

# D5.1

## C3I/IMS and Augmenting the Common Operational Picture (Iteration One)

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## D5.1 C3I/IMS and Augmenting the Common Operational Picture (Iteration One)

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### About the document

This deliverable presents the first iteration of the C3I/IMS and the augmentation of the Common Operational Picture (COP) within the SYNERGISE project. It provides a comprehensive overview of the WP5 tools that include field and HQ communication, AR services, multi-source information fusion with alerting, and the C3I/IMS platform. The document outlines their design, development, integration into the SYNERGISE Toolkit, and deployment in lab and field test scenarios. This deliverable establishes a foundation for iterative improvements, driving progress towards advanced system capabilities, seamless interoperability, and enhanced decision-making support in upcoming project phases.

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**Nature of the deliverable<sup>1</sup>**

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### Dissemination level

<b>SEN</b>	Sensitive, limited under the conditions of the Grant Agreement	✓
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<sup>1</sup> Deliverable types:

R: document, report (excluding periodic and final reports). DEM: demonstrator, pilot, prototype, plan designs.

DEC: websites, patent filings, press and media actions, videos, etc. OTHER: software, technical diagrams, etc.

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## Abbreviations

<b>AI</b>	Artificial Intelligence
<b>API</b>	Application Programming Interface
<b>AR</b>	Augmented Reality
<b>ASR</b>	Assessment, Search and Rescue
<b>BLE</b>	Bluetooth Low Energy
<b>C3I</b>	Command, Control, Coordination, and Intelligence
<b>COP</b>	Common Operating Picture
<b>CP</b>	Command Post
<b>CRES</b>	Collaborative Response and Enhanced Situational Awareness
<b>DARPA</b>	Defence Advanced Research Projects Agency
<b>DNN</b>	Deep Neural Network
<b>DoA</b>	Description of Actions
<b>DoF</b>	Degrees of Freedom
<b>ECK</b>	Emergency Communication Kit
<b>FR</b>	First Responder
<b>GCS</b>	Ground Control Station
<b>GIS</b>	Geographical Information System
<b>GNSS</b>	Global Navigation Satellite System
<b>GPS</b>	Global Positioning System
<b>GPU</b>	Graphical Processing Unit
<b>GUI</b>	Graphical User Interface
<b>HMI</b>	Human Machine Interface
<b>HMT</b>	Human-Machine Teaming
<b>HQ</b>	Headquarter
<b>HTTPS</b>	Hypertext Transfer Protocol Secure
<b>HUD</b>	Head-Up Display
<b>ID</b>	Identity Document
<b>IMS</b>	Incident Management System
<b>INSARAG</b>	International Search and Rescue Advisory Group
<b>IoT</b>	Internet of Things
<b>IS</b>	Information System
<b>JSON</b>	JavaScript Object Notation
<b>KHNP</b>	Korea Hydro & Nuclear Power Co. Ltd.
<b>KPI</b>	Key Performance Indicator
<b>LEO</b>	Low Earth Orbit
<b>LoS</b>	Line of Sight
<b>mAP</b>	mean Average Precision
<b>MEMS</b>	Microelectromechanical System
<b>MQTT</b>	Message Queuing Telemetry Transport
<b>n.a.</b>	Not applicable
<b>NUI</b>	Natural User Interface
<b>NIT</b>	Novel Integrated Toolkit
<b>NFC</b>	Near Field Communication
<b>ONOS</b>	Open Network Operating System
<b>P5G</b>	Private-5G
<b>PTP</b>	Point-To-Point
<b>RMF</b>	Resilient Micro Flyer

<b>RTT</b>	Real-Time-Text
<b>SSL</b>	Secure Sockets Layer
<b>SSID</b>	Service Set Identifier
<b>STT</b>	Speech-to-Text
<b>TOC</b>	Table of Contents
<b>TTS</b>	Text-to-Speech
<b>UAV</b>	Unmanned Aerial Vehicle
<b>UC</b>	Use Case
<b>UE</b>	User Equipment
<b>UNDAC</b>	United Nations Disaster Assessment and Coordination team
<b>USAR</b>	Urban Search and Rescue
<b>UWB</b>	Ultra-wideband
<b>VMS</b>	Video Management Server
<b>VOSOCC</b>	Virtual On-Site Operations Coordination Centre
<b>VOST</b>	Virtual Operations Support Team
<b>WebRTC</b>	Web Real-Time Communication
<b>WP</b>	Work Package
<b>WISCE</b>	Wiki for Socio-Cognitive Engineering
<b>WER</b>	Word Error Rate
<b>XAI</b>	Explainable AI

## Executive summary

The SYNERGISE project, entitled “A Novel Integrated System of Systems Strengthening Technical and Logistical Capacities to Ensure Better Response to Emergencies by Synergistically Addressing First Responders’ Capability Gaps”, aims at enhancing the safety, preparedness, coordination, and operational effectiveness of first responders (FRs) in both natural and man-made disasters. The project develops the Novel Integrated Toolkit for Collaborative Response and Enhanced Situational Awareness (NIT-CRES) to better manage complex disaster scenarios, through the integration of aerial, snake-like and legged swarms of robots, leveraging advanced wearables for real-time vital signs monitoring of FRs and gas environmental sensing, as well as localisation devices, augmented reality technologies for robotic control, video conferencing and FR training, also enhanced alerting information, and interoperable platform for multi-agency collaboration across all phases of disaster management.

Deliverable D5.1 contributes to this objective by documenting the first iteration of the Command, Control, Communications, and Intelligence / Incident Management System (C3I/IMS) and the augmentation of the Common Operational Picture (COP). It compiles information on the design and development of technologies developed in WP5, as well as their integration into the SYNERGISE Toolkit. The WP5 components that are addressed in this deliverable include:

- **Field and HQ Communications (T5.1):** Development of a modular, multi-layer communications architecture combining Private-5G, Wi-Fi mesh, and satellite technologies, which provides connectivity between field teams and headquarters, enabling ad-hoc networking, redundancy, and communication between all relevant SYNERGISE components.
- **Augmented Reality (AR) Services (T5.2):** AR-enabled solutions support FRs’ training, remote assistance via video conferencing, and real-time operational collaboration.
- **Multi-Source Information Fusion (T5.3):** This task develops advanced AI-driven data fusion and alerting mechanisms addressing the critical needs of FRs. It integrates heterogeneous sensor inputs of wearables and leverages explainable AI (XAI) to generate predictive, actionable insights. Key developments also include AI-based recognition of people, objects, and hazards (integrated in the outdoor drone modules), a resource logistics optimisation capability, and the visualisation of alerting information within the C3I environment.
- **Interoperability Framework (T5.4):** This task delivers a robust messaging and data exchange framework that ensures seamless integration between SYNERGISE components as well as with legacy and external incident management systems. Adopting established protocols enables the efficient sharing of alerts, resources, and situational data across agencies, strengthening multi-agency collaboration and operational effectiveness.
- **C3I/IMS and COP (T5.5):** Development of the C3I/IMS platform focused on FRs requirements, aggregating data from all SYNERGISE components into a unified COP. It provides a single integration point to support decision-making, coordination, and situational awareness across heterogeneous response teams.

The above-outlined technologies represent the comprehensive work undertaken in WP5. Additional elements are addressed, like AI people, objects, and hazards detection, logistics optimisation module, interoperability framework, which were not listed as tools in D1.3 entitled ‘Technical specs & Toolkit architecture’.

The components addressed in this document, together with other SYNERGISE technologies developed in WP2, 3, and 4, have been tested and validated in four Component Field Tests (CFTs), providing valuable insights that form a strong basis for the final two System Field Tests (SFTs). This deliverable evaluates the KPIs and system requirements achieved to date and discusses recommendations for further enhancements. By consolidating the developments achieved so far, along with the outcomes of tools testing and validation, D5.1 establishes the operational and technical foundation for iterative improvements in subsequent project phases.

# 1. Addressing the SYNERGISE Description of Action

## 1.1. Addressing DOA

Deliverable D5.1 is the direct outcome of WP5: 'Multi-agency collaboration and Incident Management and Augmenting the Common Operational Picture', led by ASTRIAL with ETRI, VIRNECT, CERTH, and SATWAYS as contributing partners.

All five tasks under WP5 commenced in Month 4 and will conclude in Month 39. Table 1 maps the DoA requirements for all tasks under WP5 to the content presented in D5.1.

This document consolidates all activities relevant to the design, development, testing, and validation of the SYNERGISE WP5 tools, ensuring full alignment with the objectives and scope of WP5.

Table 1. SYNERGISE DoA Requirements

SYNERGISE DoA WP5 Tasks Description	Relevant D5.1 sections addressing requirements DoA	Notes
T5.1 Field and HQ communications and networking: A multi-layer architecture supported by multiple access technologies (namely, federated 5G, Wi-Fi mesh, and Satellite) will be developed and implemented for the worksite communications and routing under this task.	Section 2.2.1 Section 2.2.2 Section 3.1 Section 3.2	Field and HQ communications and networking solutions are addressed by ASTRIAL and ETRI, outlining the architecture and developments.
T5.1: The deployed infrastructure (at hardware and software levels) will offer seamless services to all platforms deployed (robots, wearables, AR headsets, and smartphones/tablets) with the C3I controlled by one or more deployed gateway(s) at a crisis site. This task will define and implement the architecture of the interoperable communication system.	Section 3.1 Section 3.2 Chapter 4 Chapter 5	Interconnections with other SYNERGISE tools and deployments in test scenarios are described.
T5.1: This task will also consider the interface requirements of every hardware module for the design and development of a modular gateway. The specific characteristics of the connectors will be adapted to provide Plug-and-Play capabilities for different devices. Additionally, the communication gateway will integrate different types of communication interfaces (multiple RAN technologies, at the local level (LAN) and remotely connecting the HQ (WAN)) for redundancy purposes.	Chapter 2 Chapter 3 Chapter 6	The development of communications and networking solutions addresses requirements to provide a Plug-and-Play system for SYNERGISE components by integrating different types of communication interfaces.
T5.1: This task will also develop/integrate specialised routing protocols for wireless ad-hoc networking that will store, carry, and forward capabilities. Routing will be done by the selection of the best forwarding or/and ferrying node. The different available communication technologies and channels will be considered for redundancy purposes as well as for selecting the optimum communication link.	Chapter 3	Communications and networking protocols are defined.

<p>T5.2: Enhancing operations with Augmented Reality services: This task aims to create AR (augmented reality) enhanced services to support first responders that can be used to connect stakeholders in the field and off-site immersively. Additionally, offer a range of tools that will help to gain access to centralised know-how and real-time data to assist in the understanding of the site.</p>	<p>Section 2.2.3 Section 3.3</p>	<p>AR services developed by VIRNECT in the SYNERGISE project to improve FRs activities and training are addressed.</p>
<p>T5.2: Both seamless communication and knowledge and data contribute to enhanced operations and developing a more unified and in-depth Common Operational Picture or COP. It is challenging to deploy multi-party collaboration and AR visualisation in environments with low speeds or limited connectivity.</p>	<p>Section 3.3 Section 4.2.3</p>	<p>Interactions with other tools to enhance COP are described.</p>
<p>T5.2: Another objective of this task is to link sensor data to the visualisation system in real-time, which is in itself challenging but further constrained by the network conditions.</p>	<p>Section 2.2.3 Section 3.3 Section 5.3</p>	<p>Functionalities and performance of AR services are outlined.</p>
<p>T5.2: By optimising these two areas based on VIRNECT's Remote (AR remote collaboration platform) and VIRNECT View (AR visualization software) in connection to the AR smart glasses it is expected that first responders can give first responders a robust and reliable solution that gives them the clarity and information they need instantly to save lives untethered from their current limitations</p>	<p>Section 2.2.3 Section 3.3 Section 6.3</p>	<p>Functionalities, system requirements, and KPIs of AR services are addressed to fulfil user requirements.</p>
<p>T5.3: Multi-source information fusion and map-based visualisation across teams: A warning, alerts, and notifications system will be developed in order to early predict hazardous situations for the First Responders.</p>	<p>Section 2.2.4 Section 2.2.5 Section 2.2.6 Section 2.2.7</p>	<p>To enhance the alerts, warning, and notification system to assist FRs, different modules were developed by CERTH, ASTRIAL, and SATWAYS</p>
<p>T5.3: AI fusion algorithms will be explored for merging heterogeneous data acquired from various sensors, relevant to the project (originating from the robots, wearables, AR headsets, and smartphones/tablets and their equipped sensory modules), such as gas sensor measurements, vitals of the First Responders, etc.</p>	<p>Section 2.2.4 Section 2.2.5 Section 2.2.6 Section 2.2.7 Section 3.4 Section 3.5 Section 3.6 Section 3.7</p>	<p>Multiple algorithms have been explored to fuse information originating from SYNERGISE sensors.</p>
<p>T5.3: Towards producing efficient and comprehensive alerts, early, intermediate, and late fusion strategies will be employed to join multiple modalities, in an efficient way, and integrate them with Machine Learning algorithms for more sophisticated and accurate predictions. To promote a trustable warning, alerts, and notifications system, those AI algorithms will be imbued with explainable capabilities to enable users to understand the output through human-centered explanations.</p>	<p>Section 3.4 Section 3.5 Section 3.6 Section 3.7</p>	<p>AI algorithms are developed to enhance the alerts, warning, and notifications system.</p>
<p>T5.3: Last, the entirety of generated alerts will be visualised onto various map layers, reaching the actors responsible to take decisions upon them.</p>	<p>Chapter 2 Chapter 4 Section 5.4</p>	<p>The entirety of alerts is designed, visualised, and</p>

	Section 5.5 Section 5.6 Section 5.7	tested in real-time scenarios.
T5.4: Establishing the interoperability framework among IMS: This task will deliver a holistic interoperable framework for Incident Management. For this purpose, a data model will be developed and implemented that allows seamless integration with legacy and external systems (command and control systems of various vendors, 3rd party emergency management applications, early warning systems, etc.) via APIs and messaging brokers that are tuned into exchanging alerting, resources, tasks, and multimedia notifications protocols (e.g., EDXL-family, CAP, TSO, etc.). As such, SYNERGISE will deliver a “black box” in the form of a messaging gateway that enables collaboration among agencies regardless of their system of choice.	Section 2.2.8 Section 3.8 Chapter 4 Section 5.8	An interoperable framework for SYNERGISE Toolkit is outlined.
T5.5: Multi-agency Incident Management and sharing the COP: This task will develop and deliver a novel C3I/IMS platform for emergency responders of all disciplines that gathers and aggregates all data from the components of the SYNERGISE technological ecosystem (from the robots, wearables, AR headsets, and smartphones/tablets and their equipped sensory modules).	Chapter 2 Section 3.9 Chapter 4 Chapter 6	The C3I/IMS platform is designed to accommodate the needs of FRs.
T5.5: The C3I/IMS will share the common operational picture among participating actors in the form of 2D/3D maps of various formats and visualising incoming information using appropriate semantic representations over multiple layers.	Chapter 4 Chapter 5	The interconnections of C3I/IMS with other SYNERGISE components and data flow within the toolkit are described.
T5.5: It will enhance the standard functions of response personnel in terms of: status of tasks, assignment of teams and team members, visualisation of actionable information (e.g., personnel’s vitals and position, threats’ notifications), communication between team members across chain of command, logistics handling, assets and resources management, duty rostering whilst allowing implementation and customisation (predefined and in real time) of the standard operating procedures.	Section 3.9	All functionalities are outlined.
T5.5: Moreover, the C3I/IMS will declutter the information, providing a simplified view of the complex aggregate of data that can emerge from the gathering of such amount of material. Last but not least, the SYNERGISE C3I/IMS will be the single integration and visualisation point of all gathered data from all components of the project, including integration with legacy ones.	Section 2.2.9 Section 3.9 Section 5.9	The C3I/IMS platform is fully described from the development point of view as well as deployment as the single integration and visualisation point of the SYNERGISE toolkit.

## 1.2. Deliverable Input and Output

The required inputs for this deliverable, outlined in Table 2, represent the foundational information used in the development of D5.1.

Table 2. Reference documents for input

Reference	Title
D1.1	FR scenarios, use cases, and requirements
D1.3	Technical specifications and Toolkit architecture
D1.4	User Evaluation Protocol
D6.1	Report on CLTs and TIWS testing and evaluation results

D5.1 is a valuable source of information for future developments of the SYNERGISE tools and the overall toolkit, as well as for the upcoming testing in SFTs. The document serves as a reference for the remaining deliverables listed in Table 3.

Table 3. Reference documents for output

Reference	Title
D1.6	Human-Machine Teaming framework
D2.2	Robots mobility and manipulation capabilities (Final)
D3.2	Advancing the environment representation and robot autonomy (Final)
D4.2	Wearables techs for FRs (Final)
D5.2	C3I/IMS and Augmenting the Common Operational Picture (Final)
D6.3	Report on the SYNERGISE system field testing and evaluation results
D6.4	Lessons learned and recommendations from all the field tests
D6.5	Training Material
D7.3	Business Plan

## 1.3. Document Structure

This deliverable is structured to provide a systematic presentation of the developments, integrations, and evaluations relevant to the tools developed in the framework of WP5.

- **Chapter 1** establishes the link to the DoA, defining the inputs and outputs for this deliverable and providing a short guide to its structure.
- **Chapter 2** introduces the overarching concept of the Common Operational Picture (COP) and its role within SYNERGISE, while also presenting an overview of the SYNERGISE components developed in the framework of WP5 tasks, grouped by their functions in field and HQ communication, AR services, multi-source information fusion, interoperability, and incident management.
- **Chapter 3** describes the design, development, and functionalities of each WP5 component in detail, including aims, timeline, and technical specifications.
- **Chapter 4** examines component interconnections, focusing on the flow of data across the different tools and how integration is achieved within the SYNERGISE Toolkit.
- **Chapter 5** documents the deployment of tools in lab and field test scenarios, providing practical insights into their performance in controlled and operational environments.
- **Chapter 6** presents the evaluation of system requirements and KPIs, structured both by SYNERGISE components to assess compliance with specifications and performance targets.
- **Chapter 7** concludes the deliverable, summarising key findings and outlining directions for future work and further refinement.

## 2. Multi-agency Collaboration and Incident Management Augmenting the Operational Picture Overview

### 2.1. Role of COP for the SYNERGISE Toolkit

Effective incident management, in both natural and man-made disasters, requires coordinated action between specialised response units such as USAR teams and firefighters, as well as law enforcement, civil protection, and other agencies. Within the SYNERGISE context, the COP is not only a collaboration tool but the central integration point for all data generated by the toolkit components.

By consolidating sensor inputs, communication streams, autonomous and semi-autonomous robots' reconnaissance, vitals of FRs, and environmental data, AR services, and analytical outputs into a single unified situational view, the COP ensures that information is consistently available both at Command-and-Control HQs and for field team leaders. This enables real-time decision-making during operations, where commanders and responders rely on the same validated information to coordinate search, rescue, and firefighting efforts.

Thus, the COP in SYNERGISE goes beyond supporting multi-agency collaboration: it acts as the backbone of operational awareness, linking all system components, bridging field and HQ information, and ensuring that disaster response decisions are based on a comprehensive and up-to-date information flow.

The main COP aims are:

- To integrate real-time and historical data from SYNERGISE components, including communications systems, UAVs, robotic assets, localisation devices, health wearables, environmental sensors, and XAI services.
- To enable decision support by visualisation of early warning and alerting information, resource availability, and the dynamic evolution of the incident in a unified view.
- To provide a shared situational awareness platform tailored to SYNERGISE disaster-response operations, supporting coordinated actions of USAR teams, firefighters, and civil protection agencies.
- To strengthen trust and transparency across command levels by ensuring all actors – from HQ commanders to field leaders – have reliable access and up-to-date information layer.

Within SYNERGISE, the COP acts as the integration point for outputs from all toolkit components, between which a message exchange is enabled via communication and networking systems (Wi-Fi, satellite, private 5G), that provide continuous connectivity for operational activities across distributed field units. C3I/IMS platform delivers command and control functions for HQ personnel and field team leaders, including task allocation, resource tracking, incident reporting, and coordination between HQ and deployed units. Robotic assets, such as ANYmal, SNAKE, indoor OWLs, and outdoor drones, provide live video streams, area surveillance, 2D and 3D mapping, people, objects, and hazards detection, and environmental sensors outputs. Vitals and environmental wearables capture the health status of FRs, and environmental readings, respectively, enhancing safety and situational awareness. Augmented Reality services: AR video conferencing, AR visualisation, AR training support FRs in the field with context-aware overlays. Analytics, such as AI detection modules, process incoming information to identify people, objects, and hazards, while XAI services analyse data related to FR health parameters, providing risk assessment, predictive modelling, and decision recommendations.

The SYNERGISE COP architecture is designed as a federated, modular integration layer, ensuring that all toolkit components contribute to a coherent and actionable operational picture:

- Data Ingestion Layer – gathers live feeds and logs from communications, robotic sensors, wearables, AR services, and external databases.
- Processing, Data Fusion and AI Layer – normalises, aggregates, and correlates heterogeneous data into validated, mission-relevant information.
- Visualisation and User Interface – provides map-based situational displays, interactive dashboards, and time-series views accessible both at HQ and via field devices.
- Communication and Collaboration Layer – enables secure role-based access, information exchange, incident reporting, and cross-agency coordination in real time.

This architecture ensures that SYNERGISE COP is scalable, interoperable, and field-ready, acting as the backbone of operational awareness. It not only reflects the current disaster situation but also supports planning, foresight, and resilient decision-making by seamlessly linking HQ command structures with field rescue teams.

## 2.2. WP5 Tools Overview

### 2.2.1. Field and HQ Communication: ASTRIAL Solution

A modular, multi-layer communications architecture was designed to ensure robust, flexible, and redundant connectivity between field units and headquarters. The architecture leverages multiple access technologies, federated 5G, 4G, Wi-Fi mesh, Point-to-Point, and satellite to address diverse operational environments and provide continuous service availability across the SYNERGISE ecosystem. The comprehensive communication solution was developed by ASTRIAL in order to address different stages of connectivity readiness of the SYNERGISE components to provide a functioning network for CFTs, with the first CFT taking place already at M16. The ETRI Emergency Communication Kit has been under development and was not ready to provide the network to all SYNERGISE tools taking part in CFTs.

For satellite communications (SATCOMM), ASTRIAL integrated a Starlink terminal to enable high-bandwidth backhaul connectivity, complemented by public 5G SIM cards for direct access to commercial networks. To ensure reliable coverage in areas with limited cellular reach, a 4G signal amplifier is included in the communication toolkit. These elements are managed through a multi-WAN 5G NR Wi-Fi 6 router (GL.iNet), providing seamless failover and load balancing across heterogeneous links.

For land-based communications (LANCOMM), a scalable Wi-Fi mesh system was established, comprising several outdoor and indoor Wi-Fi nodes. Each node is designed to extend ad-hoc networking capabilities. The indoor nodes are powered by dedicated power banks for autonomous operation. Additional infrastructure, including Ethernet, and power cabling, DC-to-AC inverters, PoE injectors, and mounting tripods, was procured to facilitate rapid deployment and interoperability in field conditions.

Both SATCOMM and LANCOMM equipment form the backbone of the WP5 communication layer, providing FRs with continuous connectivity between all SYNERGISE components, such as robotic assets, localisation devices, wearables, AR services, and the C3I/IMS. The modular design ensures plug-and-play integration, redundancy through multiple communication channels, and the ability to adapt to dynamic incident scenarios, thereby strengthening the operational resilience and effectiveness of multi-agency disaster response.

### 2.2.2. Field and HQ Communication: ETRI Emergency Communication Kit

The ETRI Emergency Communication Kit (ECK) consists of two types: LAN+Ethernet+Wi-Fi and Private-5G+Ethernet+WiFi. The former has been developed in the project funded by Korea Hydro & Nuclear Power Co. Ltd. (KHNP) during 2018 - 2019. KHNP provided us a set of specific requirements that the emergency communications toolkit should meet due to the unique environment that a nuclear power plant has. The latter has also been initially developed in the succeeding project funded by KHNP during 2021-2022, in which the private 5G technology is utilised to interconnect two Ethernet-based nuclear power plant buildings. Both toolkits consist of

Spine Node (for Auto-Configuration and Plug-and-Play Management), Leaf Node (for Link Routing) and AP Node (wireline Voice Phone via Ethernet cable, wireless Smartphone via Wi-Fi) so that in the event of a nuclear power plant accident, non-professionals can build communication networks autonomously within an hour (optimally within 30 minutes) without the need for external electrical power. ETRI ECK, in the framework of this EU-Horizon SYNERGISE project, extended the functionality of Private-5G for the general mobile communication purposes to support field communications among FRs, recovery robots, wearables, and C3I HQ, etc., at a disaster site (Figure 1). The solution consists of an all-in-one box capable of Private-5G core network functionality and multiple gNodeB small boxes. The network solution falls into TRL 3 to 5 levels, which means that the solutions are research prototypes, but not commercialised products.

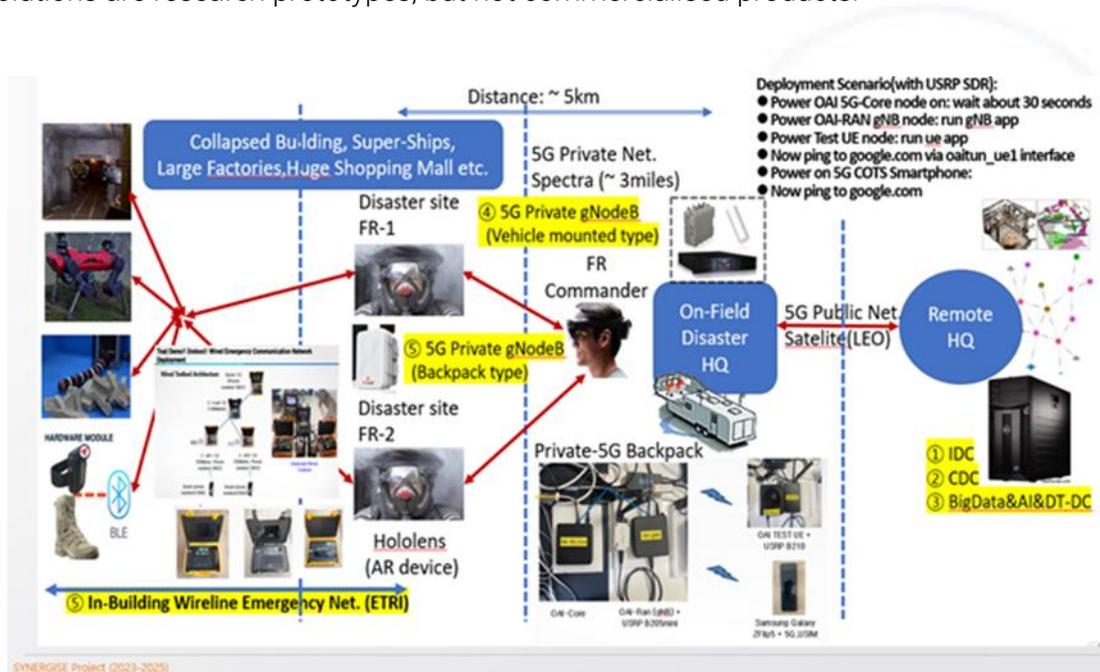


Figure 1. Overview of ETRI Emergency Communication Kit

A Private-5G-based quality assurance self-organising emergency field communication solution provides hyper-immersive augmented reality services essential for quick and safe emergency rescue activities at extreme disaster sites. It includes both mobile and fixed integrated autonomous communication equipment with a portable battery, which supports disaster site communication. It can, thus, cover not only the open area where mobile communication is allowed but also the blocked area where Line of Sight (LoS) is not guaranteed. It enables real-time field status information sharing based on AR and WebRTC for disaster rescue and communication quality support of the rescue team collaboration system. Since ETRI is conducting Korean government-supported non-commercial technology development research project, the end result will fall into TRL 5.

### 2.2.3. Augmented Reality Services: VIRNECT AR Training/Video Conferencing/ Visualisation

VIRNECT's Augmented Reality (AR) service is designed to innovatively enhance the operational capabilities and safety of FRs at the disaster site. This comprehensive solution is developed around three core components: AR Training, AR Video Conferencing, and AR Visualisation. Each element has the shared goal of maximising the situational awareness and decision-making abilities of responders, from the training phase to actual mission execution.

The currently developed AR Training application, based on VIRNECT's proprietary 'Make' and 'View' platforms, supports the safe mastery of complex equipment like the ANYmal and SNAKE robots in a virtual environment (Figure 2). This enables repetitive practice without physical hardware, significantly increasing training efficiency and safety. The AR Video Conferencing application

implements multi-platform communication connecting field agents (Meta Quest 3), mobile commanders (mobile), and the central command post (CP) (Figure 3). It notably features a specialised Speech-To-Text (STT) model that accurately recognises voice commands even in the extreme noise of a disaster scene, providing a true hands-free environment for responders to focus on their mission and playing a key role in establishing a Common Operational Picture.



Figure 2. AR Training Application for ANYmal, and SNAKE robots



Figure 3. AR Video Conferencing Application captured from HQ CP



Figure 4. AR Video Conferencing at CFT4

The AR Visualisation function, planned for development in CFT4, was conceived based on lessons learned from CFT3 testing. To solve the issue of the video conference screen obstructing the view, this feature uses key disaster information, such as drone locations and mission objectives, in the form of non-intrusive AR overlays. This allows responders to stay focused on rescue activities while

checking essential information in real-time, and they can call up the AR video conferencing application via voice command when needed. Furthermore, FRs can operate most of the visualisation menu through voice commands to continue their rescue activities in a hands-free environment. Once the AR Visualisation function is complete, VIRNECT's AR service will evolve into an integrated solution, where training, communication, and information access occur seamlessly in a single augmented reality environment, elevating field response capabilities to a higher level.

#### **2.2.4. Multi-Source Information Fusion: CERTH XAI Services**

The Explainable AI (XAI) service provides a backend tool for real-time alerting for both environmental hazards, like gas exposure, and critical physiological vitals, such as abnormal heart rate. It enhances these alerts with Explainable AI techniques, providing clear, actionable insights into why an anomaly was flagged - not just that it occurred. Furthermore, by performing parallel analysis on disparate environmental and biometric data streams, the system intelligently infers potential causal relationships, offering a proactive understanding of how external threats impact human health in the absence of a pre-existing combined dataset.

#### **2.2.5. Multi-Source Information Fusion: ASTRIAL Logistics Optimisation Module**

The Logistics Optimisation Module is a specialised tool designed to support FRs in emergency situations. Integrated within the SYNERGISE C3I/IMS, it provides intelligent, map-based routing and optimises the allocation of critical supplies and resources. By leveraging real-time data on inventory levels, vehicle status, transportation constraints, and incident locations, the module dynamically determines the most effective routes and assignments. This ensures that emergency response operations are faster, more efficient, and more equitable, enabling responders to make informed decisions under pressure.

#### **2.2.6. Multi-Source Information Fusion: ASTRIAL AI People, Objects, and Hazards Detection**

The AI people, objects, and hazards detection module leverages advanced computer vision to identify and classify people, objects, and hazards in real-time from drone footage during outdoor emergency situations. Its primary goal is to enhance situational awareness by automatically recognising different types of human activity, e.g., detecting when a person has fallen (potentially indicating a victim), distinguishing civilians from FRs, identifying fire, smoke, debris, and holes, and classifying various vehicles. All detections are fused with geolocation data, and alerts are streamed to the SYNERGISE C3I/IMS for real-time visualisation and coordinated response.

#### **2.2.7. Multi-Source Information Fusion: ASTRIAL C3I Alerting information**

The SYNERGISE Command, Control, Coordination, and Intelligence (C3I) & Incident Management System (IMS) is an advanced information system designed to support call-taking, dispatching, resource tracking, and administrative functions during both routine operations and high-intensity disaster management scenarios. A key functionality of the system is the management and visualisation of alerts. The SYNERGISE project incorporates multiple components and tools that can interact directly with the incident area and the personnel deployed on site. These tools gather environmental and vital measurements, generate alarms, and forward the information to the C3I platform. Commanders can then view these alerts in real-time, enhancing situational awareness and decision-making.

The system supports a wide range of critical alarms, such as detection of hazardous gas concentrations in a specific area or alerts indicating personnel at risk based on vital sign monitoring. By consolidating and presenting these alerts in a clear and actionable manner, SYNERGISE significantly improves operational effectiveness, coordination, and the safety of FRs.

### 2.2.8. Interoperability Framework among IMS: ASTRIAL IMS Interoperability (Kafka, MinIO)

The transmission of alert and measurement data to the C3I platform is enabled through a robust, scalable data pipeline built on modern streaming and storage technologies. At the core of this pipeline is Apache Kafka [1], which serves as the high-throughput messaging backbone. All data originating from field devices, sensors, and monitoring tools is published into Kafka topics, ensuring reliable, real-time delivery. This architecture allows for seamless integration of diverse data sources, fault tolerance, and the ability to process events at scale without loss of information. To complement real-time streaming, MinIO [2] provides a distributed object storage layer for persisting large volumes of structured and unstructured data, such as media files captured during incidents. MinIO ensures that all information is securely stored, easily retrievable, and highly available for both immediate operational needs and longer-term analysis.

Through this combination, the system guarantees that time-critical alerts (e.g., hazardous gas detections or personnel health warnings) are instantly transmitted to the C3I for visualisation and decision-making.

### 2.2.9. Multi-agency Incident Management and the COP: ASTRIAL C3I/IMS

In the context of the SYNERGISE project, an advanced C3I/IMS system is being developed. This system is based on a legacy C3I/IMS system provided by ASTRIAL. It provides capabilities for Incident Management, Computer-Aided Dispatch, and Situation Management, optimising the response process by ensuring that all stakeholders in the operational chain have a clear understanding of the situation and their required actions.

The system is designed to be used by field teams, on-site coordinating officers, and headquarters personnel. In multi-agency and multi-team operations, the SYNERGISE C3I/IMS facilitates cross-organisational collaboration, ensuring that each actor, according to their role and responsibilities, receives the right level of information to support effective decision-making and incident coordination.

To achieve this, the SYNERGISE C3I/IMS integrates all tools and components of the SYNERGISE ecosystem into map-, form-, and dashboard-based visualisations, providing a unified view of operations, producing the Common Operational Picture, and improving the situation awareness. Additionally, the system strengthens collaboration, communication, and coordination by enabling agencies to access common situational views, exchange multimedia information, and manage task assignments effectively.

## 3. Development of the tools in WP5: Aims, Timeline, Hardware and Software, Functionalities

### 3.1. Field and HQ Communication: ASTRIAL Solution

The primary objective of the Field and HQ Communication toolkit is to establish a resilient, multi-layer communications infrastructure that ensures continuous connectivity across diverse and challenging operational environments. The architecture integrates satellite, Public-5G, and Wi-Fi mesh networking to provide redundancy, scalability, and interoperability. These capabilities directly support FRs by enabling resilient communication between HQs and field teams, while also ensuring seamless integration of all SYNERGISE components.

The development of the communication toolkit commenced with the beginning of the project and was accomplished with the final CFT, providing functionalities outlined in Table 4. Progress has followed an iterative approach aligned with testing and field validation activities. Initial acquisitions and integration of the first hardware set were completed in M4, followed by configuration and preliminary lab testing of multi-WAN routing, Wi-Fi mesh, and satellite backhaul in the subsequent

months. All four field testing activities provided opportunities to validate redundancy, throughput, and ease of deployment by users under realistic conditions. After each CFT, refinements including software configuration, routing protocol optimisation, and integration with other SYNERGISE tools have been systematically carried out to enhance the resilience and overall performance of the communication network.

**Table 4. Functionalities for Field and Communication solutions developed by ASTRIAL**

No	Functionality description	Milestone	Status
1	Satellite Backhaul (Starlink): Provides high-bandwidth SATCOMM connectivity for HQ–field communication	CFT1-CFT3	Achieved
2	Multi-WAN Router Integration: GL.iNet 5G NR Wi-Fi 6 router enabling seamless failover/load balancing across SAT, 5G, and Wi-Fi.	CFT1-CFT4	Achieved
3	4G/5G Connectivity: Public SIM cards and 4G amplifier to ensure mobile broadband availability in variable coverage areas.	CFT1- CFT4	Achieved
4	LANCOMM Wi-Fi Mesh: Outdoor and indoor nodes with power banks for rapid deployment and ad-hoc networking.	CFT1-CFT4	Achieved
5	Accessories & Deployment Toolkit: PoE injectors, tripods, inverters, and cabling to enable fast and reliable field deployment.	CFT1-CFT4	Achieved
6	Routing Protocols & Redundancy: Development of specialised routing protocols with carry-and-forward capability for ad-hoc operations.	CFT1-CFT4	Achieved

## Hardware

- **Satellite Communication (SATCOMM):** Starlink satellite terminal for high-throughput, low-latency backhaul.
- **Mobile Broadband:** 5G SIM cards, 4G signal amplifier for coverage extension.
- **Multi-WAN Router:** GL.iNet 5G NR Wi-Fi 6 router providing integrated management of heterogeneous access technologies.
- **LAN Nodes:** Outdoor Wi-Fi mesh nodes, indoor Wi-Fi nodes, supported by dedicated power banks for autonomous operation.
- **Deployment Accessories:** Ethernet/power cabling, DC–AC inverter cables, PoE injectors, and tripods for rapid on-site deployment.

## Software

- **Router Management Console:** Configured for load balancing, automatic failover, and link prioritisation across SATCOMM, 5G, and Wi-Fi.
- **Wi-Fi Mesh Firmware (Deco App):** Customised for deployment of new nodes, node diagnostics, monitoring, and reporting.
- **Routing Protocols:** Development of specialised carry-and-forward routing schemes enabling resilient communication in disrupted or ad-hoc topologies.
- **Monitoring & Diagnostics Modules:** Software tools for real-time monitoring of link performance, bandwidth, speed test, and fault detection.

### 3.2. Field and HQ Communication: ETRI Emergency Communication Kit

ETRI has been developing P5G communication, including wireless gNodeB and Core-Plane, and Wi-Fi-based wireline communication with Spine (root node), Leaf (relay node), and Access Point (AP) (terminal node) (Figure 5, and Figure 6). Network parameters optimisation is ongoing to improve performance. ETRI Private-5G ECK focuses on the connection between Private-5G User Equipment (UE) terminals (e.g., P5G smartphones, P5G NAT routers, P5G Control Plan to Wi-Fi-Mesh to Satellite antenna) and the connection between wireline AP nodes inside the building, which is successfully achieved for P5G connectivity.

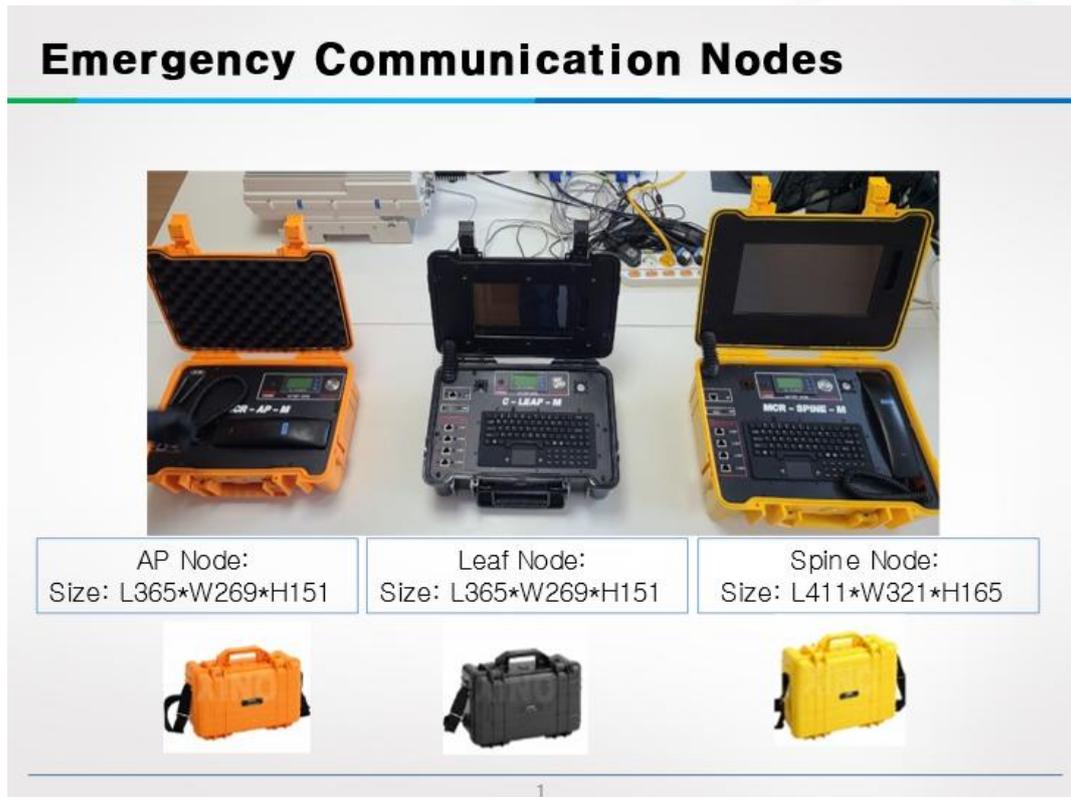


Figure 5. Emergency Communication Nodes developed by ETRI

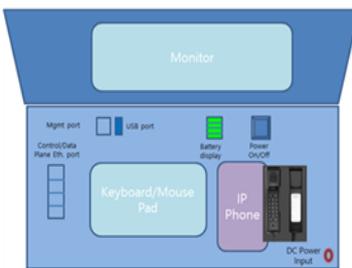
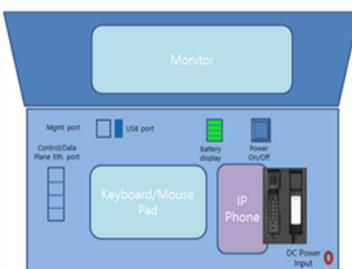
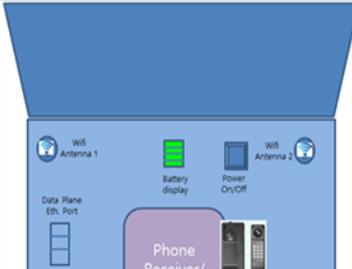
Node Types	Outer Shapes	Interface Capability Schematic Specs.
Spine Node		<ul style="list-style-type: none"> <li>• HDMILCDmonitor, USB wired keyboard/mouse pad</li> <li>• Control/data plane Gigabit ethernet port(RJ45 UTP) <ul style="list-style-type: none"> <li>- 4 ethernet port: 2.5GbE(onboard), 2.5GbE(USB-C to GbE), 2.5GbE(USB-C to GbE), 1GbE(USB-A to GbE)</li> </ul> </li> <li>• Management port <ul style="list-style-type: none"> <li>- 1 GbE(RJ45 UTP)</li> <li>- 1 USB 3.0 port</li> </ul> </li> <li>• Display status/remains of battery</li> <li>• DC input port for charging battery</li> <li>• Power On/Off button switch (status light)</li> <li>• Case Size : L411 * W321 * 165H (Middle size of Leaf and AP)</li> </ul>
Leaf Node		<ul style="list-style-type: none"> <li>• HDMILCDMonitor <ul style="list-style-type: none"> <li>- Remove Keyboard/Mouse pad, if possible to put keyboard or phone</li> </ul> </li> <li>• Control/data plane Gigabit ethernet port(RJ45 UTP) <ul style="list-style-type: none"> <li>- 4 ethernet port: 2.5GbE(onboard), 1GbE(USB-C to GbE), 1GbE(USB-C to GbE), 1GbE(USB-A to GbE)</li> </ul> </li> <li>• Management port-1 GbE(RJ45 UTP)-1 USB 3.0 port</li> <li>• Display status/remains of battery</li> <li>• DC input port for charging battery</li> <li>• Power On/Off button switch (status light)</li> <li>• Case Size : L365 * W269 * H151</li> </ul>
AP Node		<ul style="list-style-type: none"> <li>• SIP Phone Receiver/Dial Button</li> <li>• Data-plane Gigabit Ethernet port (RJ45 UTP) <ul style="list-style-type: none"> <li>- 3 GbE port</li> </ul> </li> <li>• Data-plane Gigabit WiFi port (RJ45 UTP) [AP WiFi port - WiFi extension cable - External WiFi antenna]</li> <li>• 3 Wireless WiFi Antennas</li> <li>• Display status/remains of battery</li> <li>• DC input port for charging battery</li> <li>• Power On/Off button switch (status light)</li> <li>• Case Size : L365 * W269 * H151</li> </ul>

Figure 6. Description of ETRI Spine, Leaf, and AP Nodes

## Description of ETRI's Wireline (Ethernet LAN Cable) Toolkits

When extreme natural disasters such as earthquakes, tsunamis, or storms destroy the existing wired and wireless communication networks of industrial facilities like nuclear power plants, it becomes critical to establish reliable alternatives. In such situations, nuclear power plant operators, who are not telecommunications experts, must be able to quickly set up portable and easy-to-use emergency communication networks. These networks should ensure the reliability and safety of both voice and data services.

In the event of a disaster at a nuclear power plant, the focus is on providing basic voice and data services through emergency communication. In other words, communication services for autonomous construction and disaster recovery must be available both inside and outside nuclear power plant facilities where extreme disasters, such as the Fukushima accident, may occur. To this end, technologies have been developed and secured for systems and construction methods that enable the rapid establishment of emergency communication networks capable of restoring services in disaster situations.

Rapid establishment and restoration of communication is essential to minimising secondary and tertiary damage and to maintaining the overall safety of industrial facilities.

Requirements of In-building DRS Wireline serving in ETRI's Toolkits:

- Easily and quickly deploy emergency networks (should)
- Voice and data service is available between the main control room and the on-site operator
- Redundancy/multiplexing of communication lines to enhance viability
- Communication is still possible in fire door shielding environments (e.g., thick bulkheads)
- Capable of operating Plug-in-and-Operation equipment by field operators

- Installation of Leaf nodes at up to 10 sites
- VoIP wired/wireless service between the main control room and the field sites
- Remote video communication between the main control room and the sites
- In case of radio interference with nuclear power plant instrumentation equipment, only a wired communication network is possible
- Flat-UTP or window-Wi-Fi/BLE connections under the shielding door

### Main Functions of In-building DRS Wireline serving in ETRI's Toolkits

Operations Management Interface:

- Enable Internet communication such as SSH, Telnet, FTP, etc.
- The management console can provide external connections (with an emergency communication server)
- Network Interface (I/F): Giga-bits I/F available

Emergency Communication System Performance Criteria:

- The entire emergency disaster communication network can be installed and established within 30 minutes
- 4-10 control nodes under Spine-Leaf structure
- VoIP concurrent users can be 200 simultaneously
- VoIP voice quality levels provide MOS 3.6 or higher
- Guaranteed minimum operation time of emergency disaster communication facilities for 6 hours
- The communication connection rate between the main control room/field operator is 99 to 99.9%

### Description of ETRI's Wireless (Private-5G) Toolkits

The Private-5G networks work similarly to 5G commercial networks, but are mobile networks that allow the private owners to provide limited access and use licensed or unlicensed radio spectrum. Basically, 5G private networks take advantage of existing 5G commercial networks in closed facilities such as manufacturing plants, harbours/ports, airports, campuses, and business parks. It is useful when deploying private wireless networks to facilities that require more than Wi-Fi, and other network technologies are provided. These can include wide coverage, fast access, improved performance, enhanced privacy, and security.

Some aspects of Private-5G are identical to 5G commercial networks provided by commercial telecommunications service providers. 5G networks are the next generation of wireless mobile technologies that provide low-latency and high-throughput communication connectivity. Private-5G is particularly attracting attention in the field of industrial or disaster sites because it has the advantages of shortening rescue-waiting times and strengthening stability. An example is large-scale industrial/disaster sites that require a stable connection from outside, as well as rescue work sites under extreme disaster situations.

ETRI's emergency communication system aims to provide real-time multimedia emergency communication services by quickly establishing intelligent private 5G emergency communication networks within one hour when extreme natural/human disasters destroy existing wired/wireless commercial communication networks in disaster areas.

ETRI Private-5G UE radio signal range is within a 1 km radius, and the traffic downlink/uplink speed is measured at 40~80 Mbps / 10~15 Mbps in the CFT4, thus its performance improvement work is ongoing into next year. Pre-preparation work and final field testing are required to work with Wearable Devices (Quectel 5G Modem) in the future. To stabilise VoIP service functions, IP services

necessary for actual emergency situations must be established and tested through the Private-5G network.

ETRI Private 5G All-In-One toolkit node external interface requirement & specification:

- SIP Soft Phone with Receiver/Dial Touch Pad Screen, microphone/speaker, and camera
- RU/DU Data Gigabit Ethernet port (RJ45 UTP): 2 GbE ports
- Local Host Edge Gigabit Ethernet port (RJ45 UTP): 1 GbE port
- WAN Internet Gigabit Ethernet port (RJ45 UTP): 1 GbE port
- Management port: 1 GbE (RJ45 UTP), 1 USB 3.0 port
- 4 Wireless 5G Radio Antenna [SDR(B210) TX/RX Radio – SMA extension cable – SMA Female Adapter - External 5G antenna]
- 5-Volt Active GPS Antenna
- Display status/remains of battery
- DC input port for charging battery
- Power On/Off button switch (status light)
- Case Size: L411 \* W321 \* 165H [Wireline spine node size]
- NANUK 933 Size: 19.9 in x 16.1 in x 10.1 in (505 mm x 409 mm x 257 mm) [Private 5G Case]

ETRI Private 5G All-In-One toolkit node external interface design (Figure 7).

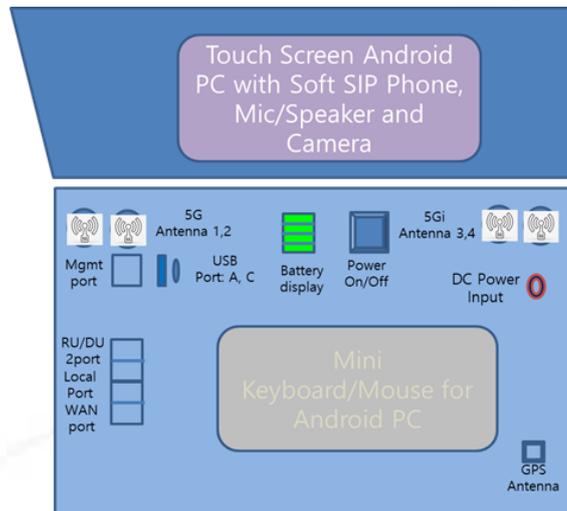


Figure 7. ETRI Private 5G All-In-One toolkit node

ETRI Private 5G All-In-One toolkit node internal component configuration architecture (Figure 8).

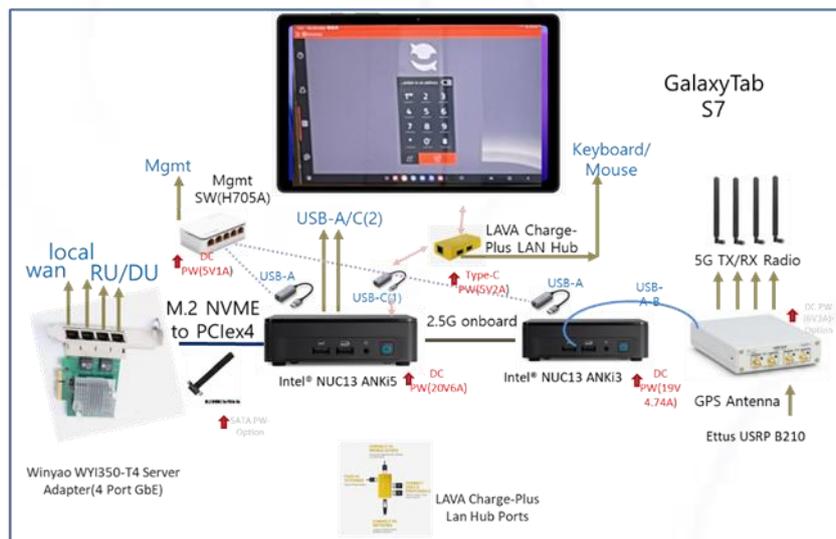


Figure 8. ETRI Private 5G All-In-One toolkit node internal component configuration architecture

ETRI Private 5G All-In-One toolkit node test package and final mobile box (Figure 9).

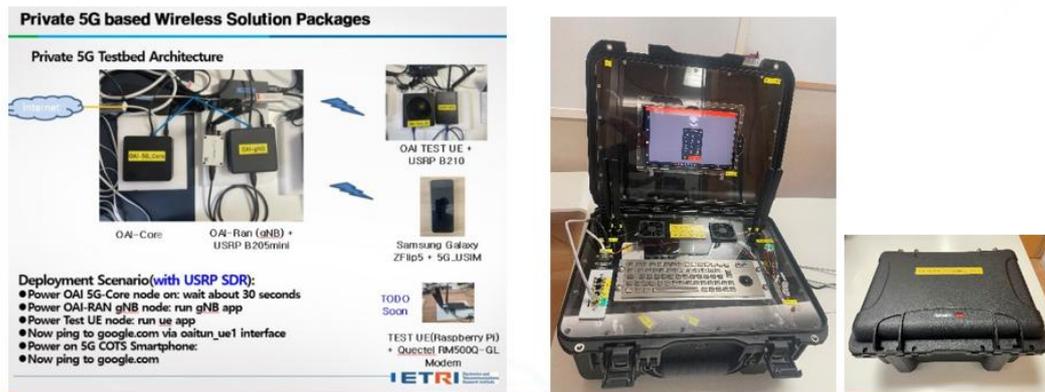


Figure 9. ETRI Private 5G All-In-One toolkit node test package and final mobile box

ETRI Private 5G All-In-One toolkits: 5G node, 5G NAT Router, smartphone UE, wireline AP, and cable reels (Figure 10).



Figure 10. ETRI Private 5G All-In-One toolkits: 5G node, 5G NAT Router, smartphone UE, wireline AP, and cable reels

In CFT1 (Figure 11), PoC verification demonstration, the outdoor wireless connection function, the SYNERGISE network, and in-building wired communication and voice communication interworking function tests were performed first, focusing on Private-5G emergency communication kit equipment.

- ETRI Private 5G All-in-One Box Drive and Internet Connectivity Test (Starlink + Wi-Fi Mesh)
- Smartphone UE connection test with Private-5G USIM
- Private 5G USIM NAT Router Connection Test: Wi-fi and GbE Interface
- Test the functionality of the 5G NAT Router in conjunction with ASTRIAL Command Control Centre (CCC)
- Test Wired AP Connectivity to 5G NAT Routers and Test SIP Smart Phone Connectivity (Wi-Fi)
- Verify the Internet connection function of all UE and perform the SIP Phone voice-phone connection function test

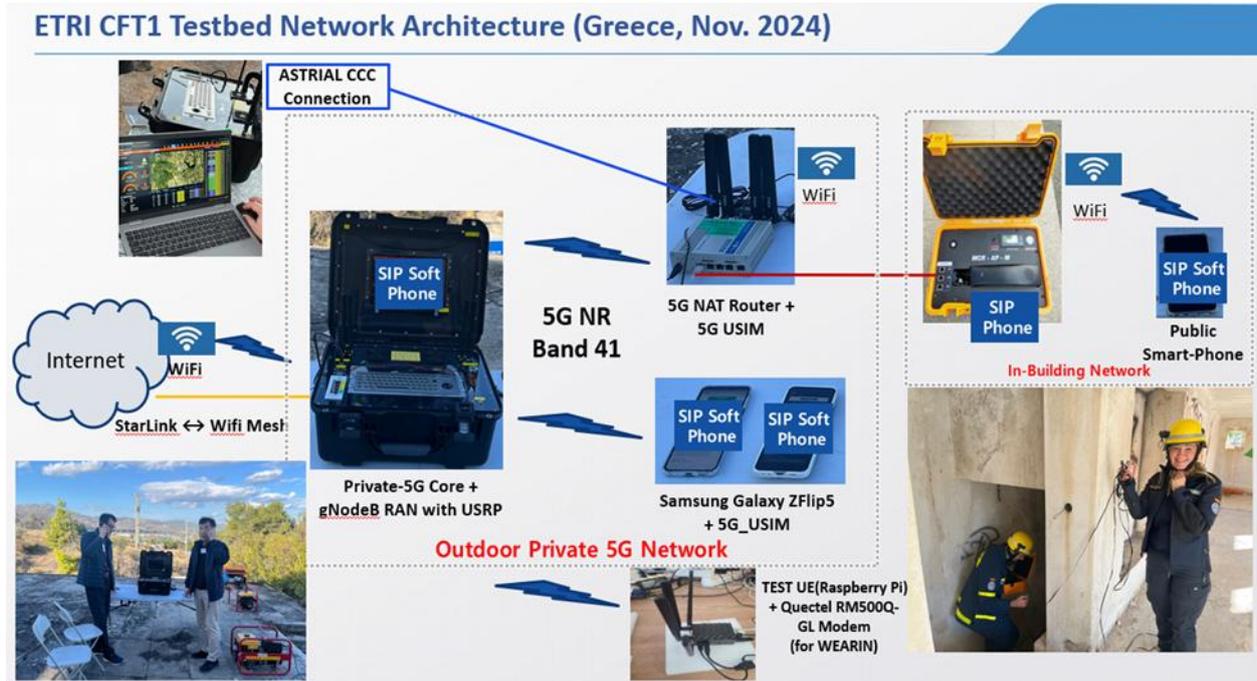


Figure 11. CFT1 ETRI Testbed Network Architecture

Table 5. Functionalities for ETRI Communications Solutions

No	Functionality description	Milestone	Status
1	Deploy ad-hoc network in max 30 mins	CFT1	Achieved Deployment and troubleshooting training (~only 1 hr)
2	Concurrent connection < 200 devices	CFT1	Achieved The scalability of 200 device support has already been proven in lab testing.
3	Uninterrupted (only with Battery) service hours: 8 hours	CFT1	Achieved Due to the battery shipping issue via air travel, this KPI could not be tested at the CFT site. The lab test was completed.
4	Private-5G system should be scalable to cover up to 1 km x 1 km	CFT4	A hybrid approach of Private-5G, Wi-Fi, and wireline solutions is used to cover the target KPI.
5	Private-5G system should support more bandwidth with Up-link 10~15 Mbps & Down-link 40~80 Mbps / Private-5G system should communicate with all SYNERGISE networking components (wearables, robots, satellite systems, LAN system, etc.)	CFT1, CFT3-CFT4	Communication with other components is advancing with CFTs. It was demonstrated that the network was successfully deployed for AR Video conferencing. Verification of connectivity with other components is in

		progress. If there is a need to extend the throughput, further development may be required.
--	--	---

### 3.3. Augmented Reality Services: VIRNECT AR Training/Video Conferencing/Visualisation

The primary aim of the VIRNECT AR tools is to enhance the operational capabilities of FRs. This is achieved through two main applications:

1. **AR Training Application:** To provide FRs with safe, repeatable, and immersive training for operating complex disaster-response robots in a virtual environment, reducing the reliance on physical hardware and minimising training risks.
2. **AR Video Conferencing Application:** To establish a robust, hands-free communication link between on-site FRs, mobile commanders, and the central command post. This facilitates a common operational picture, enables remote expert guidance, and improves decision-making during active missions.

For a timeline and functionalities being developed, see Table 6.

Table 6. Functionalities for VIRNECT AR Services

No	Functionality description	Milestone	Status
1	Core AR Training Framework (Make & View)	CFT3	Achieved
2	Immersive Training Modules (ANYmal, SNAKE Robot)	CFT3	Achieved
3	Multi-Platform Video Conferencing (Quest 3, Mobile, PC)	CFT3	Achieved
4	High-Noise Environment STT Model	CFT3	Achieved
5	Real-time Bilingual Translation & Remote Annotation	CFT3	Achieved
6	Disaster Information Visualisation App	CFT4	Achieved
7	Voice-Activated Video Conferencing UI	CFT4	Achieved

#### Hardware Used

The system utilises a range of commercial and specialised hardware:

- **Field Operative:** Meta Quest 3 Head-Mounted Display (HMD) for FRs.
- **Mobile Command:** Standard Android mobile devices for team leaders.
- **Command Centre:** Standard PCs for commanders and officers.
- **Network Infrastructure:** A portable outdoor private 5G network, NAT router, and Wi-Fi access points to ensure reliable connectivity between all units.
- **Processing:** A local on-premises server is used for intensive computations, specifically for hosting the STT and intent prediction models to enable real-time, hands-free voice commands.

#### Software Modules

The tools are built upon a foundation of proprietary and custom-developed software modules:

- **AR Training Software:**
  - **VIRNECT Make & View Platforms:** These proprietary platforms are used for authoring and deploying the AR training content. The software allows for the creation of structured, multi-stage training scenarios (theory, practical control, simulation).
- **AR Video Conferencing Software:**
  - **Multi-Platform Communication Architecture:** A custom-developed software solution that manages real-time video, audio, and data streams across heterogeneous devices (Quest 3, mobile, PC) and networks (5G, Wi-Fi, LAN).
  - **Collaboration Tools:** Includes functionalities for real-time bilingual (English/Korean) translation, screen capture and sharing, and remote annotation (drawing) on shared visuals to enhance collaborative efforts.
- **Core Enabling Technology:**
  - **Custom STT Model:** A fine-tuned version of OpenAI's Whisper model, specifically trained on a dataset with 10 types of disaster-related background noise. This module is critical for enabling accurate, hands-free voice commands in chaotic environments.
  - **Intent Prediction Model:** An LLM-based function integrated with the STT model to interpret user commands flexibly (e.g., understanding "call commander" and "connect commander" as the same "start call" intent).

### Challenges and implemented mitigation actions

- **Challenge:** It was noted that the AR video conferencing interface occupies a majority of the user's screen, which raised concerns about potential issues during rescue activities.
- **Mitigation Action (Planned for CFT4):** A separate 'Disaster Information Visualisation App' will be developed to display key data (e.g., drone locations) as an AR overlay, minimising screen clutter. The video conferencing feature will also be updated to be voice-activated for on-demand use.

### 3.4. Multi-Source Information Fusion: CERTH XAI services

The XAI services developed within Task 5.3 aim to provide explainable and actionable insights to the warning and alert system of hazardous situations for FRs. The approach relies on the fusion of multiple data sources, including wearable devices that capture physiological measurements of FRs, as well as environmental sensors monitoring gas concentration levels. Key functionalities developed so far:

- Real-time monitoring of physiological vitals and environmental gas conditions,
- Classifier for wellness (based on data from previous CFTs provided by WEARIN) index during physical activity, allowing differentiation between anomalies caused by exertion and those driven by environmental hazards.
- Integration of SHAP-based explainability, providing transparent reasoning on which features (e.g., respiration, movement, gas levels) contributed most to a prediction or alert.
- Prototype backend service implemented in Python, capable of running standalone on a laptop while exposing outputs for potential integration with front-end tools or other systems.

#### Hardware:

- Laptop (Intel i7 processor, 16 GB RAM, SSD storage) used as a standalone server for running the backend service.
- Local execution environment simulating deployment conditions without external hardware dependencies.

## Software:

- Python 3.x environment as the core runtime.
- Key libraries: scikit-learn, SHAP for explainability, pandas/numpy for data processing.
- REST-based interface (prototype) for exposing service outputs to potential front-end or integration layers.
- Local execution with Streamlit for demonstration and monitoring.

No	Functionality description	Milestone	Status
1	Integration of XAI techniques	CFT3	Achieved
2	Alert Generation	CFT3	Achieved
3	Integration with other components	CFT4	Being developed

## 3.5. Multi-Source Information Fusion: ASTRIAL Logistics Optimisation Module

The Logistics Optimisation Module is designed to make emergency logistics more efficient, adaptable, and transparent for FRs. Integrated within SYNERGISE, it combines advanced routing algorithms with real-time inventory tracking to ensure that critical resources, such as equipment, medical supplies, and relief teams, are allocated and dispatched in the most effective way, even in fast-changing disaster scenarios. The tool supports scenario-based route and load planning, matches the right vehicles with the right supplies, and generates clear, map-based plans that automatically adjust as the situation evolves.

Key functionalities (Table 7) developed so far:

- **Route Optimisation:** Calculates optimal transportation routes by factoring in distance, vehicle capacity, and type, and future developments such as road conditions, road disruptions.
- **Inventory Management:** Provides a simple table-based system to add, update, or remove details about warehouses and resources, including their status, type, location, and operational restrictions.
- **Vehicle and Load Distribution:** Assigns the most suitable vehicles for deliveries, optimises load distribution, and prevents overloading.
- **Real-Time Simulation & Recalculation:** Enables scenario adjustments on the fly, with dynamic updates to route plans and estimated delivery times.
- **ETA Calculation:** Delivers precise estimated times of arrival, including travel, loading, and unloading, with transparent breakdowns.
- **Visualisation:** Offers interactive maps (via Folium) displaying routes, delivery schedules, stops, and resource details.
- **API & Docker Support:** Integrates with VROOM and OpenRouteService via APIs and is packaged in Docker for easy deployment and testing.
- **User Input Interface:** A prototype interface (Figure 12) is developed that allows users to easily select resources and destinations, and run optimisation processes through an intuitive, interactive dashboard.

Table 7. Functionalities developed for Logistics Optimisation Module

No	Functionality description	Milestone	Status
1	Inventory and vehicle data management (with synthetic data)	CFT1	Achieved
2	Material resource matching	CFT2	Achieved
3	Vehicle and load assignment	CFT2	Achieved
4	Route optimisation & dispatch planning	CFT3	Achieved
5	Visualisation: ETA, and route map	CFT3	Achieved

6	Scenario simulation & recalculation	SFT1	Being developed
7	Integration	SFT1	Being developed
8	Route optimisation & dispatch planning (considering traffic and damage roads)	SFT2	Being developed
9	Diagnostics and reporting	SFT2	Being developed

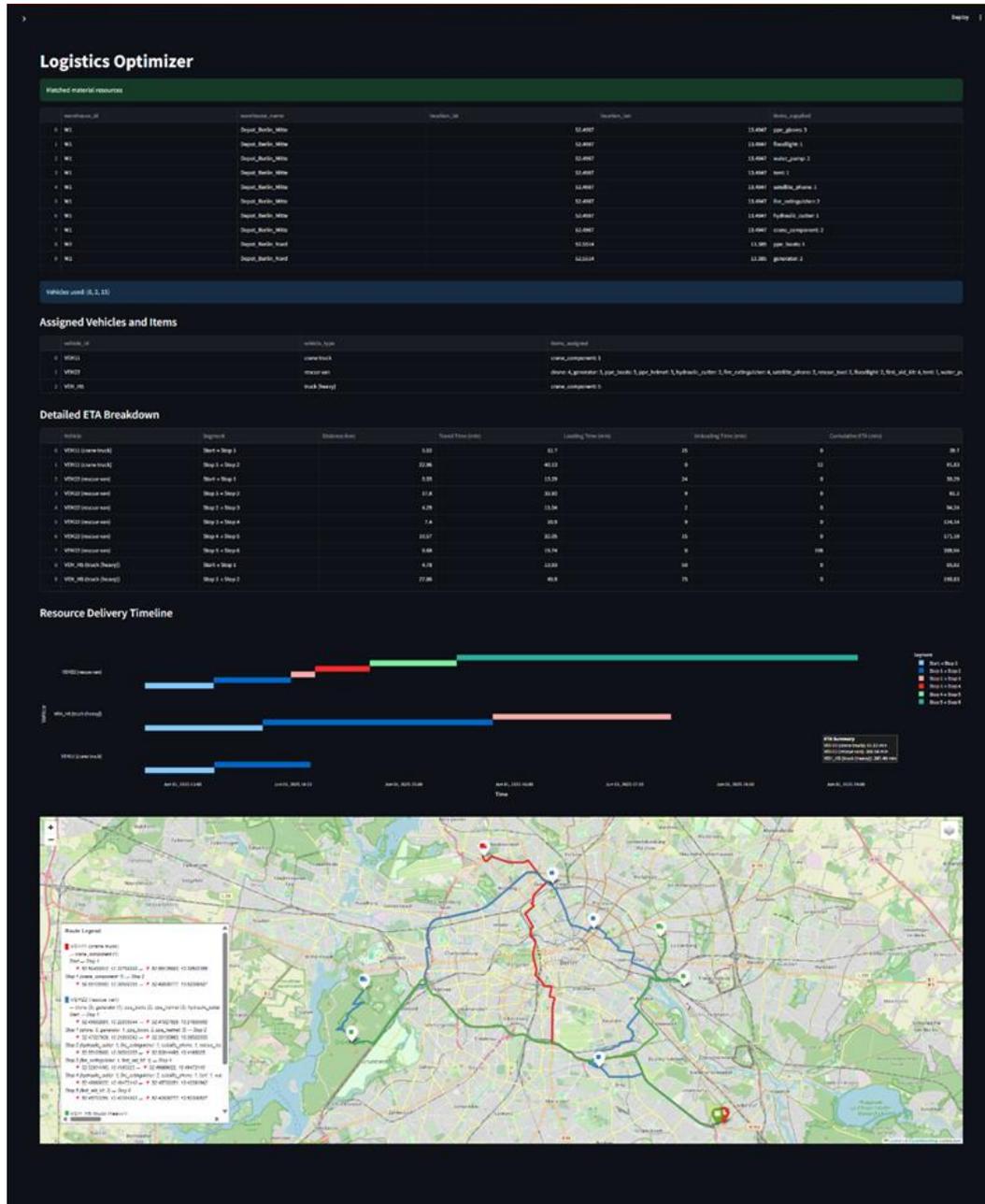


Figure 12. Dashboard for Logistics Optimisation Module

### 3.6. Multi-Source Information Fusion: ASTRIAL AI People, Objects, and Hazards Detection

The AI Detection tool is designed to reliably detect and classify individuals and objects in challenging outdoor environments using drone footage. Its goal is to achieve high accuracy and detailed profiling of human activities and objects in real-world conditions, while also identifying potential hazards. AI detections list:

- People profiling: Identifies different activity groups such as normal individuals, persons who have fallen (accident/injury), and others.
- FR classification: Differentiates FRs from the general public.
- Fire and smoke detection: Detects early signs of hazards to enhance situational awareness in the field.
- Vehicle's classification of car, truck, bus, and van.
- Holes and debris identification.

#### Timeline and milestones

- Model development and training: Initiated with the SARD dataset (normal/falling/running profiles) and open-source imagery for FRs.
- Fire/smoke detection models: Developed using DFS and Roboflow datasets.
- CFT testing: Basic people detection (normal class) successfully demonstrated during CFT2, people profiling, vehicle classification and detection of smoke were performed during CFT4, all other advanced classes and hazard detection are in development and undergoing lab evaluation.

#### Functionalities developed:

- Detection & classification: Bounding-box detection of people, activity profiling, FRs classification, vehicle classification, and hazard detection (fire and smoke) from drone live streams.
- Geolocalisation of objects: coordinates for detected objects are provided with detections.
- Output streaming: JSON-based detection results including class, confidence scores, and geolocation data, streamed directly to the C3I/IMS for visualization and coordination.

**Table 8. Functionalities developed for detection by an outdoor drone**

No	Functionality description	Milestone	Status
1	People detection and activity profiling (normal and fall down)	CFT2	Achieved
2	Fire and smoke detection	CFT4	Being developed. Demonstrated smoke detection
3	FR identification	CFT4	Achieved
4	Vehicle detection	CFT4	Achieved
5	Debris, holes detection	SFT1/SFT2	Being developed

### 3.7. Multi-Source Information Fusion: ASTRIAL C3I Alerting Information

The C3I/IMS has been integrated with other tools to support the management and visualisation of alerts (Table 9). These tools provide not only the detection and forwarding of critical alarms but also generate transparent, human-understandable explanations regarding why an alert was raised. This ensures that decision-makers can interpret, trust, and act upon the alerts with greater confidence.

The explanations generated by the tools have been seamlessly incorporated into the C3I/IMS dashboard, enabling operators to access on-demand monitoring of explained alerts. To support diverse operational roles and preferences, the visualisation framework offers flexible data presentation options. Commanders, field officers, and HQ personnel are able to customise their views through map overlays, dashboards, timelines, charts, or tabular formats, ensuring that the information is delivered in the most effective form for their specific decision-making needs.

Table 9. Functionalities being developed for C3I Alerting Information

No	Functionality description	Milestone	Status
1	Receive alert information	CFT2	Achieved
2	Visualisation of alert information	CFT3	Achieved
3	Flexibility in data visualisation options	SFT1	Being Developed

### 3.8. Interoperability Framework among IMS: ASTRIAL IMS Interoperability (Kafka, MinIO)

The interoperability framework provides the architectural backbone that connects all system components, ranging from field devices and sensors to advanced analytics modules and the C3I/IMS system. Its design ensures interoperability, scalability, and resilience, enabling seamless data exchange and coordinated functionality across heterogeneous tools and agencies. It is based on data exchange technologies (KAFKA [1] and MinIO [2]) that have been deployed on the cloud and used by the components during the development, testing, and pilot sessions (Table 10).

A set of dedicated Kafka topics has been defined to facilitate structured and efficient message exchange across system components. Each topic is designed to support the integration of a specific component/functionality, ensuring that data streams are logically separated and routed to the appropriate consumers without interference. E.g. the topic: *synergise.astrial.drone.location* -> provides the tracking locations (Live) of the ASTRIAL drone. The components that would like to have this type of information can register for the topic and receive/consume the related information that is published by the drone.

Table 10. Functionalities being developed for the interoperability framework

No	Functionality description	Milestone	Status
1	Deployment of the tools, enabling data exchange.	CFT1-CFT4	Achieved
2	Support for data exchange between the SYNERGISE components	CFT1-CFT4	Partially achieved (not only components were connected)
3	Support for data exchange between all SYNERGISE components	CFT4	Achieved

### 3.9. Multi-agency Incident Management and the COP: ASTRIAL C3I/IMS

In the context of the SYNERGISE project, the C3I/IMS system is to be enhanced to support the SYNERGISE operations, requirements, and integration with the other tools of the project. In more detail, the SYNERGISE C3I/IMS is designed to consolidate all SYNERGISE tools and components into map-, form-, and dashboard-based visualisations, providing enhanced situational awareness and enabling a shared operational picture among all participating actors and agencies. In addition, the system fosters collaboration, communication, and coordination across all agencies involved in responding to natural or man-made disasters. Users will be able to access common situational views, exchange multimedia information, and manage task assignments efficiently, ensuring a coordinated and informed response.

Since the C3I/IMS system builds upon a legacy platform, the following core functionalities form the foundation of its operation:

- Support the hierarchical structure of organizations and their jurisdiction areas
- Roles, users, and access rights management
- Intuitive browser-based and multi-screen graphical user interface

- Responsive design of the user interface
- Progressive web app
- Flexible and configurable view layout
- User authentication and authorization
- Emergency call geolocation and registration
- Address geocoding and street routing
- Efficient management of incidents according to standard operating procedures (SOPs)
- Computer Aided Dispatch
- Comprehensive resource management
- Support of diverse vehicle and personnel trackers for automatic resource location
- Three-level hierarchical configuration of incident types
- Multi-level hierarchical configuration of resource types
- Load vast amounts of data in virtualized tables
- Column sorting and multi-column filtering options for tables
- User messaging
- Geodata visualization via 2D and 3D maps
- Static and dynamic map layer management
- User-configurable dashboard
- Reports and statistics
- CCTV or other type of live video streaming and playback (VMS)

In the context of the SYNERGISE project, these functionalities have been enhanced with new functionalities related to the project.

1. Supporting the INSARAG Guidelines
  - a. Comply with INSARAG Guidelines and utilise INSARAG-specific vocabulary. Provide functionality to create and update USAR Teams and INSARAG forms, such as the USAR Team form, Worksite Triage form, Worksite Report form, and Incident-Sector Situation Report (Figure 13).
  - b. Provide the ability to assign assets/resources according to sectors, such as USAR teams and resources (Figure 14).
2. Support of the USAR team operations on the field.
  - a. Support the formulation of USAR teams.
  - b. Management and monitoring of the USAR teams' operations (either by the HQ or by the team leaders on the field, through the usage of a mobile version of the C3I/IMS) (Figure 15).
3. Integration with the AI-driver logistics recommendation system.
  - a. Reception of the information produced and depiction to the users.
4. Integration with the components on the field (ANYMAL, OWL, SNAKE, UAVs, FR vitals).
  - a. Reception of the information produced by the components. Information such as video live stream, textual information, vital signs, etc., is supported.
  - b. Visualisation of this information to users through an unintuitive graphical user interface.
  - c. Reception and visualisation of the alarms produced by those components. Those alarms could be either related to the area of operation (e.g., high concentration of a gas) or related to the status of personnel (e.g., increased pulse rate). (Figure 16).

The screenshot displays the 'engage IMS/CAD' interface. On the left, there are summary cards for 'Worksites' (3), 'Worksites Working' (0), and 'Worksites RPT Awaiting QA' (1). Below these are 'Incident Areas' and 'Worksite Forms' sections. The central 'Map' shows a satellite view of a building with a red outline and a 'Victim Location 1' marker. On the right, the 'Victim Extraction Info' section includes a 'Victim Extraction' card (1) and a 'Victim Extraction Forms' section with a form to be filled out. The form includes fields for 'Victim Number', 'Street address', 'Date & Time of extraction', 'Location of the victim', and 'Level of work needed to extricate victim'.

Figure 13. C3I/IMS INSARAG forms

The screenshot displays the 'engage IMS/CAD' interface for resource management. On the left, the 'Wearables' section for 'Nato10' shows 'Vitals' (Body Temperature: 37.0°C, Skin Temperature: 35.2°C, Heart Rate: 113 BPM) and 'Environment' (Personal Baseline: 35 to 37°C, 32 to 35°C, 90 to 150 BPM). The central 'Map' shows a satellite view of a building with a 'Nato10' marker. On the right, the 'Equipment' table lists various resources with their status and location.

EQUIPMENT ID	EQUIPMENT NAME	STATUS	INT...
ANYMAL-03	ANYMAL	Available	✓
OWL-01	OWL	Available	✓
ANYMAL-02	ANYMAL	Available	✓
OWL-02	OWL	Available	✓
OWL-03	OWL	Available	✓
ANYMAL-01	ANYMAL	Available	✓
C3ITab-01	Tablet	Available	✓
C3ITab-02	Tablet	Available	✓
SNAKE-01	SNAKE	Available	✓
DJI-RTK-350	Multirotor Drone	Available	✓
DJI-Mini-Pro	Multirotor Drone	Available	✓
C3ITab-03	Tablet	Available	✓
SYSNV-28	SYSNV WEARABLE	Available	✓
SYSNV-29	SYSNV WEARABLE	Available	✓
SYSNV-31	SYSNV WEARABLE	Available	✓
SYSNV-32	SYSNV WEARABLE	Available	✓
SYSNV-35	SYSNV WEARABLE	Available	✓
SYSNV-38	SYSNV WEARABLE	Available	✓
SYSNV4	SYSNV WEARABLE	Available	✓
GEOLC113	Garment	Available	✓
GEOLC113	SYSNV WEARABLE	Available	✓
GEOLC118	SYSNV WEARABLE	Available	✓
GEOLC119	SYSNV WEARABLE	Available	✓
SYSNV-28	SYSNV WEARABLE	Available	✓
SYSNV-29	SYSNV WEARABLE	Available	✓
GEOLC119	Garment	Available	✓
GEOLC1101	SYSNV WEARABLE	Available	✓
Mavic3E	Multirotor Drone	Available	✓
2D3F453D8278	SYSNV WEARABLE	Available	✓
2D3F453D8278	SYSNV WEARABLE	Available	✓

Figure 14: C3I/IMS Resource Management

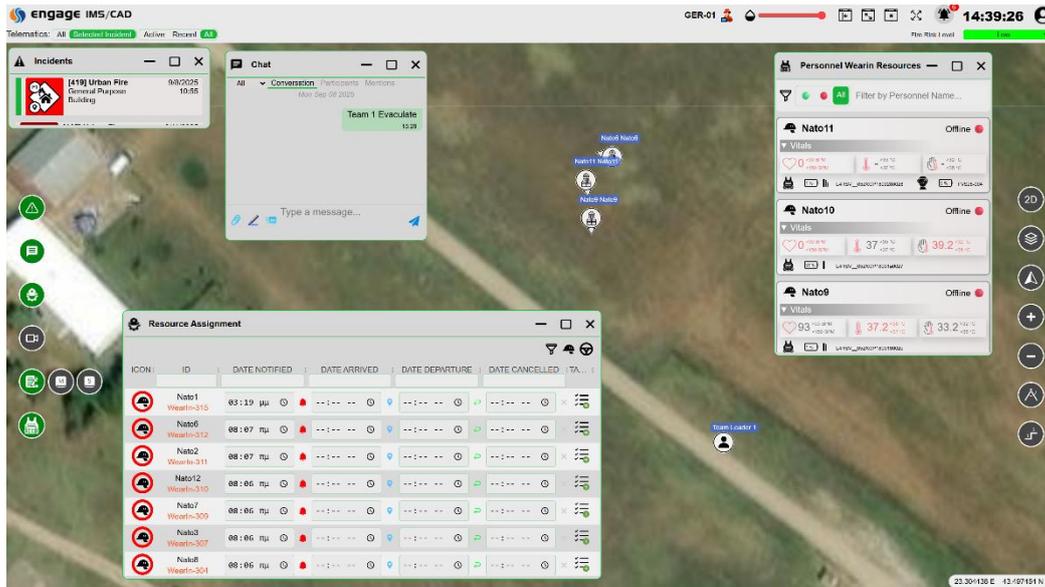


Figure 15: C3I/IMS Tablet mode

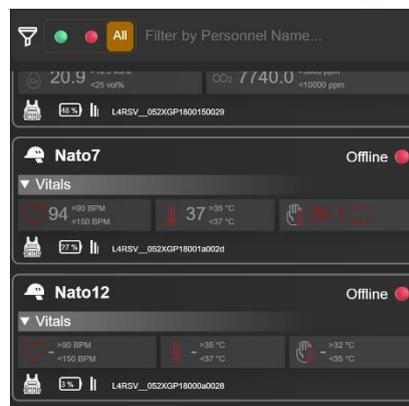


Figure 16: C3I/IMS Personnel vital signs

Table 11. Functionalities being developed for C3I/IMS

No	Functionality description	Milestone	Status
1	Incident Management	CFT1	Achieved
2	Resource Management	CFT1	Achieved
3	Multi-agency Incident Management	SFT1	Under development
4	INSARAG guidelines	SFT1	Under development
5	USAR teams' management	SFT1	Under development
6	Information from ANYMAL	CFT4	Achieved
7	Information from OWL	CFT4	Achieved
8	Information from SNAKE	CFT4	Achieved
9	Information from UAVs	CFT3	Achieved
10	Information from XAI	CFT4	In progress
11	Information from localisation system	CFT3	Achieved
12	Information from wearable devices	CFT3	Achieved

## **4. WP5 Component Interconnections in the SYNERGISE Toolkit**

### **4.1. Data flow for the components developed in WP5**

The integration of components within the SYNERGISE Toolkit is designed to ensure seamless interoperability between tools developed across different work packages. In this chapter, particular focus is paid to those developed in WP5. The integration enables data and services to be shared across modules, supporting a unified workflow and ensuring consistency of results. This process involves both technical and semantic alignment: technical integration is achieved through standardised APIs and middleware technologies, while semantic integration is ensured by adopting common data models, metadata standards, and ontologies relevant to the SYNERGISE domain.

The technologies used for integration include web services, containerisation solutions for deployment and scaling, and secure communication protocols that guarantee reliable data exchange between modules. Data models and structures are harmonised using established standards (e.g., JSON) to represent diverse datasets. This standardisation ensures that information generated by one component can be directly consumed by others without requiring complex transformations.

### **4.2. Integrations across Tools**

#### **4.2.1. Field and HQ Communication: ASTRIAL Solution**

The communication toolkit developed under Task 5.1 serves as the essential backbone for all SYNERGISE components, providing connectivity and ensuring reliable exchange of operational data between HQ, field command posts, and deployed FR units. The architecture integrates satellite backhaul, federated 5G, and Wi-Fi mesh networks into a unified multi-WAN environment managed by a central router. To provide a clearer understanding of technologies used to set up the field and HQ communication, an overview is shown in Figure 17.

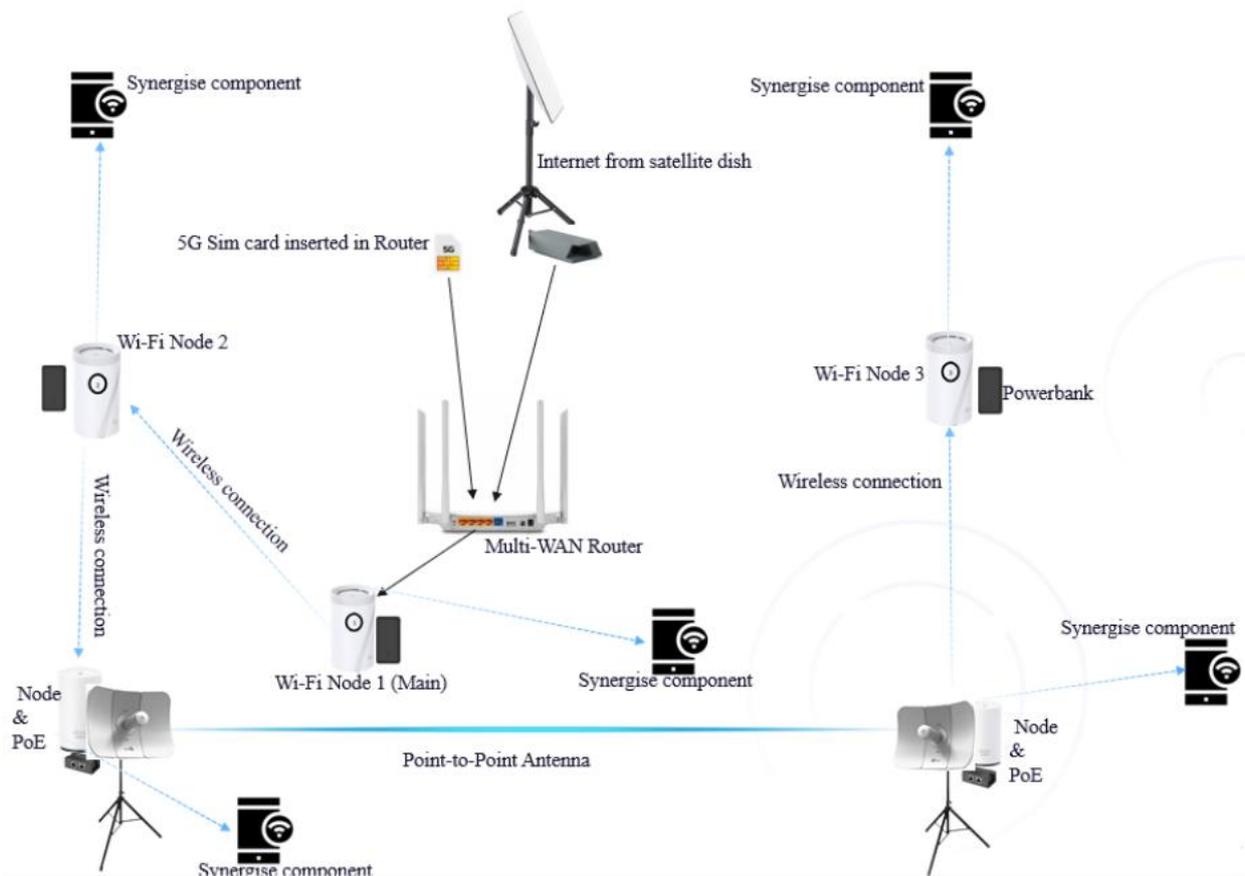


Figure 17. Communication architecture diagram combining satellite backhaul, local mesh networking and a multi-WAN router

### 1. SATCOMM Layer (Backhaul Connectivity):

- Starlink satellite dish provides high-bandwidth internet access from orbit.
- This uplink is connected to a multi-WAN Router, which also hosts a 5G SIM card for terrestrial broadband access.
- The router dynamically balances traffic across satellite and 5G links, ensuring redundancy and continuous connectivity between the field site and headquarters.

### 2. LANCOMM Layer (Local Networking):

- The multi-WAN Router connects directly to Wi-Fi Node 1 (Main), establishing the anchor point of the local Wi-Fi mesh network.
- Wi-Fi Node 2 and Wi-Fi Node 3 extend coverage via wireless links to Node 1, creating an ad-hoc mesh that field devices (e.g., tablets, wearables, drones, AR headsets) can join.
- Power banks support autonomous operation of mobile nodes (e.g., Wi-Fi Node 3), ensuring deployment flexibility in environments without grid power.

### 3. Point-to-Point Antennas (Extended Range):

- Two Point-to-Point (P2P) nodes, mounted on tripods with PoE injectors, provide long-distance connectivity between remote sites and the main mesh.
- This enables communication across geographically dispersed operational areas (e.g., extending connectivity deeper into the field).

### 4. Integrated Workflow:

- Field Devices → LANCOMM Mesh:** Data generated by SYNERGISE assets (robots, wearables, AR glasses) is transmitted to the nearest Wi-Fi node.
- LANCOMM → Router:** The mesh routes data to the main gateway (Wi-Fi Node 1), which forwards it to the Multi-WAN Router.

- c. **Router** → **SATCOMM/5G**: The router uplinks the data to HQs via Starlink or 5G, depending on availability and link quality.
- d. **HQ** → **Field Devices**: Commands, alerts, and tasking messages from HQ flow back along the same path in reverse.

This **dual-layer design** (LANCOMM + SATCOMM) provides redundancy, scalability, and modularity. It ensures that even in the absence of one channel (e.g., 5G outage), the system maintains operational communication through satellite or Wi-Fi mesh, thereby enhancing the resilience and reliability of the SYNERGISE communication Toolkit.

#### 4.2.2. Field and HQ Communication: ETRI Emergency Communication Kit

The ETRI ECK P5G communication toolkit, developed under Task 5.1, provides another backbone for the SYNERGISE components, supports 5G wireless and LAN cable wireline Ethernet/Wi-Fi connectivity between {HQ ↔ Field Command Post ↔ Deployed FR Units} and ensures reliable exchange of operational data. This architecture integrates into an integrated multi-WAN environment managed by a central router in the form of 5G federation to satellite backhaul, Wi-Fi mesh networks. ETRI P5G networks used in disaster sites and HQ communication settings are outlined in Figure 18.

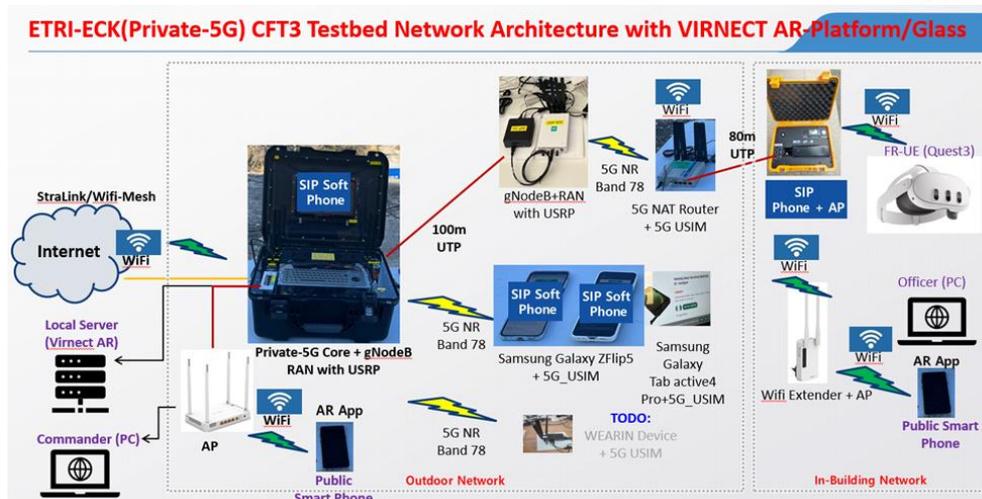


Figure 18. ETRI-ECK P5G CFT3 testbed network architecture with VIRNECT AR platform

1. P5GCOMM layer (local networking):
  - a. The P5G Core (All-in-One) Kit node with the built-in 5G gNodeB can be connected to the ASTRIAL's SATCOMM and LANCOMM to provide high-bandwidth Internet relay access services.
  - b. The P5G Core/gNodeB node can be extended to external 5G gNodeB over long distances (hundreds of meters) by wireline, allowing easy Internet access to wirelessly constrained buildings/tunnel collapses.
  - c. The P5G Core/gNodeB is wirelessly connected to a 5G NAT Router equipped with a 5G USIM, and the UL/DL transmission bandwidth and coverage transmission distance are determined by RU performance.
  - d. DRS units deployed at disaster field sites must have a built-in 5G USIM card in order to connect directly to the terrestrial broadband P5G Core node.
2. ECK-LANCOMM layer (sub-local networking in ETRI):
  - a. Spine nodes connected by wireline to 5G NAT Routers can be connected to multiple Leaf nodes or AP nodes via Ethernet LAN Cable, and can automatically and quickly configure communication connections between {Spine ↔ Leaf ↔ AP} 1:m:n Tree structure or {Spine ↔ AP} 1:n structure during power-on operation.
  - b. DRS units deployed at disaster field sites can be interconnected via Wi-Fi wireless communication at AP nodes.

- c. It ensures ease of single-person deployment and Plug & Play connectivity of autonomous communication networks even in extreme disaster environments without power grids.
3. P2P P5G wireless antenna (extended range):
  - a. Two point-to-point (P2P) nodes connected between P5G Core (All-in-One) Kit nodes can provide a multilateral long-distance connection between remote sites and HQs.
  - b. This enables communication between geographically distributed operating regions (e.g., expansion via deep on-site connections).
4. Integrated Workflow:
  - a. Field Device → ECK-LANCOMM Tree-link structure: Data generated by SYNERGISE components (e.g., AR glasses) is sent to the nearest Wi-Fi AP node.
  - b. ECK-LANCOMM → 5G NAT Router: Routes data from SYNERGISE components to main gateways (Spine nodes) and forwards it to multi-WAN routers.
  - c. 5G Core WAN → SATCOMM: This router connects data to HQ via Starlink or a remote P5G Core Kit node, depending on availability and link quality.
  - d. The other way, Field Device → P5GCOMM: Data from SYNERGISE components equipped with 5G USIM cards can also be communicated directly to P5GCOMM to connect to HQ via Starlink or 5G.
  - e. HQ → P5G Core → 5G NAT Router → (Spine/Leaf) AP Node → Field Device by Wi-Fi, or HQ → P5G Core → Field Devices by 5G: Command, notification, and action messages from HQ flow in the reverse direction along the same path.
  - f. AR Glasses framework supporting environment, which is one of the field devices, can provide additional services such as AR and STT/TTS by connecting it to a PC such as Notebook at the back of P5GCOMM.

#### 4.2.3. Augmented Reality Services: VIRNECT AR Training/Video Conferencing/Visualisation

The VIRNECT AR system (Figure 19) operates on a multi-platform architecture designed for seamless data flow between field and command units. FRs using Quest 3 and Leaders on mobile devices connect via Wi-Fi to a private 5G network on-site. This network routes data through a LAN connection to officers and commanders at the command centre. A crucial component is the local on-premises server, which processes voice commands using a specialised STT (Whisper) model and an intent prediction model. This allows for hands-free operation by converting spoken language into actionable commands and text, which is then distributed across the network. This integrated flow of video, audio, and processed data ensures that all personnel share a common operational picture.

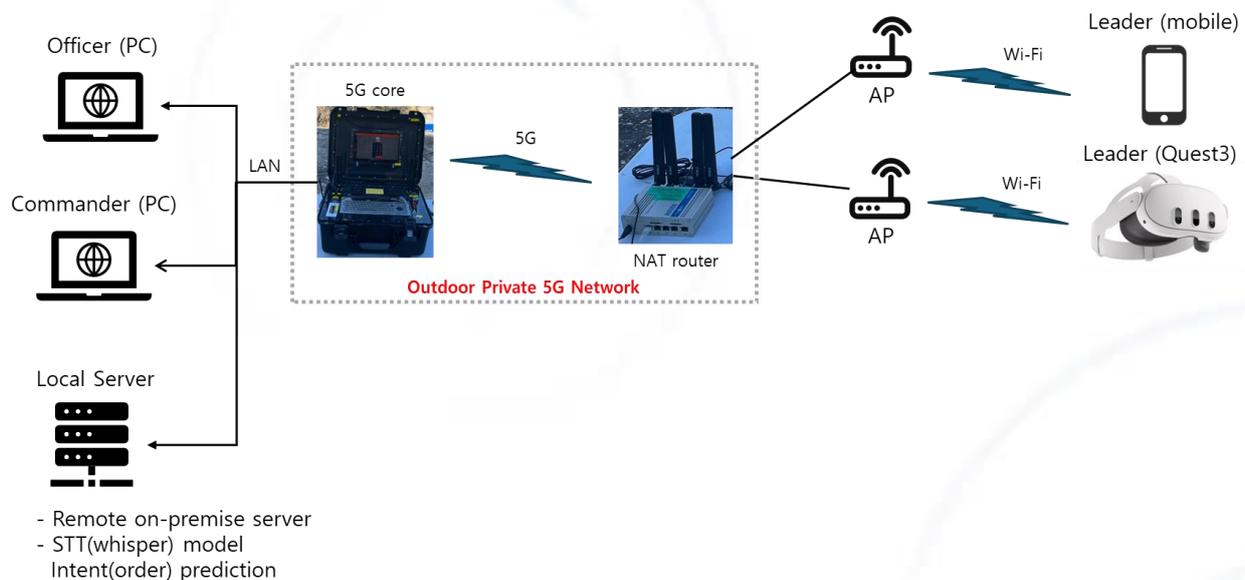


Figure 19. VIRNECT AR system in the SYNERGISE toolkit

#### 4.2.4. Multi-Source Information Fusion: CERTH XAI services

XAI workflow is as follow, and outlined in Figure 20.

Input:

- Receives live data wearables, gas sensors and geolocation

Processing:

- Classification of the health index
- Application of SHAP for extracting feature importance
- Enhances the alert based on environmental measurements

Outputs:

- Generation of alerts and visualization to C3I/IMS

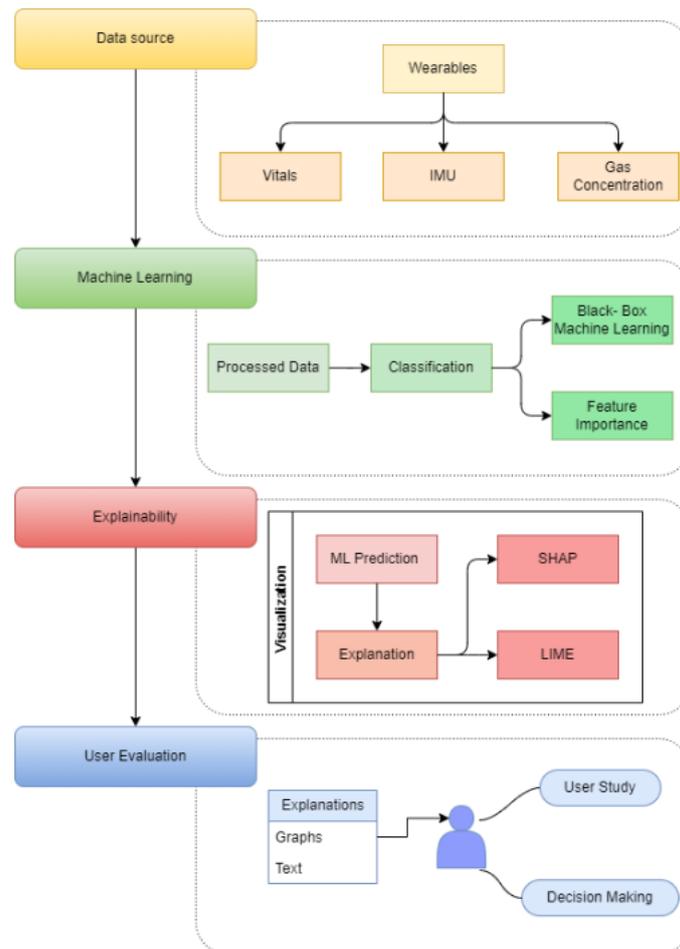


Figure 20. XAI Workflow

#### 4.2.5. Multi-Source Information Fusion: ASTRIAL Logistics Optimisation Module

The Logistics Optimisation Module fits smoothly into the SYNERGISE toolkit, making it easy to automate and improve logistics planning based on real-time data as part of the C3I/IMS environment. It serves as the central hub for connecting inventory, vehicles, and routing engines, ensuring that emergency logistics are both efficient and adaptive to real-time conditions.

Input:

- Receives live data from the IMS, including available resources, vehicles, and warehouse inventories.

- Accepts scenario parameters such as incident locations and required resource types/quantities.

Processing:

- Calls external routing engines (VROOM, OpenRouteService) via API to compute optimised vehicle assignments and delivery routes.
- Dynamically accounts for operational constraints such as blocked roads, vehicle restrictions, loading/unloading times, and capacity limits.

Outputs:

- Returns optimised dispatch plans, route assignments, and detailed ETA breakdowns directly to the IMS.
- Provides interactive maps and delivery timelines accessible to both HQs and field units.
- Exposes results to other SYNERGISE modules (e.g., ARs, HUDs, alerting systems) for status updates and operational coordination.

By combining real-time inventory management, dynamic routing, and clear visualisation, the Logistics Optimisation Module enhances decision-making across all levels of emergency response, from warehouse staff to field teams and command centres, ensuring that critical supplies and resources are delivered quickly, efficiently, and transparently.

#### 4.2.6. Multi-Source Information Fusion: ASTRIAL AI People, Objects, and Hazards Detection

The AI People Detection and Classification modules are integrated into the SYNERGISE toolkit as follows:

- Input: Ingests real-time video streams from drone-mounted cameras during missions.
- Processing: Performs edge-device inference using YOLOv8 models trained for people and object profiling, FRs identification, and fire/smoke hazard detection.
- Output: Generates detection metadata (bounding boxes, class, geolocation, timestamp, confidence score) and streams it to the SYNERGISE C3I/IMS via Kafka.
- Interoperability: Makes detection events available to other SYNERGISE modules, such as AR and Head-Up Display (HUD) services for real-time visualisation and response coordination.

#### 4.2.7. Multi-Source Information Fusion: ASTRIAL C3I Alerting information

The C3I Alerting Information Module is a key component of the SYNERGISE toolkit, designed to manage the flow of alert-related data across the system and ensure that the right information reaches the right users at the right time. The module receives alerting information through the interoperability framework, which acts as the central integration layer. This information is produced by various SYNERGISE components, including the AI analysis module and wearable devices. By leveraging the interoperability framework, the system ensures that all alerts, whether related to environmental hazards, personnel safety, or operational events, are standardised and consistently transmitted into the C3I/IMS.

Once received, the alerting information is stored, managed, and made available to authorised users. Access is governed by role-based rules that reflect each user's responsibilities, department, and position within the command structure. This ensures that sensitive or critical alerts are only visible to personnel who need them, while also avoiding information overload for users with narrower responsibilities.

#### 4.2.8. Interoperability Framework among IMS: ASTRIAL IMS Interoperability

The Interoperability Framework is the core of the SYNERGISE platform, serving as the central backbone for communication and integration among all components. It ensures that data produced by diverse modules, such as AI analysis tools, wearable devices, robots, etc., is exchanged reliably, effectively, and in a standardised format.

All information exchanged between components flows through this framework, which manages the ingestion, transformation, and distribution of data streams across the system. By acting as the single point of integration, it guarantees consistency, scalability, and fault tolerance, while also simplifying the addition of new tools or services without disrupting existing operations.

The Interoperability Framework not only provides real-time connectivity but also supports secure and role-based access, ensuring that data is shared appropriately across teams and agencies. As the foundation of interoperability within SYNERGISE, it enables the creation of a unified operational environment where situational awareness, alert management, and decision support can function seamlessly across all levels of command.

#### **4.2.9. Multi-agency Incident Management and the COP: ASTRIAL C3I/IMS**

The C3I/IMS functions as the main operational interface of the SYNERGISE platform, supporting command, control, coordination, and intelligence activities. Through its integration with the Interoperability Framework, it is connected with the project components, enabling it to receive real-time information from the field, including video from the field, personnel status updates, and alerts.

By consolidating this incoming information, the C3I/IMS provides a common operational picture to the HQ, improving the situation awareness and supporting the decision-making process. Additionally, commanders can make decisions and send information/commands back on the field to the team leaders. This information is transferred again through the interoperability framework.

## **5. Tools Deployment in Lab and Field Test Scenarios**

In this section, tools developed in WP5 are described in the context of their deployment in lab and field test exercises.

### **5.1. Field and HQ Communication: ASTRIAL Solution**

The Field and HQ Communication toolkit has been deployed in both laboratory and operational environments to validate its technical capabilities and resilience, and most importantly, to provide the network to all SYNERGISE components taking part in CFTs. In the lab setting phase, the focus was on integrating and configuring the SATCOMM (Starlink terminal), Multi-WAN Router, 5G SIMs, Wi-Fi mesh nodes, point-to-point antennas, and accessories. Field deployments were subsequently conducted during CFT1-CFT4, where the system was evaluated in realistic conditions by connecting FR units and mobile terminals to the wider SYNERGISE network.

During CFT1 (Figure 21), the network was successfully provided via satellite antenna, Wi-Fi indoor (5) and outdoor (7) mesh nodes, Point-to-Point (P2P) connection, and 4G connectivity. The deployed network coverage area was 3650 m<sup>2</sup> outdoor and 1185 m<sup>2</sup> indoor. On the first day, an average download speed of 650 Mbps and an upload speed of 380 Mbps were achieved. On the second day, an average download speed of 580 Mbps and an upload speed of 300 Mbps were recorded.

During CFT2 (Figure 22), the internet was deployed via Starlink backhaul supported by two 5G SIM cards. The network covered an area of 16 800 m<sup>2</sup> with a total distance of 594 m. On the first day, an average download speed of 90 Mbps and an upload speed of 40 Mbps were achieved. However, a noticeable lag was observed on the second day of testing. In total, 7 indoor nodes and 9 outdoor nodes, including P2P antennas, were deployed. The network successfully supported 40 connected devices. Following CFT2, significant improvements were implemented to enhance the Field and HQ Communication network in preparation for CFT3, and these proved highly effective.

In CFT3 (Figure 23), the network covered a total area of 3 590 m<sup>2</sup> across a distance of 360 m. Average network speeds were 53 Mbps / 30 Mbps on the first day and 67 Mbps / 33 Mbps on the second day. Internet provision was enabled via Starlink backhaul and two 5G SIM cards, just like in the previous CFTs. The system successfully supported 46 devices on Day 1 and 53 devices on Day

2. A total of 7 indoor nodes and 9 outdoor nodes were deployed, ensuring complete coverage of all required areas. Notably, the P2P antennas were not deployed during this event due to the smaller size of the area covered by the network. Interoperability was tested during this field-testing activity by successfully combining the ASTRIAL network and the eKIT equipment provided by THW to work as one.

In CFT4 (Figure 24), the network area coverage was 26 825 m<sup>2</sup> with a distance of 757 m. Average network speeds were 80 Mbps / 50 Mbps. Internet provision was enabled with 5G SIM cards. The satellite antenna got damaged during transport to the site. P2P antennas were not deployed as the area was covered with Wi-Fi mesh nodes. The connectivity was established with ASTRIAL solution during the set-up and training days. The Wi-Fi mesh network of 9 indoor and 12 outdoor nodes has been implemented. On day 1 of CFT1, eKIT was incorporated into the network and deployed for connectivity with other components. FRs were in full control and were the decision makers for a network set-up at CFT4. This highlights a remarkable progress from CFT1, where ASTRIAL was fully handling the deployment with FR mainly as observers.

Evaluation of the Field and HQ Communication Deployment focused on:

- Connectivity Performance: Throughput, latency, and redundancy across SATCOMM, 5G, and Wi-Fi mesh.
- Deployment Agility: Ease and speed of setting up mesh nodes and P2P antennas in field conditions.
- Interoperability: Seamless integration with AR services, wearable devices, robots, UAVs, and the C3I/IMS.
- Resilience: Failover performance when one communication channel was degraded or unavailable.

Lessons Learned:

- In both CFT1 and CFT2, weather elements such as strong winds caused P2P antennas to shift or fall, disrupting connections. These incidents informed better preparation and equipment stabilisation measures for CFT3, preventing recurrence.
- In CFT2, users and evaluators highlighted noticeable network lag on the second day of testing. This issue was addressed before CFT3, where connectivity was significantly more stable, with almost no interruptions.
- In CFT4, difficulty in establishing a network inside the buildings (especially with metal walls) with Wi-Fi nodes placed outdoors. The Wi-Fi mesh nodes had to be set inside the buildings.



Figure 21. Deployment of HQ and Field Communication at CFT1



Figure 22. Deployment of HQ and Field Communication at CFT2



Figure 23. Deployment of HQ and Field Communication at CFT3



Figure 24. Deployment of HQ and Field Communication at CFT4

## 5.2. Field and HQ Communication: ETRI Emergency Communication Kit

The communication connection between the Disaster Field Site and HQ using the ETRI ECK P5G network equipment was deployed in both the laboratory and the operating environment to verify technical performance capabilities and fault resilience. The laboratory setup phase focused on the connectivity between SATCOMM/LANCOMM and P5GCOMM, the connectivity between P5GCOMM and ECK-LANCOMM, and the connectivity between ECK-LANCOMM and field devices (e.g., VIRNECT AR glasses). Subsequently, the disaster training centre field distribution was carried out during CFT1, CFT3, CFT4, and the FR units and mobile terminal (e.g., smartphones) were connected to a wider SYNERGISE network to evaluate this system under realistic conditions.

During CFT1 (Figure 25) testing, ETRI ECK P5G was evaluated on wide hill planes, rooftops of collapsed buildings, and underground entrances of a building. On the first day, it was assessed on a wide hill plane, and the average download/upload speed was less than 1 Mbps (actual measurement: 320 Kbps or more). On the second day, the test was conducted on the roof of the collapsed building and on the underground entrance. The connection between the ASTRIAL's

SATCOMM/LANCOMM was verified, the connection between ETRI ECK P5GCOMM and the ECK-LANCOMM, and the FR device, smartphones was successful, and the low-performance RU was adopted to record bandwidth performance below several tens of meters (~40 m in real testing) for P5GCOMM coverage and P5GCOMM 1Mbps or less. The goal of CFT1 was to focus on testing 5G Core networks and Internet connectivity between wireless terminals with concentration.



Figure 25. ETRI ECK P5G CFT1 Testbed Network Architecture and Testing Results

ETRI did not participate in CFT2.

During the CFT3 (Figure 26) testing, the connection performance (transmission bandwidth and transmission distance) of the upgraded ETRI ECK P5G was improved in fire disaster sites, far from wide flat distances, and successfully supported high-quality video AR glasses and teleconferencing applications. ETRI Private-5G radio coverage was still limited to no more than 40 m due to the low performance of the RU. In this CFT3 PoC verification, transmission bandwidth DL 58.5 Mbps and UL 12.1 Mbps were achieved.

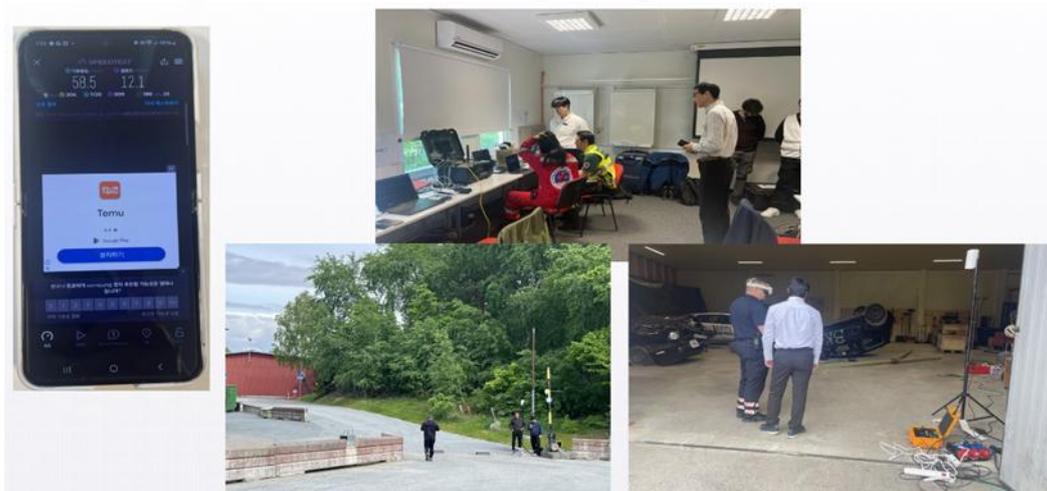


Figure 26. Deployment of ETRI communication solution at CFT3



- CFT4 aimed to address dual radio connectivity failure measures by expanding wireless coverage through RU high performance and securing multiple gNodeBs connectivity. But long-distance's connectivity with wireless signal coverage was not achieved because of P5G RU's low performance. The P5G network coverage was expanded up to 400 m above by using Wi-Fi extender. Good quality of network performance was provided for AR video conferencing app of VIRNECT in the CFT4 disaster training field site environment.

### 5.3. Augmented Reality Services: VIRNECT AR Training/Video Conferencing/Visualisation

As part of the SYNERGISE project, VIRNECT developed and tested AR applications for training and video conferencing. The tests, conducted on the Meta Quest 3 platform, focused on enhancing the training and on-site communication capabilities of FR.

The key results are as follows:

- **AR Training Application:** Successfully delivered immersive training modules for complex robots (ANYmal, SNAKE robot), meeting the criteria for non-intrusive visualisation (KPI-30).
- **AR Video Conferencing Application:** Demonstrated a stable multi-platform communication link and the feasibility of core functionalities, achieving the goal of facilitating hands-free communication (KPI-31).
- **Core Technology Secured:** Successfully developed a specialised STT model for the extreme noise environments of disaster sites, securing a key technology for hands-free operation.

The results of CFT3 and CFT4 (Table 12 **Error! Reference source not found.**) demonstrate the strong validity of the core functions and technologies of AR applications.

Table 12. Summary of SYNERGISE CFT3 KPIs and test results

KPI ID	KPI Description	Related Application	CFT3 Result
KPI-30	Visualise the environment in a non-intrusive way.	AR Training	Achieved. Successfully delivered training content without obstructing the user's field of view in a laboratory environment.
KPI-31	Facilitate automatic/hands-free multimedia communication between operational and tactical personnel.	AR Video Conferencing	Achieved. Established a stable communication link and implemented core hands-free functions through a high-accuracy, noise-resistant voice command system.

The AR training application was developed based on VIRNECT's proprietary "Make" (content authoring) and "View" (content experience) software platforms. For this test, two key modules for operating the ANYmal and SNAKE robots were deployed via the Meta Quest 3 HMD. The training process was systematically structured into three stages to allow users to acquire skills progressively: theoretical education on robot functions, practical control training, and application in a virtual disaster simulation. To control external variables and evaluate the application's pure functionality, all tests were conducted in a laboratory environment where participants used controllers to interact with virtual robots and complete training scenarios.

The AR video conferencing application is based on a heterogeneous, multi-platform communication architecture that connects FRS on-site (Meta Quest 3), leaders on the move (mobile), and commanders at the command centre via Wi-Fi, LAN, and a 5G core network. The CFT3 test covered basic video call functions between field agents and remote experts, as well as comprehensive collaboration features with HQ. Notably, real-time bilingual translation between English and Korean, screen capture and image sharing, and remote annotation (drawing) on shared visuals were all successfully demonstrated. These features fulfilled the key requirements of KPI-31 to facilitate automatic/hands-free multimedia communication among operational personnel. It

was proven that these functions are a powerful mechanism for creating a 'Common Operational Picture,' synchronizing visual understanding between the field and command, going beyond simple communication.

The extreme noise of a disaster site can neutralise the performance of standard voice recognition systems, making true hands-free operation impossible. To solve this problem, VIRNECT developed a fine-tuned STT model based on OpenAI's Whisper model. This was achieved by using a specialised dataset synthesised with 10 types of disaster-related noise data, such as earthquakes, sirens, and helicopter sounds. This model goes beyond simply converting speech to text; it also integrates an LLM-based intent prediction function that interprets various utterances like "call commander" and "connect commander" as the single intent "start call," maximizing user convenience and flexibility. Performance evaluations showed that the fine-tuned model reduced the average Word Error Rate (WER) by 34.4%, from 0.3747 to 0.2457, compared to the original Whisper model. This achievement is the most critical breakthrough that makes the 'hands-free' goal of KPI-31 technically feasible, elevating voice control technology from a mere convenience feature to an essential capability for mission execution.

#### Lessons Learned

In CFT3, an issue was identified where the AR video conferencing (Remote) function occupied most of the screen, making it difficult to check other disaster information simultaneously during a call. To address this, CFT4 involved the development of a separate 'Disaster Information Visualisation App.' This app displays additional information, such as drone locations and mission objectives, as augmented reality visualizations to maximize the situational awareness of field agents.

### **5.4. Multi-Source Information Fusion: CERTH XAI services**

In CFT3, a demonstration was developed and presented, utilising data collected and processed by WEARIN from CFT1 and CFT2. The alert system utilises two components: a classifier that predicts a wellness index for the FR using his vital signs (heart rate, respiratory rate, body temperature) and movement measurements, and an environmental alert engine that outputs alerts for hazardous situations based on the gas concentration levels (Oxygen, Carbon Monoxide, Carbon Dioxide, Hydrogen Sulfide). The developed XAI service utilises SHAP values to interpret the system's decision based on the importance of each input feature, presenting explanations in both visual and natural language form to the operator.

The process above was demonstrated via a standalone demo, with our XAI service running on the back end and a simple dashboard so the alerts can be visualised (Figure 28 and Figure 29).

## Real-time Gas Alert Monitoring Dashboard

### Current Alerts

	timestamp	device_id	gas	value	unit	severity
0	2025-09-12 13:38:14+00:00	GXRPRO-00123	LEL	19.7	%LEL	medium
1	2025-09-12 13:38:14+00:00	GXRPRO-00123	CO	215.5	ppm	high
2	2025-09-12 13:38:14+00:00	GXRPRO-00123	H2S	19.3	ppm	high

### Alert Severity Distribution

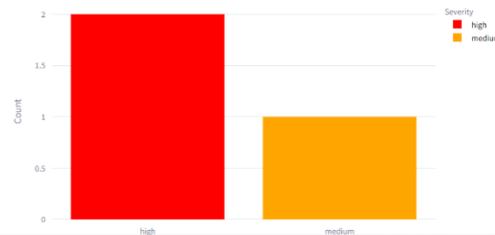


Figure 28. XAI alert monitoring dashboard

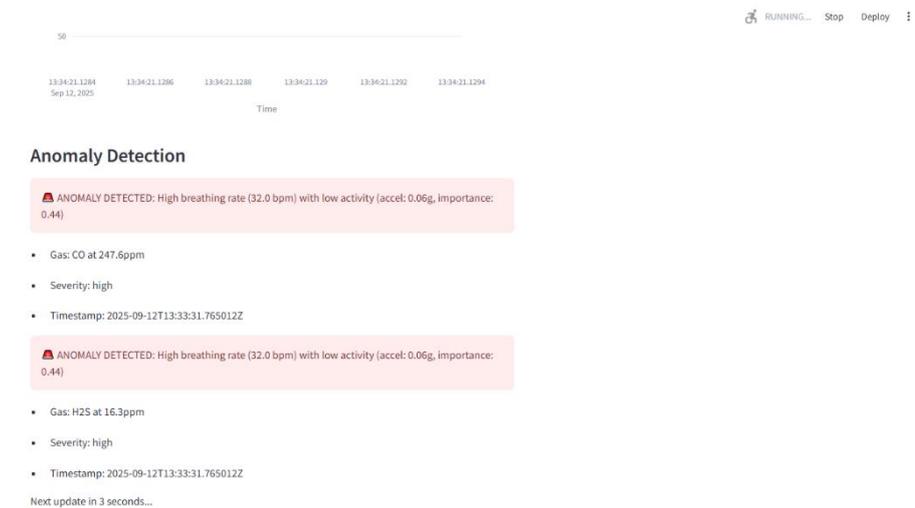


Figure 29. XAI anomaly detection alert

During the demonstration of the XAI monitoring service, FRs highlighted two key points for improvement. First, the importance of clarifying and communicating the baseline used for model outputs to make the explanations more interpretable and actionable in real-time contexts. Second, the a need for mechanisms to incorporate user feedback, particularly false alerts, into the retraining process so the system can adapt over time and reduce unnecessary distractions during operations. Although CERTH did not participate in CFT4, its efforts focused on the remote integration of the XAI component with the C3I/IMS platform and the data provided by WEARIN.

## 5.5. Multi-Source Information Fusion: ASTRIAL Logistics Optimisation Module

The Logistics Optimisation Module was initially tested in a controlled lab environment using synthetic datasets designed to replicate real-world conditions such as warehouse inventories,

vehicle fleets, and emergency response scenarios. These preliminary tests validated core functionalities, including inventory management, vehicle assignment, route planning, ETA calculation, and dashboard-based visualisation.

The first time the module was presented to the consortium was at CFT3 in the form of a demonstration workshop using simulated datasets, and showcasing the full workflow:

- User-driven input: Resource requests and incident locations provided by operators.
- Automated processing: Matching of warehouse inventories with available vehicles.
- Optimisation: Real-time calculation of optimal routes and load distribution.
- Output: Generation of ETA breakdowns, delivery timelines, and interactive route maps per vehicle.

The demonstration walked through the complete process, from inputting a scenario to producing optimised dispatch plans, all presented on a prototype dashboard designed for FRs and logistics teams.

Evaluation Aspects:

- Functionality: The system effectively supported flexible scenario configurations, automated resource allocation, and ensured transparency through delivery tracking and visualisation.
- Integration: API connections and deployment of the optimisation module were carried out smoothly, with no major technical issues observed during the testing process.

## **5.6. Multi-Source Information Fusion: ASTRIAL AI People, Objects, and Hazards Detection**

The people, objects, and hazards detection models were successfully deployed and evaluated during CFT2 and CFT4, where effective real-time detection and localisation were demonstrated from live drone video streams. In particular, the models for people profiling, FR classification, vehicles, and smoke detection were validated. Algorithms for the detection of debris and holes are currently in active lab testing and are scheduled for deployment and evaluation in the upcoming system field trials.

## **5.7. Multi-Source Information Fusion: ASTRIAL C3I Alerting information**

For the pilot operations, the C3I/IMS has been deployed on a cloud-based infrastructure, ensuring that the system remains accessible, reliable, and scalable throughout the testing phase. This setup has been prepared and deployed before the CFT2 to cover the needs of this session. According to the plan, this deployment will continue to be hosted on the cloud, enabling the connectivity between the interoperability framework and the C3I/IMS system.

## **5.8. Interoperability Framework among IMS: ASTRIAL IMS Interoperability (Kafka, MinIO)**

The Interoperability Framework has been deployed on a cloud-based infrastructure to ensure that it is easily discoverable and reachable by all SYNERGISE components. Hosting the framework in the cloud guarantees seamless connectivity, enabling every integrated module, from field devices to advanced analytics services, to exchange data reliably and efficiently.

The framework has been deployed in the cloud since CFT1 and is planned to remain there until the completion of the pilot phase. This approach provides a consistent and accessible integration backbone throughout the pilots, supporting interoperability, scalability, and smooth coordination across the entire SYNERGISE ecosystem.

## 5.9. Multi-agency Incident Management and the COP: ASTRIAL C3I/IMS

The C3I/IMS has been deployed on a cloud-based infrastructure to ensure that it can be easily accessed and used by the different users and agencies participating in the pilots. By operating in the cloud, the system provides a unified environment where all stakeholders, ranging from field teams to headquarters personnel, can connect seamlessly, regardless of their organisational boundaries or physical location.

The deployment (Figure 1Figure 30) has been active since CFT1 and will remain in place for all pilot sessions, ensuring consistent availability and usability throughout all pilot phases. This setup supports cross-agency collaboration, situational awareness, and coordinated response in a secure and scalable manner.



Figure 30. Deployment of HQ C3I/IMS during CFTs

## 6. Evaluation of System Requirements and KPIs

The status of system requirements and KPIs is addressed in this chapter for the components developed in the framework of WP5.

### 6.1. Field and HQ Communication: ASTRIAL Solution

#### Evaluation of System Requirements

##### SATCOMM (Starlink and 5G)

The SATCOMM component of the Field and HQ Communication toolkit was evaluated against the system requirements, defined in D1.3, with a focus on rapid deployment, operational resilience, and

adaptability to diverse environments. Deployment times during field tests consistently fell within the required 30-minute maximum, and the system could be set up by a single operator. The integration of Starlink satellite backhaul with 5G WAN interfaces supported redundancy and failover, ensuring consistent performance even in areas with degraded internet connectivity. Portability requirements were satisfied, with all equipment fitting into two carry-on cases, allowing easy transport to remote sites.

Operational tests confirmed continuous performance for extended shifts of up to 14 hours, with power provided by both fixed supplies and field-deployable batteries. The system demonstrated tolerance to interference, automatically switching between satellite and 5G, thereby validating redundancy features. The self-forming and self-healing properties of the network were partially achieved: auto-configuration was successful for initial deployment, while resilience in re-establishing disrupted links improved significantly from CFT1 to CFT3.

Compatibility with multiple data types, including audio, video, images, sensor data, and GIS was demonstrated through integration with SYNERGISE tools and partner platforms. Environmental resilience was also validated, with the equipment performing reliably in varying weather and temperature conditions. However, earlier trials highlighted vulnerabilities to wind gusts affecting antenna alignment, an issue later mitigated with reinforced mounts. Overall, SATCOMM met its system requirements, with ongoing refinements focused on further enhancing autonomous self-healing and improving robustness against extreme environmental factors.

### **LANCOMM (Wi-Fi Mesh)**

The LANCOMM component was evaluated as a complementary capability to SATCOMM, providing local ad-hoc Wi-Fi coverage to personnel and devices in both indoor and outdoor scenarios. The system consistently met the 30-minute deployment requirement, with real users' setups validated during field trials. The plug-and-play configuration of Wi-Fi mesh nodes ensured minimal complexity, allowing rapid network establishment with automatic discovery and meshing.

Portability requirements were fully achieved, with the mesh nodes, P2P antennas, and supporting accessories fitting into compact, field-transportable cases equivalent to two carry-on pieces. During CFTs, the deployment scaled effectively to support up to 53 connected devices, confirming its ability to adapt to incident size and scope. Nodes were strategically placed to extend coverage in complex terrain, e.g., a tower 43 m in height, while ensuring reliable long-range connections between the field and HQ.

Resilience and redundancy were also validated. In cases of node failure, the mesh automatically rerouted traffic, maintaining operational connectivity. However, power supply constraints were noted as a limiting factor in CFT2, with connecting the outdoor nodes to grid power emerging as a critical issue. Improvements were implemented by CFT3 using additional power banks for all indoor nodes and more stable mounting solutions to withstand environmental factors such as wind.

In summary, LANCOMM successfully addressed its key system requirements, demonstrating agility, ease of deployment, and strong scalability. While the mesh achieved high reliability and seamless integration with SYNERGISE services, ongoing work is focused on extending power autonomy and further simplifying long-range P2P antenna alignment for FRs in time-critical deployments.

## **Evaluation of KPIs**

### **SATCOMM (Starlink and 5G)**

The SATCOMM component was evaluated against the defined KPIs, listed in D1.3 and reviewed before each pilot taking place, with a focus on rapid deployment, communication performance, device capacity, and environmental resilience. While the target deployment time of <10 minutes was ambitious, current field tests confirmed deployment in under 20 min with trained operators, showing ongoing progress toward full compliance. The system consistently provided reliable outdoor coverage well above the 185 m<sup>2</sup> benchmark, as validated during CFT3 deployment, where coverage extended across large operational perimeters. However, CFT2 witnessed a noticeable lag in coverage, but was addressed in time for CFT3.

Latency measurements were generally within the <150 ms target, although fluctuations were observed under congested network conditions or during satellite handovers. Power consumption remained within the expected 50 – 100 W range, aligning with manufacturer specifications and validated during continuous operation tests. Device capacity was robust, with up to 53 devices connected simultaneously in CFT3 without significant performance degradation, demonstrating compliance with the requirement to support <128 devices.

Environmental operability was also confirmed, with the system performing effectively across a range of weather and temperatures. However, strong winds highlighted the need for reinforced mounting for the satellite dish, a challenge resolved in later deployments. Overall, SATCOMM KPIs were mostly met. Although the deployment speed KPI requires further optimisation through simplified mounting solutions and enhanced operator training.

### **LANCOMM (Wi-Fi Mesh)**

The LANCOMM component was assessed against KPIs focusing on deployment speed, coverage, latency, scalability, and environmental robustness. The system consistently achieved deployment within <30 min, fulfilling the KPI across multiple field exercises. Coverage met the required area thresholds, where outdoor range was supported through point-to-point (P2P) antennas and indoor coverage was achieved with mesh nodes during CFTs.

Latency remained well within the <150 ms target, especially in CFT3, ensuring reliable communication for data, video, and voice streams across the mesh. Scalability was confirmed by supporting up to 53 devices in CFT3, which demonstrates compliance with the requirement for <128 devices. The system integrated seamlessly with SYNERGISE services and external devices, showing no bottlenecks during peak usage.

Environmental operability was validated, with equipment performing under varying conditions, e.g., the system continuously performed while it was raining during the CFT3. The need for training of users was highlighted in all the field deployments. Noticeably, there was difficulty in organising the FRs to set up and monitor the system as required at the initial CFTs. This has improved significantly towards CFT4, in which trained FRs were in control of the network setup and its maintenance. The majority of technical KPIs were effectively met, with improvements ongoing to enhance resilience in extended system field operations.

## **6.2. Field and HQ Communication: ETRI Emergency Communication Kit**

### **Evaluation of System Requirements**

#### **P5GCOMM (5G/LAN with Spine-Leaf deployment and Wi-Fi connection)**

The P5GCOMM component, a communication toolkit between the disaster field site and HQ, was evaluated with a focus on the rapid installation of emergency communication kits, the resilience of communication operations, and adaptability to different disaster environments compared to the system requirements defined in D1.3. During the disaster field site (in other words, disaster safety training centre) testing, installation time was consistently verified to the maximum of 30 minutes required, and a single FR operator confirmed that the system could be initially installed and serviced by setting to Plug-&-Play method. The integrated connection between the Starlink satellite backhaul and the Private-5G WAN interface supports redundancy and failover, ensuring consistent emergency communication service performance even in areas with no commercial Internet connection. Portability requirements were met, and all equipment was fitted in two portable cases to facilitate remote communication from the HQ to the disaster site via wired/wireless connection.

The sustainability of the on-site battery of up to 14 hrs could not be confirmed at the site of the European Disaster and Safety Training Centre, but the test results of the Korea ETRI Lab showed that it lasted for 8 hrs in the Power-on & Idle state. However, the battery survival time of more than 14 hrs is related to the sustainability of the secondary battery, which requires a high-spec battery in the future. This system could not confirm the resistance to 5G spectrum interference, and the automatic switching function between satellite and P5G should be verified in the future. The self-

forming and self-healing characteristics of this ETRI ECK P5G network were partially achieved. The automatic configuration was successful when the initial network was installed, but the resilience to reset the suspended link should be confirmed after CFT4.

Compatibility with various data types such as audio, video, image, sensor data, GIS, etc., has been demonstrated through integration with SYNERGISE disaster rescue tools and partner platforms (e.g., VIRNECT AR Glass/AR smartphones in Korea). Disaster environment resilience has also been verified, and the waterproof manual processing of communication kits and relay connections has achieved stable performance under various weather and temperature conditions. Initially, there was no KPI for communication processing performance in this domestic project in Korea, but we added a new KPI for communication processing performance in the SYNERGISE international joint research project to set Downlink (DL) / Uplink (UL) processing performance to DL 50 Mbps / UL 10 Mbps. As a result of measurement on the actual CFT4 Internet network, DL 94.3 Mbps / UL 12.9 Mbps processing performance results were confirmed, which in general P5GCOMM has met emergency communication system requirements for most applied voice/data services including AR application and video service processing, and continuous improvement will focus on further strengthening autonomous and self-healing and improving the robustness against extreme disaster environmental factors.

In summary, P5GCOMM has demonstrated installation agility, ease of deployment, and robust scalability, and has successfully addressed key system requirements. While the installation of this Spine-Leaf Tree deployment has achieved high reliability and seamless integration with SYNERGISE emergency communication services, ongoing work will focus on expanding 14 hrs operational power continuity for emergency rescue FRs in an emergency network installation where reducing the rapid rescuing golden-time is critical, and further enhancing the scalability of long-coverage distance (over 1~3 km radius in the open area) P2P wireless connections.

## Evaluation of KPIs

### P5GCOMM (5G/LAN with Spine-Leaf deployment and Wi-Fi connection)

The CFT evaluation of P5GCOMM's extreme disaster environment application KPIs was conducted in the following aspects:

1. In case of power-on after installation of the emergency communication network, the time required to start the communication service is within 30 min.
2. Communication Coverage Distance Range within a radius of 1 km of reaching radio signal transmission over the P5G spectrum.
3. Up/down transmission bandwidth for P5G wireless over UL 10 Mbps, over DL 20 Mbps.
4. Data communication/service connectivity between FR's AR Glass and HQ via wired/wireless connection between P5G wireless and Ethernet LAN Cable.
5. Communication connection distance between FR's AR Glass/AR smartphone in the disaster field site and HQ in the remote site.
6. Possible operation of the communication connection in a rainy weather disaster environment.

In the process of verifying CFT4,

1. The start of the communication service was confirmed within 15 min.
2. Radio coverage has reached a distance of several tens of meters due to radio unit (RU) performance degradation.
3. E2E communication bandwidth was identified as average from UL 10 to 15 Mbps and DL 90 to 100 Mbps radio bandwidth.
4. Through Korea VIRNECT's AR Glass and AR smartphones, it was confirmed that AR, (voice-to-text) conversion into Korean/English, video conference call, and gesture UI were connected and communicated.
5. In CFT3 it was confirmed that P5G AP node's Wi-Fi connecting distance through Private-5G, P5G gNodeB and Ethernet LAN Cable AP nodes could be hundreds of meters.

6. Waterproof protection was required for covering communication equipment and connections under rainy weather disaster training field site.

The connection between other disaster-rescue robots and P5GCOMM could be supplemented by the difference between the European 5G USIM and the European 5G spectrum. If you connect to the ETRI ECK AP node at the end of the P5GCOMM communication, there is no problem with complementary communication connectivity, which was verified at CFT4. In addition, one FR person does not have any problem installing this equipment in the disaster area, but operation training is necessary.

This P5GCOMM equipment has a higher P5G equipment price and installation cost compared to Wi-Fi Mesh, but it can provide emergency service priority through specific network slices (AloT dedicated network), such as valley/cliff hazard sections where Wi-Fi Mesh wireless and LAN wirelines cannot be installed directly.

It is an important solution for the blind spots in complex buildings with high P5G communication connectivity, widening communication coverage, and lower connectivity congestion among AloT sensor robots and wearable devices.

The aimed final KPIs of ETRI Private-5G ECK Performance are as follows:

- ECK Network Set-up Time (just only Plug-&Play connecting): within 30 min
- Maximum concurrent users/devices: 200 subscribers (in Lab. VoIP emulation testing)
- Duration of operation with only battery in communication equipment: 8 hrs
- Radio frequency reach: 1.000 m<sup>2</sup>, (CFT4 aimed for 100 x 100 m<sup>2</sup>)
- UpLink/DownLink Bandwidth: 20 Mbps/100 Mbps.

### 6.3. Augmenting Reality Services: VIRNECT: AR Training/Video Conferencing/Visualisation

The VIRNECT AR applications were evaluated against their core KPIs, with a focus on non-intrusive visualisation for training (KPI-30) and hands-free communication for on-site operations (KPI-31). The tests, conducted during CFT3 on the Meta Quest 3 platform, confirmed the successful implementation and functionality of both the AR Training and AR Video Conferencing components.



Figure 31. AR training application for ANYmal and SNAKE

The requirement for non-intrusive visualisation (KPI-30) was fully met. The AR Training application successfully delivered immersive training modules for complex robots (ANYmal, SNAKE) without obstructing the user's field of view, as validated in a controlled laboratory setting (Figure 31). This confirmed the system's readiness for effective skill transfer without compromising situational awareness.

The goal to facilitate hands-free multimedia communication (KPI-31) was also successfully achieved. The system demonstrated a stable, multi-platform communication architecture connecting field agents, mobile leaders, and the command centre. A key achievement was the development of a specialised Speech-to-Text (STT) model that reduced the Word Error Rate by 34.4% in high-noise environments, making true hands-free operation feasible. While core functionality was validated, a challenge was identified where the video interface occupied a large portion of the screen. This is being addressed in CFT4 through the development of a separate, less obtrusive visualisation app for mission-critical data.

Overall, all technical KPIs for the VIRNECT AR applications were met. The system proved to be a robust and effective tool for both training and communication, with clear plans for UI optimisation in the next phase to further enhance field usability.

#### **6.4. Multi-Source Information Fusion: CERTH: XAI services**

Given that the demonstration was conducted in a standalone setup, the KPI evaluation is limited. Full validation against all KPIs will require integration within the next testing session of the platform.

#### **6.5. Multi-Source Information Fusion: ASTRIAL: Logistics Optimisation Module**

##### **Evaluation of System Requirements**

The Logistics Optimisation Module has been carefully developed and tested to meet all key system requirements, ensuring it is ready for effective use in real emergency situations.

Key Requirements:

- **Rapid Deployment:** The tool enables quick creation and adjustment of scenarios, providing clear visualisation of results. It is designed to meet the field teams' need for speed and flexibility during operations.
- **Compatibility & Interoperability:** The module integrates seamlessly with the SYNERGISE C3I/IMS, allowing smooth data exchange with other components and future modules.
- **Scalability:** Tested with simulated data across multiple depots, vehicles, and resource types, the system is capable of handling more complex scenarios and can scale as operational demands increase.
- **Operational Flexibility:** The module can process live updates and recalculate routes in real-time, adjusting instantly to new incidents, resource changes, or transportation constraints.
- **Resilience and Reliability:** Tested across diverse scenarios and network conditions, the system maintains smooth operation while updating data or integrating with other systems. It also ensures data integrity and security throughout all processes.

The module has successfully met all key requirements for initial setup and demonstration. Moving forward, efforts will focus on integrating real field data, enhancing automation, and supporting larger-scale incidents in upcoming System Field Tests (SFTs).

##### **Evaluation of KPIs**

The technical performance of the Logistics Optimisation Module has been evaluated against a set of KPIs, derived from the project's initial goals and refined during real-world testing to ensure accuracy and reliability.

- **Optimisation Speed:** The system quickly generates optimal vehicle assignments and route plans, typically within less than 5 seconds for standard CFTs scenarios involving multiple resources and vehicles.
- **Deployment and Usability:** Docker-based deployment allows rapid setup of a fully operational optimisation environment within minutes. The user dashboard is intuitive, enabling logistics staff to manage workflows effectively with minimal training.
- **Scenario Capacity & Scalability:** Successfully tested across multiple depots, vehicle types, and large-scale simulated incidents, confirming the system can support multiple vehicles and resource items without performance degradation.
- **Integration Robustness:** Seamless connectivity with C3I/IMS and other SYNERGISE components was confirmed, with no critical integration issues encountered.
- **Accuracy and Reliability:** Route and load assignments are consistent and reproducible. ETA calculations align with reference values within an acceptable margin of error, ensuring dependable operational planning.
- **Flexibility:** The module supports real-time scenario updates and immediate re-optimization, a critical requirement for dynamic and rapidly changing field operations.

## 6.6. Multi-Source Information Fusion: ASTRIAL AI People, Objects, and Hazards Detection

### Evaluation of System Requirements

- **Detection Accuracy:** The model has achieved good accuracy on synthetic and test datasets for normal people (Figure 32). Improvements for additional classes, including falling, other activity profiles (Figure 33), and FR identification (Figure 34), smoke (Figure 35) and fire (Figure 36) are ongoing as more annotated data becomes available.
- **Operational Performance:** Model inference is fully compatible with edge and GPU hardware, supporting near real-time operation on field-deployable servers.
- **Integration:** Initial integration for people detection was successful. Extended outputs, including multi-class profiles and hazard detection, will be validated in the next phase of the project.
- **Adaptability:** The system is designed for easy model updates and the incorporation of new classes as additional annotated data is collected, ensuring continued improvement and relevance in field operations.
- **Limitations:** Advanced features like (FRs and fire/smoke) are still under testing and require live field validation for full operational assessment.



Figure 32. People detection by AI detection from an outdoor drone

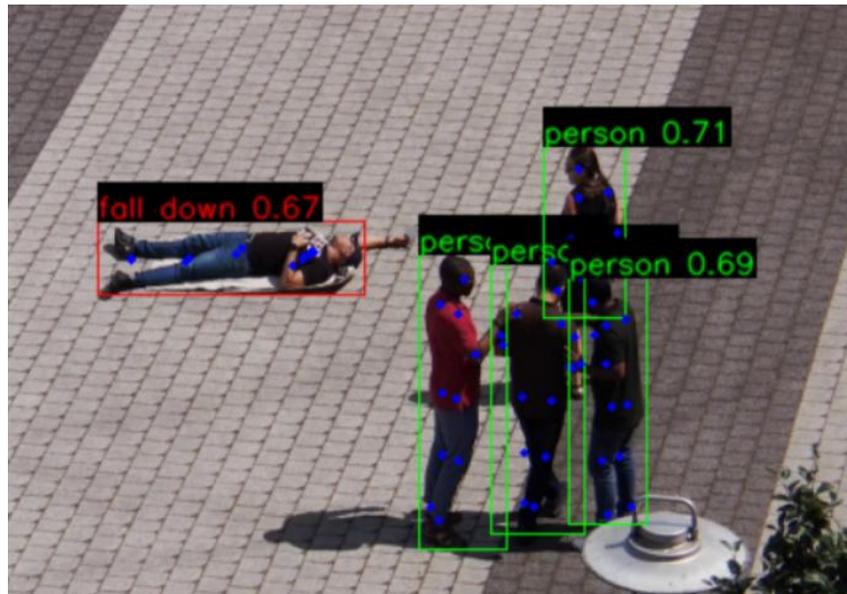


Figure 33. Fall down profile by AI detection from an outdoor drone



Figure 34. FR classification by AI detection from an outdoor drone



Figure 35. Smoke by AI detection from an outdoor drone



Figure 36. Fire by AI detection from an outdoor drone

### Evaluation of KPIs

- Detection Speed: The model achieves inference times of less than 50 ms per frame on standard field GPUs, supporting real-time processing of live drone video streams.
- Scalability: The architecture supports multi-stream inputs and is designed to expand easily to additional detection targets as required.
- Integration: Outputs are fully compatible with major SYNERGISE C3I/IMS components, with no critical bottlenecks observed during current integration testing.

- Accuracy: Achieved >80% mean Average Precision (mAP) on the SARD dataset for normal and falling detection. Validation for First Responder (FR) and fire/smoke hazard classes is ongoing.
- Robustness: The model has been tested on a variety of datasets, including both open-source and project-specific data, ensuring reliable performance across different environmental conditions and operational scenarios.

## 6.7. Multi-Source Information Fusion: ASTRIAL C3I Alerting information

### Evaluation of System Requirements

The C3I Alerting Information Module has been evaluated against the system requirements defined in D1.3, ensuring compliance with the expected functional and operational specifications. Particular emphasis was placed on the ability of the module to provide flexibility in data visualisation, allowing users to tailor how information is presented according to their roles, responsibilities, and individual preferences.

Through map-based views, dashboards, charts, timelines, or tabular representations, users can adapt the interface to suit their decision-making needs. This flexibility not only improves usability and efficiency but also ensures that alerts and situational data are communicated most effectively to different types of operators, whether they are field responders, coordination officers, or headquarters staff.

### Evaluation of KPIs

Taking into consideration the content of D3.1, no KPI is directly related to the C3I alerting information module. However, the functionalities provided by the module could be covered by the following C3I KPI: “>95% of data represented in COP in various layers”. Thus, the alerting module depicted all the types of alerts that are produced by the other components and forwarded to the module, filtering this information to the users, according to their responsibilities and roles.

## 6.8. Interoperability Framework among IMS: ASTRIAL IMS Interoperability (Kafka, MinIO)

### Evaluation of System Requirements

The Interoperability Framework has been evaluated against the system requirements defined in D1.3, ensuring that it meets the expected performance, security, and operational standards. The framework supports encrypted transmission of data through protocols such as SSL, TLS, SSH, and VPN, and ensures encrypted storage using methods like TDE and EFS, guaranteeing the confidentiality and integrity of sensitive information.

Designed for scalability and accessibility, the framework can be used by many components simultaneously, including components spread across extensive geographical areas, without compromising performance. Its architecture is optimised to minimize delays in data transmission, enabling real-time exchange of alerts, sensor measurements, and operational information between all integrated SYNERGISE components.

By combining robust security, high availability, and low-latency communication, the Interoperability Framework ensures reliable, secure, and efficient integration across the entire SYNERGISE ecosystem.

### Evaluation of KPIs

The Interoperability Framework has been evaluated against the KPIs defined in D1.3, confirming that it supports all functionalities required by the project. Specifically, it has been designed and tested to manage more than three components simultaneously producing data, while supporting

multiple data formats, including textual information, images, videos, and point clouds. The framework has also been optimised to ensure low latency in data transmission between components, enabling real-time communication and seamless integration across the SYNERGISE toolkit.

## 6.9. Multi-agency Incident Management and the COP: ASTRIAL C3I/IMS

### Evaluation of System Requirements

The C3I/IMS has been evaluated against the system requirements defined in D1.3, confirming that it supports all the functionalities required by the project. The system provides comprehensive capabilities for managing and visualising operational information across diverse scenarios and user roles. It allows the management of the incidents and assignment of resources to incidents according to the standard operating procedures of the agencies that are involved in the emergency. For USAR team operations in the field, the C3I/IMS will facilitate the formulation of USAR teams and support the management and monitoring of their activities. This can be performed either by HQ personnel or by team leaders on-site, leveraging the mobile version of the C3I/IMS to maintain situational awareness and operational control. An initial version of the mobile version of the C3I/IMS has already been developed and used by the commanders during the previous testing sessions, supporting the monitoring of the vital signs of the team members.

Furthermore, the C3I/IMS integrates with field components, including ANYMAL, OWL, SNAKE, UAVs, localisation devices, FR vitals, and environmental gas monitoring systems. It supports the reception of diverse types of information, such as live video streams, textual updates, and personnel vital signs, and provides visualisation through an intuitive graphical user interface. The system also handles the reception and display of alarms generated by these components. Alarms may relate to hazards in the operational area (e.g., high gas concentration) or personnel status (e.g., elevated pulse rate), ensuring that all relevant operational information is available to decision-makers in real time. According to the plan, the initial version of those functionalities has already been evaluated through CFT1 to CFT4. After the completion of CFT4, refinements of those functionalities are executed (according to the feedback received) and re-evaluated to implement the improvements for the upcoming SFTs.

### Evaluation of KPIs

The C3I/IMS has been evaluated against the KPIs defined in D1.3. The C3I/IMS provides a COP environment designed to integrate the outputs from all SYNERGISE project components, as well as at least one legacy system, into a unified operational interface. This environment enables simultaneous access for at least three users, supporting coordinated decision-making across different roles and agencies. By consolidating diverse data sources and supporting multiple user perspectives, the C3I/IMS COP ensures that all stakeholders share a synchronised operational view, facilitating efficient coordination, resource management, and decision-making during both routine operations and emergency scenarios.

Within the COP, more than 95% of incoming data is represented across multiple layers, ensuring a comprehensive visualisation of the operational scenario. The system integrates data from three or more SYNERGISE components, including sensor readings, AI outputs, and field device information, with support for at least three different data formats, such as textual information, images, and video streams.

The COP environment is designed to accommodate multiple user roles for each agency, with at least three roles configured, each having access to different features and capabilities according to operational responsibilities. It supports full management of resources, allowing users to track, assign, and visualise assets in real time, and provides the capability to display more than 50 virtual objects on the map for enhanced situational awareness.

## 7. Conclusions and Future Work

This deliverable D5.1 consolidates the design, development, testing, and validation activities of the SYNERGISE WP5 tools, which include field and HQ communications, augmented reality services, multi-source information fusion modules, interoperability frameworks, and the COP with the C3I/IMS platform. Each component has been developed to address the operational needs of FRs with the goal of enhancing safety, collaboration, and situational awareness in demanding disaster scenarios. The tools have been tested and validated in four Component Field Tests, demonstrating their robustness, novelty, and operational relevance for disaster-response operations.

The work carried out so far highlights the following:

- Communication and networking systems composed of Wi-Fi, satellite, 4G, and Private-5G allow for continuous and resilient connectivity across HQ and field units, enabling coordination and system interoperability. Lessons learned from each CFT have been invaluable for strengthening robustness. Private 5G has shown strong potential as an innovative solution, though further improvements in speed and coverage are required.
- Augmented reality services enhance training and situational awareness through interactive visualisation and video conferencing. Feedback from FRs on the use of AR glasses and services has been critical for ongoing refinements.
- Multi-source information fusion tools (XAI services, logistics optimisation, objects, people, and hazards detection, and alerting modules) transform heterogeneous inputs into actionable insights. Their incorporation into operational missions provides significant added value for disaster management.
- Interoperability frameworks ensure that diverse IMS and toolkit components function together as a coherent and integrated system.
- The COP and C3I/IMS platform form the backbone of multi-agency collaboration, providing an integrated operational view that supports coordination between HQ and field responders such as USAR teams and firefighters. Effective handling of incoming information in real-time by the command-and-control centre and field team leaders has been an ongoing learning process throughout the project.

Looking ahead, the next phase of work will focus on consolidating these tools into an operationally robust and field-ready SYNERGISE toolkit to be validated during the upcoming two SFTs.

The forthcoming D5.2 (final version) will expand this analysis with dedicated subchapters highlighting:

- The added value of each functionality or tool for FRs in real operational contexts.
- The innovation achieved by each tool, both in terms of technical advancements and practical application in multi-agency disaster management.
- The exploitation potential, including opportunities for integration into operational practice, alignment with market needs, and future adoption pathways.

In this way, D5.2 will provide not only the final technical validation of the WP5 tools but also a strategic perspective on their impact, usability, and sustainability within and beyond the SYNERGISE project.

## 8. References

[1] „[www.kafka.apache.org](http://www.kafka.apache.org),” [Online].

[2] „[www.min.io](http://www.min.io),” [Online].