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Abstract

This document presents the Economic Evaluation (ECO-EVAL) for the ATMACA (Air Traffic Management and Communication over ATN/IPS) solution at TRL2. ATMACA introduces an innovative air traffic management and communication framework based on the Internet Protocol Suite (IPS), integrating a specialized datalink protocol, a foundational Data Link Context Management (DLCM) application, and advanced operational applications such as Controller-Pilot Data Link Communications (CPDLC) and Green Route Operations (GRO). This qualitative assessment evaluates potential economic benefits and high-level cost drivers across Key Performance Areas (KPAs), including cost efficiency, safety, human performance, environmental sustainability, and operational efficiency. The objective is to establish an early economic baseline for transitioning from legacy ATN/OSI systems to a modular, service-oriented digital ATM infrastructure in Europe.

Authoring & approval

Author(s) of the document

Organisation name	Date
Fulya Aybek Çetek / ESTU	30/06/2026
Emircan Özdemir / ESTU	30/06/2026
Enes Özçelik / ESTU	30/06/2026
Emre Aydoğan / ESTU	30/06/2026

Reviewed by

Organisation name	Date
Michael Regnault / ENAC	26/06/2026
Sergun Özmen / THY	28/06/2026
Angel Carmona Fernández / SAERCO	24/06/2026

Approved for submission to the SESAR 3 JU by

Organisation name	Date
Fulya Aybek Çetek / ESTU	30/06/2026
Stefano Bonelli and Tommaso Vendruscolo / DBL	30/06/2026
Raouf Hamzaoui / DMU	30/06/2026
Georges Mykoniatis / ENAC	30/06/2026
Angel Carmona Fernández / SAERCO	30/06/2026
Sergun Özmen / THY	30/06/2026
Rosa María Arnaldo / UPM	30/06/2026

Rejected by[1]

Organisation name	Date

[1] Representatives of the beneficiaries involved in the project.

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ATMACA

AIR TRAFFIC MANAGEMENT AND COMMUNICATION OVER ATN/IPS

ATMACA

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1 Executive summary

This document provides the Economic Evaluation (ECO-EVAL) for the ATMACA (Air Traffic Management and Communication over ATN/IPS) solution, which is currently being matured from TRL1 to TRL2. ATMACA introduces a scalable Air Traffic Management and communication framework based on the Internet Protocol Suite (IPS), designed to facilitate the transition from legacy ATN/OSI systems to a flexible and resilient digital infrastructure. The solution addresses critical mobility management challenges in multilink aeronautical environments by integrating a specialized datalink communication protocol, Data Link Context Management (DLCM) middleware, operational applications (CPDLC and GRO), and role-based Human–Machine Interfaces (HMIs).

A central innovation of the ATMACA concept is the "flight session," which establishes a unique and persistent association between a flight and all its air–ground datalink communications, flight data (planning, radar, and trajectory), and operational context. By managing this context as a single entity, ATMACA ensures service continuity across heterogeneous links (VDLm2, SATCOM, AeroMACS) and sector boundaries, significantly reducing the manual intervention required from pilots and air traffic controllers (ATCOs) during transitions.

The key benefits of the ATMACA solution are identified across several Key Performance Areas (KPAs):

- *Operational Efficiency*: The automation of handovers and persistent session management reduce manual datalink setup tasks and communication disruptions. This supports improved en-route throughput and higher predictability in tactical datalink operations.

- *Environmental Sustainability*: The Green Route Operations (GRO) application leverages real-time wind and temperature networking (WTN) to optimize flight profiles. This data-driven approach enables more accurate ETA predictions and fuel-optimal routing, which is expected to reduce fuel burn and CO_2 emissions.

- *Human Performance*: Enhanced role-based HMIs improve situational awareness by providing a unified view of the flight session context. This integration reduces cognitive workload and the risk of miscommunication during complex traffic scenarios.

- *Safety*: The use of persistent logical links and application-layer mobility management reduce the likelihood of communication gaps and ensures that operational context information remains consistent and synchronized as aircraft move across different Air Traffic Services Units (ATSUs). This improved continuity and situational awareness are expected to mitigate the risk of communication-related operational errors during transitions.

- *Digitalisation*: ATMACA facilitates the transition from monolithic legacy systems to a modular, IP-based infrastructure, enhancing interoperability with SWIM-enabled services and future digital ATM platform.

The **primary beneficiaries of ATMACA** include ANSPs, Airspace Users (Airlines), the Network Manager, and Airport Operators. **Key cost drivers for stakeholders adopting and operating the ATMACA solution** are expected to include ATN/IPS infrastructure adaptation, middleware integration, HMI deployment, and specialized training for ATCOs and technical staff.

At TRL 2, this evaluation provides a qualitative assessment of these economic and operational impacts. Quantitative investment figures and specific performance metrics are expected to be developed and refined at higher TRL, particularly at TRL4. The validation evidence generated through the project's six validation exercises—ranging from protocol simulations and emulations to human-in-the-loop studies and an end-to-end flight trial—provides a solid foundation for refining the identified benefit mechanisms and cost drivers in future economic assessments.

2 Introduction

2.1 Purpose of the document

This document defines the Economic Evaluation (ECO-EVAL) for the ATMACA (Air Traffic Management and Communication over ATN/IPS) solution, identified as SESAR Solution 0513 at TRL2.

As a fundamental technical deliverable within the SESAR development lifecycle for exploratory research projects, this ECO-EVAL serves several key objectives:

- *Early Economic Relevance*: It establishes an initial baseline for the solution's economic viability within the European ATM environment, specifically addressing the transition from legacy ATN/OSI systems toward a modern, IP-based digital infrastructure.
- *Assessment of Benefit Impact Mechanisms* (BIMs): It defines how the core components of the ATMACA framework—including the specialized datalink protocol, Data Link Context Management (DLCM) middleware, Controller-Pilot Data Link Communications (CPDLC), Green Route Operations (GRO), and role-based Human-Machine Interfaces (HMIs)—contribute to Key Performance Areas (KPAs) such as operational efficiency, cost efficiency, safety, human performance, and environmental sustainability.
- *Strategic Decision Support*: The document provides stakeholders and decision-makers with a strategic foundation to assess the feasibility of the concept and supports the transition from TRL1 (Concept Formulated) to TRL2 (Proof of Concept) at the exit maturity gate.
- *Input for Future Quantitative Analysis*: This qualitative evaluation acts as a primary input for more detailed quantitative Cost-Benefit Analysis (CBA) activities required during the TRL4 maturation phase and subsequent industrialisation stages.

By consolidating the results of the project's six validation exercises—ranging from protocol simulations and emulations to human-in-the-loop studies and flight trials—this document ensures that the ATMACA solution remains aligned with the European ATM Master Plan and the Digital European Sky vision.

2.2 Scope

The scope of this ECO-EVAL encompasses the qualitative assessment of the anticipated benefits and high-level cost drivers associated with the ATMACA framework. In accordance with its definition as ATMACA Solution (0513), the evaluation focuses on the following core components and their integration into the future European ATM infrastructure:

- The ATMACA datalink communication protocol and Data Link Context Management (DLCM) middleware, which provide application-layer mobility, session, and connection management.
- Advanced operational applications, specifically Controller–Pilot Data Link Communications (CPDLC) and Green Route Operations (GRO).

- Role-based Human–Machine Interfaces (HMIs) tailored for both flight deck and ground-based Air Traffic Control (ATC) positions.

The analysis considers an ECAC-level deployment across multiple operational domains, following a gate-to-gate philosophy that includes airports, Terminal Manoeuvring Areas (TMAs), en-route sectors, and oceanic segments. The evaluation time period for this analysis is defined from 2026 to 2050, aligning with the strategic horizons of the European ATM Master Plan [27] and standard SESAR performance framework assumptions [14].

Primary stakeholders addressed in this scope include Air Navigation Service Providers (ANSPs), Airspace Users (Airlines), the Network Manager (NM), and Airport Operators. In alignment with TRL 2 maturity expectations, this document provides a qualitative description of Benefit Impact Mechanisms (BIMs) rather than a quantitative cost-benefit analysis. Furthermore, while technical dependencies on System-Wide Information Management (SWIM) and the Future Communication Infrastructure (FCI) are identified as foundational assumptions, the industrial development of these underlying infrastructures remains outside the scope of this project's specific evaluation.

Given the TRL2 maturity level, the document does not provide a quantitative cost-benefit analysis. Instead, it provides an initial qualitative basis for future economic evaluations and for the further maturation of ATMACA within the SESAR solution development lifecycle.

2.3 Intended readership

This document is intended for a broad range of stakeholders within the Air Traffic Management (ATM) community, particularly those involved in the SESAR 3 Joint Undertaking programme and the transition toward the Digital European Sky. The primary audience includes:

- *ATMACA Consortium Members*: To provide a strategic baseline for the ongoing research, development, and validation of the IP-based communication framework.

- *SESAR 3 JU Programme Management*: To evaluate the solution's contribution to the European ATM Master Plan and its alignment with Strategic Deployment Objectives (SDOs).

- *Air Navigation Service Providers (ANSPs)*: Specifically operational and technical divisions interested in improving communication continuity, reducing controller workload through automation, and enhancing trajectory efficiency via Green Route Operations (GRO).

- *The Network Manager (NM)*: Regarding the solution's potential to improve network-wide predictability, trajectory adherence, and the integration of future digital communication services.

- *Airspace Users and Airlines*: For the assessment of datalink service reliability, potential fuel savings derived from GRO, and improvements in gate-to-gate operational predictability.

- *Air Traffic Controllers (ATCOs) and Pilots*: As the primary end users of the enhanced HMIs and the persistent "flight session" management concepts introduced by the solution.

- *ATM Industry Stakeholders*: Including communication infrastructure providers, ground system suppliers, and avionics manufacturers seeking to understand the architectural requirements and deployment implications of the ATN/IPS framework.

- *Regulatory and Standardization Bodies*: Such as EASA and EUROCAE, to support the development of future standards for IP-based aeronautical communications.

- *The scientific community*: Who may build on the concepts, validation results, and technological developments generated by the project to advance the state-of-the-art in aeronautical communications.

- *Other SESAR and R&D projects*: Working in related areas, including ATN/IPS, Future Communication Infrastructure (FCI), multilink datalink technologies, mobility management, CPDLC, HMI design, and Green Route Operations (GRO), to foster interoperability and knowledge sharing across the SESAR and other R&D programmes.

2.4 Background

The current aeronautical communication landscape is characterised by a strong reliance on legacy communication systems, primarily voice communications over Very High Frequency (VHF) radio links and datalink services such as Controller–Pilot Data Link Communications (CPDLC) operating over VHF Data Link Mode 2 (VDLm2). While these technologies have successfully supported Air Traffic Management (ATM) operations for decades, they face significant limitations in terms of bandwidth availability, frequency congestion, line-of-sight dependency, coverage constraints, and the ability to support the increasing data exchange requirements of future ATM environments [27], [28], [29].

To address these challenges, the aviation sector is progressively transitioning towards the Aeronautical Telecommunication Network using the Internet Protocol Suite (ATN/IPS), which constitutes a key enabler for the future Digital European Sky vision. ATN/IPS supports the evolution from legacy ATN/OSI architectures towards scalable, interoperable and IP-based communication services, facilitating both air–ground and ground–ground information exchange. In parallel, future communication technologies such as the L-band Digital Aeronautical Communications System (LDACS), Aeronautical Mobile Airport Communications System (AeroMACS), and satellite communication (SATCOM) are expected to establish a heterogeneous multilink communication environment capable of supporting resilient and data-intensive ATM services [30], [31], [32], [33].

Despite these technological advances, a major challenge remains the provision of seamless mobility management. Aircraft routinely transition between different communication coverage areas, access networks, ground stations, Flight Information Regions (FIRs), Air Traffic Services Units (ATSUs), and communication technologies during flight operations. In the current reference scenario, communication handovers are largely managed through sequential and partially manual processes. When aircraft move between ATSUs or network domains, datalink connections often require manual re-establishment, increasing workload for both pilots and Air Traffic Control Officers (ATCOs) while creating operational discontinuities. This mobility gap—defined as the inability of existing communication architectures to maintain persistent communication sessions and service continuity during transitions—represents a critical obstacle to the deployment of highly integrated, data-centric ATM services [34], [35], [36], [37].

Existing IP mobility solutions provide important foundations for supporting mobility; however, they predominantly focus on terminal mobility and frequently require adaptations at the network or transport layers. Such approaches may introduce deployment complexity and are not fully aligned with the stringent operational, safety, and interoperability requirements of ATM environments [34], [35], [36], [37].

Building upon these developments, the ATMACA project has been initiated as a direct response to the identified mobility and communication challenges. The project builds upon the theoretical and technological foundations established by the patent "*Air Traffic Communication and Management System and Method*" (Turkish Patent No. 2016/20184) and subsequent academic research. ATMACA aligns with the long-term objectives of the European ATM Master Plan Phase D and contributes to the vision of fully integrated air–ground systems and distributed information services envisaged for deployment by 2045 [30], [37].

ATMACA proposes an innovative IP-based datalink communication framework for ATM operations over ATN/IPS. The solution integrates the ATMACA datalink communication protocol, Data Link Context Management (DLCM), operational applications such as Controller–Pilot Data Link Communications (CPDLC) and Green Route Operations (GRO), and advanced Human–Machine Interfaces (HMIs). Unlike conventional mobility solutions, ATMACA introduces mobility management at the application layer, enabling terminal, session, user, and service mobility while minimising the need for disruptive modifications to certified avionics systems and existing commercial off-the-shelf IP infrastructures [30], [34], [35].

Furthermore, ATMACA complements key SESAR technological enablers, including the Future Communication Infrastructure (FCI), LDACS, SATCOM, AeroMACS, and System-Wide Information Management (SWIM). Through its application-layer mobility management framework, ATMACA provides an architectural bridge capable of maintaining service continuity, session persistence, and operational consistency across heterogeneous communication links and network domains.

Through this approach, ATMACA aims to support seamless communication handovers, persistent flight-session management, multilink communication capabilities, enhanced datalink service continuity, improved operational predictability, and trajectory optimisation through Green Route Operations. These capabilities establish the technical and operational foundation for the economic, operational, human-performance, and environmental benefits assessed within this ECO-EVAL, including reduced manual coordination, improved communication efficiency, enhanced safety and situational awareness, and more efficient trajectory management with associated environmental gains [38], [39].

2.5 Structure of the document

This ECO-EVAL document is organized into the following chapters:

- *Section 1 (Executive Summary)*: Provides a high-level overview of the ATMACA solution, identifying its core architectural innovations, anticipated qualitative performance benefits, and the primary economic drivers for relevant stakeholders.
- *Section 2 (Introduction)*: Defines the purpose, scope, intended readership, and background of the evaluation, providing a glossary of terms and a comprehensive list of acronyms.

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- *Section 3 (Objectives and scope of the ECO-EVAL)*: Outlines the operational problems addressed by the solution, provides a detailed technical description of the ATMACA framework and its interdependencies, identifies the impacted stakeholder categories, and defines the deployment scenarios and assumptions used for the assessment.

- *Section 4 (Benefits)*: Presents a qualitative analysis of the Benefit Impact Mechanisms (BIMs) across SESAR Key Performance Areas (KPAs), specifically cost efficiency, environmental sustainability, human performance, safety, and digitalisation.

- *Section 5 (Cost assessment)*: Identifies and qualitatively describes the high-level investment and operating cost drivers for Air Navigation Service Providers (ANSPs), Airspace Users, the Network Manager (NM), and other relevant ATM stakeholders.

- *Sections 6 (CBA Model), 7 (CBA Results), and 8 (Sensitivity and Risk Analysis)*: These sections are outside the scope of this assessment, as Cost–Benefit Analysis and associated sensitivity evaluations are not applicable at TRL2.

- *Section 9 (Recommendations and next steps)*: Summarises the findings of the economic evaluation and outlines strategic recommendations and the maturation pathway required to transition the solution toward higher readiness levels.

- *Section 10 (References)*: Lists the applicable and reference documents upon which this evaluation is based.

- *Appendix A (Maturity criteria self-assessment)*: Provides a self-assessment of the document against the applicable SESAR TRL2 maturity criteria as defined in the SESAR programme library.

2.6 Glossary of terms

Term	Definition	Source of the definition
ATN/IPS	Aeronautical Telecommunication Network using the Internet Protocol Suite.	ICAO Doc 9896 / ATMACA FRD and OSED [1], [2], [31]
DLCM (Data Link Context Management)	A foundational application within the ATMACA solution that provides context, session, connection and mobility management services, acting as a runtime coordination layer between aeronautical applications and the underlying communication infrastructure.	ATMACA FRD, OSED and ERP [1], [2], [3]
ECO-EVAL reference scenario	The scenario against which the solution is compared, i.e. the situation without the proposed SESAR solution, while including other improvements implemented in the meantime.	DES HE SESAR ECO-EVAL template for TRL2 [8]
ECO-EVAL solution scenario	The scenario includes the proposed SESAR solution and other improvements implemented in the meantime.	DES HE SESAR ECO-EVAL template for TRL2 [8]
Flight Session	A unique and persistent association between a flight and its air–ground datalink communications, relevant	ATMACA FRD and OSED [1], [2]

Term	Definition	Source of the definition
	flight data and context information, managed as a single communication session entity.	
GRO (Green Route Operations)	An operational concept supporting trajectory prediction and trajectory improvement by using relevant weather and environmental data, such as wind and temperature, to improve flight efficiency and reduce environmental impact.	ATMACA FRD and OSED [1], [2]
Investment cost	The investment cost covers pre-implementation costs, such as feasibility studies, and implementation costs, such as system integration. SESAR R&I costs shall not be included.	SESAR 3 JU Project Handbook [25]
Mobility Management	A set of functions supporting continuity of service and communication as nodes, users, sessions or services change their point of attachment, role or operational context within the network.	ATMACA OSED [2]
Operating cost	All costs related to the change in daily operations brought about by the SESAR solution.	DES HE SESAR ECO-EVAL template for TRL2 [8]
Pre-implementation cost	All costs that need to be used up to define the needs, to develop solutions, and to decide which solution best serves the needs. Note that the SESAR R&I costs shall not be included as costs in any DES CBA/ECO-EVAL.	DES HE SESAR ECO-EVAL template for TRL2 [8]

Table 1: Glossary of terms

2.7 List of acronyms

Term	Definition
ACC	Area Control Centre
ADS-C	Automatic Dependent Surveillance – Contract
ADSP	ATM Data Service Provider
AeroMACS	Aeronautical Mobile Airport Communications System
ANS	Air Navigation Services
ANSP	Air Navigation Service Provider
ATCO	Air Traffic Control Officer
ATM	Air Traffic Management
ATMACA	Air Traffic Management and Communication over ATN/IPS
ATN/IPS	Aeronautical Telecommunication Network using the Internet Protocol Suite
ATS	Air Traffic Services

Term	Definition
ATSU	Air Traffic Services Unit
AUC	Airspace User Costs
BIM	Benefit Impact Mechanism
CAA	Civil Aviation Authority
CAP	Capacity
CBA	Cost–Benefit Analysis
CEF	Cost Efficiency
CDPLC	Controller–Pilot Data Link Communications
CISP	Common Information Service Provider
CSP	Communication Service Provider
CWP	Controller Working Position
DAC	Dynamic Airspace Configuration
DES	Digital European Sky
DLCM	Data Link Context Management
DLIC	Data Link Initiation Capability
ECAC	European Civil Aviation Conference
ECO-EVAL	Economic Evaluation
EFB	Electronic Flight Bag
ENV	Environment
FAA	Federal Aviation Administration
FCI	Future Communication Infrastructure
FCDI	Future Connectivity and Digital Infrastructure
FDPS	Flight Data Processing System
FEFF	Fuel Efficiency
FIR	Flight Information Region
FOC	Final Operating Capability
FRD	Functional Requirements Document
GA	Grant Agreement
GBAS	Ground-Based Augmentation System
GDPR	General Data Protection Regulation

Term	Definition
GRO	Green Route Operations
HC	High Complexity
HE	Horizon Europe
HMI	Human–Machine Interface
HP	Human Performance
ICAO	International Civil Aviation Organization
ID	Identifier
IFR	Instrumental Flight Rules
IOC	Initial Operating Capability
IRR	Internal Rate of Return
KPI	Key Performance Indicator
LC	Low Complexity
LDACS	L-band Digital Aeronautical Communications System
MC	Medium Complexity
NMOC	Network Manager Operations Centre
NSA	National Safety Authority
OSED	Operational Service and Environment Description
PI	Performance Indicator
PRD	Predictability
PUN	Punctuality
RES	Resilience
R&I	Research and Innovation
SA	Scheduled Airline
SATCOM	Satellite Communication
SDO	Strategic Deployment Objective
SESAR	Single European Sky ATM Research
SESAR 3 JU	SESAR 3 Joint Undertaking
SOD	Start of Deployment Date
SWIM	System-Wide Information Management
TEFF	Time Efficiency

Term	Definition
TMA	Terminal Manoeuvring Area
TRL	Technology Readiness Level
UAS	Unmanned Aerial System
USSP	U-space Service Provider
VFR	Visual Flight Rules
VHC	Very High Complexity
VL	Very Large
WOC	Wing Operations Centre

Table 2: List of acronyms

3 Objectives and scope of the ECO-EVAL

This chapter defines the operational and strategic context of the ATMACA economic evaluation. It identifies the core problems being addressed, describes the proposed SESAR solution and its interdependencies, and outlines the stakeholders and deployment scenarios used as the basis for this qualitative assessment.

3.1 Problem addressed by the SESAR solution

ATMACA is initiated in response to a significant gap in the current air–ground communication infrastructure, which continues to rely heavily on legacy communication systems. The solution addresses this gap through an innovative IP-based datalink communication framework over ATN/IPS, supporting more resilient, continuous and efficient air–ground and ground–ground communication services for future Air Traffic Management (ATM) operations.

The gap in current aeronautical communications and mobility management can be summarised as follows [4].

- Conventional aeronautical communication primarily relies on voice communication over Very High Frequency (VHF) radio links and data communication through Controller–Pilot Data Link Communications (CPDLC) over VHF Data Link Mode 2 (VDLm2). Although these technologies support current operational services, they present several technical and operational limitations, including VHF bandwidth constraints, frequency congestion, line-of-sight dependency, message-size limitations and coverage constraints. These limitations restrict the ability of current communication infrastructures to support the seamless, high-capacity and data-centric services required for future ATM operations.

- A central challenge is the management of mobility in a heterogeneous multilink environment. During flight operations, aircraft routinely transition between different coverage areas, access networks, ground stations, Flight Information Regions (FIRs), Air Traffic Services Units (ATSUs) and communication technologies. Existing IP-based mobility protocols were not originally designed to fully support seamless mobility across heterogeneous aeronautical communication links and may result in performance issues such as handover delays, packet loss, latency and signalling overhead. Furthermore, conventional mobility solutions mainly focus on terminal mobility and generally lack integrated mechanisms to ensure continuity of user, session and service mobility across multiple communication domains.

- Another significant operational challenge is the fragmentation between flight data management and air–ground communication handover processes. In current operations, flight data transfer and communication handovers are frequently managed as separate and sequential activities. Consequently, Air Traffic Control Officers (ATCOs) and pilots may be required to perform additional manual coordination during sector or ATSU transitions, increasing workload and creating the risk of communication gaps and context discontinuities. When communication sessions are interrupted, manual intervention is often required to re-establish connectivity and restore operational continuity.

This difference between the level of seamless, high-availability and high-continuity communication required for future ATM operations and the limitations of existing communication and mobility-management approaches constitutes the mobility gap addressed by ATMACA. Bridging this gap is expected to support high-availability, high-integrity and high-continuity communication services while enabling more efficient management of operational resources.

The ATMACA solution addresses these challenges by introducing the concept of a “flight session”, whereby a flight and all associated air–ground datalink communications, relevant flight data and contextual information are integrated into a single persistent communication session entity. This concept supports communication continuity across operational transitions and enables more integrated management of flight-related communication, context and service information.

Other SESAR exploratory research projects and industrial initiatives have contributed to this evolution through research on integrated Communication, Navigation and Surveillance (CNS) services, Future Communication Infrastructure (FCI), LDACS-based communications, satellite datalinks and software-defined communication management. While these initiatives have advanced the development of future multilink and IP-based communication concepts, ATMACA proposes a distinct mobility-management approach at the application layer.

In contrast to traditional IP mobility solutions, such as Mobile IPv6 (MIPv6) and related approaches operating primarily at the network or transport layers, ATMACA introduces application-layer mobility management designed to minimise deployment barriers by avoiding modifications to existing commercial off-the-shelf IP technologies. Through this architecture, ATMACA supports terminal, session, user and service mobility while enabling seamless handovers, persistent flight-session management, robust communication continuity, consistent datalink operations and more efficient utilisation of operational resources.

3.2 ATMACA solution description

ATMACA is a scalable and flexible air traffic management and communication framework designed to operate over the Aeronautical Telecommunication Network using the Internet Protocol Suite (ATN/IPS). The solution enables seamless, mobility-enabled and resilient air–ground connectivity through an application-layer communication architecture specifically developed to support future data-centric Air Traffic Management (ATM) operations.

The framework introduces an application-layer datalink protocol with integrated mobility, session, context and connection management capabilities. These functions enable continuous and secure data exchange across multiple datalinks, communication technologies and network environments while maintaining service continuity during operational transitions. By embedding mobility management at the application layer, ATMACA supports terminal, user, session and service mobility, ensuring continuous connectivity and consistent service delivery across heterogeneous aeronautical communication infrastructures.

ATMACA supports operational applications such as Controller–Pilot Data Link Communications (CPDLC) and Green Route Operations (GRO). Through these applications, the framework enhances controller–pilot communication, improves operational efficiency and predictability, and supports more sustainable trajectory management. The solution also incorporates advanced Human–Machine

Interfaces (HMIs) for both air traffic control and flight deck environments, contributing to improved situational awareness, reduced workload and enhanced human performance.

The framework is based on a modular architecture and is compatible with commercial off-the-shelf (COTS) technologies, facilitating interoperability, scalability and cost-effective deployment within current and future CNS/ATM infrastructures. Its design supports integration with evolving ATN/IPS communication environments and contributes to the digital transformation of ATM through the adoption of IP-based communication and mobility-management concepts.

From a standards and regulatory perspective, ATMACA is conceptually aligned with the evolution of international frameworks for IP-based aeronautical communication, particularly ICAO Doc 9896 on ATN/IPS, EUROCAE ED-315 addressing interoperability requirements, ICAO Doc 10037 (GOLD) for datalink operations, and ICAO Doc 10039 defining the SWIM Concept [9], [10], [11], [12]. While the solution does not require regulatory or standardisation changes, it provides technical insights that may support future developments related to IP-based mobility management, service continuity and interoperable air–ground communication services.

The implementation of ATMACA is expected to generate benefits across operational, technical, human-performance and environmental dimensions. These include seamless mobility and continuous air–ground connectivity, improved operational efficiency and safety through enhanced communication continuity, support for trajectory-based and environmentally sustainable operations, interoperability and cost-efficient scalability through its COTS-based architecture, and enhanced human performance through advanced HMIs. Collectively, these capabilities contribute to more resilient, efficient and sustainable ATM operations in line with the European ATM evolution roadmap.

3.2.1 ATMACA solution interdependencies

ATMACA, identified as SESAR Solution 0513, is designed as a modular framework that operates within the broader context of the Future Communication Infrastructure (FCI), Future Connectivity and Digital Infrastructure (FCDI), and System-Wide Information Management (SWIM) environments. While ATMACA is a standalone solution, several interdependencies and complementary relationships have been identified with other SESAR solutions and technological enablers supporting future ATM communication and digital information exchange.

ATMACA builds upon and is designed to be compatible with FCI/FCDI communication solutions, including future satellite communication datalinks, terrestrial datalink technologies such as LDACS, and other ATN/IPS-based communication services. The solution relies on the underlying IP-based connectivity provided by these infrastructures, including technologies such as LDACS, SATCOM and AeroMACS. While FCI/FCDI services primarily provide connectivity, IP reachability and terminal mobility, ATMACA complements these capabilities by providing application-layer mobility, session and context management. In this role, ATMACA functions as a Context Management Application (CMA), maintaining service continuity, flight-session persistence, role-based context management and seamless datalink operations as aircraft transition across heterogeneous communication links, access networks and operational domains.

ATMACA is also designed to be fully interoperable with SWIM-enabled services and infrastructures. The framework can operate alongside SWIM as a middleware layer, using standardised Application Programming Interfaces (APIs) and aviation information exchange models, including FIXM, AIXM and

WXXM, to support the exchange of operational context, flight information and trajectory-related data across ATM stakeholders and global aviation networks.

The solution ensures technical compatibility with relevant FCDI components and emerging IP-based communication environments, including established mobility mechanisms such as Proxy Mobile IPv6 (PMIPv6) and Generalised Border Gateway Locator/Identifier Separation Protocol (GB-LISP). Through this interoperability, ATMACA can operate within future multilink communication environments while preserving communication continuity and operational consistency.

ATMACA also provides strong synergies with Trajectory-Based Operations (TBO) and Green Route Operations (GRO). Through its persistent “flight session” concept, the framework supports high-integrity and real-time exchange of operational information, including aircraft-derived meteorological data, trajectory intent and contextual flight information. These capabilities facilitate advanced trajectory optimisation and decision-support services developed within related SESAR and research initiatives.

Furthermore, the modular architecture of ATMACA aligns with the objectives of the Digital European Sky and the New Service Delivery Model [27]. By separating communication and information-management services from underlying infrastructure components, the solution supports the evolution towards service-oriented ATM environments and facilitates future concepts such as Virtual Centres (VCs) and Dynamic Airspace Configuration (DAC).

ATMACA does not replace existing or planned communication infrastructure solutions. Instead, it acts as an enabling framework operating over current and future communication infrastructures, supporting interoperability between SWIM-enabled services, multilink communication environments and future IP-based aeronautical communication systems. The combined deployment of ATMACA with these complementary SESAR enablers is expected to improve network-wide operational performance by bridging the current **mobility gap**, reducing manual coordination requirements during operational and technical handovers, and enhancing communication continuity across the European ATM network.

At the current stage of development, no mutually exclusive solutions have been identified. Some functionalities of the ATMACA solution may require further alignment with implementation approaches adopted by other SESAR solutions. This is considered a natural consequence of the current maturity of the solution and highlights areas for further harmonisation, interoperability refinement and validation as ATMACA progresses towards higher TRLs.

3.3 Objectives of the ECO-EVAL

The objective of this TRL2 ECO-EVAL is to assess whether ATMACA is a viable solution for deployment across the ECAC region from an economic and operational perspective. The evaluation provides a consolidated assessment of the potential costs and benefits of deploying ATMACA either as (i) a decentralized air–ground communication framework integrated across ATSUs and aircraft fleets, or (ii) a centralized set of communication and trajectory-management services delivered through SWIM and Network Manager (NM) infrastructure to local ATSUs included in the ECO-EVAL solution scenarios (see Section 3.5.2).

The assessment is based on qualitative evidence gathered from the project's validation activities and focuses on identifying high-level impacts across relevant stakeholder groups, including ANSPs, Airspace Users and the Network Manager. It provides an overview of anticipated costs and benefits, outlines their potential contribution to key performance areas such as cost efficiency, safety, human performance and environmental sustainability, and formulates recommendations and next steps for future economic assessments and solution maturation. As a TRL2 evaluation, no quantitative Cost–Benefit Analysis (CBA) is performed.

3.4 Stakeholder identification

This section identifies and describes the stakeholder categories affected by the implementation, operation and expected benefits of the ATMACA solution, together with their deployment locations and associated cost drivers. The stakeholder identification is aligned with the Benefit Impact Mechanisms (BIMs) defined in the OSED and supported by evidence gathered during the project's validation activities.

The ATMACA solution scenario considered in this ECO-EVAL encompasses both local and network-level deployment elements. The solution is expected to be deployed progressively, initially through the implementation of the ATMACA framework within relevant Air Traffic Services Units (ATSUs), Area Control Centres (ACCs), ATC working positions and aircraft fleets, and subsequently through the provision of selected services, such as Green Route Operations (GRO), flight-session management and context-management functions, at network level through SWIM infrastructure and the Network Manager (NM).

Although the stakeholder groups remain broadly the same throughout the deployment process, the nature and distribution of costs and benefits may vary depending on whether impacts arise primarily at local operational level or through network-level service provision. The stakeholder assessment therefore considers both deployment dimensions within a single solution scenario to provide a comprehensive qualitative evaluation of stakeholder-specific cost drivers and expected operational benefits.

Table 3 identifies the primary stakeholder groups involved in the deployment and operation of ATMACA, together with their expected cost drivers, operational benefits and contributions to the ECO-EVAL assessment.

Stakeholder	Deployment locations (or sub-operating environments)	Cost drivers	Benefits in operations	Involvement in the ECO-EVAL analysis
ANSP	En-route and TMA ATSUs/ACC sectors, ATC working positions, and SWIM-connected operational environments.	Acquisition and integration of the ATMACA framework; ATN/IPS adaptation; integration with operational ATM systems and SWIM services; training for	Improved communication continuity and trajectory predictability; reduced ATCO workload and manual coordination; enhanced situational	Operational and technical input from consortium partners (SAERCO, ENAC, ESTU).

Stakeholder	Deployment locations (or sub-operating environments)	Cost drivers	Benefits in operations	Involvement in the ECO-EVAL analysis
		ATCOs and technical personnel.	awareness and operational efficiency.	
Airspace Users (Airlines)	Aircraft fleets, flight decks and airborne communication environments operating within relevant ECAC airspace.	Aircraft-side software adaptation, EFB integration, operational application enablement and associated training activities.	Gate-to-gate service continuity; improved trajectory efficiency resulting in lower fuel consumption and emissions; reduced communication disruptions.	THY contributes as a consortium partner and provides operational feedback through simulations and flight-trial activities.
Network Manager (NM)	NM operational environments, SWIM infrastructure and network-level service platforms.	Integration of GRO, flight-session management and context-management services within network-level service environments; staff familiarisation and service management activities.	Enhanced network predictability, trajectory management, information sharing and network-wide operational efficiency.	Advisory Board review of network-wide deployment assumptions and implementation considerations.
Airport Operators	Airport communication infrastructure and airport-domain connectivity environments (e.g. AeroMACS-enabled areas).	Integration of airport-side communication components and interfaces with relevant ATMACA-enabled services.	Improved resilience, predictability and continuity of airport-related communication and operational processes.	Consulted through operational environment definition activities and the Advisory Board.
Personnel (ATCOs/Pilots)	ATSUs, ACCs, NM-supported operational environments and flight decks.	Initial training, familiarisation and adaptation to ATMACA-enabled services and HMIs.	Reduced manual communication tasks; improved access to operational information; enhanced coordination and decision support during operational transitions.	Active participants in HMI evaluations, operational simulations and flight trials.

Table 3: SESAR solution 0513 ECO-EVAL stakeholders and impacts

3.5 ECO-EVAL scenario and assumptions

This section describes the scenarios considered in the ECO-EVAL. The objective is to assess the delta (differential impact) between the ECO-EVAL reference scenario, in which the ATMACA solution is not deployed, and the ECO-EVAL solution scenario, which represents the potential deployment of ATMACA across ECAC where operationally relevant.

The comparison considers the point in time at which the solution is assumed to be available for deployment and focuses on identifying the impacts resulting from the transition from the reference scenario to the solution scenario. These impacts may include the deployment of new technical systems, integration requirements, training needs, changes in operating costs and expected operational performance benefits. Given the uncertainty associated with future developments in the reference environment, this TRL2 ECO-EVAL also considers the current operational situation as a complementary reference in cases where future operational conditions and deployment assumptions cannot yet be established with sufficient confidence.

ATMACA is an innovative IP-based datalink communication framework operating over ATN/IPS. The solution provides application-layer mobility management, persistent flight-session management, advanced operational applications such as Controller–Pilot Data Link Communications (CPDLC) and Green Route Operations (GRO), and enhanced Human–Machine Interfaces (HMIs) for pilots and Air Traffic Control Officers (ATCOs).

Considering the flexibility and scalability of the ATMACA framework, the ECO-EVAL solution scenario is based on a progressive deployment concept. The solution is expected to evolve from local ATSU/ACC and aircraft-level implementation towards the provision of selected network-level services through SWIM infrastructure and the Network Manager (NM). These deployment stages are treated as complementary elements of a single solution scenario rather than as separate implementation alternatives. This approach enables the assessment to capture a broad range of operational, technical and organisational impacts associated with the deployment and maturation of the ATMACA framework.

On this basis, the ECO-EVAL assesses the potential costs, benefits and stakeholder impacts associated with ATMACA deployment, taking into account both local operational implementation and network-level service provision within a unified deployment framework.

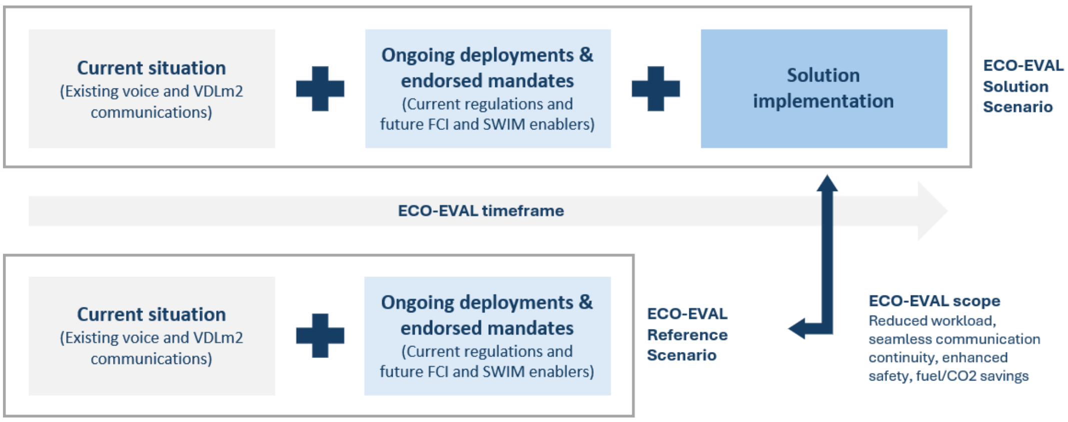

Figure 1: ECO-EVAL scenarios overview

3.5.1 ECO-EVAL reference scenario

The reference scenario represents current and planned ATM operations without the deployment of ATMACA. It is characterised by a mobility gap between the seamless air–ground connectivity, service continuity and mobility-management capabilities required for future ATM operations and the capabilities of existing aeronautical communication infrastructures.

Legacy datalink services, such as CPDLC and ADS-C operating over VDLm2 and other fragmented communication sub-networks, function largely independently. When aircraft transition between control sectors, Air Traffic Services Units (ATSUs) or network coverage areas, communication sessions often need to be manually re-established by flight crews and Air Traffic Control Officers (ATCOs). In addition, flight data transfer and air–ground communication handovers are typically managed as separate processes. This fragmentation results in communication delays, increased tactical workload, reduced operational efficiency and a higher risk of communication gaps or context discontinuities.

From an operational perspective, ATCOs are required to manage traffic flows and coordination activities using communication and information systems that provide limited support for seamless mobility and integrated session management. As a result, additional manual coordination is often required during operational transitions, increasing workload and reducing predictability.

Trajectory management in the reference scenario relies primarily on pre-departure flight planning and meteorological forecasts rather than continuous integration of real-time aircraft-derived information. Although initial flight plans and forecasts are generally accurate, variations in atmospheric conditions, such as wind and temperature, together with changes in network conditions during flight, may lead to growing trajectory prediction errors. These inaccuracies can result in less reliable Estimated Times of Arrival (ETAs), additional tactical interventions by ATCOs, holding patterns, congestion and less efficient flight trajectories.

Overall, the reference scenario is characterised by fragmented communication services, limited mobility-management capabilities and constrained trajectory predictability. These limitations contribute to increased operational workload, reduced efficiency, suboptimal use of airspace capacity, and higher fuel consumption and emissions compared with the capabilities envisaged under the ATMACA solution scenario.

3.5.2 ECO-EVAL solution scenario

The ECO-EVAL solution scenario represents the operational and technical environment resulting from the potential deployment of the ATMACA (Air Traffic Management and Communication over ATN/IPS) solution across the ECAC region. In accordance with the "delta" approach, this section identifies the differential value and systemic changes introduced by ATMACA compared with the reference scenario.

The ATMACA solution scenario is based on a progressive deployment concept. Initially, the ATMACA framework is deployed within relevant Air Traffic Services Units (ATSUs), Area Control Centres (ACCs), ATC working positions and aircraft fleets to provide mobility-enabled datalink communications and persistent flight-session management. As deployment matures, selected capabilities, including Green Route Operations (GRO), flight-session management and context-management services, may be extended to network level through SWIM infrastructure and the Network Manager (NM). These deployment elements are considered complementary components of the same solution scenario and together represent the target operational environment assessed in this ECO-EVAL.

Deployment Components

The implementation of the ATMACA solution involves the deployment of an integrated IP-based communication framework over the ATN/IPS infrastructure. The specific elements to be deployed include:

- *Technical Systems/Infrastructure*: The IP-based ATMACA datalink communication protocol and Data Link Context Management (DLCM) middleware providing application-layer mobility, session and connection management. Depending on the deployment environment, this may also require upgrades to ground communication infrastructure, operational platforms and network interfaces to support ATN/IPS-based services. On the airborne side, implementation may involve the adaptation or upgrade of Electronic Flight Bags (EFB Class 2 or 3), avionics interfaces and onboard communication equipment, with associated avionics certification activities. Supporting operational services, including the management of flight-session identifiers, user identities and configuration data, are also required to ensure secure and continuous service provision.

- *Operational Applications*: Deployment of advanced operational applications, including Controller–Pilot Data Link Communications (CPDLC) and Green Route Operations (GRO), the latter utilising Wind and Temperature Networking (WTN) to support real-time trajectory optimisation. The ATMACA framework is also designed to support the future integration of additional operational applications and digital ATM services through the same communication and mobility-management environment.

- *Human Factors and Procedures*: Introduction of role-based Human–Machine Interfaces (HMIs) for pilots and ATCOs designed to handle high data volumes and improve situational awareness. New operational procedures include automated handovers and the management of persistent flight sessions, integrating communication, operational context and trajectory-related information within a unified framework and reducing the need for manual coordination during operational transitions.

Progressive Deployment Approach

The ATMACA solution scenario is based on a two-stage deployment approach.

Stage 1 – Local ATSU/ACC and Aircraft Deployment: ATMACA capabilities are deployed within relevant ATSUs, ACCs, ATC working positions and aircraft fleets to provide mobility-enabled datalink communications, persistent flight-session management and enhanced operational applications. The specific deployment scale is not predefined at TRL2 and will depend on operational priorities and stakeholder readiness. Stage 1 therefore represents a flexible initial deployment involving one or more operationally relevant stakeholders.

Stage 2 – Network-Level Service Provision: As deployment matures, selected services, including Green Route Operations (GRO), flight-session management and context-management functions, may be extended to network level through SWIM infrastructure and the Network Manager (NM), enabling wider information sharing, trajectory optimisation and network-level coordination.

These stages are complementary elements of a single solution scenario and represent the expected evolution of ATMACA deployment rather than alternative implementation options.

Interdependencies with Other Solutions

ATMACA is identified as SESAR Solution 0513 and is designed to complement, rather than replace, existing digital sky enablers.

- *Future Communication Infrastructure (FCI)*: ATMACA relies on the underlying connectivity provided by FCI technologies, including LDACS, SATCOM and AeroMACS. The solution provides application-layer mobility, session and context management capabilities that ensure communication continuity across heterogeneous communication links.

- *System-Wide Information Management (SWIM)*: The solution is designed to be fully interoperable with SWIM infrastructures and services, enabling the exchange of operational context, flight-session and trajectory information across ATM stakeholders and network domains.

For the purposes of this ECO-EVAL, it is assumed that the relevant FCI and SWIM capabilities are operationally available to support ATMACA deployment.

Geographical Scope and Sub-Operating Environments

The analysis considers an ECAC-level deployment following a gate-to-gate operational philosophy.

The ATMACA solution is primarily intended for operational environments where air–ground datalink communication, mobility management and communication continuity are critical. In particular, the solution is expected to provide the greatest benefits within en-route sectors and Terminal Manoeuvring Areas (TMAs), where aircraft frequently transition between Air Traffic Services Units (ATSUs) and communication domains. In these environments, ATMACA supports seamless handovers, persistent flight-session management and improved communication continuity, reducing the need for manual intervention during operational transitions.

Although the solution is applicable across the ECAC region, deployment is expected to be prioritised in operational contexts where high traffic density, complex communication requirements or multilink environments create a strong need for enhanced mobility management and resilient datalink services. In such environments, the transition from legacy communication systems to an IP-based framework can improve operational efficiency, communication reliability and trajectory predictability while supporting future data-centric ATM operations.

Deployment Environment and Flight Phases

The ATMACA solution is designed to provide gate-to-gate air–ground communication support across all operational domains of the European ATM network. Unlike legacy systems that are often constrained by line-of-sight limitations or regional communication infrastructures, ATMACA's IP-based framework is applicable in:

- *Terminal Manoeuvring Areas (TMAs)*: Supporting high-density arrival and departure operations;

- *En-route Airspace*: Supporting continuous datalink services across multiple ATSU boundaries;

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- *Oceanic and Remote Regions*: Utilising satellite and multilink communication capabilities where terrestrial coverage is limited;
- *Airports*: Supporting ground movements, delivery and taxiing operations.

The solution supports the entire flight lifecycle, including pre-flight and departure, en-route operations, and arrival and approach phases. This ensures that the flight session and its associated operational context remain continuously available throughout the flight.

End Users and Stakeholders

The primary end users of ATMACA are pilots and Air Traffic Control Officers (ATCOs), who interact with the solution through dedicated role-based Human–Machine Interfaces (HMIs). These users directly benefit from enhanced communication continuity, persistent flight-session management and improved access to operational information throughout all phases of flight.

Pilots (Flight Deck Users) utilise the Flight Deck HMI, typically hosted on Class 3 Electronic Flight Bags (EFBs), to manage CPDLC communications and access GRO services.

ATCOs (Tower, Approach and En-route Controllers) utilise ATC HMIs to monitor flight sessions, issue clearances and manage automated handovers between sectors and operational units.

At organisational level, Air Navigation Service Providers (ANSPs), Airspace Users (Airlines) and the Network Manager (NM) are expected to benefit from the deployment of ATMACA through improved operational efficiency, trajectory predictability, communication continuity and network performance.

Operational Concept

ATMACA operates as an application-layer mobility-management framework that unifies air–ground communications over the ATN/IPS infrastructure. The core operational concept is the flight session, which establishes a unique and persistent association between a flight and its communication, trajectory and operational-context information.

The framework operates through the following key functions:

1. *Context-Aware Middleware*: The Data Link Context Management (DLCM) middleware manages the lifecycle of flight sessions and maintains synchronised operational information (e.g., CPDLC logs, flight plans, and meteorological data) across the network.
2. *Persistent Connectivity*: Communication sessions are decoupled from underlying communication links, enabling service continuity during transitions between heterogeneous communication technologies (e.g., VDLm2, SATCOM, LDACS) and operational domains.
3. *Automated Coordination*: Technical handovers and Data Authority Transfers (DATs) are automated, reducing manual intervention and supporting seamless operational transitions.
4. *Operational Applications*: Applications such as CPDLC provide digital text-based communications, while GRO utilises real-time wind and temperature information to optimise flight trajectories dynamically. The framework also supports the integration of future operational applications and digital ATM services.

Scalability

The ATMACA framework is designed as a modular and software-defined architecture that supports progressive deployment and growth across the ECAC region.

Scalability is achieved through dedicated agents, middleware services and distributed server components that can be deployed at facility, area, national or regional levels. The framework supports increasing numbers of aircraft, users and operational services while maintaining interoperability with existing ATM systems.

The deployment model supports progressive evolution from local ATSU/ACC implementations towards network-level service provision through the Network Manager and SWIM infrastructure. Standardised interfaces and APIs also enable the future integration of additional digital services without requiring changes to the core communication protocol.

Flexibility

The ATMACA solution introduces flexibility by decoupling logical communication sessions from physical communication infrastructures and fixed organisational boundaries. This flexibility can be observed across four key dimensions:

1. *Operational Flexibility*: ATMACA facilitates an ATS session-based system that allows Air Traffic Control Officers (ATCOs) to group, aggregate, transfer, replicate, or divide flight sessions and responsibilities dynamically. This enables "Cross-Domain Session Management," where a single ATCO can operate across multiple roles (e.g., Delivery, Ground, and Tower) within a unified interface, maintaining centralised control over aircraft operating in different domains. Furthermore, it supports enhanced mobility for operational staff, allowing them to move within or outside control rooms while maintaining full situational awareness and decision-making capabilities.

2. *Tactical and Handover Flexibility*: With the progression and management of logical "flight sessions," traffic can be transferred between controllers with complete flexibility. ATCos can seamlessly redistribute workload by transferring specific flights to any other authorised controller, regardless of their geographical location or the specific organisation of the airspace (whether sector-based or flight-centric). This capability is critical for dynamic workload reallocation and ensures that geographical constraints no longer limit the operational response to traffic surges or sector complexity.

3. *Architectural and Deployment Flexibility*: The solution is built on a modular, software-defined node architecture. By using software-defined nodes to decouple control functions from hardware, ATMACA can dynamically adjust routing decisions and prioritise critical services based on real-time network conditions. This architectural agility supports the transition toward Virtual Centres (VCs) and Dynamic Airspace Configuration (DAC), allowing the system to scale and adapt to evolving ATM requirements without requiring disruptive hardware reconfiguration. Additionally, the framework supports a progressive deployment model, enabling implementation to evolve from local ATSU/ACC environments towards network-level service provision through SWIM infrastructure and the Network Manager. This allows deployment to be scaled according to operational needs and maturity levels while maintaining interoperability across the ATM network.

4. *Contingency and Resilience Flexibility*: In emergency or contingency scenarios, such as the evacuation of a control centre, ATMACA allows for the immediate transfer of active flight sessions to alternate locations or even portable mobile devices. This ensures uninterrupted service and allows controllers to retain control and situational awareness remotely, significantly enhancing the resilience of the European ATM network.

ECO-EVAL timeline

The ECO-EVAL covers the period from 2026 to 2050 as defined in the common assumptions.

Table 4 lists the key dates used in the ECO-EVAL and Figure 2 shows them over a timeline.

Dates	SESAR Solution 0513 ATMACA
Start of deployment date (SOD): the start of investments for the first deployment location	2030
End of deployment date: the end of the investments for the final deployment location, same as FOC	2033
Initial operating capability (IOC): the time when the first benefits occur following the *minimum deployment* necessary to provide them. Costs continue after this date as further deployment occurs at other locations.	2045
Final operating capability (FOC): maximum benefits from the *full deployment*[2] of the SESAR solution at applicable locations. Investment costs are considered to end[3] here although any operating cost impacts would continue.	2050

Table 4: ECO-EVAL investment and benefit dates

[2] Where ***full deployment*** means deploying the SESAR solution in all the locations where it makes sense to deploy it (i.e. it does not mean it has to be deployed everywhere)

[3] The basic assumption is that infrastructure does not need to be replaced during the ECO-EVAL period.

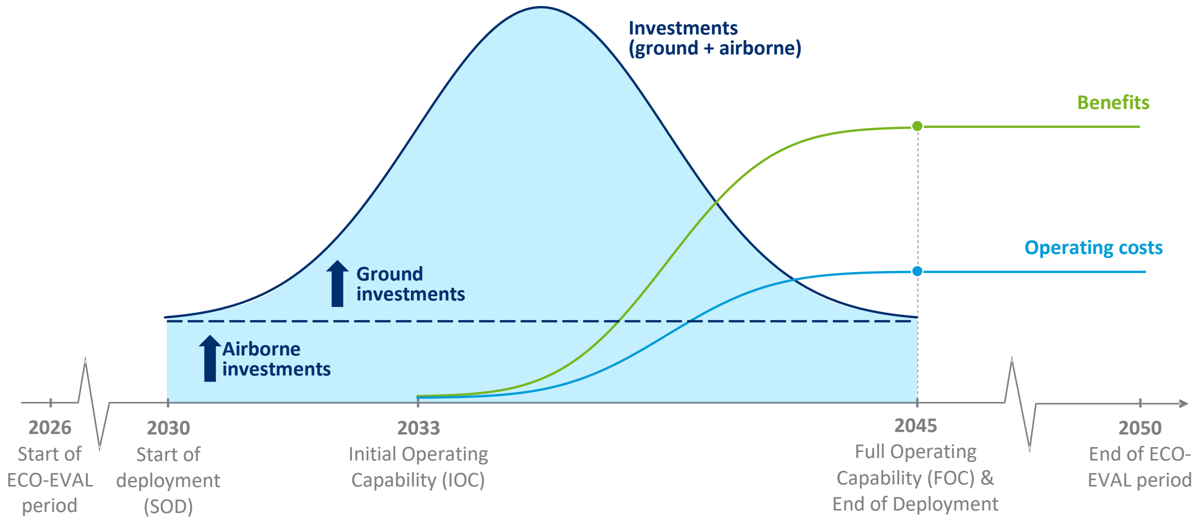

Figure 2: Overview of ECO-EVAL dates

Figure 2 illustrates the assumed deployment profile for the ATMACA solution throughout the ECO-EVAL period.

- **Investment costs** consist of both ground and airborne investments. **Ground investments** mainly consist of ATN/IPS infrastructure adaptation, ATMACA platform deployment, SWIM integration, HMI implementation, system integration and training activities at ATSU/ACC and Network Manager environments. **Airborne investments** include aircraft-side software integration, operational application enablement and associated deployment activities. Ground investments are assumed to follow a bell curve[4] shaped deployment profile between the Start of Deployment (SOD) and Full Operational Capability (FOC), while airborne investments are assumed to be distributed progressively throughout the deployment period. Airborne investment requirements are expected to remain limited compared with ground investments, as ATMACA is designed to operate over existing ATN/IPS-compatible and commercial off-the-shelf communication infrastructures.
- **Benefits** are assumed to materialise progressively following an S-shaped adoption curve[5] between Initial Operational Capability (IOC) and Full Operational Capability (FOC). The main benefits include improved communication continuity, reduced manual coordination and controller workload, enhanced trajectory predictability, increased operational efficiency, and reduced fuel consumption and emissions through Green Route Operations (GRO). Benefits continue to accrue after FOC for the remainder of the ECO-EVAL period.
- **Operating costs** are assumed to begin at IOC and increase progressively following an S-shaped adoption curve until FOC. These costs mainly relate to system operation, maintenance,

[4] The bell curve is based on the diffusion of innovation theory.

[5] The bell curve is based on the diffusion of innovation theory.

technical support, communication services and lifecycle management activities. After FOC, operating costs are assumed to remain relatively stable throughout the remaining evaluation period.

3.5.3 Assumptions

The assumptions presented in this section provide the basis for the qualitative economic assessment of the ATMACA solution at TRL2. They reflect the expected operational, technical and deployment conditions under which the solution may be implemented and evaluated. In accordance with the SESAR Common Assumptions approach, the assumptions presented below are **solution-specific (local) assumptions developed** to address ATMACA-specific characteristics not covered by generic SESAR assumptions. As no quantitative Cost–Benefit Analysis (CBA) is conducted at TRL2, the assumptions are qualitative in nature and intended to support the identification of potential costs, benefits and stakeholder impacts. In particular, they reflect the key features of the ATMACA framework, including mobility management, persistent flight-session management, interoperability with ATN/IPS and SWIM environments, and Green Route Operations (GRO). Given the early maturity level of the solution, these assumptions are primarily qualitative and are intended to support the identification of potential costs, benefits and stakeholder impacts without requiring detailed quantitative estimates. For clarity, the assumptions are grouped into five categories: Operational Assumptions, Deployment Assumptions, Human Performance Assumptions, Green Route Operations (GRO) Assumptions, and Economic Evaluation Assumptions.

<u>Operational Assumptions</u>

- *ATN/IPS Availability Assumption*: ATMACA is deployed in operational environments where ATN/IPS connectivity services are available through existing or future FCI communication technologies (e.g. LDACS, SATCOM and AeroMACS).
- *Multi-link Communication Assumption*: Aircraft are capable of accessing multiple communication links during flight and may transition between communication technologies without loss of service availability.

<u>Deployment Assumptions</u>

- *Incremental Deployment Assumption*: TMACA deployment is assumed to progress from local ATSU/ACC and aircraft-level implementation towards the provision of selected network-level services through SWIM infrastructure and the Network Manager, without requiring simultaneous implementation across all ECAC stakeholders.
- *System Integration Assumption:* Existing ATM systems are assumed to accommodate the integration of ATMACA services without requiring major modifications to core operational systems.
- *SWIM and FCI Availability Assumption*: SWIM services and future FCI/FCDI communication infrastructures are assumed to be available and capable of supporting the interoperability requirements of ATMACA.

Human Performance Assumptions

- *Operational Acceptance Assumption*: ATCOs and flight crews are assumed to effectively use ATMACA-enabled services and HMIs following appropriate training and familiarisation.

Green Route Operations (GRO) Assumptions

- *Meteorological Data Availability Assumption:* Real-time or near-real-time aircraft-derived wind and temperature data are assumed to be available to support GRO services and trajectory optimisation functions. It is further assumed that the acquisition, downlink, processing and access to these data do not introduce significant additional operational costs.

- *Operational Flexibility Assumption:* Sufficient operational flexibility is assumed to exist to allow the implementation of GRO recommendations when operationally feasible.

Economic Evaluation Assumptions

- *Progressive Adoption Assumption:* Adoption of ATMACA services is assumed to increase progressively over time following deployment.

- *Regulatory Evolution Assumption:* The deployment of ATMACA is assumed to take place within the evolution of existing ATM, ATN/IPS, SWIM and FCI frameworks without requiring major new regulatory initiatives.

4 Benefits

The ATMACA solution is expected to improve operational predictability and reduce communication-related complexity through the implementation of the flight-session concept, application-layer mobility management, automated datalink handovers, and Green Route Operations (GRO). These capabilities are designed to support more continuous, resilient and context-aware air–ground communication over the ATN/IPS infrastructure, representing a transition from fragmented legacy communication architectures towards integrated and mobility-enabled ATM operations.

At TRL2, the benefits described in this section are assessed qualitatively based on evidence gathered from protocol simulations, emulations, human-in-the-loop studies and end-to-end validation activities. As no quantitative Cost–Benefit Analysis (CBA) is performed at this stage, the assessment provides an indication of the expected operational and economic value of ATMACA and establishes a foundation for future quantitative evaluations at higher maturity levels.

Based on the Benefit Impact Mechanisms (BIMs) defined in the OSED [2], the ATMACA solution is expected to contribute to the following key operational benefits:

- *Reduced ATCO and Pilot Workload*: Automated datalink handovers, persistent flight-session management and reduced reliance on repeated logon procedures may decrease manual communication and coordination activities for both Air Traffic Control Officers (ATCOs) and pilots.

- *Improved Communication Continuity*: Application-layer mobility management and multilink communication support are expected to maintain service continuity during sector transitions, ATSU handovers and changes between communication technologies, reducing the likelihood of communication interruptions.

- *Enhanced Operational Predictability*: By maintaining persistent flight-session, context and communication information, ATMACA may improve the predictability of datalink operations and support more effective coordination between ATSUs, ACCs, airspace users and network-level stakeholders.

- *Support to Capacity Management and Operational Flexibility*: Reduced communication-related workload and improved handover continuity may facilitate more flexible workload distribution between sectors, operational units and control centres. This may contribute to more efficient use of operational resources, although direct capacity benefits would require validation at higher maturity levels.

- *Improved Trajectory Efficiency through GRO*: The GRO capability may support more accurate trajectory prediction and optimisation through the use of real-time meteorological information, including aircraft-derived wind and temperature data. This may contribute to improved flight efficiency, lower fuel consumption and reduced CO_2 emissions.

- *Improved Safety and Situational Awareness*: More robust and continuous datalink connectivity, combined with enhanced HMIs and persistent operational context information, may improve situational awareness for pilots and ATCOs while reducing the risk of communication gaps during operational transitions.

From an economic perspective, the primary beneficiaries are expected to be Air Navigation Service Providers (ANSPs), airspace users (airlines), airports, and the Network Manager. These stakeholders may benefit from reduced manual coordination, more efficient use of operational resources, enhanced operational predictability, improved trajectory efficiency, potential fuel savings, the digitalisation of air–ground communication through IP-based service provision, and reduced communication-related disruption. Pilots and ATCOs, as the primary operational end users of the ATMACA solution, are expected to benefit primarily from improved human performance, reduced workload and enhanced situational awareness. These operational improvements may, in turn, contribute indirectly to the economic benefits realised by their respective organisations.

4.1 Benefits overview

The BIMs defined in the OSED [2] identifies the expected high-level benefits of the ATMACA solution across several Key Performance Areas (KPAs), including cost efficiency, safety, human performance, operational efficiency, environmental sustainability, digitalisation and security.

The core operational and economic value of ATMACA is derived from its ability to address the existing mobility gap in aeronautical communications through persistent flight-session management, application-layer mobility management, automated datalink handovers, enhanced Human–Machine Interfaces (HMIs) and Green Route Operations (GRO). Together, these capabilities support more continuous, resilient and context-aware air–ground communications over the ATN/IPS infrastructure.

The principal Benefit Impact Mechanisms (BIMs) identified for ATMACA include the reduction of manual coordination activities through automated handovers and simplified communication processes, enhanced communication continuity through persistent flight sessions and context management, improved operational predictability through consistent access to communication and trajectory information, and improved environmental and operational efficiency through the use of real-time meteorological information within GRO services.

From an operational perspective, ATMACA may support Air Navigation Service Providers (ANSPs), Air Traffic Control Officers (ATCOs), pilots, airspace users and the Network Manager through improved datalink service continuity, reduced communication-related workload, enhanced situational awareness and more effective use of operational and trajectory information. Through GRO, the solution may also contribute to improved trajectory efficiency, lower fuel consumption and potential reductions in CO_2 emissions.

Given the TRL2 maturity level of the solution, the benefits presented in this ECO-EVAL are assessed qualitatively based on evidence gathered through simulations, emulations, human-in-the-loop studies and validation activities. As such, they provide an initial basis for understanding the expected operational and economic value of ATMACA and support future quantitative assessments at higher maturity levels.

4.2 Benefit summary

Table 5 summarises the expected benefits of the ATMACA solution, the associated Benefit Impact Mechanisms (BIMs), and their anticipated impacts on relevant KPIs/PIs. It also explains how the solution is expected to generate these benefits and provides a qualitative assessment of their expected impact.

KPI / PI	BIM impact	How the solution provides the benefit and evaluation (low, medium, high impact)
CEF1 – Direct ANS gate-to-gate cost per flight	Reduction in communication-related operational costs	Dynamic flight-session handling, automated handovers and reduced logon procedures decrease communication-related coordination effort and improve operational efficiency. The integrated ATMACA framework may also reduce system complexity and technology-related operating costs. **Medium impact** on cost-efficiency.
CEF2 – Flights per ATCO-Hour on Duty	Improved productivity of ATCO resources	Persistent flight-session management and automated datalink handovers reduce workload associated with communication management and sector transitions. **Medium impact** on cost-efficiency and resource utilisation.
CEF3 – Technology cost per flight	More efficient utilisation of communication infrastructure	ATMACA leverages ATN/IPS, SWIM and future FCI infrastructures through a software-based and interoperable architecture, supporting scalable deployment and improved use of existing assets. **Medium impact** on cost-efficiency.
HP1 – Consistency of human role with respect to human capabilities and limitations	Improved human-system interaction	Automated communication continuity and contextual information management reduce operational complexity and support human-centred decision making. **Medium impact** on human performance.
HP2 – Sustainability of technical systems in supporting human tasks	Improved support to operational personnel	Persistent flight sessions, enhanced HMIs and mobility management provide continuous access to operational information. **High impact** on human performance.

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KPI / PI	BIM impact	How the solution provides the benefit and evaluation (low, medium, high impact)
HP3 – Adequacy of team structure and team communication	Improved coordination between operational actors	Shared communication context and automated information transfer improve coordination between pilots, ATCOs and operational units. **High impact** on human performance.
HP4 – Feasibility with regards to HP-related transition factors	Easier operational transition to digital services	Role-based HMIs and integrated communication processes support the adoption of future digital ATM services while maintaining compatibility with existing voice communication procedures. **Medium impact** on human performance.
DIGI1 – Digitalisation	Increased digital transformation of ATM communications	ATMACA enhances IP-based air–ground communications through application-layer mobility management, persistent flight-session management and mobility-enabled datalink services. **High impact** on digitalisation.
DIGI2 – Connectivity	Enhanced air–ground connectivity	Application-layer mobility management and multilink support maintain connectivity across communication technologies and operational domains. **High impact** on digitalisation.
DIGI3 – Data Sharing	Improved information exchange and interoperability	Flight-session management and SWIM interoperability support consistent sharing of communication, trajectory and context information. **High impact** on digitalisation.
TEFF1 – Gate-to-gate flight time	Improved trajectory efficiency	GRO uses real-time meteorological information to support trajectory optimisation and reduce inefficiencies during flight. **Medium impact** on operational efficiency.
PRD1 – Average difference between actual and planned flight duration	Improved predictability	Real-time trajectory updates and persistent operational context improve trajectory prediction accuracy. **Medium impact** on predictability.
PRD2 – Variance of difference between actual and planned flight duration	Reduced variability in operations	Enhanced trajectory management and continuous information sharing reduce uncertainty during flight execution. **Medium impact** on predictability.
ENV1 – Average CO_2 Emissions per Flight	Reduced average CO_2 emissions per flight through improved trajectory efficiency	Green Route Operations (GRO) utilise real-time aircraft-derived wind and temperature information to support more fuel-efficient trajectories. Reduced flight time and fuel burn directly contribute to lower CO_2 emissions. Validation studies indicated potential reductions of

KPI / PI	BIM impact	How the solution provides the benefit and evaluation (low, medium, high impact)
		approximately 830–1,180 kg CO_2 per flight under representative operational conditions. **High impact** on environmental sustainability.
FEFF1 – Actual average fuel burnt per flight	Reduced fuel consumption	GRO supports more efficient trajectories through the use of aircraft-derived wind and temperature information. **High impact** on fuel efficiency.
SAF1 – Total number of estimated accidents with ATM contribution	Improved operational safety and situational awareness	Continuous communication availability, persistent flight sessions and enhanced HMIs reduce the likelihood of communication-related errors and information loss. **Medium impact** on safety.

Table 5: Solution performance benefits

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4.3 Direct ANS Gate-to-Gate Cost per Flight (CEF1)

Impact: Reduced direct ANS cost per flight through more efficient communication, coordination and technology utilisation.

Expected impact level: Medium

Description: Dynamic flight-session handling, automated handovers and reduced logon procedures decrease communication-related coordination effort and improve operational efficiency. The integrated ATMACA framework may also reduce system complexity and technology-related operating costs by consolidating communication, mobility and context-management functions within a common architecture.

Applicability: This benefit and the corresponding description are valid for the ECO-EVAL solution.

4.4 Flights per ATCO Hour on Duty (CEF2)

Impact: Improved productivity of ATCO resources through reduced communication-related workload.

Expected impact level: Medium

Description: Automated datalink handovers, persistent flight-session management and reduced manual coordination requirements improve controller productivity and support more efficient traffic management during operational transitions.

Applicability: This benefit and the corresponding description are valid for the ECO-EVAL solution scenario.

4.5 Technology Cost per Flight (CEF3)

Impact: Improved cost-efficiency through more effective utilisation of communication infrastructure and digital services.

Expected impact level: Medium

Description: The modular and interoperable ATMACA architecture supports efficient utilisation of ATN/IPS, SWIM and future FCI infrastructures, reducing duplication of communication and mobility-management functions and supporting scalable deployment.

Applicability: This benefit and the corresponding description are valid for the ECO-EVAL solution scenario.

4.6 Consistency of Human Role with Respect to Human Capabilities and Limitations (HP1)

Impact: Improved alignment between operational tasks and human capabilities.

Expected impact level: Medium

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Description: Role-based HMIs, automated communication management and persistent operational context reduce operational complexity and support more intuitive interaction with ATM systems.

Applicability: This benefit and the corresponding description are valid for the ECO-EVAL solution scenario.

4.7 Sustainability of Technical Systems in Supporting Human Tasks (HP2)

Impact: Improved support for pilots and ATCOs during operational activities.

Expected impact level: High

Description: Continuous access to communication history, flight-session information and contextual data supports operational decision-making and reduces the likelihood of information loss during operational transitions.

Applicability: This benefit and the corresponding description are valid for the ECO-EVAL solution scenario.

4.8 Adequacy of Team Structure and Team Communication (HP3)

Impact: Improved coordination and communication between operational actors.

Expected impact level: High

Description: Persistent flight sessions and shared operational context improve information exchange and coordination between pilots, ATCOs and operational units.

Applicability: This benefit and the corresponding description are valid for the ECO-EVAL solution scenario.

4.9 Feasibility with Regards to Human Performance Transition Factors (HP4)

Impact: Improved transition towards digital and data-centric ATM operations.

Expected impact level: Medium

Description: Enhanced HMIs and integrated communication workflows facilitate user acceptance and support adaptation to future ATM operational concepts.

Applicability: This benefit and the corresponding description are valid for the ECO-EVAL solution scenario.

4.10 Digitalisation (DIGI1)

Impact: Increased digitalisation of ATM communications and operations.

Expected impact level: High

Description: ATMACA introduces mobility-enabled IP-based communications over ATN/IPS and supports the transition towards integrated digital ATM environments.

Applicability: This benefit and the corresponding description are valid for the ECO-EVAL solution scenario.

4.11 Connectivity (DIGI2)

Impact: Improved air–ground communication connectivity and service continuity.

Expected impact level: High

Description: Application-layer mobility management and multilink communication support maintain connectivity across heterogeneous communication technologies and operational domains.

Applicability: This benefit and the corresponding description are valid for the ECO-EVAL solution scenario.

4.12 Data Sharing (DIGI3)

Impact: Enhanced interoperability and information sharing between ATM stakeholders.

Expected impact level: High

Description: Persistent flight-session management and SWIM interoperability support consistent exchange of communication, trajectory and contextual information across ATM stakeholders.

Applicability: This benefit and the corresponding description are valid for the ECO-EVAL solution scenario.

4.13 Gate-to-Gate Flight Time (TEFF1)

Impact: Improved operational efficiency through more efficient flight trajectories.

Expected impact level: Medium

Description: Green Route Operations (GRO) utilise real-time meteorological information to improve trajectory optimisation and reduce operational inefficiencies during flight.

Applicability: This benefit and the corresponding description are valid for the ECO-EVAL solution scenario.

4.14 Average Difference Between Actual and Planned Flight Duration (PRD1)

Impact: Improved trajectory predictability and ETA accuracy.

Expected impact level: Medium

Description: Continuous integration of operational context and real-time meteorological information improves trajectory prediction accuracy and supports more reliable Estimated Times of Arrival (ETAs).

Applicability: This benefit and the corresponding description are valid for the ECO-EVAL solution scenario.

4.15 Variance of Difference Between Actual and Planned Flight Duration (PRD2)

Impact: Reduced variability and uncertainty in flight operations.

Expected impact level: Medium

Description: Improved trajectory management and access to real-time environmental information reduce uncertainty and variability in flight execution.

Applicability: This benefit and the corresponding description are valid for the ECO-EVAL solution scenario.

4.16 Average CO_2 Emissions per Flight (ENV1)

Impact: Reduced average CO_2 emissions per flight through improved trajectory efficiency.

Expected impact level: High

Description: Green Route Operations (GRO) utilise aircraft-derived wind and temperature information together with trajectory optimisation algorithms to identify more efficient flight paths. By reducing unnecessary flight time and fuel consumption, the solution contributes directly to lower CO_2 emissions. Validation studies performed within the project demonstrated that GRO-enabled trajectories can reduce fuel burn and may achieve estimated CO_2 emission reductions of approximately 830–1,180 kg per flight under representative operational conditions.

Applicability: This benefit and the corresponding description are valid for the ECO-EVAL solution scenario.

4.17 Actual Average Fuel Burnt per Flight (FEFF1)

Impact: Reduced fuel consumption through trajectory optimisation.

Expected impact level: High

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Description: GRO supports more efficient trajectory planning using aircraft-derived wind and temperature information, reducing unnecessary fuel burn.

Applicability: This benefit and the corresponding description are valid for the ECO-EVAL solution scenario.

4.18 Safety (SAF1)

Impact: Improved operational safety and situational awareness.

Expected impact level: Medium

Description: Persistent flight sessions, automated handovers, enhanced HMIs and continuous communication availability improve situational awareness and reduce the likelihood of communication-related errors.

Applicability: This benefit and the corresponding description are valid for the ECO-EVAL solution scenario. The expected impact level is based on the available validation evidence and reflects the current maturity of the solution, with no major unforeseen impacts identified at TRL2.

5 Cost assessment

This chapter describes the high-level costs associated with the deployment and operation of the ATMACA solution. In accordance with the TRL2 maturity level, this assessment focuses on the qualitative identification of cost drivers rather than on a quantitative financial analysis. The objective is to identify the additional investments and operating costs required to transition from the reference scenario to the ATMACA solution scenario.

The ATMACA solution scenario is based on a progressive deployment approach, evolving from local ATSU/ACC and aircraft-level implementation towards the provision of selected network-level services through SWIM infrastructure and the Network Manager (NM). Consequently, the identified cost drivers reflect both local deployment requirements and potential network-level service integration activities.

The costs presented in this chapter are organised according to the stakeholder groups involved in the deployment, operation and governance of the ATMACA solution.

Stakeholder	Cost category	Yes/No	Cost driver	Deployment locations (or sub-operating environments)
ANSPs	Investment cost	Yes	Acquisition and integration of the ATMACA framework; supporting hardware and ATM system upgrades; implementation of mobility and session-management capabilities; certification activities where required; and staff training.	En-route and TMA ATSUs/ACCs; Controller Working Positions (CWPs).
	Operating cost	Yes	Recurrent training; software maintenance and updates; interoperability management and operational support activities.	
Airport Operators	Investment cost	Yes	Integration of airport-side communication infrastructure and supporting systems with ATMACA-enabled	Airport communication domains and associated operational systems.

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Stakeholder	Cost category	Yes/No	Cost driver	Deployment locations (or sub-operating environments)
			services where operationally relevant.	
	Operating cost	Yes	Maintenance of communication interfaces and supporting operational services.	
Network Manager	Investment cost	Yes	Integration of GRO, flight-session management and context-management services into network-level operational environments; staff training and service deployment activities.	Network Manager Operations Centre (NMOC)
	Operating cost	Yes	Maintenance and operation of network-level services; recurrent training and service management activities.	
Airspace Users (Airlines)	Investment cost	Yes	Upgrade or adaptation of EFBs, avionics software and airborne applications supporting ATMACA services and mobility-enabled datalink operations.	Aircraft fleets and operational environments.
	Operating cost	Yes	Limited direct operating cost changes identified at TRL2; operating impacts are expected to be largely offset by operational efficiency gains.	
Personnel (ATCOs/Pilots)	Investment cost	Yes	Initial training, familiarisation and transition activities associated with new HMIs, operational procedures and	ATSUs, ACCs and flight decks.

Stakeholder	Cost category	Yes/No	Cost driver	Deployment locations (or sub-operating environments)
			ATMACA-enabled services.	
	Operating cost	Yes	Recurrent training and competency maintenance activities.	

Table 6: Identification of solution's cost drivers and deployment locations

5.1 ANSPs costs

Air Navigation Service Providers (ANSPs) are expected to incur the most significant ground-based costs associated with the deployment and operation of the ATMACA framework.

<u>**Investment Cost Drivers**</u>

- Acquisition and integration of the ATMACA framework, including DLCM, mobility-management and flight-session management capabilities.
- Adaptation of existing ATM systems and operational platforms to support ATN/IPS-based communication services.
- Implementation of enhanced HMIs and supporting operational applications.
- Initial training for ATCOs, engineers and technical personnel.

<u>**Operating Cost Drivers**</u>

- Recurrent training and competency maintenance activities.
- Software maintenance, updates and technical support.
- Interoperability management and configuration control activities.
- Operational support required to maintain service availability and system compatibility.

5.2 Airport operators costs

Although airport operators are not primary users of the ATMACA framework, they may incur costs associated with supporting gate-to-gate communication continuity.

<u>**Investment Cost Drivers**</u>

- Integration of airport-side communication infrastructure and operational systems with ATMACA-enabled services where operationally relevant.
- Adaptation of supporting communication interfaces for airport-surface operations.

Operating Cost Drivers

- Maintenance of airport-side communication interfaces.
- Technical support and operational monitoring activities.
- Management of airport communication service integration.

5.3 Network manager costs

As deployment evolves towards network-level service provision, the Network Manager may incur costs associated with supporting selected ATMACA services at European network level.

Investment Cost Drivers

- Deployment of supporting hardware for Context Management (CM) and network-level service provision.
- Integration of GRO, flight-session management and context-management services into NM operational environments.
- Integration with SWIM-enabled service infrastructures.
- Software development, system integration and service deployment activities.
- Initial training for operational and technical personnel.

Operating Cost Drivers

- Operation and maintenance of supporting hardware and network-level service infrastructure.
- Maintenance and operation of network-level services.
- Service monitoring and operational support.
- Recurrent training activities.
- Coordination of deployment and service evolution across the European ATM network.

5.4 Airspace user costs

Airspace users (airlines) are expected to incur costs associated with the airborne implementation of ATMACA services.

Investment Cost Drivers

- Upgrade or adaptation of EFBs, avionics software and airborne applications.
- Integration of ATMACA communication, mobility-management and operational application functions.

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- Validation and deployment activities for airborne systems.

Operating Cost Drivers

- No significant additional operating costs have been identified at TRL2.
- Operational efficiency improvements may offset part of the recurring operational expenditure associated with deployment.

5.5 Military costs

No representative military-specific cost drivers have been identified at the current TRL2 maturity level. This aspect may be revisited as the solution matures and potential civil–military interoperability and integration requirements are further assessed.

5.6 U-space stakeholder costs

No representative U-space-specific cost drivers have been identified at the current TRL2 maturity level. This aspect may be revisited as the solution matures and potential integration with U-space services is further assessed.

5.7 Other relevant stakeholders

Since **ATCOs and pilots** are the primary operational end users of the ATMACA solution, they are considered a key stakeholder group in this ECO-EVAL. Successful deployment will depend not only on the technical implementation of the solution but also on the effective adoption of new communication concepts, operational procedures and Human–Machine Interfaces (HMIs) by operational personnel. Consequently, Air Navigation Service Providers (ANSPs) and airspace users (airlines) are expected to support organisational change through appropriate training, familiarisation and competency development activities that facilitate user acceptance and operational transition. In addition to initial training, recurrent training, competency maintenance and periodic updates associated with procedural or system enhancements may be required to ensure sustained operational proficiency and effective utilisation of ATMACA capabilities throughout the operational lifecycle of the solution.

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6 CBA model

Not applicable at TRL2.

7 CBA results

Not applicable at TRL2.

8 Sensitivity and risk analysis

Not applicable at TRL2.

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9 Recommendations and next steps

This TRL2 ECO-EVAL assessed the potential economic and operational impacts of the ATMACA solution, an IP-based air–ground communication and mobility-management framework operating over ATN/IPS. The qualitative assessment indicates positive impacts across several Key Performance Areas (KPAs), particularly in communication continuity, operational predictability, human performance, environmental sustainability, digitalisation and safety.

The results suggest that ATMACA has the potential to improve communication continuity through persistent flight-session management and application-layer mobility management, reduce manual coordination requirements through automated datalink handovers, and enhance trajectory efficiency through Green Route Operations (GRO). The solution also supports the transition towards a more integrated and data-centric ATM environment through interoperability with ATN/IPS, SWIM and future communication infrastructures.

The findings presented in this ECO-EVAL are supported by evidence gathered through simulations, emulations, human-in-the-loop activities and end-to-end validation exercises. Overall, the results provide a moderate-to-high level of confidence in the technical feasibility and operational relevance of the ATMACA concept while recognising that further quantitative assessment and higher-maturity validation activities are required.

Based on the results of this qualitative assessment and the supporting validation activities, the following recommendations are proposed to support both the further development of the ATMACA solution and the refinement of future economic and performance assessments.

Recommendations for Future ECO-EVAL Activities

- *Quantitative Assessment Refinement*: Future work should focus on collecting quantitative operational, environmental and economic data to support the refinement of Benefit Impact Mechanisms (BIMs), deployment assumptions, stakeholder inputs and future Cost–Benefit Analysis (CBA) activities.

- *Refinement of Assessment Inputs:* Future assessments should continue improving scenario descriptions, deployment assumptions, stakeholder consultation and performance indicators to increase the robustness and confidence of future ECO-EVAL and CBA activities.

Recommendations for Future R&I Activities

- *Human–Machine Interface and Operational Procedure Refinement*: Further development should improve pilot and ATCO interaction models, enhance situational awareness and ensure that ATMACA-supported procedures remain efficient and usable under different operational conditions.

- *Scalability and Operational Robustness Assessment*: Additional validation should be conducted in larger-scale and more realistic ATM environments to demonstrate the scalability, resilience and operational robustness of the ATMACA framework under higher traffic loads and diverse communication conditions.

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- *Protocol and Service Expansion*: Future research should further mature the ATMACA protocol and mobility-management capabilities while enabling the integration of additional SWIM-enabled services and future ATM applications.

- *Voice and Data Communication Integration*: Further studies should assess how voice and datalink communications can be used in a complementary manner, particularly in time-critical, contingency or highly dynamic operational situations.

- *Deployment Planning and Stakeholder Engagement*: Future activities should refine deployment strategies, assess progressive implementation pathways and strengthen stakeholder engagement to support operational acceptance, interoperability and future deployment planning.

Next Steps

The following next steps are derived from the findings of this qualitative ECO-EVAL and are intended to support the continued maturation, validation and deployment planning of the ATMACA solution:

- *Progression Towards Higher Maturity Levels*: The ATMACA concept should continue its maturation through prototype development, larger-scale demonstrations and additional flight-trial activities to increase confidence in its operational and technical performance.

- *Refinement of Economic Assessment Inputs*: Future work should improve the quality of the inputs required for quantitative economic evaluation, including deployment assumptions, operational performance indicators, stakeholder impacts, cost drivers and benefit estimates.

- *Regulatory and Standardisation Alignment*: The project should continue aligning its technical and operational specifications with evolving ICAO, EUROCAE, EASA and SESAR frameworks to support future interoperability, certification and standardisation activities.

- *Integration with Future ATM Enablers*: Further research should investigate the integration of ATMACA with FCI, SWIM, Network Manager services and other Digital European Sky initiatives to maximise interoperability and operational benefits.

- *Alignment with the New Service Delivery Model*: Future research and validation activities should further assess the contribution of ATMACA to the **New Service Delivery Model** (SDO 8) and the Digital European Sky vision [27]. Particular attention should be given to the role of ATMACA in supporting modular and software-defined service architectures, the unbundling of ATM data services from physical infrastructure, interoperability with SWIM-enabled environments, and the provision of location-independent ATM services. Additional work should also evaluate how ATMACA can support emerging concepts such as Virtual Centres (VCs), Dynamic Airspace Configuration (DAC), service-oriented ATM architectures and future multi-vendor digital ecosystems. This will help clarify the long-term deployment potential of ATMACA within future European ATM service delivery models.

- *Progressive Deployment Assessment*: Future studies should assess realistic deployment pathways, starting from local ATSU/ACC and aircraft-level implementations and progressively expanding towards network-level service provision through SWIM and the Network Manager.

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- *Deployment Decision*: While the current TRL2 ECO-EVAL supports the continued development and validation of the ATMACA concept, additional quantitative evidence, large-scale demonstrations and higher-TRL validation activities are required before a full deployment decision can be supported.

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10.1 Applicable documents

SESAR solution pack

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Content integration

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Appendix A Maturity criteria (self-assessment)

In accordance with the Maturity Assessment Criteria for TRL2 defined in the SESAR 3 Joint Undertaking Multiannual Work Programme 2022–2031 [26], the ECO-EVAL self-assessment of the ATMACA ATM solution is presented in Table 7.

TRL2 Assessment Criterion	Criterion Compliance	Reference Section(s)	Assessment Comments
Scope of the solution	YES	Sections 3.5.1 and 3.5.2	Reference and solution scenarios, operational scope and deployment context are defined.
Interdependencies with other solutions	YES	Section 3.5.2 – Interdependencies with Other Solutions	Interoperability with ATN/IPS, SWIM and FCI is described.
Implementation/deployment options	YES	Sections 3.5 and 3.5.2	Progressive deployment approach from local to network-level implementation is described.
Identification of the impacted stakeholders	YES	Section 3.4	Key stakeholders, impacts, cost drivers and benefits are identified.
Qualitative description of the benefits, in line with the BIMs in the OSED (TRL2), including the most impacted KPAs and KPIs	YES	Chapter 4	Benefits are qualitatively assessed and linked to BIMs, KPAs and KPIs.
Identification of cost drivers	YES	Chapter 5	Stakeholder-specific investment and operating cost drivers are identified.
Recommendations and next steps	YES	Chapter 9	Recommendations and future activities for solution maturation are provided.

Table 7: ATMACA ECO-EVAL Self-Assessment Against the TRL2 Maturity Assessment Criteria

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