HUCAN: Towards Certification-Aware Design For Advanced Automation Solutions

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***Abstract*—This paper presents the outcome of research carried out in the SESAR Joint Undertaking's HUCAN project, which aims to develop a holistic, unified certification framework for highly automated systems, to ensure their safe and efficient integration into air traffic management. Based on an analysis of current and innovative certification approaches, the project developed two solutions: 1) a structured, iterative methodology that facilitates certification alignment and validation of advanced automation; 2) preliminary guidelines, which, based on a gap analysis between EASA AI guidance for Level 1 and 2 Machine Learning (ML) applications and the SESAR Project Handbook, offer directions for addressing these gaps along the research pipeline. The approach proposed by these solutions offers significant benefits by promoting an early and proactive alignment of design strategies with certification objectives, thereby mitigating late-stage risks and fostering a more efficient and predictable path to deployment for these innovative systems.**

Keywords- advanced automation; artificial intelligence; certification objectives; certification approach; key performance areas; technology readiness levels; civil aviation; harmonised approach

I. INTRODUCTION

As highlighted by the SESAR Masterplan 2025 (MP25) [1], the integration of advanced automation (AA) and artificial intelligence (AI) into the Air Traffic Management (ATM) environment is expected to fundamentally reshape the aviation domain, offering significant enhancements in safety, capacity and efficiency of operations. AI-based systems, particularly those leveraging machine learning (ML) algorithms, can analyse vast datasets from sources like radar and weather sensors to provide real-time decision support. This enables the dynamic optimization of air traffic flow, ultimately reducing human workload. This technological evolution moves beyond simple task automation to systems that can perform complex cognitive functions previously thought to be exclusive to humans, marking a true paradigm shift. The expected impact is so high that one of the key transformation levers for achieving the MP2025 objectives focus exactly on increased automation.

While EASA provided initial guidance for certifying these novel solutions [2] (and its anticipated updates), the Research and Innovation (R&I) community faces the primary challenge of implementing these evolving requirements, ensuring that solution designs are progressively aligned with stepwise certification objectives, thereby accelerating the market adoption of research outcomes. In this context, the technological shift exposes a different tension: the need to reconcile the fluid, iterative nature of engineering development with the rigid temporal checkpoints imposed by conventional certification regimes. As demonstrated by several SESAR projects engaging with the EASA AI Roadmap 2.0 [3], addressing this tension requires a paradigm in which compliance is not a static end state but a continuously managed process, where design choices and regulatory expectations co-evolve throughout the entire development lifecycle.

To drive this transition and contribute to the development of new tools that support R&I initiatives in meeting these emerging requirements, the HUCAN (Holistic Unified Certification Approach for Novel systems based on advanced automation) project has developed two solutions designed to embed a certification mindset into the design of highly automated systems. The present paper presents these solutions, focusing on their theoretical foundations and expected usage as well as on the results of the validation activities carried out with stakeholders and on some possible way forwards.

II. PROBLEM STATEMENT

The introduction of highly automated and AI-powered solutions is widely recognized as a key enabler for innovation and operational efficiency across the global aviation sector. The industry is actively working to leverage the benefits of this digital transformation [3], underscoring the profound impact of AI across multiple operational and non-operational domains. However, the successful integration necessitates the rapid development of novel and robust standards and certification conditions to ensure that the AI-driven solutions maintain the highest levels of safety and operational performance. Historically certification relied on a prescriptive regulatory approach, which mandates strict compliance with detailed implementation requirements. Now, this conventional method emerges as insufficient for highly automated and ML-based AI systems [5] [6]. This inadequacy stems from the fact that it relies on the verification of deterministic rule-based systems, while AI models are inherently data-driven, exhibit opacity, and may operate as non-deterministic systems, thereby preventing the conventional auditing of detailed implementation steps. Systems of this nature characterized by varying levels of autonomy and

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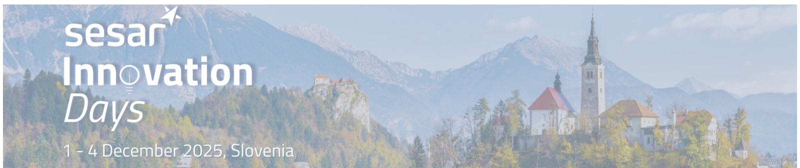


often diverging from traditional software development paradigms, raise significant concerns about the suitability of existing regulatory frameworks.

. The analysis of innovative certification approaches [7] has highlighted several key themes that have emerged as central to the evolution of aviation safety. A significant finding is that certification must transition from a singular static compliance event to a continuous, lifecycle-centric process. This dynamic approach is necessary to accommodate the inherent variability of AI systems, mandating a framework that scales with the specific level of automation and ensures holistic governance by integrating the interests of diverse operational stakeholders, from Air Traffic Control (ATC) to maintenance personnel.

The research also revealed the importance of addressing multiple KPAs, which extend beyond the technical-functional aspects of the AI system to encompass human factors for understanding uncertainty and safety & security risks in sociotechnical systems with diverse levels of automation, the impact on accountability in design and operations, assuring public oversight and collaboration with diverse stakeholders, the incorporation of sustainability criteria for societal and environmental impacts, and data governance policies as part of certification [7], [8] and [9]. This holistic view is essential for developing a framework that is both technically sound and socially robust.

These findings demonstrate the necessity of a comprehensive certification approach that extends beyond purely technical considerations. A core tenet of this strategy is the proactive integration of compliance objectives and requirements from the initial design phases (often termed “Certification by Design”). This proactive integration is crucial, as attempting to apply certification rules late in the development cycle can lead to costly and time-consuming redesigns and, in the worst case, even the outright failure of a project to achieve certification. Implementing this approach requires an iterative and interdisciplinary process, necessitating the active participation of multiple stakeholders and the coordination of various areas of expertise. For instance, this involves not only engineers and AI developers, but also regulators to interpret and apply new guidelines, human factors specialists to assess the impact on air traffic controllers and pilots, and operational experts to ensure the solution is both practically usable and seamlessly integrated into existing workflows.

Despite these recognized requirements, to date, no standardized method exists to systematically harmonize certification objectives with the progressive development of AI solutions. This lack of a structured approach can result in limited awareness of the certification burdens associated with higher levels of automation enabled by AI and increases the risk that misalignments may arise. Such misalignments could ultimately necessitate revisiting design and development choices that, if properly aligned with certification requirements from the outset, could have been addressed proactively.

To illustrate, a solution at an early stage might prioritise foundational aspects such as data integrity and model explainability. However, in the absence of a structured development and compliance roadmap, there is no formal mechanism to ensure that later development stages adequately consider requirements for robustness, operational performance across diverse scenarios, and safe degradation. Consequently, the absence of a stepwise approach risks leaving gaps that could compromise certification readiness or require retroactive design modifications.

Against this background, the HUCAN project has developed a certification-aware design approach and a set of preliminary operative guidelines to support the application of certification-aware design in R&D projects on AI and advanced automation in aviation. This commitment produced two SESAR solutions:

- SOL.0445 – New holistic certification approach for novel ATM related systems based on higher levels of automation, that iteratively incorporates strategic AI certification objectives and requirements, onwards from the early development cycles of ATM systems based on higher levels of automation.
- SOL.0446 – Preliminary Guidelines to design ATM-related systems based on higher levels of automation, a set of operative recommendations to integrate and meet the guidance and objectives prescribed for AI into the SESAR validation frameworks.

This contribution is in line with the approach and methodologies provided by SESAR 3 JU Project Handbook (SESAR, 2024) and the guidance defined by the SESAR ATM Masterplan 2025 (SESAR, 2025).

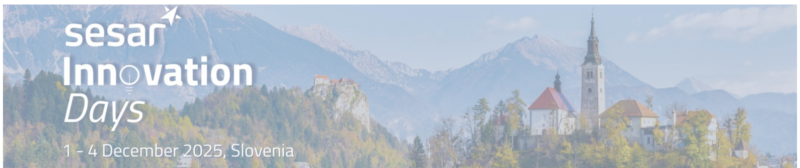
III. CERTIFICATION-AWARE DESIGN APPROACH

Driven by the need for a comprehensive certification approach that goes beyond purely technical considerations, the HUCAN project has initiated the development of a novel framework. The targeted scope is human-centred ATM sociotechnical systems at various levels of automation. This automation includes, though is not restricted to, AI-based systems. This section outlines the motivation and scope for this development, describes the elements of the HUCAN holistic framework, and explains the benefits. For more detail the reader is referred to [9].

A. *Certification-aware system design as target*

To address the need for effective validation and feedback in the iterative design of sociotechnical systems with high levels of automation (LOAs), the HUCAN holistic framework aims to provide dedicated support. By providing effective feedback to the design, the sociotechnical system is matured, and its performance is improved, with as target its future certification. As such, the framework supports the development of a certification-aware system design.

The areas in which the system needs to perform well to achieve its overall goals towards certification are referred to as KPAs. For sociotechnical systems with advanced automation, the role of the human operator changes, which means that areas such as liability, accountability, and ethics become more



important considerations. The HUCAN framework, being holistic, therefore covers a wide range of KPAs: Human factors, Accountability, Responsibility, Liability, Safety, Resilience, Security, Environmental sustainability, Societal sustainability, and Efficiency. In addition, certification objectives such as those in EASA's AI guidelines [2] are systematically addressed.

The maturity of the design is determined in terms of Technology Readiness Levels (TRL), which describe the maturity of the technology, and Human Readiness Levels (HRL) [10], which describe the readiness of a technology for use by the intended human users.

B. *HUCAN holistic framework for certification-aware design*

At a high level, the HUCAN holistic framework follows a cyclic approach as shown in Fig. 1. Input is a system design at a low level of maturity, which is guided through the HUCAN holistic cycle multiple times, towards a more mature design that increasingly fulfils KPAs and certification objectives.

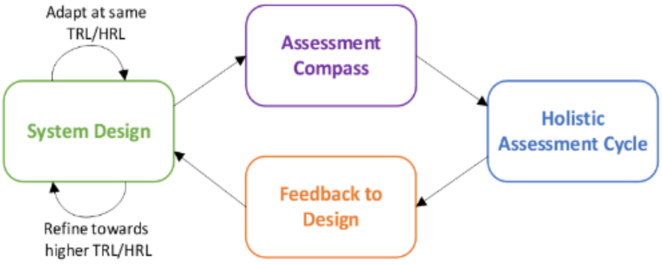


Figure 1. HUCAN holistic framework for certification-aware design

In this figure, System Design is the start- and endpoint of the cycle. At the start-point, it provides the input design for the assessment; at the endpoint, it provides the adapted/refined design that uses the feedback from the assessment, aiming at higher levels of maturity. The Assessment Compass sets the scene for the holistic assessment of the design by determining LOAs, TRLs/HRLs, KPAs, and certification objectives. The Holistic Assessment Cycle is the core of the framework by assessing multiple KPAs for critical scenarios of the sociotechnical system with (AI-based) advanced automation. It is described in more detail below. Finally, the Feedback to Design step identifies, based on the combined KPA results from the holistic assessment cycle, issues in the current design or it identifies/refines requirements or assurance levels towards a more mature design.

C. *Holistic Assessment Cycle*

The holistic assessment cycle supports assessment of multiple KPAs for critical scenarios of the sociotechnical system with automation using a HUCAN Toolbox of methods. It encompasses 7 steps:

<u>1. Identify objectives, scope, criteria</u>: In coordination with relevant stakeholders and proportional to the TRL/HRL and LOA of the sociotechnical system, step 1 defines the KPAs and certification objectives to be considered; the boundaries of the operational area and the types of functions or the types of equipment/procedures/people that are in the scope; and performance criteria for the KPAs, which specify the difference between acceptable and unacceptable performance.

<u>2. Describe sociotechnical system</u>: This step describes the objective of the operation, the operational context, environmental conditions, the functioning and interface of the advanced automation and of other technical systems, the roles, tasks and responsibilities of human operators and their interaction with all relevant AI-based and other technical systems. It also explicitly includes assumptions and constraints in the description of the sociotechnical system. This serves as an agreed, documented basis for the KPA assessments.

<u>3. Identify varying conditions</u>: Step 3 is to identify all kinds of disturbances and performance variability that can influence operations of the sociotechnical system. These can include frequently occurring conditions, like normal sensor errors, normal transmission delays, typical reaction times of human operators, differences in interpretations by humans, normal weather variability. But they also include rarer conditions, like system failures, extreme weather, particular errors by human operators.

<u>4. Construct critical scenarios</u>: Step 4 aims to construct scenarios that represent a critical impact on a KPA, e.g. a scenario leading to reduced safety, a scenario leading to an environmental problem, a scenario leading to a liability issue, etc. The critical scenarios are expanded by describing how agents of the sociotechnical system and related varying conditions may contribute to the KPA-critical effect.

<u>5. Assess KPAs</u>: Step 5 aims to evaluate the constructed critical scenarios to get an assessment of the KPAs and associated criteria. For example, a quantitative assessment of safety or security risks, or a qualitative assessment of responsibility and liability issues. The step can be supported by a variety of methods and tools from the Toolbox, depending on the specific KPAs, on the types of results (qualitative/quantitative), and on the acceptable level of uncertainty in the results.

<u>6. Evaluate combined KPA results</u>: In step 6, the results of the assessment of the KPAs are combined and evaluated with respect to acceptability criteria. Depending on the certainty by which the design performance is acceptable or not for one or more KPA, this may lead to an adaptation of the design at the same TRL/HRL, to a refinement of requirements towards a higher TRL/HRL level, or to a refinement of the holistic assessment cycle.

<u>7. Improve assessment data/methods/tools</u>: If the level of uncertainty in one or several KPA assessment results is too high to reach a conclusion on the acceptability of the design, it may be decided to improve the assessment(s). Gather additional information such as supporting data or expert opinion, or extend the models or techniques used in the assessment(s). This leads to an iteration of step "5. Assess KPAs".

D. *HUCAN Toolbox of Methods*

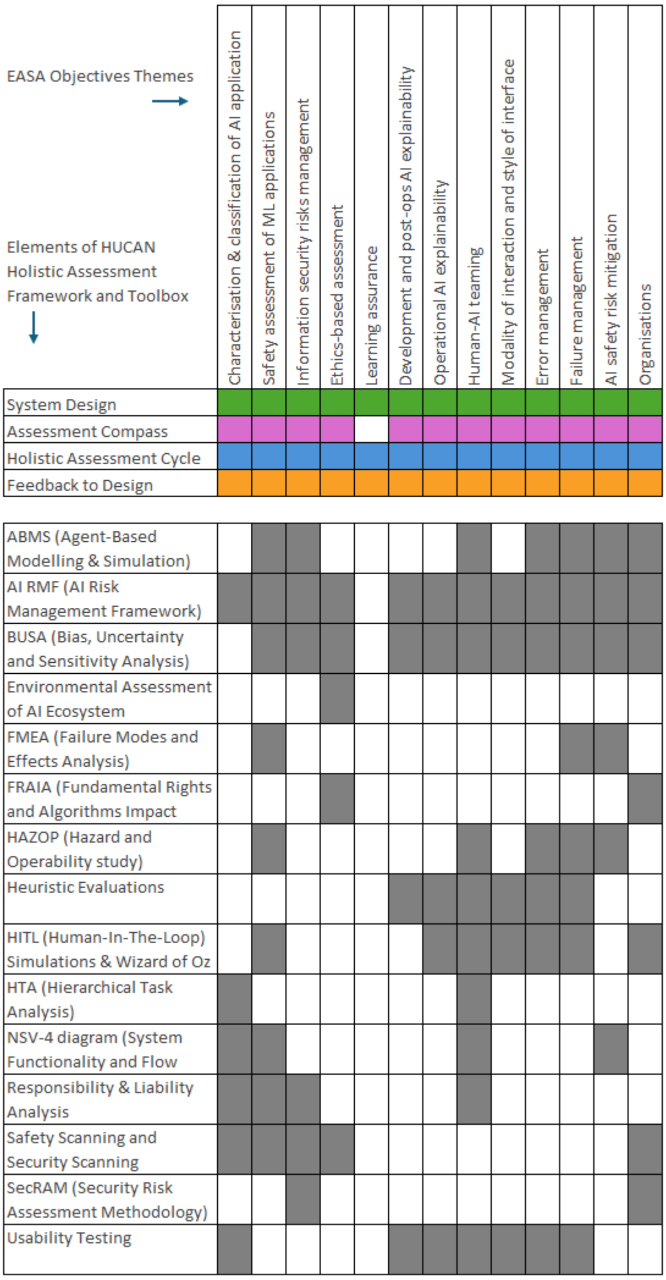
The HUCAN holistic framework proposes a comprehensive suite of methods and tools for the assessment of AI-driven and advanced automation systems. The methods can be used to address one or more of the steps in the Holistic Assessment Cycle, for one or more KPAs. This HUCAN toolbox of methods has been generated internally by the project. It integrates established methods as well as innovative approaches, recognizing the inherent complexity and unique challenges of integrating AI into safety-critical systems.

Table I provides an overview of the methods in the toolbox and the associated KPAs and TRL/HRL. More details for each method are documented in [9], including a brief description, key benefits and limitations, and associated themes of EASA AI certification objectives.

TABLE 1. HUCAN TOOLBOX OF METHODS

Method	KPAs	TRL/HRL
ABMS (Agent-Based Modelling & Simulation)	Safety, Security, HF, Resilience	TRL 2-9 HRL 2-8
AI RMF (AI Risk Management Framework)	Accountability, Responsibility, HF, Safety, Security	TRL 4-9 HRL 4-9
BUSA (Bias, Uncertainty and Sensitivity Analysis)	All	TRL 2-9 HRL 2-9
Environmental Assessment of AI Ecosystem	Environmental sustainability	TRL 3-9
FMEA (Failure Modes and Effects Analysis)	Safety	TRL 3-6
FRAIA (Fundamental Rights and Algorithms Impact Assessment)	Societal sustainability	TRL 4-9 HRL 4-9
HAZOP (Hazard and Operability study)	HF, Safety	TRL 3-6 HRL 3-6
Heuristic Evaluations	HF, Safety, Efficiency	HRL 3-6
HITL (Human-In-The-Loop) Simulations & Wizard of Oz	HF, Safety, Efficiency	HRL 5-9
HTA (Hierarchical Task Analysis)	HF, Efficiency	HRL 3-6
NSV-4 diagram (System Functionality and Flow model)	Safety	TRL 2-6
Responsibility & Liability Analysis	Liability, Responsibility, Accountability	TRL 4-9 HRL 4-9
Safety Scanning and Security Scanning	Safety, Security	TRL 1-6 HRL 1-6
SecRAM (Security Risk Assessment Methodology)	Security	TRL 2-6
Usability Testing	HF, Safety, Efficiency	HRL 3-6

A summary of the coverage of the EASA objectives themes [2] by the HUCAN holistic assessment framework and the methods in the toolbox is provided in Fig. 2. It follows that the elements of the framework can largely support the objectives themes. In particular, the evaluation of KPAs in the assessment cycle provides feedback to mature the system design for the objectives and KPAs set in the assessment compass. The methods in the toolbox provide a broad range of support for the EASA objectives themes, e.g. operational AI explainability, human-AI teaming, and error management, with some methods providing wide scope support and other methods being more focused. No methods are included for the theme Learning Assurance in the current toolbox and we refer to [2] [11] [12] [13] for a range of associated methods. Given this wealth of these recently developed methods for learning assurance, the focus in the HUCAN project has not been on the identification of additional methods for that topic.



	Characterisation & classification of AI application	Safety assessment of ML applications	Information security risks management	Ethics-based assessment	Learning assurance	Development and post-ops AI explainability	Operational AI explainability	Human-AI teaming	Modality of interaction and style of interface	Error management	Failure management	AI safety risk mitigation	Organisations
System Design	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Assessment Compass	🟪	🟪	🟪	🟪		🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪
Holistic Assessment Cycle	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Feedback to Design	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
ABMS (Agent-Based Modelling & Simulation)		■	■					■		■	■	■	■
AI RMF (AI Risk Management Framework)	■	■	■	■		■	■	■	■	■	■	■	■
BUSA (Bias, Uncertainty and Sensitivity Analysis)		■	■	■		■	■	■	■	■	■	■	■
Environmental Assessment of AI Ecosystem				■									
FMEA (Failure Modes and Effects Analysis)		■									■	■	
FRAIA (Fundamental Rights and Algorithms Impact				■									■
HAZOP (Hazard and Operability study)		■						■		■	■	■	
Heuristic Evaluations						■	■	■	■	■	■		
HITL (Human-In-The-Loop) Simulations & Wizard of Oz		■					■	■	■	■	■		■
HTA (Hierarchical Task Analysis)	■							■					
NSV-4 diagram (System Functionality and Flow	■	■						■				■	
Responsibility & Liability Analysis	■	■	■					■					
Safety Scanning and Security Scanning	■	■	■	■									■
SecRAM (Security Risk Assessment Methodology)			■										■
Usability Testing	■					■	■	■	■	■	■		

Figure 2. Mapping between the elements of the HUCAN holistic approach and the EASA objectives themes.

E. *Expected impact*

Recognizing the need for a comprehensive and harmonized assessment of the broad range of KPAs essential for the design and certification of AI-based advanced automation, the HUCAN holistic framework provides an integrated approach to address this challenge. In particular, its holistic assessment cycle applies a unified way for multi-KPA evaluation of the sociotechnical system. This not only gives feedback to design on the relevant

KPAs, but it also allows to understand relations among the impacts on KPAs and to balance possibly conflicting interests in the design of the advanced automation. Such holistic and structured feedback enables two courses of action: either an iterative redesign of the system is conducted to meet the KPA conclusions before TRL/HRL progression or, if the conclusions are satisfied the design is refined and validated as part of the formal transition to the next higher TRL/HRL. This provides a balanced approach for accounting for multiple KPAs that goes beyond ticking the box of attaining specific objectives.

The HUCAN toolbox (Table I) contains a range of methods that supports the assessment of relevant KPAs for many maturity levels. In future R&D it may be extended with additional assessment methods, including those for learning assurance of a range of ML approaches. Also, the holistic framework will need to be applied to multiple use cases, allowing to get feedback on its approaches and to further improve the maturity of the framework.

IV. PRELIMINARY GUIDELINES FOR SESAR

A. *Early-Certification Perspective in SESAR*

Technological innovation consistently poses challenges for airworthiness, which must ensure safety to enable certification. Initiating the development of a new technology and guiding its maturation from TRL 2 to TRL 6, before engaging with regulatory authorities for certification, introduces significant risks to time-to-market and overall success. These risks often result in rework or reveal gaps against existing standards and regulations, delaying deployment.

Over the past decade, in an effort to mitigate these risks, EASA has established Innovation Partnership Contracts (IPCs) and Pre-Application Services Contracts (PACs) [14], that allow early identification of potential regulatory issues and gaps, enabling parallel workstreams. Simultaneously, research and innovation projects have increasingly incorporated regulatory and standards analysis activities to facilitate convergence between development and certification. Going further, the Clean Sky programme introduced two complementary maturity metrics alongside TRL: CRL (Certification Readiness Level) [15] and MRL (Manufacturing Readiness Level). These frameworks help better define the maturation process and the multiple perspectives required to consider certification from the earliest stages—even when the product is still immature. Integrating and harmonising the development process with the certification pathway—while acknowledging their distinct objectives but mutual influence—is the strategic direction identified to ensure a predictable, and potentially shortened, time-to-market.

In the ATM domain, the SESAR programme governs the development of new technologies and operational concepts through a structured maturity progression. Certification processes are guided by different reference frameworks depending on whether the solution is airborne or ground based.

Today, with increasing automation and the emergence of AI, the risk of delayed time-to-market is high and potentially impactful. To mitigate this, the core question addressed in this section is: how can the SESAR-defined development process [4] be aligned with the EASA Concept Paper [2], particularly for solutions with high automation and AI-based capabilities?

Recognizing the complexity of the evolving AI-based solutions, a comprehensive comparative analysis of SESAR and EASA Concept Paper subprocesses is advisable to map commonalities and differences across the main thematic areas—safety, security, ethics, and human factors—and key mandatory activities—operational concept design—with a particular focus on identifying gaps, overlaps, and complementarities. Such analysis serves as the foundational step for defining an integrated set of guidelines to be used as a reference for setting up a future certification approach tailored specifically for SESAR-developed AI-based solutions. By bridging SESAR's R&D methodologies and related documents and EASA's compliance-driven frameworks, these guidelines aim to support a coherent and streamlined design of automated systems towards their eventual certification, considering also evidences available at low TRL stages (Fig. 3). This may ensure that innovative AI technologies can be already assessed at the earliest design stages, for effectively and efficiently meeting regulatory requirements and operational needs.

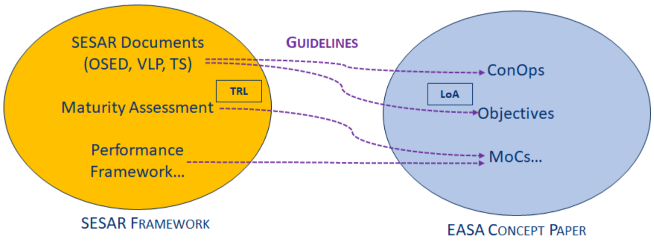


Figure 3. Scope of the proposed guidelines.

Some of the key advantages of the proposed harmonization could be:

- Reduction of duplicated activities – By aligning evidence generation and documentation requirements, teams can avoid performing the same tasks twice
- Faster time-to-market – Streamlining interactions between development and certification allows early identification of regulatory constraints and enables parallel planning
- Improved resource efficiency – Shared use of data, simulation and testing environments across processes leads to more efficient use of personnel/infrastructure
- Better traceability and consistency – Ensuring alignment from requirements definition to certification evidence improves traceability and reduces the risk of non-compliance
- Enhanced collaboration across domains – Interdisciplinary collaboration is fostered earlier in the lifecycle, especially across engineering, safety, security, human factors, and regulatory teams

- More predictable and cost-effective certification – By anticipating certification needs, organizations can reduce last-minute redesigns and unplanned iterations
- Early identification of gaps and risks – Harmonization allows earlier detection of potential gaps between what is being developed and what can be certified or accepted by regulators.

B. *Definition Approach of the Guidelines*

The analysis to harmonize the processes considers the overall SESAR project lifecycle and the EASA concept paper [2]. The harmonization of development and certification processes represents a strategic objective for organizations aiming to bring innovative solutions to market more efficiently. In this context, the work undertaken in the project aims to explore and structure a methodology that enables this harmonization, starting from a low TRL perspective.

The approach is designed with a dual perspective: (i) on the one hand, to provide a practical example of gap analysis that can serve as a basis for initiating targeted harmonization actions; (ii) on the other hand, to identify a repeatable methodological framework that offers a foundation for future work, supporting the maturation of the guidelines themselves.

The approach is based on a structured, step-by-step analysis (Fig. 4), designed to progressively build a shared understanding of the processes, identify critical gaps and synergies, and ultimately support the formulation of preliminary harmonization guidelines.

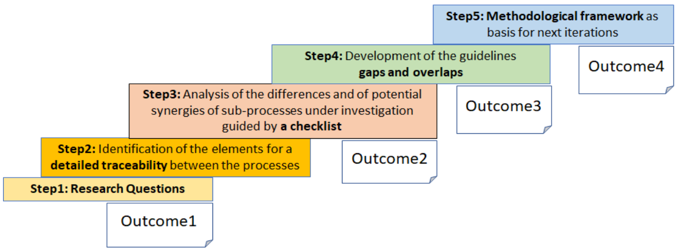


Figure 4. Definition approach of the guidelines.

The following steps summarize the approach:

- Step 1: Definition of Research Questions (Framing the scope) – The process begins with the formulation of key research questions (Outcome1), that guide the investigation, defining the scope, identifying the main challenges of harmonization, and clarifying the added value of aligning development and certification workflows from the earliest design phases.
- Step 2: Identification of the Subprocesses to Be Analysed (Which elements of the processes should be considered?) – Specific subprocesses from the broader development and certification frameworks are selected for detailed analysis. These include areas such as: Operational concept definition; Safety; Security; Human factors; Ethics. This selection provides a focused yet representative basis for exploring process interactions and harmonization opportunities.
- Step 3: Comparative Analysis of Subprocesses (How to identify gaps and synergies?) – A dedicated checklist (Outcome2) is defined to guide the comparative analysis of each subprocess. This checklist helps identifying differences in objectives, documentation, stakeholders, and timing between the development and certification paths. The analysis aims at highlighting: redundancies and duplications; points of misalignment; potential synergies and shared activities. It is important to note that this work deliberately focused on checking the coverage of the objectives and did not extend to Certification Specifications (CS). This distinction is maintained because the crucial task of ensuring consistency between objectives and CS, along with developing the necessary Means of Compliance (MOC), rests definitively with EASA and its official standardization efforts.
- Step 4: Development of Preliminary Guidelines (Where is harmonization needed?) – Based on the checklist from Step 3, gaps and synergies are derived and a set of preliminary guidelines (Outcome3) is developed. These guidelines provide structured recommendations on where an alignment would be needed; which activities or evidence can be shared. The result is a preliminary understanding of where harmonization could be considered in the targeted subprocesses. The guidelines represent a first, foundational version, to be enhanced in future work. Subsequently, a toolkit is developed to distal the guidelines into more practical and actionable information.
- Step 5: Methodological Framework and Roadmap for Future Work (How should the guidelines evolve?) – The final step outlines a methodological framework and roadmap (Outcome4) to guide future work. This includes: assessing the impact of the gaps and overlaps and defining actions to leverage them; defining next steps for validating and refining the guidelines; proposing extensions to additional sub-processes or domains; engaging stakeholders to ensure relevance and adoption; linking the approach to TRL advancement and time-to-market optimization.

C. *Results*

The first key finding is the clear alignment between subprocesses, which are reflected in the Trustworthiness analysis outlined in the EASA Concept Paper [2]. This alignment is further reinforced by the integration of SESAR’s Human Factors (HF) process, which can encompass elements such as Human-AI teaming, trust, and ethics.

In SESAR, Safety is one of the key performance aspects to be ensured, but it also considers many others, if safety is preserved. For EASA, it is the primary objective, and all technical system performances are evaluated in relation to their impact on safety. This is reflected in the differences observed across their subprocesses. However, by focusing on individual subprocesses and analysing them in detail, it becomes possible to obtain deeper insight into these difficulties and identify areas of alignment despite the overarching differences.

The comparative analysis between the EASA concept paper [2] and the SESAR framework [4] across the key subprocesses highlights distinct but complementary approaches, offering a strong foundation for future harmonization aimed at enabling the safe, secure, and trustworthy integration of AI/ML in ATM:

- Operational Concept: EASA emphasizes AI-user interaction, differentiated explainability, and automation classification; SESAR has a wider system-level view, focusing on integration into the ATM architecture and structured operational models.
- Safety: EASA provides regulatory rigor and AI-specific safety guidance, whereas SESAR contributes operational tools and dual success/failure perspectives. Harmonization could standardize validation processes and reduce certification complexity.
- Security: EASA focuses on AI-related information security aligned to certification, while SESAR uses a broader TRL-based approach according to its Security Risk Assessment Methodology (SecRAM) [16]. Their shared risk-based philosophy supports integrated security across the system lifecycle.
- Ethics: EASA targets certification-oriented ethical assurance, using the ALTAI framework, while SESAR ensures ethical governance throughout research projects. Both support "ethics by design" but would benefit from more aviation-specific guidance.
- Human Factors: SESAR offers a mature, structured HF framework with clear guidance, TRL alignment, and practical tools. EASA, while focused on certification, lacks standardized HF assessment methods and AI-specific KPIs. Bridging this gap by integrating SESAR's methodological strength into EASA's compliance-driven process would improve consistency, traceability, and human-centric design assurance.

By the way of example, Table II and Table III report the key differences for Safety and Security subprocesses, based on our analysis.

Considering the overlaps and existing gaps between SESAR and EASA frameworks, some preliminary hints can be leveraged to support harmonization:

- Operational Concept – The inclusion of semi-formal descriptions of Operational Design (OD) and Operational Design Domain (ODD) within the OSED (Operational Services and Environment Definition) and TS (Technical Specification) documents could serve as concrete evidence to address related objectives outlined in the EASA Concept Paper. This would help bridge the conceptual alignment between SESAR's operational maturity and EASA's trustworthiness criteria. Another key aspect broadly related to the EASA operational concept is represented by operational and post-operational explainability. The conceptual design of the new operating method requested in SESAR, could be integrated with specific elements addressing these topics when applicable. It is worth noting that explainability also touches on ethics, particularly in relation to human oversight and human performance aspects. In connection with these areas, the SESAR Performance Framework could be enhanced with metrics that assess the quality of explainability.
- Security Objectives – SecRAM could be proposed as a Means of Compliance (MoC) within the EASA Concept Paper, provided that SecRAM catalogues are enriched with specific AI-based assets, threat scenarios, mitigation strategies, and traceability to regulatory requirements. This would enhance its applicability and robustness in certification contexts.
- Trustworthy Human-Machine Teaming – Human performance assessment could be enriched by incorporating metrics related to Human-AI teaming, as well as trust and ethics factors. These elements, in turn, could be considered as key performance indicators (KPIs) for evaluating the degree to which the objectives outlined in the EASA Concept Paper are being met.
- Safety – Future convergence efforts should aim to integrate EASA's regulatory rigor and AI specificity with SESAR's operational detail and practical support tools. This integration will help close existing gaps, standardize safety practices across aviation domains, and ensure safer deployment of AI/ML-enabled systems in the evolving aviation ecosystem. Developing a unified set of safety performance indicators tailored for such systems could promote consistency and comparability across projects.

The identification of the subprocesses analysed within the gap analysis should be considered preliminary and does not aim to provide comprehensive coverage of all SESAR processes on the one hand, nor of all EASA concept objectives on the other. For instance, the Learning Assurance process -one of the key processes within the EASA framework- does not appear to have a direct correspondence in the SESAR framework. This observation suggests that only a more extensive and systematic analysis, to be carried out as part of future work, can ensure adequate coverage and enable a clearer understanding of which elements can be effectively assured early in the design phase and which require assurance at a later stage.

V. VALIDATION

Dedicated validation activities were organised at different stages of the project work to collect feedback on the relevance and applicability of the proposed solutions.

A Stakeholder Consultation Group (SCG) was established involving representatives from most of the ongoing SESAR projects involving AI. In two separate workshops the SCG helped shape the direction by providing input on research and certification needs, thus laying the foundation of the solutions not only on the results of the theoretical research but also on practical needs collected from prospective users.

At later stages, for the validation phase of the proposed solutions, an Expert Group (EG) was involved, comprising representatives from regulatory authorities (including EASA), developers and deployers, and R&I experts.

Looking at SESAR-SOL.0445, the EG appreciated the soundness and practical utility of the HUCAN approach. However, developers and deployers pointed to the need for the toolbox to be further refined and better aligned with current industrial validation processes, in order to improve its usability in future R&I contexts. They also identified difficulties in applying the proposed process and recommended the creation of dedicated operational guidelines to facilitate adoption. However, there was widespread recognition of the value in incorporating certification considerations within the existing KPAs used for aviation system design and validation - an approach that was seen as complementary to established practices, avoiding the need for entirely new methodologies.

Considering SESAR Solution 0446, there was a general endorsement of the usefulness and completeness of the gap analysis conducted between the SESAR validation framework and the EASA concept paper. These were recognised for their future potential to not only streamline research and development efforts towards market readiness but also to enable a more informed approach to addressing the implications of automation and AI level classification in view of future certification requirements. The gap analysis is also seen as a means to consolidate and strengthen existing expertise within the SESAR community, while maintaining the necessary flexibility to accommodate exploratory research alongside compliance-driven objectives. More broadly, it is suggested that the rationale and methodology underpin both the gap analysis and the development of the associated toolkit, consolidating the approach within SESAR with further studies.

The overall quality and significance of the results was considered promising, especially considering the early stage of development. In particular, looking at these solutions in the perspective of the objectives stated in the SESAR MP2025, interesting insights were collected concerning the possible support offered by the proposed approach and solutions in relation to the Strategic Deployment Objective (SDO 4) focused on increased automation support.

From an internal perspective, SESAR has already launched a revision process of its validation methodologies, also in response to the specific challenges posed by AI-related features. In this regard, clear synergies can be identified between the work carried out within HUCAN and that developed under projects such as AMPLE3 – SESAR3 ATM Master Planning and Monitoring (GA ID 101114738) and PEARL – Performance Estimation, Assessment, Reporting and Simulation (GA ID 101114676). Monitoring the outcomes of these projects can help reinforce and further consolidate the approach developed by HUCAN. Conversely, the solutions and methods elaborated within HUCAN may provide valuable input for the operationalisation of results emerging from other initiatives, particularly in the context of promoting a certification-aware approach within SESAR.

VI. CONCLUSIONS AND WAY FORWARD

The necessity for a safe and sustainable increase in European ATM capacity, driven by the MP2025 vision for high-level automation (Levels 2 to 4), requires an adaptive regulatory shift capable of addressing non-deterministic ML systems and the changing human role. The SESAR HUCAN project (2022–2026) provided critical initial responses to this challenge by developing a certification-aware design approach (Certification by Design) and establishing preliminary guidelines to ensure proactive alignment among emerging solutions and certification requirements. These foundational solutions directly enable developers to mitigate major compliance risks early, thereby significantly reducing the potential for costly, retroactive redesigns and accelerating the path from research to operational deployment. They also help the R&I projects within the SESAR framework to adopt a common and homogenous approach.

While these foundational outputs have been well-received by stakeholders, thus demonstrating a clear potential to embed certification objectives and harmonized methodologies directly into the design lifecycle, their full potential requires further refinement, maturation, and integration with evolving standards and regulations, such as the forthcoming EUROCAE ED-324, relevant ISO/IEC standards, and the EASA AI roadmap. In particular, the project clearly delineates two pressing areas for future research maturation. The first area concerns practical implementation and tooling as the R&D teams urgently require specific, practical tools and guidance that can be seamlessly embedded into existing development processes to effectively implement the certification-aware approach for solutions targeting higher levels of automation. The second area concerns dedicated assurance methodologies for advanced AI. There is a systemic risk in overextending assurance requirements in current standardization efforts for supervised learning models (primarily used for detection and classification tasks) to recent innovative AI paradigms. The integration of techniques like Generative AI (GenAI) and Reinforcement Learning (RL)-based AI Agents necessitates the development of dedicated assurance methodologies to address their unique certification challenges (e.g., hallucinations and RL's emergent behaviours).

Future work in this area will benefit from the systematic development of concrete, actionable methodologies and from synergies with ongoing initiatives across the European ATM ecosystem, such as SESAR projects. These efforts are expected to contribute to the broader advancement of certification-aware design practices, supporting safer, more reliable, and more efficient deployment of AI-based automation systems.

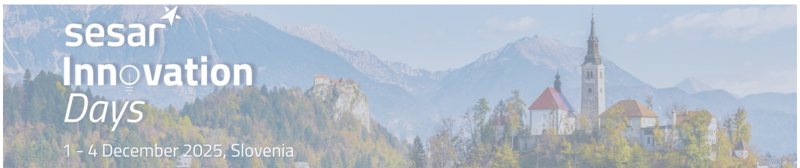


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TABLE 2. GENERAL KEY DIFFERENCES FOR SAFETY SUBPROCESS.

Topic	EASA [REF]	SESAR [REF]
Target Audience	Broad: Applicants demonstrating AI/ML system safety across all aviation stakeholders	Focused: Safety practitioners in R&I, VLD projects, SESAR JU members, NSAs, EASA in rulemaking
Scope	Complete aviation system lifecycle: on-board, ground, ATM/ANS, maintenance, and training	ATM/ANS systems during development phases; dual perspective of success and failure
Terminology	AI-specific terms; assumes basic safety process knowledge	Comprehensive safety and SESAR-related definitions
Inputs	Aviation standards (e.g., ARP4761, EU regulations, etc) as major inputs	All existing project documentation (OSED, SPR, etc.)
Outcomes	General documentation of safety assessment and Means of Compliance	Strict deliverables: Validation Plan and Validation Report including safety documentation
Inputs	Aviation standards (e.g., ARP4761, EU regulations, etc) as major inputs	All existing project documentation (OSED, SPR, etc.)
Outcomes	General documentation of safety assessment and Means of Compliance	Strict deliverables: Validation Plan and Validation Report including safety documentation
Assessment Methodology	Detailed guidance for compliance with AI trustworthiness and regulatory standards	Compliance responsibility assigned to ANSP Safety Managers using expert judgment
Performance Indicators	Metrics defined by system developers for each application	Predefined KPAs and KPIs guide projects

TABLE 3. GENERAL KEY DIFFERENCES FOR SECURITY SUBPROCESS.

Topic	EASA [REF]	SESAR {REF]
Scope of Risk Assessment	Focuses on information security, particularly for AI/ML systems	Broader scope including information, physical, and operational security via SecRAM
Treatment of Residual Risk	No strict thresholds; contextual judgment in certification	High residual risks not accepted; medium risks require documented justification
Assessment Methodology	Subsystem-level focus, especially AI components and data	Service-oriented, evaluating service interactions, data flows, and interfaces
Impact Areas of Risk	Primarily safety impacts	Multiple impacts considered: safety, performance, economic, environmental, reputational
Technology Readiness Level	Not tied directly to TRLs	TRL-driven security requirements; structured progression from TRL2 to TRL8
Validation of Security Controls	Early validation of AI/ML-specific controls required	Focus on final-stage testing (e.g., TRL8) with earlier-stage documentation