visits. Weather stations at the Kilkis site stream environmental parameters, air temperature, humidity, rainfall, solar radiation, wind speed, and soil moisture, in near-real-time to the FIWARE Orion-LD broker at the Farm Management domain. Simultaneously, Copernicus Sentinel-2 satellite imagery is automatically retrieved and processed by AgroApps 360 to generate vegetation indices (NDVI and related) over the registered parcels, providing a macro-level baseline of crop development.
Following plant emergence, TOR NFC-based electrochemical wearable sensors are deployed on representative spinach plants. These sensors transmit biochemical readings, primarily oxalate concentration as a proxy for antinutrient accumulation and plant stress, through the over OTE public 5G to the FIWARE broker (Phase 2: via 5G MPN) to the FIWARE broker, where they are ingested by AgroApps 360 for integration with the broader crop health dataset.
At scheduled intervals, or on demand when FMIS anomaly thresholds are triggered, BAR agronomists launch UAV missions. The UAV executes a pre-planned flight path over the spinach plots, capturing high-resolution multispectral imagery. Upon completion, the images are transmitted over OTE public 5G to FIWARE (Phase 2: via 5G MPN), to FIWARE and onwards to both AgroApps 360 and the AUA Pest Detection service. AgroApps 360 computes vegetation indices and crop zone maps, while the AUA AI service performs object-based image classification to generate weed/crop/soil segmentation maps and estimate weed cover percentage per plot zone.
At this point, the workflow branches into two intervention scenarios depending on whether the UAV-based assessment alone is sufficient to trigger UGV deployment, or whether an independent UGV inspection is required first.

Scenario A: UAV-triggered UGV tasking. When the UAV-derived weed cover assessment exceeds a pre-defined agronomic threshold, the FMIS generates an intervention recommendation via the COP-PILOT orchestration layer. A tasking command, including GPS-tagged coordinates of the infested zones and a weed pressure map, is transmitted to the UGV through FIWARE. The UGV navigates autonomously to the flagged zones and, following human operator confirmation via the FMIS interface, proceeds directly to precision spot-spraying of the identified areas.

Scenario B: UGV-led inspection and confirmation. When weed pressure from the UAV assessment is inconclusive, or when a proactive ground-level inspection is required, the UGV is dispatched to the zones of interest without a pre-confirmed spraying mandate. The UGV navigates to the tafed (Copernicus mission satellite data) indices, and FMIS predictive models converge on harvest readiness, AgroApps 360 compiles a harvest readiness report and notifies BAR agronomists and the logistics supervisor, as well as the iLink -Powerfllet system to initiate Workflow 2.

Workflow 2: Smart Harvest Routing and JIT Logistics (UC3A.4, From Farm to Industry to the Market)
Upon receiving the harvest readiness event from AgroApps 360, the PowerFleet platform (iLink, Domain 5) computes an optimal harvesting and dispatch plan. This plan is communicated to BAR's harvester fleet: harvesters are routed to the specific Kilkis farm parcels identified as ready, with GPS-tagged coordinates and timing windows derived from the FMIS crop maturity data. Harvest operations are executed by BAR's harvesters on the designated plots, and completion events are logged by AgroApps 360 and registered on the Hyperledger Fabric blockchain ledger.
Following harvesting, BAR's trucks are loaded with the freshly harvested crop at the farm. PowerFleet computes and communicates the optimal route for each loaded truck to reach the Barba Stathis processing facility gate in Sindos, Thessaloniki, minimising transit time, fuel consumption, and quality degradation/exposure risk. During transit, IoT sensors aboard the vehicles continuously monitor and transmit cargo geolocation data via 5G/LTE to the PowerFleet platform and to the FIWARE broker. PowerFleet monitors this telemetry in real time against freshness thresholds; if a

deviation is detected, the orchestration layer is notified and PowerFleet recalculates the optimal route or triggers an alert to the logistics operator.
On arrival at the Sindos processing facility, each batch is unloaded, weighed, inspected, and processed. The Production ERP registers the batch intake, linking it to the AgroApps crop calendar and the iLink blockchain. Each packaged unit is assigned a unique code linked to its full lifecycle record on the Hyperledger Fabric ledger, covering field origin, cultivation inputs, transport conditions, and processing metadata.
Packaged products are then dispatched (when the orders are to be fulfilled) to retail or wholesale points of sale via the Industry-to-Market moving domain. PowerFleet computes outbound delivery routes dynamically, accounting for delivery priorities, distances, and time windows. Telematics data continues to flow during this leg, and final delivery events are recorded on the blockchain. At the retail point of sale, consumers can scan the QR code to access the complete, tamper-proof product traceability record.

Workflow 3: Secure Data Management and Blockchain Traceability (UC3A.3 & cross-cutting)
This workflow is not a sequential process but a continuous, cross-cutting data governance layer that underpins Workflows 1 and 2. All significant operational events, sensor readings, UAV mission outputs, UGV intervention logs, farmer activity records, harvest registrations, batch packaging events, transport telemetry milestones, and delivery confirmations, are signed and timestamped by iLink's Hyperledger Fabric infrastructure. AgroApps 360 acts as the primary data collector and blockchain writer for field-side events, while BAR ERP/WMS manages the processing transformation (raw to processed and then packaged) and PowerFleet manages the logistics-side event chain.
Data flows between domains through the FIWARE Orion-LD context broker, which acts as the shared interoperability fabric. Each domain exposes its services and data via standardised NGSI-LD interfaces, and the COP-PILOT Secure Integration Fabric (SIF), implemented via OpenZiti, ensures that all inter-domain communication is encrypted and authenticated end-to-end. The COP-PILOT Domain Orchestrators deployed at each compute domain manage service lifecycle, whilst the End-to-End Orchestrator at the COP-PILOT Central layer coordinates cross-domain workflows, monitors SLA compliance, and triggers automated responses to deviations. Role-based access control enforced across the platform ensures that each actor, farmer, agronomist, logistics operator, consumer, accesses only the data and services relevant to their role.

7.3 CHALLENGES AND CONSTRAINTS

The following challenges and constraints, ranked by potential integration impact, have been identified as capable of affecting the full realisation of Cluster 3A activities. Cluster 3A partners have already designed mitigation actions to address each, should they materialise.

#	Challenge	Detail
1	**5G MPN coverage and rural connectivity**	The primary testbed is located in the Kilkis agricultural region, where stable wide-area wireless connectivity cannot be assumed across all farm parcels. UAV, UGV, and IoT sensor operations depend on low-latency, high-reliability 5G connectivity provided by the OTE private mobile network. Partial coverage gaps, signal attenuation due to terrain or crop density, and connectivity interruptions during critical field operations must be handled without loss of operational continuity. OTE is deploying the Ericsson RAN base station directly at the farm site as part of the Phase 2 5G MPN rollout to maximise on-field coverage, and local data buffering mechanisms at the edge nodes ensure that field operations and data collection continue uninterrupted during transient connectivity loss. In addition, OTE's public 5G network is available as a failsafe connectivity layer,

		providing a fallback uplink path for sensors, UAV, and UGV data transmission in the event of private MPN degradation or outage
2	**Seasonal and weather-dependent operation windows**	Spinach cultivation in Central Macedonia follows a narrow seasonal calendar, constraining the available windows for field integration testing, UAV missions, UGV trials, and end-to-end pilot execution to specific months of the year. UAV flight operations are additionally subject to wind speed, precipitation, and visibility conditions, which can disrupt planned missions and reduce the frequency of aerial data collection. The Cluster 3A pilot planning explicitly aligns integration phases with the spinach cultivation calendar, and Copernicus Sentinel-2 satellite imagery is used as a fallback data source when UAV flights cannot be executed. Furthermore, the UGV can complement or substitute UAV operations when flight is not possible, performing ground-level field inspection and, where conditions allow, targeted intervention autonomously, ensuring continuity of monitoring and response capability regardless of aerial availability.
3	**Heterogeneous device, protocol, and infrastructure diversity**	The cluster integrates a wide range of device types (NFC-based plant wearables, weather station networks, multispectral UAVs, AI-enabled UGVs, vehicle-mounted GNSS and RPi units, and industrial ERP systems) operating across different communication protocols and hosted on heterogeneous compute environments spanning Kubernetes clusters, OpenStack, and RPi edge nodes. Harmonising these into a unified platform whilst maintaining real-time data quality across seven domains adds significant integration complexity. FIWARE Orion-LD has been adopted as the shared interoperability fabric across all domains, with API harmonisation and data schema alignment completed early in the preparatory phase, and all cluster services are packaged as HELM charts for consistent deployment across heterogeneous infrastructure.
4	**AI model cold-start and training data scarcity**	The AUA weed detection and segmentation models, and the AgroApps - TOR antinutrient models, require field-specific training datasets that can only be accumulated progressively through actual pilot seasons. In the early integration cycles, limited historical data increases the risk of model underperformance on rare or edge agronomic conditions, such as atypical weed species distributions or unusual soil chemistry. To mitigate this, baseline datasets have been collected during preparatory field runs, human-in-the-loop confirmation protocols are embedded in both intervention scenarios to catch model errors before execution, and iterative model retraining is planned across successive cultivation seasons to progressively improve detection accuracy and reduce false positives.
5	**UGV autonomous operation and regulatory constraints**	Agricultural fields present unpredictable operational conditions including uneven terrain, variable crop density, GPS signal interference, and obstacle variability, all of which affect semi-autonomous UGV navigation and precision spraying reliability. Importantly, the current EU and national regulatory framework governing the operation of autonomous ground vehicles in open agricultural environments does not permit full unsupervised autonomy; human oversight and explicit confirmation are legally required before any intervention is executed. Both intervention scenarios in Cluster 3A explicitly embed a mandatory human operator confirmation step before any spraying action is undertaken, ensuring full regulatory compliance regardless of AI confidence levels. Initial field trials conducted by AUA have already validated UGV mobility and detection accuracy under realistic farm conditions at the Kilkis testbed, and the human-in-the-loop architecture is designed to remain compliant as the regulatory landscape evolves.
6	**Multi-stakeholder data governance, blockchain integration and**	Cluster 3A spans multiple data owners (BAR, AgroApps, AUA, iLink, OTE, and TOR) each with distinct data sensitivity levels, access rights, and regulatory obligations, whilst the Hyperledger Fabric permissioned ledger introduces configuration and operational complexity in coordinating Certificate Authorities, peer nodes, and chaincode across organisations with varying blockchain

	cross-actor adoption	expertise. It should be noted that Hyperledger Fabric is not natively supported by FIWARE, requiring iLink to develop and maintain a dedicated integration layer to bridge blockchain events and traceability data into the FIWARE Orion-LD context broker, adding an additional point of complexity in the overall data architecture. Onboarding downstream actors such as logistics operators, retailers, and certification bodies into the traceability framework further requires organisational alignment that extends beyond the technical integration scope. Hyperledger Fabric private data channels are used to isolate commercially sensitive information while preserving shared auditability, and a phased onboarding approach is planned for downstream actors, beginning with BAR and iLink and progressively extending to retail and certification partners in later pilot phases.

7.4 INTEGRATION OF COP-PILOT CAPABILITIES, COMPONENTS AND SERVICES

Cluster 3A engages the full breadth of the COP-PILOT platform stack, spanning orchestration, connectivity, data management, security, and decision support layers. The cluster's multi-domain architecture, combining field IoT, aerial and ground robotics, blockchain traceability, and JIT logistics across seven distributed domains, requires coordinated deployment and lifecycle management of services through both the End-to-End and Domain Orchestrators. Data interoperability across heterogeneous assets is achieved through the FIWARE Orion-LD fabric, whilst the Secure Integration Fabric enforces encrypted, authenticated communication across all domain boundaries. The table below summarises which COP-PILOT platform capabilities are in scope for Cluster 3A integration, the applicable use cases, and what the cluster must expose or consume in each case.

COP-PILOT Capability	Scope (UCs)	Cluster Must Expose / Consume
End-to-End Service Orchestration (ESO / Maestro)	All four UCs. Deploy and lifecycle-manage containerised microservices across all Cluster 3A domains, coordinating cross-domain workflows from field sensing through logistics execution.	**Expose:** service blueprints (Helm charts) for AgroApps 360 FMIS, AUA AI Pest Detection, iLink PowerFleet, and iLink Blockchain Traceability applications; endpoint metadata and resource requirements per service. **Consume:** multi-domain Helm-as-a-Service deployment API; service registry; cross-domain SLA monitoring and automated remediation triggers.
Domain Orchestration (DO / OpenSlice)	All four UCs. Manage compute service provisioning and lifecycle at each near-edge Kubernetes domain (Farm Management, Pest Detection, Logistics & Traceability) and at the OTE OpenStack infrastructure.	**Expose:** Kubernetes cluster endpoints at AgroApps (Domain 3), AUA (Domain 4), and iLink (Domain 5); OTE OpenStack compute resources (Domain 6); RPi edge node availability on moving vehicles (Domain 7). **Consume:** K8s-as-a-Service and single-domain Helm-as-a-Service APIs; dynamic resource allocation and scaling interfaces per domain.
5G Network Slice Management (DO / OpenSlice + OTE Slice Manager)	UC3A.1, UC3A.2. Enable low-latency, high-reliability 5G connectivity for UAV and UGV data uplink, UGV command and control, and IoT sensor streaming at the Kilkis farm site.	**Expose:** OTE 5G Slice Manager interface; Athonet 5G Core configuration; Ericsson RAN availability and coverage parameters at Domain 1. **Consume:** dynamic 5G slice selection and configuration API via OpenSlice; URLLC slice parameters for UGV actuation; eMBB slice parameters for UAV high-resolution image transfer.

Data Management (FIWARE / Orion-LD)	All four UCs. Ingest, route, and manage heterogeneous data streams from field sensors, UAV, UGV, IOT, satellite, logistics telematics, and ERP/WMS systems across all seven domains through a unified NGSI-LD interoperability fabric.	**Expose:** structured NGSI-LD data streams from weather stations (MQTT), plant wearable sensors (NFC/HTTPS), UAV imagery pipelines (HTTPS), UGV operational telemetry (FIWARE Orion-LD), vehicle telematics (GNSS/MQTT), and BAR Production ERP/WMS (REST API). **Consume:** FIWARE Orion-LD context broker for data routing and subscription; federated data ingestion pipelines; data access APIs for cross-domain service consumption.
Secure Integration Fabric (SIF / OpenZiti)	All four UCs. Ensure end-to-end encrypted, authenticated communication between all Cluster 3A domains and the COP-PILOT Central layer, with network isolation enforced across domain boundaries.	**Expose:** domain credentials and access policies per data owner (BAR, AgroApps, AUA, iLink, OTE); SIF client deployments at each compute domain. **Consume:** TLS-secured inter-domain tunnels; zero-trust network access enforcement;
Time Management and Closed-Loop Automation	UC3A.1 (UAV mission response time; weed detection-to-intervention ≤24h), UC3A.2 (UGV edge inference; human confirmation loop), UC3A.4 (freshness; on-time delivery rate >95%; routing response <10 minutes).	**Expose:** Data streams from FMIS, AI Pest Detection service, and PowerFleet platform (latency, uptime, detection accuracy, delivery adherence counters). **Consume:** Time and threshold violation detection and alerting; automated remediation triggers for route recalculation and service redeployment; closed-loop feedback to orchestration layer.

7.5 INTEGRATION & DEVELOPMENT PLAN

Cluster 3A's integration roadmap was organised in three phases aligned to the COP-PILOT project timeline and the agricultural calendar of the Kilkis spinach testbed. Phase 0 (M1–M12) covered preparatory activities including baseline infrastructure setup, API design, and alignment of each partner's components to the FIWARE Orion-LD data model. Phase 1 (M13–M20) was the first operational integration phase, delivering initial end-to-end connectivity across all four use cases over the OTE public 5G network, validated through the first rounds of farm piloting during the Autumn/Winter Spinach Season 2025–2026. Phase 2 (M21–M32) will consolidate full operational deployment, introduce the OTE 5G Mobile Private Network (MPN) deployment at the Kilkis farm site (approval processes are almost finalised acquiring the licence to operate it), validate the JIT logistics and dynamic routing under real operational conditions, and complete the integration of the blockchain Hyperledger Fabric, to support full traceability across the supply chain. The full operational validation will take place in the second farm pilot rounds, during the Autumn/Winter Spinach Season 2026–2027. Phase 3 (M33–M36) finalises integration with the consumer-facing traceability interface, puts once more all components and services in piloting/ and validation and delivers the end-to-end supply chain demonstration as Farm Demo 3.

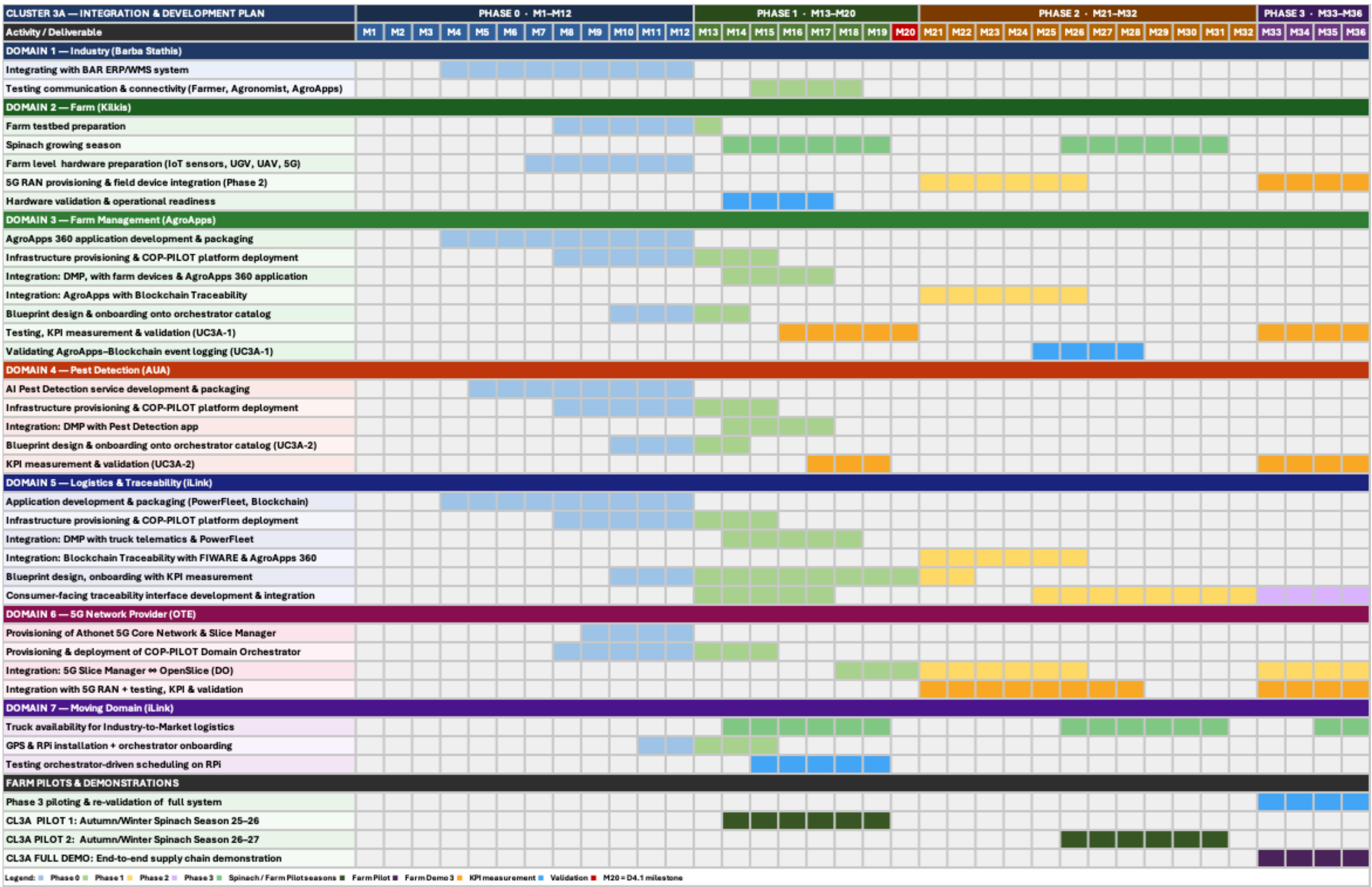


Figure 7-2 Cluster 3A GANTT (also available in the Annex C)

7.6 USE CASE DEVELOPMENT STATUS

All four Cluster 3A use cases have reached initial operational deployment, validated during the first round of farm pilots during the Autumn/Winter Spinach Season 2025–2026. Connectivity across all seven domains operates over the OTE public 5G network; the 5G Mobile Private Network (MPN) at the Kilkis farm site is targeted for Phase 2. JIT logistics has been functionally deployed but full end-to-end validation is reserved for Phase 2. Blockchain traceability integration into the COP-PILOT platform is a Phase 2 objective, with the Hyperledger Fabric has been deployed internally at iLink but is not yet connected to the FIWARE data fabric. The consumer-facing traceability interface will be integrated in Phase 2 and demonstrated in Phase 3.

Functional Capability	Development Status at M20	Outstanding Items
Crop monitoring and advisory (UC3A.1)	AgroApps 360 FMIS adapted to consume FIWARE Orion-LD context data. TOR NFC plant wearable sensors deployed at Kilkis and transmitting electrochemical stress indicators over OTE public 5G, enabling early agronomic intervention before visible symptoms appear. Weather station	Full-season agronomic model calibration under second round of farm pilots conditions (Autumn/Winter 2026–2027). Integration of AI advisory outputs into Maestro SLA feedback loop. Migration of sensor telemetry path

Functional Capability	Development Status at M20	Outstanding Items
	telemetry live. DJI Matrice 350 RTK UAV multispectral flights (MicaSense RedEdge) executed during Farm Pilot 1 and imagery fed to AgroApps dashboards. Copernicus Sentinel-2 satellite integration operational. Agronomic alert and recommendation pipelines functional for spinach production.	from public 5G to 5G MPN in Phase 2.
Autonomous pest detection and precision intervention (UC3A.2)	AUA UGV deployed in the Kilkis testbed. AI-based weed and pest detection model containerised and running on AUA Kubernetes domain. Initial UAV-guided UGV field trials executed during Farm Pilot 1. Inter-domain command and telemetry exchange via FIWARE Orion-LD operational.	Autonomous UGV navigation refinement for field terrain variability. Pest detection model expansion to additional crop stress signatures. Full coordinated UAV/UGV operations leveraging 5G MPN dynamic slice management (Phase 2).
Secure data management and traceability (UC3A.3)	Hyperledger Fabric permissioned blockchain deployed and configured internally at the iLink domain. Role-based access control via Hyperledger Fabric private data channels and QR code generation logic prepared. The REST/API bridge to FIWARE Orion-LD is designed but not yet active; blockchain integration into the COP-PILOT platform data fabric is a Phase 2 objective. BAR ERP integration has been scoped and will be configured once the FIWARE bridge is in place.	Full Hyperledger Fabric and FIWARE Orion-LD integration in Phase 2. End-to-end on-chain traceability recording across a the second round of farm pilots. Onboarding of downstream actors (logistics partners, retail, certification bodies). Consumer-facing traceability interface development and demonstration deferred to Phase 3.
Smart JIT logistics and supply chain optimisation (UC3A.4)	iLink PowerFleet deployed as RaaS. GNSS telematics from Barba Stathis refrigerated vehicles live. Harvest readiness triggers from FMIS configured to initiate logistics dispatch. BAR ERP linked for fulfilment status updates. AI-based route optimisation module running. First end-to-end trigger tested in a controlled configuration during the first round of farm pilots.	Full JIT and dynamic route optimisation validation under real harvest-to-delivery conditions during the second round of farm pilots (Autumn/Winter Spinach Season 2026–2027). Freshness deviation alert, route recalculation, and delivery confirmation loop to be validated in Phase 2. PowerFleet telemetry integration with COP-PILOT SLA Manager.
Platform orchestration and service management	All CL3A microservices (AgroApps 360 FMIS, AUA AI Pest Detection, iLink PowerFleet, and iLink Blockchain Traceability) are packaged as Helm charts and are available through Helm registries. OpenSlice endpoints registered for all three Kubernetes domains and OTE OpenStack compute pool. Maestro-driven cross-domain deployments validated. SIF (OpenZiti)	Completion of OpenSlice–OTE Slice Manager interface for dynamic 5G MPN slice management (Phase 2). Full multi-domain SLA telemetry closed-loop remediation validation.

Functional Capability	Development Status at M20	Outstanding Items
	tunnels operational across all seven domains.	

7.7 INTEGRATION & DEPLOYMENT STATUS

Cluster 3A has achieved functional end-to-end integration across all four use cases, validated during the first round of in farm pilot/demonstrators that took place during the Autumn/Winter Spinach Season 2025–2026. All seven distributed domains have been interconnected through FIWARE Orion-LD as the common data fabric, with domain-to-domain communication secured by the SIF (OpenZiti) encrypted overlay. Connectivity at the Kilkis farm testbed during Phase 1 was provided over the OTE public 5G network; deployment of the 5G Mobile Private Network (MPN) is a Phase 2 objective. JIT logistics components are deployed and functionally connected but will be fully validated in Phase 2 under the second round of pilots/demonstrators in operational conditions. The Blockchain traceability integration is planned to be finalised during phase 2; the Hyperledger Fabric has been deployed internally at iLink pending the FIWARE Orion-LD bridge activation. The consumer-facing traceability interface has not been developed and is expected to be deployed during phase 2 and is planned for piloting/validation during Phase 3

Component / Interface	Status at M20	Evidence / Remarks
AgroApps 360 FMIS & FIWARE Orion-LD	Deployed & operational	Live data ingestion from weather stations, plant sensors, and UAV imagery; NGSI-LD entities validated.
TOR plant wearable sensors & FIWARE (via OTE public 5G)	Deployed & operational	Sensors deployed at Kilkis plots; telemetry flowing to context broker via OTE public 5G.
UAV & AgroApps / FIWARE	Deployed & operational	Multispectral flights executed during Farm Pilot 1; imagery processed and fed to FMIS dashboards.
UGV & FIWARE (command & telemetry)	Deployed & operational	Field trials executed during Farm Pilot 1; inter-domain FIWARE Orion-LD messaging validated.
Hyperledger Fabric & FIWARE (REST bridge)	Integration planned for Phase 2; Piloting & validation for Phase 3.	Fabric deployed and configured internally at iLink; FIWARE Orion-LD integration bridge not yet active; full traceability integration targeted for Phase 2.
iLink PowerFleet, FMIS & BAR ERP	Deployed & operational	GNSS live; harvest trigger to dispatch workflow configured; first end-to-end test executed during Farm Pilot 1; full JIT validation in Phase 2 & 3.
ESO (Maestro) & CL3A microservices (Helm)	Deployed & operational	All service packages onboarded; Maestro-driven cross-domain deployments validated.
DO (OpenSlice) & AgroApps / AUA / iLink K8s domains	Deployed & operational	All three Kubernetes domains registered; single-domain Helm-as-a-Service functional.
SIF (OpenZiti) encrypted tunnels at all CL3A domains	Deployed & operational	Encrypted overlay active across all seven domains.

Component / Interface	Status at M20	Evidence / Remarks
OTE 5G Mobile Private Network (MPN) at Kilkis farm	Planned deployment & validation in Phase 2 & 3	Public 5G used throughout Phase 1; MPN commissioning targeted for Phase 2 & 3.
DO (OpenSlice) & OTE Slice Manager (5G NRM)	In progress	Interface partially implemented; pending 5G MPN availability for full validation.
Consumer-facing traceability interface	Planned for integration at Phase 2; Validation in Phase3	Design in progress; demonstration and validation targeted for CL3A Demo 3 (M33–M36).

8 CLUSTER 3E — EDGE INTELLIGENCE FOR ENHANCING GRID RELIABILITY IN RES-RICH DISTRIBUTION GRIDS (GREECE)

8.1 CLUSTER INFRASTRUCTURE & DOMAINS

Cluster 3E spans three distinct physical sites across Western Greece, each representing a different energy domain and computing tier. Together they form a distributed, interconnected ecosystem for deploying advanced ICT and energy technologies.

Site	Domain / Operator	Hardware	Connectivity
Patras UoP Lab + pNET 5G testbed	Active Distribution Grid / University of Patras	NVIDIA Jetson Orin (near-edge), Raspberry Pi cluster (far-edge), pNET cloud	5G URLLC via pNET; protocols: OpenADR, IEC 61850, MQTT, OPC-UA
Preveza Biogas plant	Renewable Energy / BPO (2 MW biogas co-gen)	Jetson Orin Nano (edge), Ewon Flexy 205 gateway (far-edge), AwiFLEX gas analyzer, CPS11E pH sensor	5G via pNET; Modbus (sensor–gateway); MQTT/HTTPS (gateway–edge)
Patras Highway EV charging network	EV Charging Infrastructure / DEI – PPC Blue	Jetson-based edge AI units (per station), high-resolution inductive sensors, EV Management System	5G via pNET; protocols: MQTT, HTTPS

Compute tiers: (1) Cloud – pNET-hosted infrastructure for service orchestration and AI model training/calibration; (2) Near-edge – NVIDIA Jetson Orin nodes at each site for containerized microservice execution and real-time inference (sub-second DER activation, fault classification, demand forecasting); (3) Far-edge – Raspberry Pi devices (Patras) and Ewon Flexy 205 gateway (Preveza) acting as low-latency data aggregators and relay nodes.

IoT/OT categories: Simulated DER controllers (Patras, OT/IT); industrial gas analyzers and pH sensors via Modbus/IIoT (Preveza, OT); high-resolution inductive sensors and EV management systems via MQTT (EV sites, IoT/OT). All edge-resident services are deployed as Docker/Kubernetes containerized microservices managed through the COP-PILOT platform.

Co-funded by the European Union

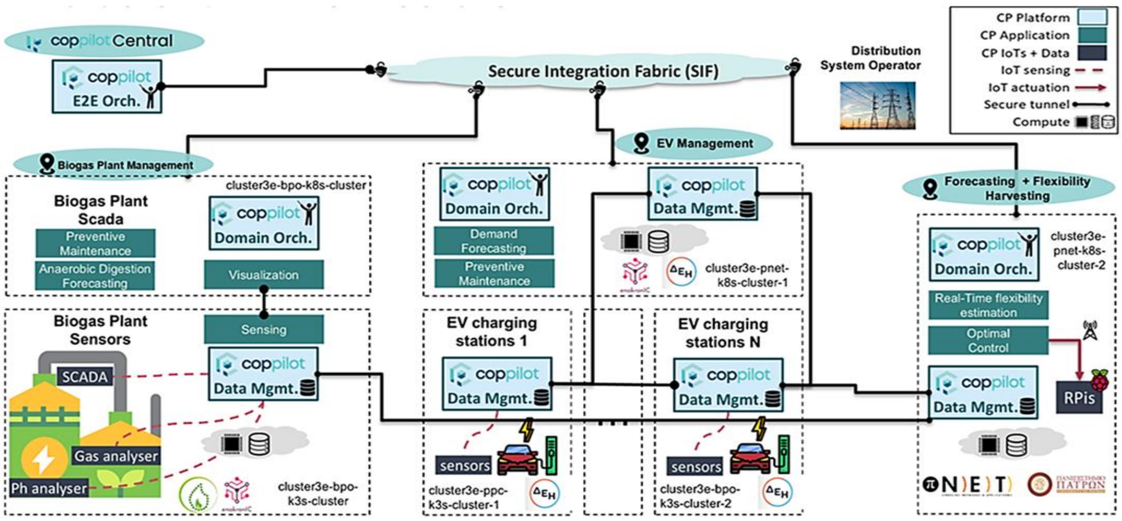


Figure 8-1 Cluster3E Architecture Diagram

8.2 KEY WORKFLOWS AND DATA PATHS

Three primary workflows operate across the cluster, each following the same architectural pattern: COP-PILOT Platform → pNET Cloud → Near-edge → Far-edge/Sensors → Edge analytics → COP-PILOT/Operator dashboard.

Workflow 1 – Real-time Flexibility Harvesting (UC3E.1, Patras) The COP-PILOT platform deploys microservices to the pNET cloud, which configures connections to the Patras lab and to the Biogas/EV data feeds. Real-time production and consumption data from DERs flow to the Raspberry Pi far-edge cluster, which forwards telemetry to the Jetson Orin near-edge node. The edge generates synthetic datasets from the grid simulator and sequentially executes: (MS#1) a flexibility estimation service assessing available DER capacity at a refresh rate of ≤1 minute, and, if flexibility is sufficient, (MS#2) an optimal DER control service issuing actuation setpoints targeting sub-700 ms end-to-end activation. Two scenarios are handled: full DER activation when flexibility is sufficient, and passive operator notification when it is not.

Workflow 2 – EV Charger Predictive Maintenance & Demand Forecasting (UC3E.2, Patras) Two applications run in parallel at each charging station. Inductive sensors continuously capture high-resolution amperage and voltage data, forwarding it through the EV Management System to the local Jetson edge server. MS#1 applies anomaly detection to identify component degradation patterns (target: 90% fault prediction accuracy up to 24 hours in advance); MS#2 runs time-series demand forecasting per charging point within a 15-minute horizon (target: ≥85% accuracy). Maintenance alerts and demand forecasts are relayed to the COP-PILOT platform and surfaced to EV operators for proactive scheduling and grid load coordination.

Workflow 3 – Biogas Plant Monitoring & Predictive Maintenance (UC3E.3, Preveza) The AwiFLEX gas analyzer (CH_4, CO_2, H_2S, O_2, H_2) and CPS11E pH sensor continuously sample the anaerobic digestion process. Data is forwarded via Modbus to the Ewon Flexy 205 gateway, which transmits it to the local Jetson Orin Nano edge server on request. MS#1 forecasts anaerobic digestion stability parameters; MS#2 performs predictive maintenance analytics to classify anomalies (target anomaly detection within ≤2 seconds). Results are pushed to an operator dashboard with early-warning alerts. In the no-anomaly scenario, normal operation is passively logged and confirmed to COP-PILOT.

Co-funded by the European Union

8.3 CHALLENGES AND CONSTRAINTS

The following challenges are ranked by their potential impact on cluster-platform integration:

#	Challenge	Detail
1	**Strict real-time latency requirements**	UC3E.1 requires end-to-end DER activation within 700 ms and edge processing below 1 second. UC3E.2 requires edge AI inference within 200 ms per packet and sensor-to-alert latency below 2 seconds. These constraints demand careful 5G network slicing (URLLC) and optimized microservice pipelines at the edge.
2	**Cold-start AI training data scarcity**	All three UCs face limited historical training data. UC3E.1 rely on synthetic datasets from the grid simulator and fault condition emulation; UC3E.2 and UC3E.3 draw on limited logs from the infrastructure owners. This increases risk of model underperformance on rare real-world edge conditions and requires robust uncertainty handling.
3	**Legacy and proprietary field interfaces**	The biogas plant uses Modbus for sensor communication and a SCADA system for process control; EV stations use OCPP. These must be bridged to COP-PILOT standard interfaces (MQTT, OPC-UA, IEC 61850, OpenADR) via gateway-level protocol translation, adding complexity and potential failure points.
4	**Multi-stakeholder data governance**	The cluster spans three data owners (UoP, DEI/PPC Blue, BPO) with different access rights, sensitivity levels, and integration interfaces. Role-based access control, end-to-end encryption, and GDPR-compliant handling must be coordinated across all sites and enforced consistently by the platform.
5	**Physical deployment constraints**	Industrial and highway environments impose constraints on hardware housing, thermal tolerance (edge devices must operate from -40°C to +85°C), maintenance accessibility, and physical security of edge nodes. Rugged hardware selection and redundant backup units are required at remote stations.
6	**AI model drift over project lifetime**	Grid topologies, EV usage patterns, and biogas feedstock compositions will evolve, requiring periodic model retraining and seamless redeployment to edge devices via COP-PILOT orchestration without disrupting ongoing operations.

8.4 INTEGRATION OF COP-PILOT CAPABILITIES, COMPONENTS AND SERVICES

The table below summarises which COP-PILOT platform capabilities are in scope for Cluster 3E integration, the applicable use cases, and what the cluster must expose or consume in each case.

COP-PILOT Capability	Scope (UCs)	Cluster Must Expose / Consume
Service Orchestration (IoT-Edge-Core)	All three UCs. Deploy and lifecycle-manage containerised microservices (flexibility estimation, predictive maintenance, demand	Expose: microservice container images, endpoint metadata, resource requirements.

	forecasting) on Jetson Orin devices across all three sites.	Consume: deployment API, service registry, containerised runtime (Docker/Kubernetes).
Secure Integration Fabric (SIF)	All three UCs. End-to-end encrypted, authenticated communication between sites and the platform; network isolation via 5G slicing.	Expose: site credentials and access policies per data owner (UoP, DEI, BPO). Consume: TLS termination, role-based access control, 5G URLLC network slice allocation.
SLA Management & Closed-Loop AI	UC3E.1 (DER activation latency <700 ms, uptime >99.9%), UC3E.2 (inference <200 ms, uptime >99.5%), UC3E.3 (alert generation <2 s, uptime >99.5%).	Expose: SLA telemetry streams (latency, uptime counters). Consume: SLA violation detection, predictive threshold alerts, automated remediation triggers.
Zero-touch Orchestration	UC3E.1 (automated DER flexibility activation), UC3E.2 (automated maintenance scheduling).	Expose: standardised health/status interfaces for all edge nodes. Consume: automated deployment, scaling, and fault-recovery workflows managed by the platform.
Federated / Hierarchical Data Management	All three UCs. Multi-source heterogeneous telemetry (electrical, chemical, environmental) must flow through the platform data management layer.	Expose: structured data streams via MQTT (EV), OPC-UA (grid), Modbus bridge (biogas). Consume: data routing, ingestion pipelines, federated storage, data access API.
Operator Dashboard & Explainability Services	All three UCs. Human-in-the-loop review of AI decisions, alerts, and control authorisation.	Expose: AI model outputs formatted for explainability (decision thresholds, confidence scores, anomaly markers). Consume: dashboard hosting, audit logging, visual diagnostics services.

8.5 INTEGRATION & DEVELOPMENT PLAN

The cluster integration and development activities are structured across three parallel workstreams corresponding to the three pilot sites, converging on a joint platform onboarding phase and a final end-to-end demonstration. Activities cover the reporting period M12-M18 (Phase 1).

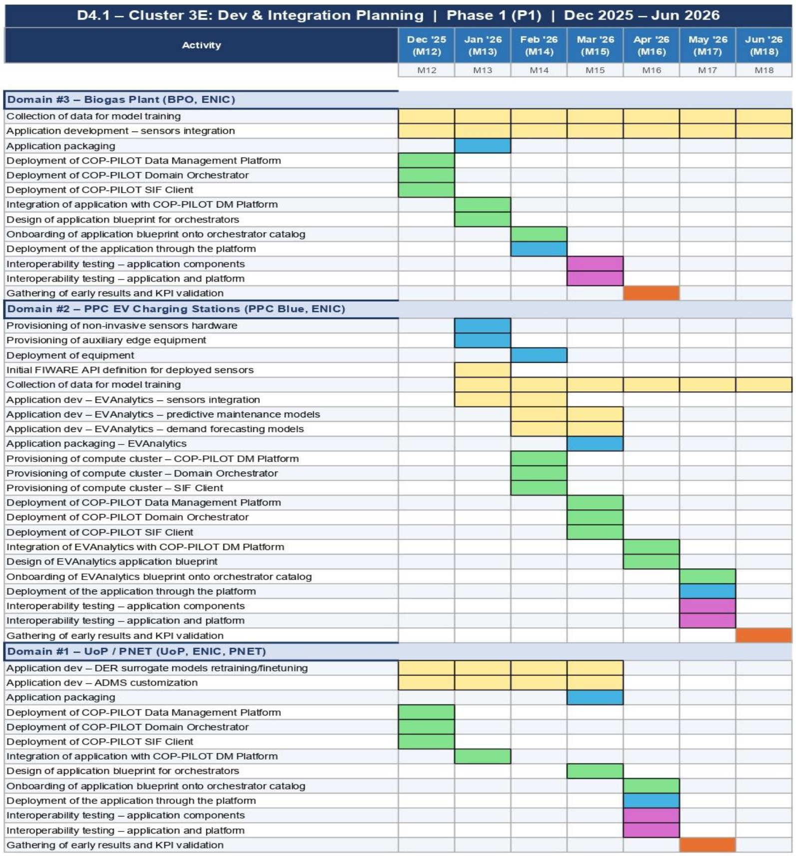


Figure 8-2 Cluster 3E Gantt Chart

8.6 USE CASE DEVELOPMENT STATUS

All three Cluster 3E use cases have reached measurable levels of technical readiness across their respective domain environments, with UC3E.3 (Biogas) being the most advanced and UC3E.2 (EV Charging) the most constrained by pending physical site access. Connectivity and data management infrastructure — context broker deployment, containerised runtimes, and initial dashboard integrations — are operational across all three domains. AI analytics components are in place for UC3E.2 and UC3E.3, with model training ongoing or imminent; UC3E.1 application logic remains under active development.

Functional Capability	Development Status at M20	Outstanding Items
Real-time flexibility harvesting and DER coordination (UC3E.1)	DER simulation environment and NVIDIA Jetson Orin near-edge node are deployed and operational at the UoP/PNET lab. The FIWARE context broker is in place and receiving telemetry from the Raspberry Pi far-edge	Completion and containerisation of MS#1 (flexibility estimation) and MS#2 (DER control signal generation). End-to-end latency validation of the sub-700 ms DER activation target against the live PNET 5G URLLC slice. Integration of the flexibility

	cluster. The flexibility estimation microservice (MS#1) and the optimal DER control microservice (MS#2) are under active development, with containerisation and unit testing ongoing against synthetic grid simulator datasets.	estimation output into the COP-PILOT SLA monitoring loop.
EV charger predictive maintenance and demand forecasting (UC3E.2)	The data management layer — context broker and application dashboard — has been deployed and validated in a lab environment using test data. The EVAnalytics microservices for predictive maintenance (MS#1) and demand forecasting (MS#2) are developed and containerised, but model training on real-world sensor data is pending physical deployment at the EV charging stations. Sensor hardware and the Jetson edge AI unit are procured and ready; on-site installation at the PPC Blue highway stations is planned for May 2026.	Physical sensor and Jetson installation at EV charging stations (May 2026). Model retraining on live inductive sensor data post-deployment. End-to-end inference latency validation (target: <200 ms) under real operational conditions. Full integration of demand forecasting outputs with grid coordination workflows.
Biogas plant monitoring and predictive maintenance (UC3E.3)	The AwiFLEX gas analyser and CPS11E pH sensor are installed and transmitting process data via the Ewon Flexy 205 Modbus gateway to the local Jetson Orin Nano edge node. The FIWARE context broker is operational and ingesting sensor streams. The operator dashboard is live and displaying real-time process parameters. Both analytics microservices — anaerobic digestion stability forecasting (MS#1) and predictive maintenance anomaly detection (MS#2) — are deployed and containerised; model training on live process data is ongoing.	Completion of model training on accumulated real-process data and validation of the anomaly detection latency target (≤2 seconds). Integration of model outputs and alert pipelines into the COP-PILOT SLA management layer.

8.7 INTEGRATION & DEPLOYMENT STATUS

Cluster 3E has established a consistent integration baseline across all three domains, with the core COP-PILOT platform stack — Domain Orchestration (OpenSlice), Secure Integration Fabric (SIF), and containerised Kubernetes runtimes (K3s) — operational at both cloud and edge tiers in each site. UC3E.1 and UC3E.3 are the most advanced in terms of physical deployment, with field hardware in place and platform connectivity confirmed. UC3E.2 is fully integrated at the infrastructure level and validated in a lab environment; physical deployment at the EV charging stations is the sole remaining precondition for end-to-end operational validation. No deviations from the planned integration architecture described in Section 6.4 have been identified at this stage.

Component / Interface	Status at M20	Evidence / Remarks
UC3E.1 — Field & edge infrastructure (RPi 5G cluster, Jetson Orin, K3s)	Deployed & operational	RPi nodes equipped with 5G HATs and integrated with UoP/PNET 5G infrastructure; Jetson Orin connected to PNET compute layer; K3s running and microservice containers deployable.
UC3E.1 — Platform stack (OpenSlice, SIF, HiPO)	Deployed & operational	OpenSlice deployed in PNET and integrated with cloud and edge resources; SIF operational at both cloud and edge nodes; HiPO integrated with local OpenSlice through SIF.
UC3E.1 — Application microservices (MS#1 flexibility estimation, MS#2 DER control)	In progress	Containerisation and unit testing ongoing against synthetic grid simulator data; end-to-end latency validation (target: <700 ms) pending completion of application logic.
UC3E.2 — Field & edge infrastructure (inductive sensors, Jetson, K3s)	Lab-validated; field deployment pending	Sensors and Jetson integrated and tested with synthetic data in lab; physical installation at PPC Blue highway EV stations targeted for May 2026; 5G gateway connection to cloud confirmed.
UC3E.2 — Platform stack (OpenSlice, SIF, HiPO)	Deployed & operational	OpenSlice deployed in PNET and integrated with cloud and Jetson resources; SIF operational at cloud and edge nodes; HiPO integrated with local OpenSlice through SIF.
UC3E.2 — Application microservices (MS#1 predictive maintenance, MS#2 demand forecasting)	Lab-validated; field retraining pending	Microservices containerised and passing lab validation; retraining on live sensor data and end-to-end inference validation (target: <200 ms) deferred until on-site deployment.
UC3E.3 — Field & edge infrastructure (AwiFLEX, CPS11E, Ewon Flexy 205, Jetson Orin Nano, K3s)	Deployed & operational	Sensors installed at Preveza biogas plant; Modbus path to gateway confirmed; Jetson connected to local cloud over public 5G; K3s running.
UC3E.3 — Platform stack (OpenSlice, SIF, HiPO)	Deployed & operational	OpenSlice deployed in local Preveza cloud and integrated with cloud and edge resources; SIF operational at both nodes; HiPO integrated with local OpenSlice through SIF.
UC3E.3 — Application microservices (MS#1 AD stability forecasting, MS#2 anomaly detection)	Deployed; training ongoing	Both microservices containerised and running on Jetson via K3s; model training on live process data ongoing; anomaly detection latency target (≤2 s) not yet formally validated.
FIWARE context broker — all domains	Deployed & operational	Instances operational across all three domains; data ingestion confirmed for UC3E.1 and UC3E.3; lab-validated for UC3E.2.

9 CLUSTER 4 — SMART VINEYARDS & SUSTAINABLE WINERY ECOSYSTEMS (PORTUGAL, SPAIN, IRELAND AND SWITZERLAND)

9.1 CLUSTER INFRASTRUCTURE & DOMAINS

Cluster 4 follows the federated architecture of COP-PILOT in which central services, partner-domain services, field assets, and public-cloud components are combined through a shared orchestration and secure-interconnection model. The architecture shown for Cluster 4 makes this explicit: a central end-to-end orchestration layer is hosted in the COP-PILOT central domain, while each participating domain retains its own local COP-PILOT building blocks, in particular a Domain Orchestrator (DO) and a Data Management (DM) function. In COP-PILOT terms, this means each domain is expected to expose its compute, network, or data capabilities as consumable services, without collapsing all partner assets into a single infrastructure. Instead, the domains remain distributed and are connected through the Secure Integration Fabric (SIF), which provides the secure east-west fabric for inter-domain communication, service exposure, and data federation.

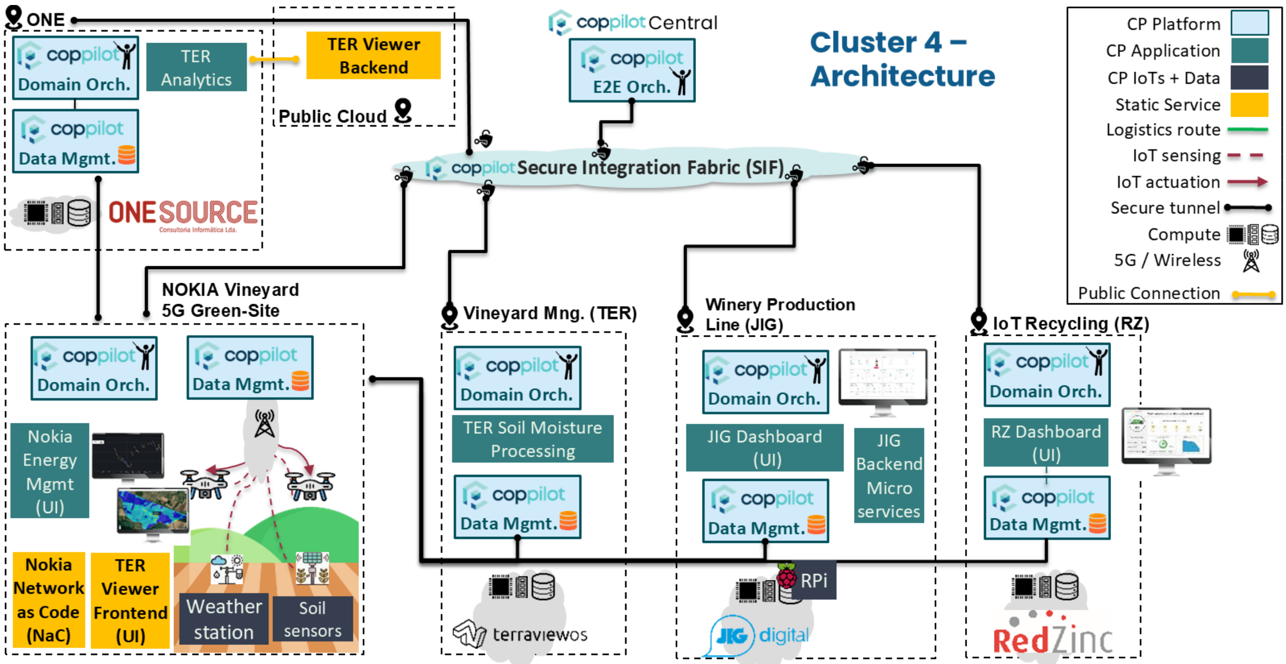


Figure 9-1 - Cluster 4 domains architecture overview

ONE domain acts as the main integration anchor for the cluster. In the current architecture, it hosts a COP-PILOT domain orchestrator and data-management capabilities, while also providing the main testbed resources used for development, validation, and controlled deployment of shared cluster functions. The architecture also shows that the TER Viewer Backend is positioned in a public-cloud environment rather than fully inside the OneSource domain. This is relevant because it means Cluster 4 already spans different hosting models: central/testbed deployment in OneSource, domain-resident services in partner environments, and selected application components in public cloud. The Nokia domain represents the green-site and telecom-infrastructure branch of the cluster. It includes its own domain orchestrator, data-management services, all linked to physical field assets such as weather stations, soil sensors, and the 5G/wireless environment. This domain is important not only because it contributes sensing and connectivity, but because it ties infrastructure management, energy availability, and device status into the wider Cluster 4 sustainability goal. The vineyard-management domain led by Terraview contains its own domain orchestrator, soil-moisture processing, and data-management capability, and it is the main location where vineyard observations are transformed into water-use and crop-related analytics. In parallel, the JIG winery domain contains its own domain orchestrator, dashboard UI, backend microservices, and data-management function, supported by local compute including Raspberry Pi-based resources. Finally, the RedZinc domain includes its own domain orchestrator, dashboard UI, and data-management capability to support the lifecycle-management and IoT-recycling branch of the cluster.

Taken together, the architecture shows that Cluster 4 is built around a repeated domain pattern: each partner domain exposes a local operational environment with its own services, data-management layer, and compute context, while central COP-PILOT services and the SIF provide the mechanisms for secure interoperability and end-to-end orchestration. In practical terms, the central E2E orchestrator is expected to peer with domain-level orchestrators and federate their catalogues, while the SIF supports trusted service exposure and secure sharing of domain data between the participating environments. The infrastructure therefore spans several compute tiers at once: field devices and IoT sensors, local or edge-side compute in partner domains, testbed and virtualised resources in ONE, and public-cloud application components where needed.

9.2 KEY WORKFLOWS AND DATA PATHS

Cluster 4 should be understood as a set of interdependent operational loops rather than as four isolated use cases, as illustrated in Figure 9-2, which highlights how data flows between Terraview, Nokia, JIG, and RedZinc form a set of reinforcing cross-domain feedback paths.

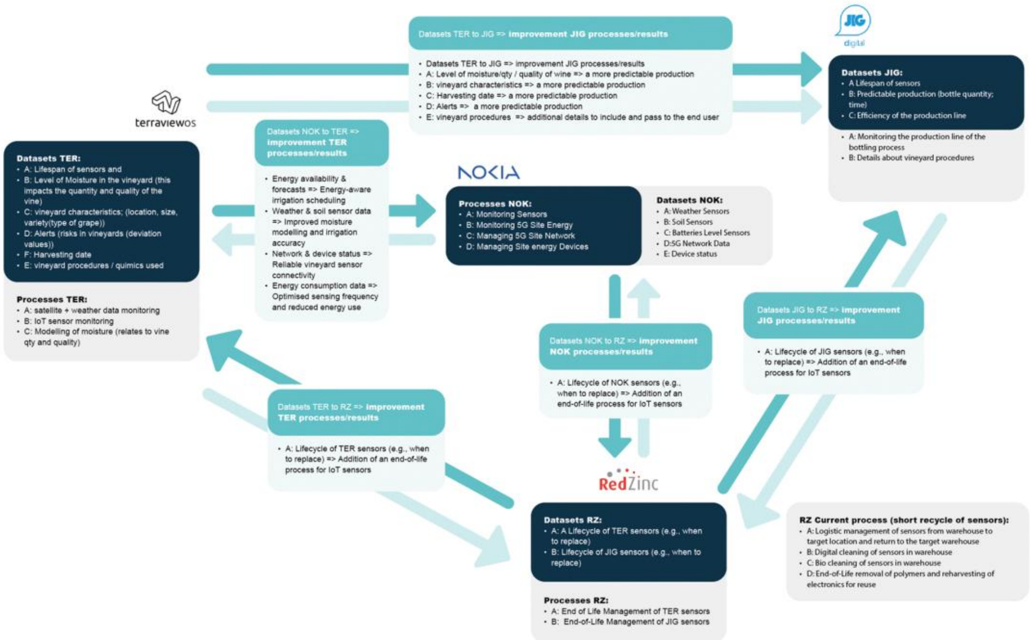


Figure 9-2 - Cluster 4 cross-domain workflow overview

The first workflow starts in the vineyard domain, where Terraview combines satellite information, weather observations, IoT sensor monitoring, and soil-moisture modelling to generate operational knowledge about field conditions. The key Terraview datasets include sensor lifespan information, soil-moisture conditions, vineyard characteristics, alerts derived from field anomalies, harvesting dates, and vineyard procedures. These outputs do not remain confined to viticulture decisions: they are intended to feed downstream planning and optimisation in the wider wine-value chain. In particular, the TER-to-JIG path provides information that can improve production predictability, for example by linking harvest timing, grape variety and expected quality, and vineyard procedures to bottling and production-line planning in the winery domain.

A second major workflow links Nokia and Terraview. In this path, Nokia contributes real-time and historical information about weather, soil, battery levels, 5G network state, and device status from the green-site infrastructure. This data is relevant to Terraview because energy availability, forecasting, and network/device status can improve irrigation planning, refine soil-moisture modelling accuracy, and increase the reliability of deployed vineyard sensors. The NOK-to-TER path is therefore not only a connectivity enabler; it is also a direct improvement loop in which green-energy and 5G infrastructure conditions affect the quality and timeliness of vineyard analytics and, by extension, water-use optimisation decisions.

A third workflow concerns the winery domain led by JIG. JIG datasets include information on sensor lifespan, predicted production values such as bottle quantity and timing, and production-line efficiency. These datasets are influenced both by vineyard-side inputs received from Terraview and by JIG's own monitoring of winery operations. The resulting winery knowledge supports production optimisation, but it also creates an onward path to RedZinc: lifecycle information about JIG sensors, especially replacement timing or end-of-life indicators, can be reused in the sensor lifecycle-management loop. In the same way, Terraview can send lifecycle-related information on vineyard sensors to RedZinc, and Nokia can do the same for its own field and infrastructure devices. These RedZinc-facing flows are important because they turn Cluster 4 into a circular, sustainability-oriented cluster rather than a set of independent technical pilots. RedZinc's current process covers logistics, cleaning, digital traceability, and end-of-life removal and harvesting of electronic components for reuse. The TER-to-RZ, JIG-to-RZ, and NOK-to-RZ flows therefore create a common lifecycle-management path in which sensor-health and replacement information from multiple domains is used to improve recovery, reuse, and end-of-life handling of IoT assets.

Taken together, the key data paths in Cluster 4 can be summarised as follows: vineyard intelligence flows from Terraview to the winery domain to improve planning and production predictability; Nokia energy, connectivity, and device-status data improves Terraview analytics and supports the wider sensing ecosystem; and lifecycle information from Terraview, JIG, and Nokia converges into RedZinc to support circular asset management. This is the most important workflow characteristic of Cluster 4: data is not exchanged only for monitoring, but to improve downstream operational decisions, strengthen cross-domain predictability, and connect sustainability objectives with practical integration paths.

9.3 CHALLENGES AND CONSTRAINTS

Cluster 4 is constrained by a combination of architectural, organisational, and operational factors. At this stage, the cluster already has a clear architectural structure and defined data flows, but the consolidation of these elements into a stable cross-domain integration baseline remains ongoing.

A first constraint concerns the transition from use-case definition to cluster-level integration. Several contributions are well articulated at use-case level, but require further consolidation to operate as part of a coherent cluster workflow. This includes clarifying which services are exposed through the platform, how data is shared across domains, and which interactions can be considered sufficiently stable to support intermediate validation. At this stage, integration therefore involves both technical deployment and architectural convergence.

A second constraint is technical heterogeneity across the cluster environment. Cluster 4 combines field devices, edge resources, partner-domain infrastructures, and public-cloud components, using different protocols, data models, and hosting assumptions. Ensuring interoperability across these elements requires connectors, data mediation, and orchestration alignment, which increases integration complexity and introduces additional dependencies between platform components and domain-specific implementations.

A third constraint relates to data availability and validation conditions in the vineyard domain, which are inherently linked to seasonal cycles and agricultural timelines and therefore directly impact integration progress. The generation of meaningful sensor data, weather inputs, and crop-related observations depends on specific vineyard phases (e.g., growth, irrigation, harvesting), which cannot be accelerated or reproduced on demand.

9.4 INTEGRATION OF COP-PILOT CAPABILITIES, COMPONENTS AND SERVICES

Table 13 summarises which COP-PILOT platform capabilities are in scope for Cluster 4 integration, the relevant use cases, and what the cluster must expose or consume in each case. The wording reflects the current WP3 deployment baseline, so it also makes explicit where Cluster 4 already has active platform anchors and where deployment is still under consolidation.

Table 13 - Table 22: Cluster 4 breakdown of COP-PILOT capabilities and their scope.

COP-PILOT Capability	Scope (UCs)	Cluster Must Expose / Consume
Service Orchestration (DO / ESO)	All four UCs. Supports onboarding, deployment, and lifecycle management of Cluster 4 services across the vineyard, winery, telecom-energy, and lifecycle-management domains.	Expose: service definitions, deployment artefacts, endpoint metadata, and domain resource descriptions. Consume: OpenSlice-based domain orchestration, catalogue peering towards the central orchestration layer, and deployment execution through the COP-PILOT orchestration path.
Secure Integration Fabric (SIF)	All four UCs. Enables secure inter-domain communication, service exposure, and data exchange across the distributed Cluster 4 architecture, including the connection between partner domains and the central COP-PILOT services.	Expose: the selected domain services and data endpoints that must be reachable across domains, together with the required access policies. Consume: zero-trust connectivity, secure service exposure, and trusted east-west interconnection for cross-domain workflows.
Data Management (DM / FIWARE-oriented federation)	UC4.2, UC4.3, and UC4.4 directly, with UC4.1 consuming lifecycle-relevant outputs. Supports the exchange of vineyard, winery, infrastructure, and device-status data needed for analytics, monitoring, and cross-domain decision support.	Expose: sensor streams, application data, alerts, and operational datasets through domain data-management functions or equivalent connectors. Consume: broker-based data exchange, domain-to-domain data federation, and shared access to the datasets required by Terraview, JIG, Nokia, and RedZinc workflows.
DIS-L Data Connectors	UC4.2, UC4.3, and UC4.4, with indirect relevance to UC4.1. These connectors are needed to ingest field, production-line, and infrastructure data into the COP-PILOT data-management path.	Expose: the actual data-ingestion mechanisms from sensors, applications, or infrastructure controllers into the domain data-management layer. Consume: the common Cluster 4 data path required for AquaView validation, JIG production monitoring, Nokia energy/connectivity integration, and downstream lifecycle-management use.
Compute Environments	All four UCs. Cluster 4 combines field or edge compute, partner-domain compute, the OneSource	Expose: executable runtime environments for domain services, analytics, dashboards, and validation workloads. Consume: Kubernetes-based

(DIS-L / Kubernetes)	testbed, and selected public-cloud application components.	hosting, virtualised resources, and edge or local compute contexts suited to each domain branch of Cluster 4.
Central Shared Platform Services	All four UCs. Business Portal, Maestro, and the central SIF domain provide the common business, orchestration, and secure-interconnection anchors for Cluster 4.	Expose: cluster-relevant service and domain information through the federated platform view. Consume: the central business and orchestration capabilities needed to discover services, coordinate domains, and support the shared COP-PILOT integration model.

9.5 INTEGRATION & DEVELOPMENT PLAN

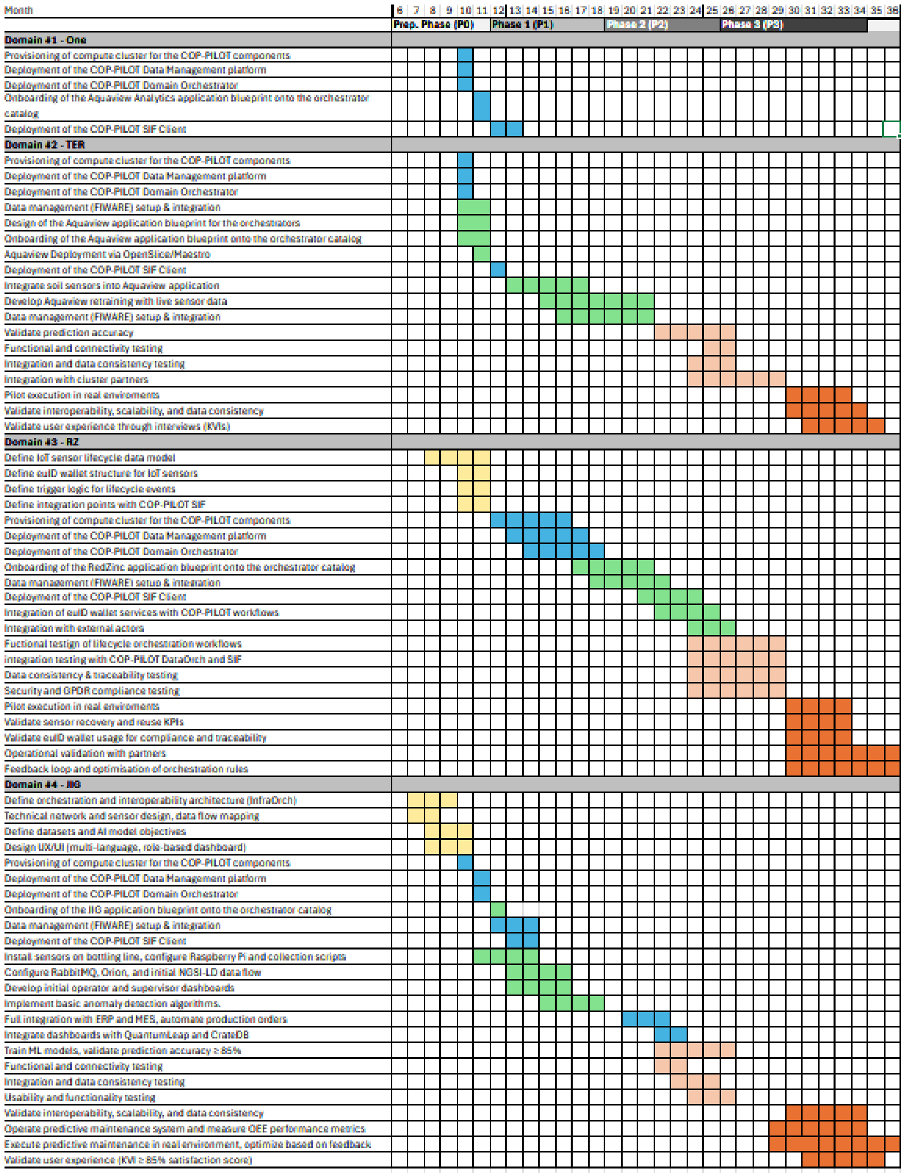


Figure 9-3 Cluster 4 Integration & Development Activities Gantt Chart

Cluster 4 follows a structured integration path in which the main partner domains are progressively brought together into a common cross-domain baseline. The critical path consists of integrating the ONE, Terraview, Nokia, JIG, and RedZinc domains through shared data management, orchestration, and secure interconnection mechanisms. The main objectives for Cluster 4 are to consolidate the domain-level platform baselines, complete the required interoperability paths, and validate cross-domain workflows linking vineyard monitoring, winery operations, connectivity-aware infrastructure management, and sensor lifecycle services. The overall project timeline and related planning are presented in the Gantt chart in Figure 9-3, and also included in Annex E of this deliverable.

The ONE domain acts as the central compute and orchestration domain for Cluster 4. Its role is to host and coordinate the deployment of the relevant COP-PILOT platform components, providing the baseline environment for onboarding partner services, managing application deployment, supporting data exchange, and enabling the progressive integration of the cluster use cases

JIG activities will address the progressive integration of the winery production-line monitoring solution into the COP-PILOT environment. This work includes completing FIWARE-based data integration, aligning production data flows with the COP-PILOT architecture, consolidating ERP linkage and dashboard functions, and preparing the relevant interoperability and validation steps. In this way, JIG will contribute production data and OEE-related indicators to the wider cluster integration path.

Terraview work is planned around consolidating field sensors, edge-side processing, and application-level analytics to support the Aquaview application and related vineyard intelligence functions. The planned steps include extending real-time data flows, strengthening FIWARE-based interoperability, and aligning Terraview services with the cluster's broader cross-domain workflows.

RedZinc development is planned around integrating its IoT recycling, maintenance, and logistics platform into the COP-PILOT environment. This includes the implementation of sensor lifecycle tracking, replacement and recycling workflows, euID wallet interactions for traceability, and the preparation of validation scenarios using RedZinc’s healthcare platform as an initial operational baseline. These steps will prepare the integration of lifecycle-management and traceability services into the wider cluster framework.

Nokia’s planned activities include integrating rural connectivity, energy-aware monitoring, and programmable 5G service capabilities into the COP-PILOT cluster environment. This includes the consolidation of real-time data ingestion from energy systems, soil and weather sensors, and 5G rural infrastructure, together with the completion of FIWARE-based interoperability, the alignment of orchestration flows, and the validation of OpenSlice/Maestro deployment mechanisms. In parallel, the 5G Network-as-Code provisioning pilot will support the validation of interoperability between NaC capabilities and COP-PILOT platform services.

9.6 USE CASE DEVELOPMENT STATUS

The current development maturity of Cluster 4 is summarised in Table 14.

Table 14 - Breakdown of use cases in Cluster 4 and their development status up to M20

Functional Capability	Development Status at M20	Outstanding Items
UC4.1 – Sensor lifecycle traceability, maintenance, recycling, and worker-health monitoring (RedZinc)	RedZinc is finalising the functional scope of its IoT recycling, maintenance, and logistics solution. Development already covers sensor lifecycle tracking, replacement and recycling workflows, and the definition of euID wallet interactions for traceability. The use case is also being extended through preparatory worker-health monitoring scenarios using	Complete the design and validation logic for the vital-sign and accident-response scenarios, finish the euID-enabled traceability flow, and consolidate the use case so it can move from baseline

	RedZinc's existing healthcare platform as a development baseline.	validation toward full integrated operation.
UC4.2 – Vineyard intelligence, field sensing, and agronomic data exposure (Terraview)	Terraview has already demonstrated the core functional capabilities of the use case, including access to field sensors, data processing across edge and cloud environments, and generation of agronomic information from acquired datasets. The development work has shown that COP-PILOT can support central management of diverse field devices and data streams within this domain.	Advance the functional integration of Terraview outputs with the other partner use cases and complete the real-time data integration improvements needed to strengthen the Aquaview application.
UC4.3 – Winery production monitoring, operational visibility, and planning support (JIG)	JIG has advanced the development of its winery production line monitoring solution with real-time bottling-line data capture, ERP linkage, and an initial monitoring and visualisation layer already in place. The use case logic for production data, OEE indicators, and alerts is now sufficiently defined to support alignment with the wider COP-PILOT collaborative model.	Complete the FIWARE-based connection, align the full winery data flow with the COP-PILOT architecture, and finalize the dashboard and supervision logic.
UC4.4 – Rural connectivity, energy-aware infrastructure monitoring, and programmable 5G support (Nokia)	Nokia has progressed the development of its pilot by consolidating real-time ingestion from energy systems, soil and weather sensors, and 5G rural-site infrastructure. Initial dashboarding and visualisation capabilities are already available, and the use case now provides a solid basis for energy analysis and contextualized decision support in precision-agriculture scenarios.	Complete the FIWARE-based interoperability layer, harmonize data flows through COP-PILOT orchestration services, and finalize OpenSlice, Maestro, and 5G Network-as-Code interoperability for automated service provisioning.

9.7 INTEGRATION & DEPLOYMENT STATUS

The current integration and deployment baseline for Cluster 4 is summarised in Table 15.

Table 15 - Deployment status of components and services within Cluster 4.

Component / Interface	Status at M20	Evidence / Remarks
UC4.1 - Sensor lifecycle traceability, maintenance, recycling, and worker-health monitoring (RedZinc)	Preparation & early validation	The RedZinc use case is not yet deployed in the COP-PILOT cluster environment, but the initial platform baseline is available through RedZinc's existing solution. This baseline will be used for the first validation activities at Nokia's facilities, where worker-health monitoring and accident-response scenarios will exercise the early use case functions before full domain and platform integration is completed.
UC4.2 - Vineyard intelligence, field sensing, and agronomic data exposure (Terraview)	Deployed & operational	Terraview has deployed its Kubernetes-based edge environment together with the services required for communication, data aggregation, and sensor-data access. The domain already demonstrates operational use case deployment across field sensing, edge processing, cloud control, and analytics, providing a concrete platform baseline that can be connected to wider cross-domain workflows.
UC4.3 - Winery production monitoring, operational visibility,	Deployed & operational	JIG has a winery setup connected and running for initial operation and testing, including production-line monitoring, ERP linkage, statistics, and production-order visibility.

and planning support (JIG)		
UC4.4 - Rural connectivity, energy-aware infrastructure monitoring, and programmable 5G support (Nokia)	Deployed and partially operational	Nokia has deployed the main pilot components required for rural-site monitoring and contextualized decision support, including ingestion and dashboarding for energy, soil, weather, battery, and 5G infrastructure data, as well as the FIWARE interoperability layer. The domain already provides an operational platform baseline, while ongoing deployment work focuses on validating OpenSlice, Maestro, and completing 5G Network-as-Code automated provisioning within the shared COP-PILOT environment.

10 CONCLUSIONS

10.1 INTERMEDIATE INTEGRATION STATUS

This deliverable reports the intermediate status of COP-PILOT cluster preparation and use-case integration activities under WP4. The work presented in D4.1 shows that the project has moved beyond the initial definition of cluster blueprints and use case concepts and has established a tangible integration baseline across the piloting environments. This baseline includes deployed or partially deployed domain orchestration components, data-management functions, secure interconnection mechanisms, containerised services, domain-specific applications, and initial end-to-end workflows.

The intermediate results reported across clusters indicate steady progress in implementing the COP-PILOT federated integration model. They also show that the COP-PILOT architecture can support heterogeneous partner environments while preserving domain autonomy and enabling cross-domain interoperability.

Such results also reflect the different stages of progress across the clusters. Several clusters have already demonstrated operational platform connectivity, data ingestion, service deployment, and initial cross-domain workflows, while others are advancing the consolidation of application components, data models, orchestration interfaces, and field deployments. This is consistent with the intermediate scope of D4.1 and with the fact that several use cases depend on real operational environments, seasonal validation windows, and physical deployment constraints.

During the first and second integration cycles, the work carried out in WP4 has also highlighted the main areas that require further consolidation. These include the stabilisation of central and domain-level orchestration, the completion of FIWARE and NGSI-LD alignment where applicable, the reliable operation of the Secure Integration Fabric across the relevant domains, and the harmonisation of service packaging and deployment artefacts. Further work is also needed in areas such as data governance, interoperability with legacy systems, the availability of field data, and the validation of AI-based or automation-driven services.

10.2 PLAN TOWARDS FINAL INTEGRATION

The next phase of WP4 will focus on consolidating the integration baseline reported in this deliverable into an operationally validated integration state across the COP-PILOT clusters. This will form the basis for final reporting in D4.2 and support the transition towards broader pilot execution.

A priority for this phase is to strengthen the common platform-to-cluster integration baseline. This includes completing the remaining service exposure and deployment paths, stabilising orchestration flows, and aligning the technical artefacts required to support consistent integration across the different cluster environments.

A second priority is to further consolidate data management and interoperability across the clusters. This includes continued alignment of data models, ingestion mechanisms, and data-sharing interfaces, with particular attention to cross-domain data flows that support end-to-end workflows and operational validation.

The next phase will also address the remaining cluster-specific dependencies that affect operational readiness. These include pending field deployments, completion of service packaging and orchestration interfaces, integration with external or legacy systems, and the further validation of AI-based or automation-driven services in their target environments.

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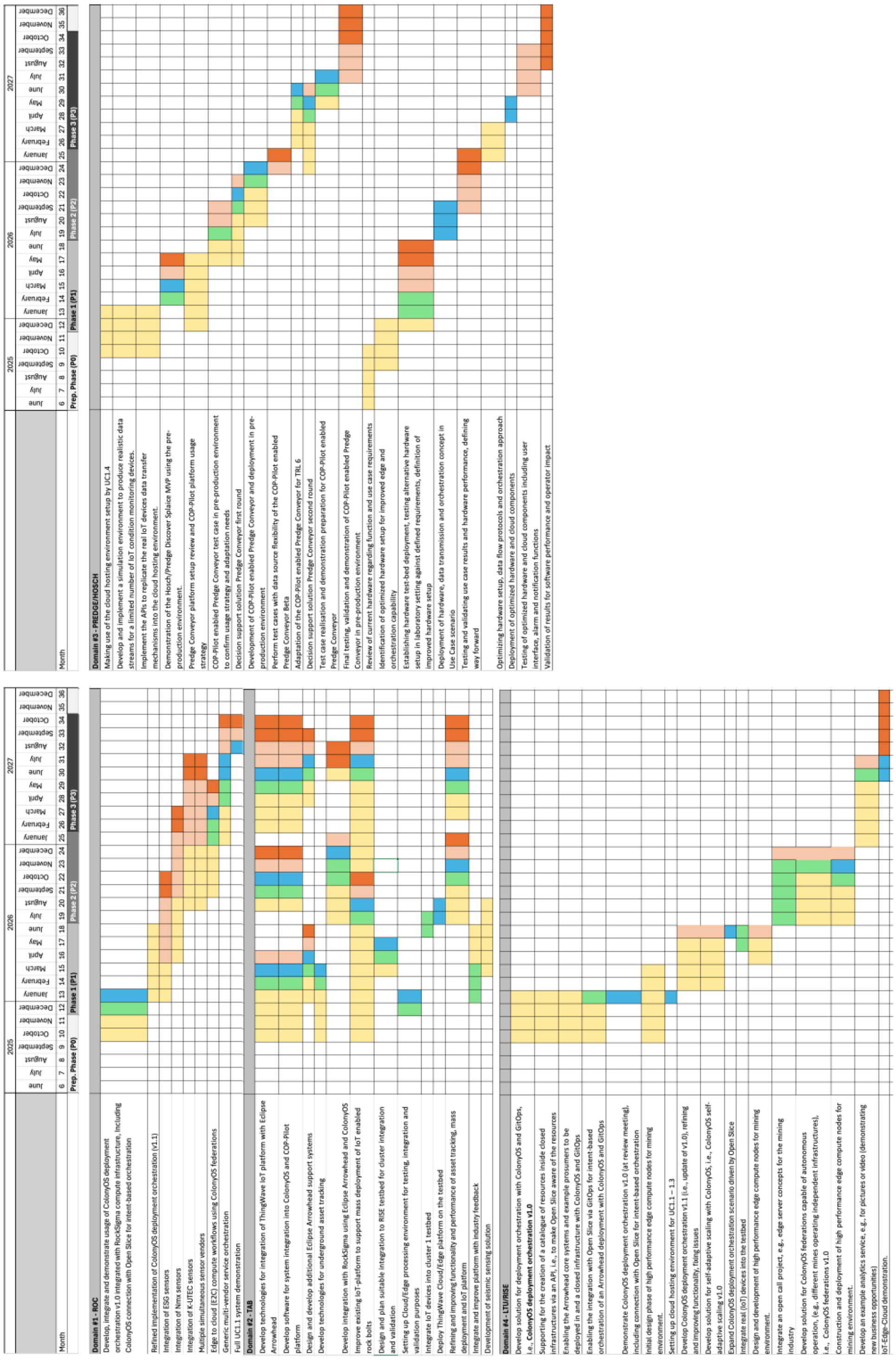
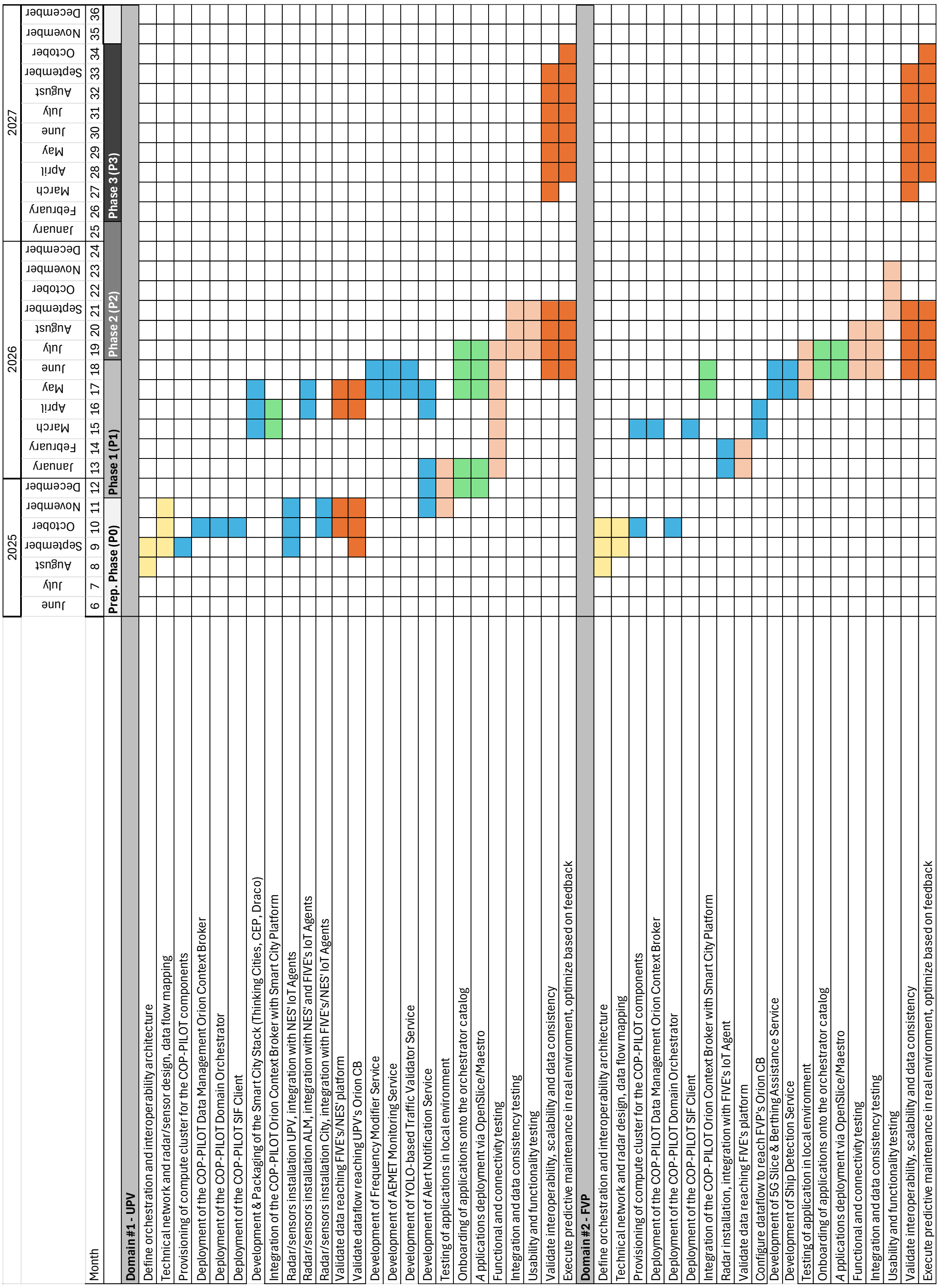
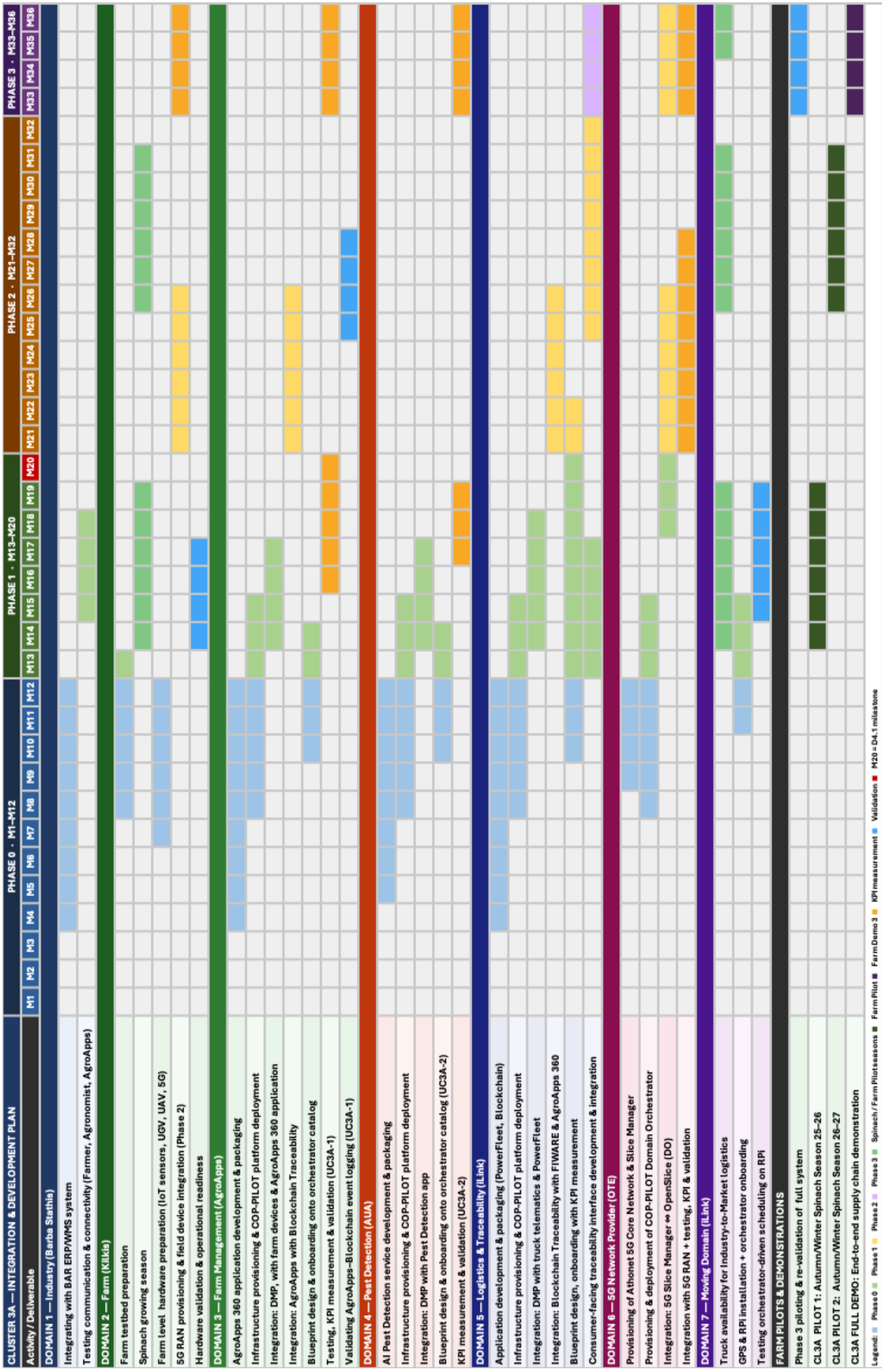
APPENDIX A - CLUSTER 1 INTEGRATION AND DEVELOPMENT GANTT CHART



APPENDIX B - CLUSTER 2 INTEGRATION AND DEVELOPMENT GANTT CHART



APPENDIX C - CLUSTER 3A INTEGRATION AND DEVELOPMENT GANTT CHART



APPENDIX D - CLUSTER 3E INTEGRATION AND DEVELOPMENT GANTT CHART

APPENDIX E - CLUSTER 4 INTEGRATION AND DEVELOPMENT GANTT CHART