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RIGHTS OF PASSENGERS WITH SPECIFIC NEEDS

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Abstract

This paper focuses on the rights of passengers with specific needs in air transport. It examines the legislative framework designed to protect these passengers and identifies the main challenges associated with its practical implementation. The study outlines key international and European regulations, with particular emphasis on the rights of persons with disabilities and reduced mobility, as well as on operational procedures at M. R. Štefánik Airport in Bratislava and other selected airports. The research findings reveal shortcomings in infrastructure, assistance services, and passenger awareness at M. R. Štefánik Airport. Based on these results, a set of recommendations was developed to improve accessibility and service quality for this passenger group. The analysis underscores the need to modernize the current system and to implement new measures that enhance the overall travel experience and ensure safe, accessible air transport for all passengers

Keywords

passenger rights, people with specific needs, reduced mobility, unaccompanied minors, proposal for improving services

1. Introduction

Air transport is one of the fastest and most efficient means of transporting people over long distances, playing a significant role in a globalized world. Air transport represents a key element of transport system, connecting regions, supporting global trade, and fostering social and economic progress (Bulíček et al., 2022). For many travellers, it is an integral part of their professional or private lives; however, for individuals with specific needs, the travel process can be considerably more complicated. Passengers with disabilities, reduced mobility, or other specific needs often face various barriers that hinder their equal access to air transport services.

For all modes of transport, there is the right to free assistance at terminals and on-board vehicles. Transport by air, bus, coach, or ship cannot be refused on the grounds of disability or reduced mobility, except where refusal is justified for safety reasons (as laid down in national, international or EU law, or by a decision of the competent national authority), or due to the design of the vehicle or infrastructure (Europa, 2025). The rights of passengers with specific needs are regulated by various international and European legal standards that establish the obligations of airlines and airports to provide appropriate assistance. Nevertheless, the practical implementation of these measures continues to encounter problems. Travelers face inadequately adapted infrastructure, missing or insufficient assistance services, poor information availability, and limited options for booking tickets and assistance. These factors can lead to significant complications and, in many cases, restrict the ability to travel.

The main objective of this paper is to thoroughly analyze the rights of passengers with specific needs in the context of air transport, focusing on their legal protection, service accessibility, and issues related to the enforcement of these rights. The paper is based on an analysis of European Union legislation, particularly Regulation (EC) No 261/2004 of the European Parliament and of the Council, which establishes common rules on compensation and assistance to passengers in the event of denied boarding, flight cancellations, or long delays, and Regulation (EC) No 1107/2006 of the European Parliament and of the Council of 5 July 2006 concerning the rights of disabled persons and persons with reduced mobility when traveling by air, as well as applicable legal standards in the Slovak Republic. Special attention is given to the conditions and measures implemented at M. R. Štefánik Airport in Bratislava, which serves as the main international airport in Slovakia.

The paper focuses not only on the theoretical analysis of current legislation but also on identifying practical problems that passengers encounter. An important part of the study is assessing the quality of services provided at the airport, evaluating the accessibility of information, and proposing measures to improve the situation. The result is a set of recommendations that could contribute to raising the standard of services provided and strengthening the protection of the rights of passengers with specific needs.

The topic of passenger rights in air transport is important not only from a legal regulatory perspective but also in terms of equal opportunities for all travellers. Airlines and airports should view the provision of assistance services not only as a legal obligation but also as an ethical commitment to their customers. Ensuring full accessibility and equal treatment for all passengers is essential for the further development of air transport and its sustainability in the future.

2. Legal Framework for the Protection of Passenger Rights

Ensuring the rights of passengers with specific needs in air transport requires a clearly defined and effectively enforced legal framework. Given the global nature of aviation, their protection is influenced not only by national but also international and European legal norms. These laws define the obligations of air carriers and airports, establish rules for compensation and assistance, and prohibit all forms of discrimination. This chapter outlines the key legal documents that form the foundation for protecting passengers with specific needs, as well as the practical implications of their implementation (Sedláčková, 2023).

The foundations of international aviation law were laid in the early 20th century, notably with the Warsaw Convention of 1929, which addressed carrier liability in cases of damage during air travel. This was later replaced by the Montreal Convention of 1999, which unified compensation rules for delays, lost baggage, and passenger injury or death, thereby reflecting the needs of a growing global aviation market.

Within the European Union, two major regulations form the backbone of passenger rights protection. Regulation (EC) No 261/2004 sets out passengers’ rights in the event of flight cancellations, delays, or denied boarding. It introduced financial compensation ranging from €250 to €600 depending on flight distance. The practical enforcement of this regulation has been shaped by rulings of the European Court of Justice, such as the Sturgeon v. Condor Flug Dienst GmbH case, where passengers were granted compensation for flight delays exceeding three hours. In that case, the Sturgeon family experienced a 25-hour delay after their flight from Toronto to Frankfurt was cancelled at check-in and replaced with a significantly delayed alternative route.

The second key document, Regulation (EC) No 1107/2006, specifically addresses the rights of people with disabilities and reduced mobility. It requires airports and airlines to aid free of charge, ensure accessible infrastructure, and properly train staff. Despite this, challenges remain in the practical enforcement of these obligations. In 2018, a British airline refused assistance to a woman with cerebral palsy because she "looked completely normal." In another case, a 56-year-old man was left waiting on a plane for nearly two hours due to the loss of his wheelchair. Such incidents have sparked debates on the need for better implementation and oversight of these regulations (SLOV-LEX, 1968) (SLOV-LEX, 2002).

Air carriers are obliged to allow people with reduced mobility to book flights without discrimination. Furthermore, airports must ensure that dedicated personnel and technical equipment are available, such as lifting platforms, wheelchairs, and specialized vehicles to support boarding and deboarding. Airports are also responsible for guaranteeing barrier-free access to check-in counters, designated waiting areas, and sanitary facilities. This includes appropriate signage and navigation systems adapted for passengers with visual or hearing impairments (Editors, 2009).

3. International Cooperation in Protecting Passenger Rights

In the context of increasing demand for air travel, international cooperation plays a key role in strengthening passenger rights and addressing challenges associated with accessibility and safety. Although many rights are guaranteed by national and EU regulations, several international institutions contribute significantly to their practical enforcement (EASA, Cooperation international civil aviation organization icao, 2024).

One such body is the European Union Aviation Safety Agency (EASA), which ensures high safety standards across all EU member states. By establishing unified safety regulations for airlines, airports, and aircraft manufacturers, EASA helps maintain a high level of operational safety—an essential element of passenger protection (EASA, International cooperation, 2024).

Another important organization is the International Air Transport Association (IATA). While it does not issue legally binding regulations, IATA sets global industry standards that airlines widely follow. It also acts as a communication bridge between carriers and passengers and supports the development of safe, efficient, and fair air transport services. Through initiatives related to pricing policies and passenger compensation, IATA influences industry-wide practices that affect passenger rights.

These collaborative efforts help shape a more inclusive and secure air travel environment, ensuring that passenger needs are acknowledged and addressed at both the European and global levels (EASA, Cooperation international civil aviation organization icao, 2024) (EASA, International cooperation, 2024) (MZV, 2023).

4. Differentiation of passenger types in air transport

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These collaborative efforts help shape a more inclusive and secure air travel environment, ensuring that passenger needs are acknowledged and addressed at both the European and global levels (EASA, Cooperation international civil aviation organization icao, 2024).

5. Proposal to improve access for passengers with specific needs at M. R. Štefánik Airport in Bratislava

5.1. Identified Deficiences at M. R. Štefánik Airport

The current system at M. R. Štefánik Airport has several shortcomings that may negatively affect the experience and satisfaction of passengers. One key issue is the lack of available lifting platforms for boarding or disembarking aircraft, or assisting passengers with reduced mobility, which complicates their boarding process. This can result in delays, discomfort, or unnecessary stress for affected passengers.

Another issue is the insufficient number of personnel designated for assistance during peak hours, leading to longer waiting times for help, delays in boarding, and general dissatisfaction. Some passengers also struggle to navigate the airport due to unclear signage and limited visual or auditory guidance systems.

Although assistance services are available, passengers may still worry about missing their flights or facing unexpected issues. While the airport provides parking spaces for holders of disability cards (ŤZP), the number of these spaces is limited and often insufficient during high travel periods (e.g., summer months). When parking is full, it becomes more difficult for passengers with disabilities to access the terminal.

Additionally, the process of requesting assistance in advance through the airline may be complicated, impractical, and confusing for some, which lowers overall satisfaction and comfort when using the airport's services.

5.2. Proposal regarding Technical Measures

One of the main challenges already mentioned is the limited physical infrastructure for passengers with disabilities. To address this, the implementation of lifting platforms and the construction of barrier-free access to aircraft is necessary. Modernization of existing facilities, such as ramps and elevators, would greatly ease mobility for passengers with limited movement.

Currently, no lifting platforms are available at the airport, often causing delays, as these passengers need to be physically lifted onto or off the aircraft with the help of staff and then guided to or from the terminal entrance.

Another proposed measure is the expansion of dedicated areas for assisting these passengers, ensuring greater privacy and comfort during check-in. Parking for disability card holders should also be expanded, with more designated spaces closer to terminal entrances and better availability during peak times.

5.3. Proposal for Personnel and Information-Based Solutions

M. R. Štefánik Airport needs to increase the number of assistance staff, especially during peak hours when the airport infrastructure is most heavily used, to reduce waiting times. The quality of assistance services could also be improved by implementing regular employee training focused not only on physical aid but also on communication with passengers with specific needs.

For parents of unaccompanied minors, introducing a digital tracking platform could be useful, allowing real-time monitoring of the child's movement within the airport. Automated check-in kiosks adapted for passengers with reduced mobility could speed up the check-in process and reduce the need for direct assistance.

5.4. Estimated Cost and Implementation

The proposed measures to improve services for passengers with disabilities and unaccompanied minors at M. R. Štefánik Airport focus on three main areas: improvement of physical infrastructure, modernization of assistance services, and increasing passenger awareness. These include specific investments and organizational changes aimed at enhancing comfort, accessibility, and efficiency.

Based on average market prices for necessary infrastructure and technological solutions, the estimated costs for implementing physical changes are outlined in Table 1. Actual prices may vary depending on selected suppliers, construction companies, and technological partners. Since exact parameters for implementation at the selected airport are not available, the prices are approximate based on general estimates. For instance, the cost of acquiring lifting platforms ranges between $95,000 and $130,000 per unit. Sarajevo Airport underwent such changes in 2017 and paid €301,000 for a single platform (Bosnian, 2017), (dimaindustry, 2023), (gov, 2022).

Table 1. Estimated costs for implementation of measures; (Source: authors)

Measure	**Estimated costs** [€]	**Implementation time** (months)
Lifting platforms and barrier-free access	250 000 – 400 000	6 – 18
Modernization of elevators and ramps	100 000 – 200 000	6 – 12
Expansion of assistance areas	80 000 – 120 000	6 – 12
Increased capacity of parking spaces for disabled	50 000 – 100 000	3 – 6

5.5. Benefits of Implementing Measures

The implementation of these measures would bring numerous positive changes, significantly improving the travel experience of passengers with disabilities and unaccompanied minors. Increased availability of physical infrastructure would enable faster and more comfortable airport movement, eliminating delays and discomfort during boarding and disembarkation.

The modernization of assistance services would provide more effective support, reduce travel-related stress, and increase overall customer satisfaction. Better access to information via mobile apps, digital displays, and social media would help passengers prepare more effectively for their journeys, reducing uncertainty and potential complications.

Enhanced communication channels would also increase passenger trust in airport services and encourage greater use of M. R. Štefánik Airport for future travel.

6. Results

The research conducted in this paper focuses on assessing the current state of services for passengers with specific needs in air transport, with a focus on M. R. Štefánik Airport in Bratislava. Based on the evaluation of the legislative framework, existing standards, and the practical operation of assistance services, several key deficiencies have been identified that directly affect the comfort, safety, and equal access of this group of passengers.

From the perspective of physical infrastructure, which is identified as problematic, the issues include insufficiently marked spaces designated for passengers with reduced mobility, the lack of guiding elements for the visually impaired and blind, and the absence of designated zones for these passenger groups. The navigation system in the airport is outdated and confusing, causing difficulties, particularly for people with limited orientation abilities. These factors reduce the level of independence for passengers, increasing their reliance on airport staff, who, in many cases, are not sufficiently trained to communicate effectively with people with disabilities.

From the perspective of assistance services, several gaps have been identified in the areas of booking and providing help. The reservation system on the airport's website does not offer an intuitive or user-friendly interface, especially for elderly people and those with intellectual disabilities. Moreover, multilingual information processing is lacking, including versions in simple language or video/audio guides. Passengers are often not sufficiently informed about their right to assistance and frequently do not know that they are entitled to free help with airport mobility, boarding, or luggage handling.

A document review and comparison with recommendations from the European Union and international organizations (ICAO, EASA, IATA) revealed that while the airport meets the basic requirements of Regulation (EC) No. 1107/2006, its practical implementation is often insufficient to ensure high-quality services.

Based on these findings, measures were proposed in three main areas: improving infrastructure (e.g., lifting platforms, barrier-free access), enhancing the quality and availability of assistance services (e.g., staff training, modernization of the reservation information system), and intensifying awareness campaigns for passengers (e.g., mobile app). These proposals are specific, feasible, and reflect the need for better access in civil aviation.

7. Conclusion

Based on the analysis of legal regulations and passenger experiences, it can be concluded that the protection of the rights of people with specific needs in air transport is still unsatisfactory and requires further improvements. Although the legal framework exists and is detailed, several practical issues prevent its effective implementation.

One of the main problems is the insufficient infrastructure at M. R. Štefánik Airport in Bratislava, where essential barrier-free elements are missing, or assistance services are underdeveloped. Recently, a lifting platform (ambulift) has been installed at the airport; however, it is not yet fully operational, which continues to limit the quality and safety of assistance provided to passengers with reduced mobility. Another issue is the lack of awareness among passengers about their rights and available assistance options. Additionally, there are discrepancies in the level of services provided by different airlines and airports, leading to inconsistent treatment of passengers with specific needs.

In addition to M. R. Štefánik Airport, which was analyzed in detail in this paper, Košice Airport also plays an important role as the second busiest airport in Slovakia. Passengers' experiences with specific needs are occasionally negative due to deficiencies that significantly affect the comfort and safety of travel for people with reduced mobility, particularly for immobile passengers.

The paper includes the experience of a passenger in a wheelchair who expressed dissatisfaction with the absence of a lifting platform (ambulift), which is necessary for a safe and dignified boarding process. Currently, assistance is provided in a makeshift manner, which often leads to unpleasant and degrading handling of passengers. Moreover, the lack of specialized and professional technical equipment for handling immobile individuals increases the risk of injury to both the passengers and the staff. These deficiencies highlight the need for significant modernization of the technical infrastructure and the establishment of standards that comply with European legislation on the rights of people with reduced mobility.

To ensure true equality in the services offered to all passengers, the implementation of legislative measures needs to be strengthened, and uniform standards for all airports should be created. This paper identifies specific solutions, such as the modernization of specific airports, better staff training, expanded information, and enhanced legal protection for passengers.

The paper emphasizes the importance of continuous improvement in conditions for passengers with specific needs and underscores that fair transport should be a priority for all airlines and airports. Implementing the recommendations in this paper could lead to significant improvements in conditions at M. R. Štefánik Airport and enhance the overall comfort and accessibility of air transport.

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References

Anon., 2018. *STALOSE zprávy.* [Online] Available at: https://www.stalose.com/item-83982- [Cit. 3 2025].

Bosnian, F., 2017. *Flying bosnian.* [Online] Available at: https://flyingbosnian.blogspot.com/2017/02/sarajevo-airport-purchased-special.html?

BULÍČEK, Jozef; ŠOUREK, David; VOJTEK, Martin; MONDEK, Norbert; ŠKORUPA, Milan (2022). Modelling of Structure of Public Transport Lines in the Agglomeration of Pardubice. Proceedings of 26th International Scientific Conference. Transport Means 2022.pp.579-584.

dimaindustry, dátum neznámy *Airport Ground Support Equipment - Ambulift.* [Online] Available at: https://dimaindustry.en.made-in-china.com/product/HwyAZvGUXQVa/China-Airport-Ambulift.html

EASA, 2024 *Cooperation international civil aviation organization icao.* [Online] Available at: https://www.easa.europa.eu/sk/light/topics/cooperation-international-civil-aviation-organization-icao

EASA, 2024 *International cooperation.* [Online] Available at: https://www.easa.europa.eu/en/light/topics/international-cooperation

Editors, A., 2009. *Air Law Digest.* [Online] Available at: https://airlawdigest.com/case/c-402-07-sturgeon-others-v-condor-flugdienst-gmbh-c-432-07-bock-and-lepuschitz-v-air-france-sa-2009/.

EUR-LEX, 2006. *Legal content.* [Online] Available at: https://eur-lex.europa.eu/legal-content/SK/TXT/PDF/?uri=CELEX:32006R1107

EUROPA, E.-L., 2001. *Rozhodnutie rady.* [Online] Available at: https://eur-lex.europa.eu/legal-content/SK/TXT/PDF/?uri=CELEX:32001D0539

Europa, 2025: Rights for travellers with disabilities or reduced mobility available at: https://europa.eu/youreurope/citizens/travel/transport-disability/reduced-mobility/index_en.htm

gov, dátum neznámy *Zmluva o poskytovaní služieb.* [Online] Available at: https://www.zmluvy.gov.sk/data/att/123845_dokument.pdf

MZV, 2023. *Slovakia in un/specialized and professional organizations.* [Online] Available at: https://www.mzv.sk/en/diplomacy/slovakia-in-un/specialized-and-professional-organizations

Sedláčková, A. N., 2023. *Letecké právo.* s.l.:s.n.

SLOV-LEX, 1968. *Zbierka zákonov Slovenskej republiky.* [Online] Available at: https://static.slov-lex.sk/pdf/SK/ZZ/1968/27/ZZ_1968_27_19680305.pdf

SLOV-LEX, 2002. *Zbierka zákonov Slovenskej republiky.* [Online] Available at: https://static.slov-lex.sk/pdf/SK/ZZ/2003/544/ZZ_2003_544_20031217.pdf

SOI, dátum neznámy *Práva cestujúcich v leteckej doprave.* [Online] Available at: https://www.soi.sk/sk/prava-cestujucich/prava-cestujucich-v-leteckej-doprave.soi

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REFRAMING AIR NAVIGATION SERVICES: A MODERN SERVICE DELIVERY MODEL

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Abstract

The increasing digitalisation and growing complexity of air traffic management require a reassessment of traditional approaches to air navigation service provision. Emerging service delivery models move away from nationally isolated structures towards data-centric, network-enabled solutions. This paper examines these new models through the lens of airspace architecture principles and analyses the evolving roles Air Navigation Service Providers (ANSPs), in particular their transformation into Air Traffic Service Providers (ATSPs) and ATM Data Service Providers (ADSPs). The proposed models promote a functional separation between operational Air Traffic Services (ATS) and ATM Data Services. This separation improves interoperability, scalability, and regulatory transparency, while maintaining safety and enhancing flight efficiency, cost effectiveness, and environmental performance. The transformation also supports the implementation of SESAR and Common Project objectives, especially those related to trajectory-based operations, system-wide information management, and cross-border service integration. Finally, the separation of ATSP and ADSP roles has the potential to improve overall network performance, and enable market-based provision of data services, provided that strong governance arrangements, data quality assurance mechanisms, and effective regulatory oversight are in place.

Keywords

Air Navigation Services, Air Traffic Service Providers, ATM Data Service Providers, Regulation (EU) 2024/2803 Single European Sky – SES2+

1. Introduction

The emerging vision for Air Navigation Service Providers (ANSPs), in the context of Air Traffic Data Providers (ADSPs), represents a fundamental shift in how air navigation services are organised and delivered.

Rather than relying on geographically bound systems, this vision promotes the transformation of ANSPs into, or their close cooperation with, ATM Data Service Providers. This shift enables service-oriented and virtual architectures that support dynamic cross-border operations and more flexible capacity sharing.

European Union (2024) suggests that the new service delivery model builds on the concept of ATM Data Service Providers, where ATM Data Services – also referred to as "Air Traffic Data Services" or "ADS" — encompass services consisting of the collection, aggregation and integration of operational data from surveillance, meteorological and aeronautical information service providers, network functions, and other relevant data-generating entities. These data are then processed and made available for Air Traffic Control and Air Traffic Management purposes.

Within this framework, an ANSP may operate solely as an Air Traffic Service Provider or combine Air Traffic Services and ATM Data Services within a single organisation, subject to full compliance with applicable regulatory requirements. These include

- certification under Commission Implementing Regulation (EU) 2017/373;
- compliance with emerging ATM Data Service Provider requirements, including those under the forthcoming Common Project 2 regulation (expected to be submitted to the European Commission before summer 2026);
- assurance of fair and non-discriminatory data access; effective oversight by the National Supervisory Authority through audits;
- maintenance of safety as the overriding objective; and compliance with SWIM and cybersecurity standards.

2. Airspace Architecture – Based Service Delivery Models

Service delivery models describe alternative approaches to organising Air Navigation Services, ranging from nationally independent provision to highly integrated or Union-wide arrangements. These models include vertically integrated structures, functionally separated configurations, and cooperative or alliance-based approaches (SESAR, 2019).

At the level of individual Air Navigation Service Providers (ANSPs), several service delivery models can be distinguished.

In the **integrated service delivery model**, an ANSP provides both Air Traffic Services (ATS) and ATM Data Services within a single organisation, reflecting a traditional vertically integrated structure.

In contrast, the **independent service delivery model** separates operational Air Traffic Services from data provision, with the ANSP acting solely as an Air Traffic Service Provider (ATSP) and relying on external ATM Data Services.

The **specialised service delivery model** further develops this functional separation by assigning specific ATM data services — such as SWIM, surveillance, or meteorological services — to dedicated ATM Data Service Providers (ADSPs), rather than offering a comprehensive service portfolio.

The **alliance service delivery model** extends this concept through shared data service platforms, whereby dedicated ADSPs deliver ATM Data Services to multiple ATSPs.

Beyond individual organisational arrangements, a Union-wide service delivery model envisions Air Navigation Services being provided at the EU level. This model is based on a common data layer accessible to all European ANSPs, capacity-on-demand mechanisms that support cross-border service provision, and service-oriented architectures that enable dynamic resource sharing across the network (SESAR, 2019).

Finally, the three-layer model addresses the transformation of the ATM system as a whole rather than individual Area Control Centres. It conceptualises service delivery across three interconnected layers — business, services, and infrastructure — providing a structured framework for system-wide evolution (SESAR, 2019).

2.1. Decision framework

Several service delivery models can facilitate the transformation of ANSPs into ADSPs; however, the three-layer model and the independent or specialised service delivery models are the most directly applicable. In particular, the specialised service delivery model, when supported by the three-layer model, provides the most robust architectural foundation for this transformation. The independent and integrated service delivery models offer pragmatic pathways for transitioning ANSPs, while the alliance service delivery model is better suited as a complementary mechanism rather than a primary framework for transformation.

2.2. Emerging opportunities

In this emerging framework, the primary service delivery models, as illustrated in Figures 1 and 2, remain under active research. Although the regulatory framework is still being developed, pilot implementations are already underway. Airspace within each State is organised into one or more Flight Information Regions (FIRs), each managed by a dedicated Area Control Centre (ACC). ACCs are further subdivided into adjacent Airspace Sectors (AS) or sector groups, with controllers typically trained and certified for a limited subset of sectors within an ACC. Each ACC relies on a tightly integrated Flight Data Processing (FDP) system that provides the Controller Working Position (CWP) with processed local flight information, weather, surveillance, and aeronautical data to support traffic planning, separation, conflict detection, and safety net operations. These FDP systems generally operate with a limited level of automation. Concurrently, the European Commission and the European Union Aviation Safety Agency (EASA) are developing the regulatory framework for ADSP certification, laying the foundation for broader implementation.

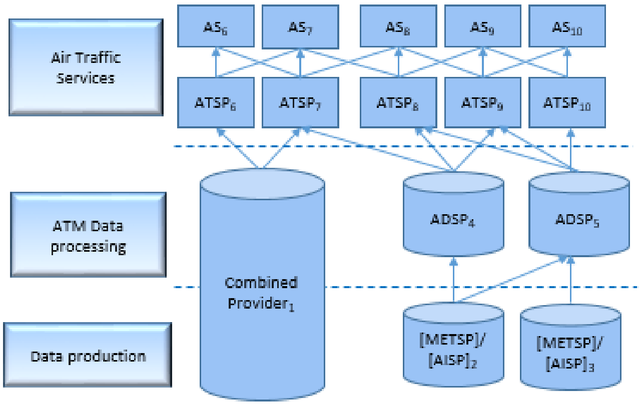

Figure 1. Specialised Service Delivery Model (Source: SESAR, 2019)

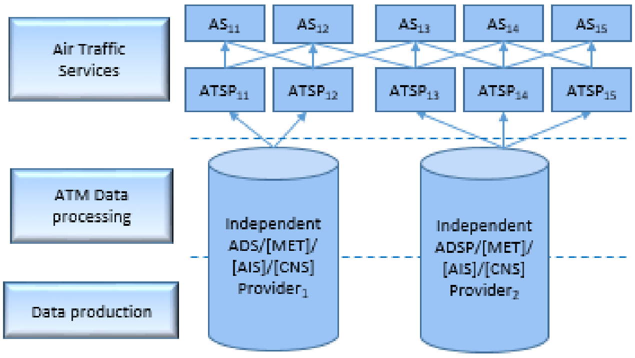

Figure 2. Independent / Integrated Service Delivery Model (Source: SESAR, 2019)

__Note 1:__ AS – Airspace Sector; ATSP – Air Traffic Service Provider; ADS – ATM Data Service; ADSP – ATM Data Service Provider; AIS – Aeronautical Information Services; AISP – Aeronautical Service Provider; CNS – Communication, Navigation and Surveillance; MET – Meteorology; METSP – Meteorological Service Provider.

3. Alternative Perspectives on the Models

As part of our research, we examined the models with a focus on the transformation of ANSPs into ATSPs and ADSPs, considering several key dimensions, suggested by the European Union (2021).

- Operationally, airspace is optimised based on traffic flows rather than national boundaries. In terms of operations and technology, Trajectory-Based Operations (TBO) serve as the core concept, supported by progressively enhanced automation for Air Traffic Controllers (ATCOs).

- The framework dimension emphasises flexible allocation of ATCO resources and seamless cross-border service provision.
- From a regulatory perspective, certification frameworks for new service providers are being developed alongside a performance-based approach.
- Finally, the models are designed to be scalable, flexible, and resilient, incorporating fall-back capabilities and redundancy to ensure operational continuity.

4. Expected timeline

The key transition years are determined by regulatory, operational, and technological readiness, with anticipated research outputs illustrated in Figure 3:

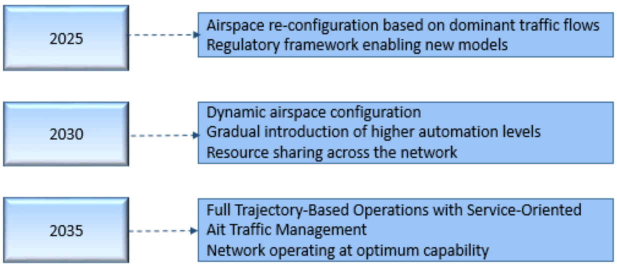

Figure 3. Milestones based on Airspace Architecture Study (Source: Authors based on SESAR, 2019)

4.1. Implementation weaknesses

Several challenges have been identified in the transition from traditional ANSPs to ATSPs and ADSPs (Commission Implementing Regulation (EU) 2017/373, 2017 and CP1 Regulation, 2021):

- Unclear Certification Framework — The introduction of future ADSPs poses significant risks if certification and licensing issues are not adequately addressed.
- Lack of Established Procedures — No standardised processes currently exist for certifying Data Service Providers independently from traditional ANSPs.
- Evolving Standards — Technical and operational standards remain under development and are not yet fully mature.
- Unclear Liability — In the event of an accident involving multiple providers, responsibilities and liability chains are insufficiently defined.
- Data Integrity and Availability — Ensuring data quality, consistency, and cybersecurity is critical for safety.
- Need for New Methodologies — Future ATM systems require novel tools, performance indicators, and analytical approaches.
- Cybersecurity Risks — Increased data sharing introduces vulnerabilities, necessitating robust backup and failover mechanisms.
- Organisational and Operational Challenges — Transitional risks arise from operating between legacy and new systems.
- Trust and Sovereignty Concerns — Cross-border data services raise issues of confidence and regulatory compliance.
- Limited Market Maturity — The scope of ADSP service delivery remains undefined; only maximum potential service boundaries are currently identified.

4.2. Pathways for Transformation

The future direction of the transformation from Air Navigation Service Providers (ANSPs) to ATS Providers (ATSPs) and Air Traffic Data Service Providers (ADSPs) is a shift toward data-centric, network-enabled, and service-oriented aviation systems, while improving flight efficiency and reducing environmental impact, maintaining safety the overriding priority (SESAR, 2019 and European Union, 2021).

It is enabled through functional separation between operational ATC services and ATM Data Services, allowing scalable and cross-border data provision.

5. Transition Options for Small ANSPs

Under applicable legislative and regulatory frameworks, any separation of an ANSP into an ATSP and ADSP requires thorough analysis and validation of processes and procedures. This ensures that service quality, accuracy, reliability, and compliance are maintained throughout the transition. Currently, these steps are under investigation within a research framework. Following legislative amendments, the separation process must be reassessed as necessary to allow the ANSP to operate under market conditions while delivering safe and reliable services.

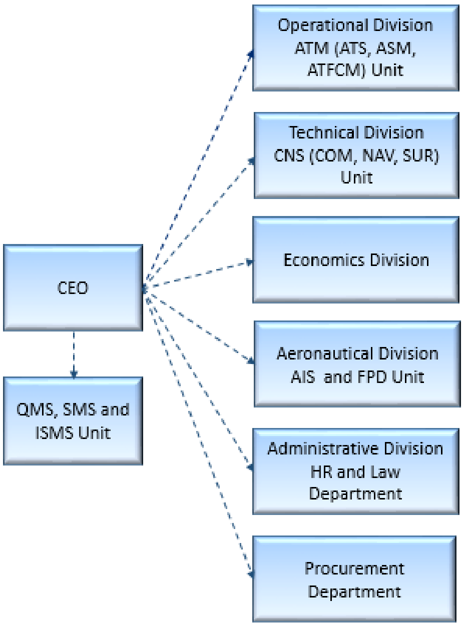

Figure 4. Simplified organisational structure for small ANSP, illustrative overview (Source: Authors)

Note 2: CEO – Chief Executive Officer; QMS – Quality Management System; SMS – Safety Management System; ISMS – Information Security and Cybersecurity Management System; ATS – Air Traffic Services; ATM – Air Traffic Management; ASM – Airspace Management; ATFCM – Air Traffic Flow and Capacity Management; CNS – Communication (COM), Navigation (NAV) and Surveillance (SUR); AIS – Aeronautical Information Service; FPD – Flight Procedure Design; HR – Human Resources.

6. Conclusion

The transformation of an Air Navigation Service Provider (ANSP) into separate Air Traffic Service Provider (ATSP) and ATM Data Service Provider (ADSP) roles represents a necessary and logical step in the evolution of air traffic management, driven by increasing digitalisation, network integration, and performance-based regulation. This separation establishes a clear distinction between operational service delivery and data-centric support functions, enhancing transparency, scalability, and regulatory oversight while maintaining safety as the paramount objective.

Analysis suggests that such a functional separation can improve interoperability, enable cross-border and network-level services, and align ANSP activities with SESAR and Common Project objectives. The feasibility and effectiveness of this transformation, however, rely on rigorous process validation, robust governance structures, and an adaptive regulatory framework that safeguards data quality, neutrality, and resilience.

Overall, the transition toward combined or distinct ATSP and ADSP roles is a key enabler for a data-centric, performance-driven, and future-ready air traffic management system.

References

EUROPEAN UNION 2017. *Commission Implementing Regulation (EU) 2017/373 laying down common requirements for providers of air traffic management/air navigation services and other air traffic management network functions and their oversight.*

EUROPEAN UNION 2021. *Commission Implementing Regulation (EU) 2021/116 on the establishment of the Common Project One supporting the implementation of the European Air Traffic Management Master Plan.*

EUROPEAN UNION 2024. *Regulation (EU) 2024/2803 of the European Parliament and of the Council on the implementation of the Single European Sky.*

SESAR 2019. *A proposal for the future architecture of the European airspace (Airspace Architecture Study).*

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AVIATION METEOROLOGY – ITS PAST, PRESENT, AND FUTURE

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Abstract

Meteorology has been connected with aviation since its beginnings. Weather has always significantly influenced flight possibilities and pilot safety; however, only with the development of air transport did a distinct field called aviation meteorology begin to take shape. Over time, this discipline evolved and adapted to technological progress, which influenced not only observation methods but also the processing and dissemination of meteorological information. Aviation meteorology is not only about forecasting but also about the development of communication networks, data standardization, and the role of international organizations in the distribution of data essential for aviation safety, efficiency, and overall economy. The article shows the path from basic and very simple information about the atmosphere and weather in aviation to today's methods of obtaining information important for ensuring aviation safety. It also shows how important it is to cooperate at the international level and to obtain and distribute information in a comprehensive way – from ground observations to data from meteorological satellites and numerical forecasting models.

Keywords

Aviation meteorology, ICAO, WMO, EUMETSAT

1. Introduction

Meteorology is one of the oldest natural sciences. Since ancient times, people have looked at the sky and tried to identify what changes in the amount and shape of clouds mean. They also tried to recognize changes in weather through variations in wind direction and speed. Although sailors were the first to study meteorology as a science, meteorology and rapid changes in meteorological elements soon began to interest the early pioneers of aviation.

2. History of Aviation Meteorology

The origins of meteorology as a scientific discipline date back to antiquity, when Aristotle became the first philosopher to systematically study meteorology. The result was his work Meteorologica, written in the 4th century BC. In this work, he addressed atmospheric phenomena such as rain, wind, lightning, fog, and others. (Neves, Gallardo and Vecchia, 2017) Although his claims were not based on practical evidence, his work represented the first attempt to explain meteorological phenomena. He attempted to explain them based on the four elements – water, fire, air, and earth. Although most of his conclusions were incorrect, his work became the foundation of meteorological studies for many centuries.

Meteorology began to develop as an observation- and measurement-based science in the 19th century. The first meteorological stations were established, systematically collecting and recording atmospheric data. Robert FitzRoy was the first to introduce meteorological forecasting. (Neves, Gallardo and Vecchia, 2017).

From the very beginning of aviation, pilots recognized that weather was a crucial factor in flight safety. World War I had a major impact on the development of meteorology in general, and especially on aviation meteorology. Weather forecasts were essential for both military and civil aviation, leading to the development of specialized military meteorological units focused on weather prediction. Data and forecasts needed to be distributed quickly. Radiotelegraphy enabled such rapid exchange of meteorological data, forming the foundation for today's information exchange and distribution systems, such as METAR and TAF. During this period, the first attempts at mathematical weather calculation were carried out by British mathematician Lewis Fry Richardson, laying the groundwork for modern numerical weather modelling. (US Department of Commerce, n.d.) (Zindel, 2020)

2.1. Aviation Meteorology Between the World Wars

From the mid-1920s, civil aviation in Europe began to develop more rapidly, increasing the demand for accurate meteorological information. Czechoslovakia responded by establishing specialized services at airports. For example, in 1923, the airline Czechoslovak State Airlines (ČSA) was founded and operated routes such as Prague–Bratislava–Zagreb. Monitoring weather conditions and developing forecasts was essential for these routes. (Musil, 2016)

In response to these needs, the first specialized aviation meteorological stations were established in present-day Slovakia. The Košice Airport station was founded in December 1921 as Aviation Weather Station No. 2, and Bratislava-Vajnory followed in July 1922 as Station No. 3. These stations were among the first professional observation points in the country, specifically focused on aviation needs and providing data for the increasing number of civil and military flights. (Slovenský hydrometeorologický ústav, 2024)

In professional literature, 1937 was a significant year. Gustav Swoboda published Aviation Meteorology and Aviation Weather Service, focusing in detail on weather observation and forecasting for aviation purposes.

2.1.1. Aviation Meteorology and World War II

Similar to World War I, World War II represented a major milestone for aviation meteorology. The renewed military conflicts created an urgent need for improved weather forecasting to support aviation, naval, and airborne operations. Around the world, including in the United Kingdom, Germany, the United States, and the Soviet Union, meteorology evolved from a supplementary discipline into a key element of military planning. (Galvin, 2020)

The importance of weather for successful air missions led to significant investments in personnel training, data collection, and the development of new technologies. The development of aviation meteorology was characterized not only by the establishment of specialized groups but also by technological advancements. Before the war, upper-air measurements were limited mainly to balloon observations with restricted range. During the war, radiosondes began to be used regularly. These devices transmitted atmospheric data wirelessly from higher layers of the atmosphere to the ground.

Another important development was radar meteorology. Radar, originally developed to detect enemy aircraft, began to be used during the war to detect precipitation systems and storm clouds. (Povetrie.sk, 2023)

Meteorology played a significant role during the war, as demonstrated by Operation Overlord – the Allied invasion of Normandy in June 1944. Thanks to accurate weather forecasts prepared by Allied meteorologists, the invasion was postponed, surprising German command. With the introduction of new computational methods and physical modelling, principles of atmospheric dynamics and mathematical forecasting began to be applied to meteorology. This trend was strongly developed by the Chicago School of Meteorology, building on the work of the Bergen School. As a result, meteorology gradually transformed from a descriptive science into a quantitative predictive discipline. The operational use of weather forecasts in wartime laid the foundation for modern aerological networks, aviation forecasting services, and radar meteorology, which later became fundamental for both military and civil aviation. (news.uchicago.edu, 2020)

3. Meteorology After World War II

The end of World War II marked a reorganization of global meteorological services, as military meteorology, previously controlled mainly by armed forces, began transitioning into civilian use. Since aviation was rapidly developing, it required the establishment of new institutions, standards, and forms of international cooperation.

The Chicago Convention was signed in 1944, but its principles were fully implemented only after the war. These principles led to the creation of the International Civil Aviation Organization (ICAO), whose goal was to ensure efficient and safe international air transport operations, including meteorological support. In 1948, ICAO adopted its first meteorological regulations, which later became the basis for Annex 3 to the Convention on International Civil Aviation, focusing on meteorological services for civil aviation. (Čech, n.d.)

At the same time, there was a need to establish a unified global meteorological institution. The World Meteorological Organization (WMO), founded in 1953, cooperates with ICAO in developing regulations, methodologies, and meteorological infrastructure for aviation. (Čech, n.d.) (Icao.int, 2026)

Formats for exchanging meteorological data were also developed. This led to the introduction of international codes such as SYNOP (surface observations), TEMP (upper-air measurements), and AIREP (pilot weather reports). These codes enabled countries to share acquired data efficiently in a unified format, forming the basis of standardized meteorological communication in aviation and paving the way for later formats such as METAR and TAF. (Icao.int, 2026)

The post-war period created conditions for meteorology to become an integral part of aviation. The introduction of upper-air measurements, the establishment of international institutions, and the first standards for simple and unified data exchange were just the beginning of processes that continued to evolve in the following years.

3.1. Aviation Meteorology in the Era of Digitalization and International Standardization

The period after 1957 marked significant progress in meteorological technologies and intensified global cooperation. In 1957, the Soviet satellite Sputnik 1 was launched, initiating the era of space-based technologies. Another major milestone was the launch of the American satellite TIROS-1 in April 1960. TIROS provided the first cloud images from orbit, opening the possibility of regularly using satellite data in practice, including weather forecasting for aviation. (Spivey, 2024)

In 1968, METAR and TAF reports were introduced based on ICAO and WMO regulations. These codes continue to provide current observations and future weather forecasts at airports. Their introduction significantly improved and simplified international communication and enhanced aviation safety.

At the same time, numerical weather prediction based on mathematical modelling of atmospheric processes was developing. The first predictive models, such as LFM and NMC, provided information useful for planning flight routes. (Icao.int, 2026) (US Department of Commerce, n.d.)

Automation during the 1970s and 1980s led to the introduction of meteorological measurement systems such as ASOS and AWOS. These systems provided continuous and up-to-date information about atmospheric conditions at airports without requiring human operation. The data were then supplied to forecasting centres for decision-making purposes. (US Department of Commerce, n.d.)

On the international level, meteorological data exchange developed through the Global Telecommunication System (GTS), operated by WMO. The European organization EUMETSAT manages meteorological satellite operations, providing near real-time data exchange between continents and improving the reliability of large-scale weather forecasts, thereby enhancing aviation safety. (EUMETSAT, 2020)

Currently, international cooperation is developing through various platforms that use meteorological data to predict weather conditions worldwide based on numerical prediction models, both at the surface and at various flight levels. These data are used daily, making aviation safer and flights more comfortable. For example, significant weather charts allow flights to be planned effectively with respect to hazardous weather phenomena. Programs such as C-SRNWP (Coordination of Short-Range Weather Prediction) enable cooperation among national services in developing and sharing regional prediction models such as AROME, ALADIN, and ICON. (Srnwp.eu, 2026) The attached images show current possibilities for displaying meteorological information for aviation.

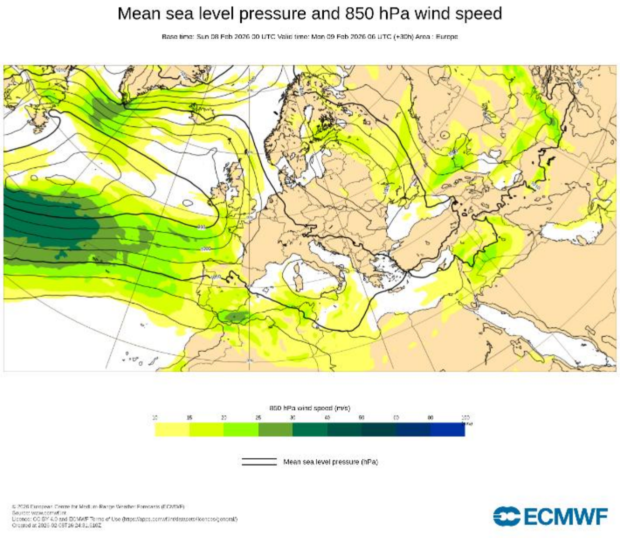

Figure 1. (ECMWF) shows the output from a numerical forecasting model – mean sea level pressure (MSLP) and wind at the 850 hPa level.

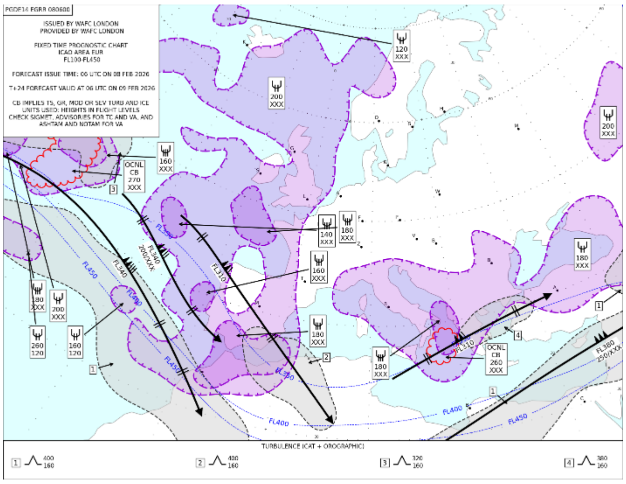

Figure 2. shows hazardous weather phenomena between flight levels FL100 and FL450.

4. The Future of Aviation Meteorology

The use of satellites, meteorological radars, and numerical models has become standard practice. However, aviation faces several challenges that aviation meteorology must address in the future.

In recent decades, the impact of climate change on aviation has become increasingly important. Continuous global temperature increases, more frequent occurrences of severe turbulence in jet stream levels, and higher risks of extreme weather events such as heat waves or heavy rainfall have affected flight times and route planning. Organizations such as Climate Central warn that adverse phenomena caused by climate change will increasingly influence the efficiency of air transport. Modern times are characterized by the integration of new technologies. (Climatecentral.org, 2025)

At the national level, fully automated reports such as METAR AUTO have been introduced, and meteorological institutes, including the Slovak Hydrometeorological Institute (SHMÚ), are incorporating diagnostic tools for identifying hazardous phenomena, moving toward the use of artificial intelligence.

As unmanned aerial systems (UAS/UAV) are increasingly used, there is also a growing need for meteorological support for these operations. New forecasting methods are being developed for low-cost operations, particularly in urban areas where data on wind conditions, temperature, and precipitation at low altitudes are crucial.

Modern aviation meteorology is characterized by fundamental transformation through digitalization, globalization of data exchange, automation, and intelligent systems. (Engage 2 - Engage 2 project website, 2023)

5. Conclusion

Over the past decades, aviation meteorology has undergone remarkable transformation. From a field based on individual observations and limited technology, it has gradually become part of highly automated, digitally interconnected systems. Technological development, output standardization, and the integration of international organizations have created the foundation for reliable exchange of meteorological data, which is now essential for safe and efficient aviation operations.

Current trends in aviation meteorology show increasing emphasis on information personalization, artificial intelligence, automated systems, and predictive models. The importance of meteorology is not declining – on the contrary, it is becoming even more essential with the development of new forms of aviation, such as unmanned systems and urban air mobility. Reliable weather information remains one of the most important pillars of aviation, both today and in the future.

References

Čech, I. n.d. *Univerzita Karlova v Praze Právnická fakulta Civilní letectví v EU a ČR z pohledu unijního práva Diplomová práce*. Available at: https://dspace.cuni.cz/bitstream/handle/20.500.11956/80844/DPTX_2013_1_11220_0_177424_0_145560.pdf

Climate Central 2025. *Study: Warming leads to longer flights, more emissions*. Available at: https://www.climatecentral.org/news/warming-longer-flights-more-emissions-19234

EUMETSAT 2020. *What we do*. Available at: https://www.eumetsat.int/about-us/what-we-do.

Engage 2 project website 2023. *Home – Engage 2*. Available at: https://engagektn.com/wp-content/uploads/2021/11/C14-METSIS-executive-summary.pdf

Galvin, J. 2020. ‘Meteorology and the Second World War’. *Weather*. Available at: https://doi.org/10.1002/wea.3687.

International Civil Aviation Organization 2026. *The Chicago Convention 1944*. Available at: https://applications.icao.int/postalhistory/1944_the_chicago_convention.htm

Musil, L. 2016. *Historie ČSA – díl 1. 1923–1939*. Available at: https://www.czechairliners.net/index.php/letecke-spolecnosti/1047-historie-csa-dil-1-1923-1939.html

Neves, G., Gallardo, N. and Vecchia, F. 2017. ‘A short critical history on the development of meteorology and climatology’. *Climate*, 5(1), p. 23. Available at: https://doi.org/10.3390/cli5010023.

Povetrie.sk 2023. *História vývoja meteorologických prístrojov a meracích zariadení*. Available at: https://www.povetrie.sk/2023-05/historia-vyvoj-meteorologickych-pristrojov-meracich-zariadeni.

Slovenský hydrometeorologický ústav 2024. *100 rokov od založenia meteorologickej stanice Košice-letisko*. Available at: https://www.shmu.sk/sk/?page=2049&id=1186 .

Slovenský hydrometeorologický ústav 2024. *Storočnica letiskovej meteorologickej stanice v Bratislave*. Available at: https://www.shmu.sk/sk/?page=2049&id=1188 .

Spivey, S. 2024. *Celebrating Earth Day: The first satellite images of the earth were taken 64 years ago*. Available at: https://www.ksat.com/weather/2024/04/23/celebrating-earth-day-the-first-satellite-images-of-the-earth-were-taken-64-years-ago .

SRNWP 2026. *35th EWGLAM and 20th SRNWP meetings*. Available at: https://www.srnwp.eu/content/annualMeetings/2013/default.htm .

University of Chicago News 2020. *The World War II-era Chicago school of meteorology that decoded weather forecasting*. Available at: https://news.uchicago.edu/story/world-war-ii-era-chicago-school-meteorology-decoded-weather-forecasting.

US Department of Commerce, National Weather Service n.d. *ASOS*. Available at: https://www.weather.gov/asos.

US Department of Commerce, National Weather Service n.d. *December 17, 2013 marks the 110th anniversary of the Wright Brothers’ first flight*. Available at: https://www.weather.gov/mhx/FirstFlight.

Zindel, H. 2020. ‘Ballooning: Aeronautical techniques from Montgolfier to Google’. *De Gruyter eBooks*, pp. 107–128. Available at: https://doi.org/10.1515/9783110647044-007.

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OPTIMIZATION & MODERNIZATION OF LEGACY NAVIGATION INFRASTRUCTURE

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Abstract

As increasingly advanced systems continue to emerge within the aviation industry, existing systems are expected to evolve accordingly. For this reason, both world's leading aviation authorities - the Federal Aviation Administration (FAA) and the European Union Aviation Safety Agency (EASA) - emphasize a shared and consistent message: despite the rapid and exponential growth of new technologies, it remains essential to preserve and maintain the legacy navigation infrastructure. This paper begins with an introduction, followed by a brief overview of the early development of Ground-Based Navigation (GBN). I then provide clear definitions of the main types of GBN equipment, accompanied by detailed explanations of their function and relevance. Afterward, I outline the methodology used in this study, describing the different phases of work that contributed to the results. Subsequently, I present and compare the current state of GBN equipment in Portugal, considering the characteristics of Portuguese airspace previously described. Finally, it will be discussed also the potential optimization and modernization of this infrastructure - exploring whether these systems should be integrated, upgraded, or gradually phased out, according to truthful literature.

Keywords

Air Traffic Service, Air Traffic Management, Legacy Navigation Infrastructure, Ground-Based Navigation, Navigation Aid, Global Positioning System, Inertial Navigation System, Microwave Landing System, Very High Frequency Omnidirectional Range, Distance Measuring Equipment, Instrument Landing System.

1. Introduction

As a famous quote says, "If you already arrived at the airport, it means that the chance of surviving the next few hours has increased exponentially."

It happens that the scenario has not always been like the one we have nowadays. It is because of Air Traffic Management (ATM) that it is possible to have thousands of aircraft flying at the same time, using the same routes and airports, taking off and landing within moments of each other - all of this with an incredibly low failure rate. Even though the first ever flight happened in 1903, it was only during the First World War that Air Traffic Control (ATC) was born. During the last year of the war, the first commercial airline was established, connecting England and Belgium to fulfil military purposes. In the first years of the following decade, 30 commercial airlines were established around the globe. By 1920, the first ever ATC tower was erected at London Croydon. From then on, Civil Aviation Traffic Officers were able to provide navigation, traffic, and weather information to pilots over the radio. (S. Golstein, 2023)

In the early days, pilots used to fly 200 to 500 feet above the ground to navigate using roads as reference. Fire was also commonly used to help pilots follow certain routes or assist them in landing the aircraft. As air travel increased, air controllers would stand in the field and wave flags to communicate with pilots. As time went by, these methods were quickly replaced by others, such as the installation of runway lights to help pilots land the aircraft when weather conditions were not ideal. (A. Novak, 2008)

A long time has passed and, with the advance of technology, there is no important word than 'safety.' This has been achieved through the continuous international cooperation on aviation safety carried out by the 193 countries that work together through ICAO, the International Civil Aviation Organization. Together, these countries have committed to reaching the global safety target of zero fatalities by 2030 – something unimaginable in the previous century. (ICAO, n.d.)

Next, I intend to explain the role of GBN in daily aircraft operations. Despite the advance of numerous and very important technologies, all supported and validated by the responsible institutions, it is crucial to take into consideration the importance of this type of navigation, so that its value is not forgotten.

2. Early days of ground- based navigation

Although briefly introduced earlier, it is essential to clearly understand how contemporary ground-based navigation systems operate. However, achieving this understanding first requires tracing their historical foundations. For this reason, this section presents a concise overview of the origins and early evolution of Ground-Based Navigation (GBN), establishing the context necessary to appreciate its current role and technological progression.

2.1. Non-radio methods of navigation

Navigation offered three main methods, excluding the radio aid, to help and successfully complete the mission: fly as safe as possible. There were pilotage, celestial navigation and dead reckoning. This last will be more developed then the other two later in this paper. Starting with the first method: pilotage. This is referred as the natural ability of the human being to find, better or worse, certain track by remembering certain places, spots or marks. In order to aid the aviators, they served themselves with the most basic human abilities, like the vision and the smell. As referred before, they used vision (and, consequently, memory) to locate familiar places/marks; but also the smell - if they were flying near the sea or near the land, they could use also the smell to take out some information (not that used, because aviators were confined inside a tight cockpit, what disabled them to use this sense in a proper way). It is important to say that pilotage was not that useful if the weather conditions were not ideal or if the aircraft was flying in open waters, because of the lack of visual references. (Doug Davis, 2021)

Secondly, there is the celestial navigation, used since the ancient times by diverse cultures. Greek and Arabs used the astrolabe which allowed them to, after some calculations, discover the time and latitude of certain object. During the 19th century, almanacs, the sextant and accurate clocks were precious. The first contained the exact location of key celestial objects at regular times above the earth, the second was able to measure the angle of the object above the earth and the third served as proof to see if the observers obtained the measurement at the precise time noted in the almanac. (Doug Davis, 2021)

Finally, and concerning the purpose of this paper, the most important of the non-radio methods of navigation, the one called dead reckoning. Inertial Navigation Systems (INS) emerged when engineers discovered that high-precision sensors, together with increasingly capable computers, could handle dead- reckoning calculations automatically; faster and more accurately than a human, and in three dimensions. Nowadays, it is commonly used as a complimentary backup to Global Navigation Satellite System, GNSS, in nearly all navigation applications. (Doug Davis, 2021)

2.2. Ground-Based Navigation

For many years, the GBN has been extremely useful in the daily aircraft operation. In fact, and according to FAA, the GBN provides very useful aid, commonly used to make the operation the most efficient and effective, with the objective of meeting operational needs. Next, it will be presented some types of GBN, like ILS, VOR, DME and NDB.

2.2.1. Instrument Landing System - ILS

The Instrument Landing System (ILS) consists of a set of equipment installed on the ground at airports, situated near the runways. Its function is to provide pilots with accurate information about their lateral and vertical position relative to the runway, in order to aid the landing. This system has 3 categories (CAT I, II and III) according to the sensitivity they provide. (M. Durgut, 2020)

Figure 1. Instrument landing System

This equipment consists of two separate infrastructures. Both systems work on their own, but their information is combined in the cockpit to provide the pilot with precise guidance in both the lateral and vertical planes. On the left, there is the Localizer (LOC), transmitting VHF signals between 108.1 MHz and 112 MHz and providing aircraft with lateral guidance; very useful to help the pilots to align the nose of the aircraft with the center of the runway. On the right side, we have the Glide Scope (GS) that transmits UHF signals between 329.15 MHz and 335.0 MHz to give vertical guidance to the pilot. (FAA, n.d.) Besides these two main structures, there is also a marker device (located on the approach line) and approach lights.

That´s with the precious help of these infrastructures that the aircrafts do a descent to the decision altitude, at a time when the pilot must be able to see the runway and decide: either he lands or declares a missed approach. (A. Novak,2008)

2.2.2. Very High Frequency Omni-Directional Range – VOR

The Very High Frequency Omni-Directional Range, or VOR, is a navigation aid that gives aircraft directional guidance to an airport by indicating their bearing from 0 to 360 degrees through visual instruments. It operates within the 108 to 118 MHz frequency band. (Djunaedi, 2024)

Figure 2. Very High Frequency Omni-Directional Range

Numerous VORs suffer from reduced signal performance due to nearby obstacles that partially block their transmissions. This can be caused not just by natural encroachments, like the existence of tall trees, but also with the presence of synthetic obstacles (radio towers, overhead transmission lines, wind farms, among others). Using a DVOR configuration mitigates signal-in-space issues that occur when obstacles reflect the VOR signal. (A. Novak, 2008)

2.2.3. *Distance Measuring Equipment – DME*

Distance Measuring Equipment is an international standardized pulse-ranging equipment system for aircraft, operating between the interval of 960 to 1215 MHz. When the ground station is collocated with a VOR station, the resulting combination forms the standard ICAO rhotheta short- range navigation system. (Kayton and Fried, 1997). The rho (distance from the facility) is supplied by the DME and the theta (azimuth bearing from magnetic north) is supplied by VOR/DVOR.

Figure 3. Distance Measuring Equipment

2.2.4. *Non-Directional Beacon*

A Non-Directional Beacon (NDB) is a ground- based radio transmitter that operates on low frequencies and helps instrument approaches at airports. It sends out a signal in all directions, which is picked up by the Automatic Direction Finder (ADF) onboard the aircraft. Using the ADF, the pilot can identify the direction of the beacon in relation to the aircraft. To navigate with it, the pilot simply tunes the NDB's frequency, and the ADF needle will point toward the station. (Goodhue, 2025)

Figure 4. Non-Directional Beacon (NAV Portugal, 2025)

3. Methodology

Considering the topic of this paper, the main goal was to understand what role legacy navigation infrastructure still plays in today's aviation environment. With so many new systems being developed and introduced, it's easy to assume that this older equipment is becoming less relevant. Because of that, the goal is understanding how these traditional navigation aids actually fit into the current reality, and whether their importance is truly disappearing or if they still hold a meaningful place in the overall system.

3.1. Research

Since the topic addressed in this paper is not among the most widely explored in existing research, especially when compared to other, I quickly realised the need to engage in deeper investigation. To do so, I consulted several important, reliable and high- quality studies that significantly contributed to the development of this paper. My research process involved using platforms such as Google Scholar, ResearchGate and Web of Science, among others. In addition, I frequently accessed the website of the Portuguese ANSP, NAV Portugal, as well as the Portuguese Aeronautical Information Publication (AIP). These resources proved to be particularly valuable, as they allowed me to understand in detail the current intentions and strategic directions of my country regarding certain topics - information that I could not find in any other source. Beyond these references, I also analysed the SESAR Master Plan 2025 and the ATM Master Plan 2015. Both documents were extremely useful and constructive for the preparation of this work, especially because they enabled me to align my research with current European trends and long-term developments in the field. Finally, and after gathering and reviewing all the material that I had collected, the next step was to cross-compare the entire information. This process was essential to synthesise the findings and ultimately produce a coherent, meaningful and worthwhile piece of work.

4. Portuguese aeronautical infrastructures

4.1. Portuguese Air Space

Portugal, despite his small size as a country, has an enormous air space. The Portuguese air space is, nowadays, one of the bigger when compared to the size of the country. It is currently divided in two different zones, covering: the Lisbon RIV and Santa Maria RIV – RIV stands for, in Portuguese, Região de Informação de Voo, that can be translated to Flight Information Region (FIR).

The first mentioned FIR aims to cover all the Portuguese continental area plus the Madeira archipelago. The second one covers all the area around the Azores archipelago, until the middle of the Atlantic Ocean. According to NAV Portugal, the Portuguese Air Navigation Service Provider (ANSP), the Lisbon FIR covers an area of 660 thousand square kilometres, which includes the Lisbon Control Center plus six control towers, which are situated in six airports: Cascais Airport, Faro Airport, Funchal Airport (in Madeira Island), Lisboa Airport, Porto Airport and Porto Santo Airport, this last one situates also in the archipelago of Madeira.

Secondly, there is the Santa Maria FIR. This one is even bigger than the other mentioned above: it covers a total area of, approximately, more than 5.1 million square kilometres. It includes, also, the Oceanic Control Center and four control towers, located in four airports in Flores, Horta, Ponta Delgada and Santa Maria. These islands mentioned are part of the Azores Archipelago. (NAV Portugal, 2024) Finally, and just for comparison, Portugal just has a total land area of 92.212 square kilometres.

Figure 5. Lisbon (right) and Santa maria (left) FIRs.

4.2. Ground-Based Navigation in Portugal (2015 – 2025)

Over the last 10 years, the navigation infrastructure in Portugal has changed quite noticeably. Some of the older systems that had been in place for decades have been updated, replaced, or even removed, while other, more reliable and modern, have been introduced. These changes reflect the normal evolution of aviation needs and the continuous effort to keep the Portuguese network safe, efficient, and aligned with current operational practices. Looking at what has been added, what has disappeared, and what has been improved provides a clear picture of how the overall system has adapted to today's requirements. According to the Portuguese ANSP, Portugal has every GBN equipment mentioned above, all over its territory. Starting with the first ground-based equipment referred in this paper, the ILS.

This navigation aid has been, in the past decade, replaced and updated for new one, to respect the demands of ICAO:

- ILS installation on runway 10 in Faro Airport, in 2015;
- ILS replacement on two runways in Lisbon Airport, in 2019. The previous equipment had been in use since 2004;
- ILS replacement on runway 17 with newer equipment at Porto Airport in 2020. The previous equipment had been in use since 2000.
- ILS installation on runway 35 at Porto Airport, in 2020.
- ILS replacement at São Miguel Airport and in Santa Maria Airport, in 2020.
- ILS installation at Montijo Airport, in 2020.
- Replacement of the antenna system and radio-signal distribution for the Localizer and Glide Path components of ILS on runways 02 and 20 at Lisbon Airport in 2022, to ensure continued CAT III operational capability.

It is important to highlight that, as of 2025, Portugal has ten airports equipped with Instrument Landing Systems. This is particularly notable given that ILS is a long-established technology, implemented many decades ago. Despite the emergence of more modern navigation and landing systems, ILS continues to demonstrate its value and reliability, showing no signs of being phased out in the next decades.

Another example of GBN equipment that has followed the same path as the ILS is the VOR/DME. Over the past decade, Portugal has made a clear effort not only to install additional stations but also to replace older ones with newer and more reliable equipment. This has been important to ensure good coverage across the entire territory and to maintain a robust network of navigation aids where they are most needed. (Online EAIP – NAV Portugal AIS, 2025)

- In 2015, it was replaced one navigation station VOR/DME, at Espichel;
- In 2016, it was replaced four navigations stations VOR/DME at Nisa, Viseu, Porto and Horta Island;
- In 2018, it was replaced one navigation station VOR/DME at Santa Maria Island;
- In 2022, it was replaced three navigation stations VOR/DME at Funchal Island, Cascais and Porto Santo Island.

The same observation made for ILS also applies to VOR/DME systems. Even though, like ILS, VOR/DME has been in use for many decades, it remains a cornerstone of the global navigation infrastructure.

Nowadays there is, across the Lisbon Flight Information Region, a total of 14 radio navigation aids of various types are installed. Concerning the Santa Maria FIR, there are 16 such aids distributed across the archipelago: five in Santa Maria Island, five in São Miguel Island, three in Horta Island, and three in Flores Island. (NAV Portugal, 2024)

Besides, a comprehensive redesign of the CNS systems implemented in the control towers aimed at fully enabling the provision of Air Traffic Control services. Over the past decade, these CNS systems have undergone continual modernization and incremental upgrades, ensuring they remain aligned with evolving international standards, technological advancements, and operational requirements. This ongoing renewal process has strengthened system reliability, improved performance, and enhanced the overall safety and efficiency (AIP's, 2015-2025)

5. Optimization & modernization

Europe's air traffic system is reaching a turning point. The skies are getting busier every year as the number of flights continues to grow, yet safety remains exceptionally high. Although, the system is struggling to follow. Six years ago, just before the COVID-19 pandemic, air traffic hit a record of nearly 11 million flights. (European Union, 2025)

By 2024, and even with the war in Ukraine since the beginning of 2022, many European countries were already having more flights than before the pandemic, and forecasts suggest traffic will keep rising, eventually reaching around 16 million flights by 2050. At the same time, the airspace will become even more complicated to manage as new kinds of aircraft are being developed, like zero-emission planes, military and non-military drones, not forgetting high-altitude vehicles. (European Union, 2025)

As a crucial component of the Single European Sky (SES), the European ATM Master Plan serves as Europe's roadmap for modernising air traffic management. It defines the goals, direction, and main priorities for achieving a fully digital European sky, with the objective of making Europe the most efficient and environmentally sustainable airspace in the world by 2045. In that year, it will be expected that every flight will be managed in the most efficient way from departure to arrival, supported by seamless communication between aircraft, air traffic control, and all ground systems. European ATM pretends to eliminate unnecessary fuel consumption and also enhance its impact on non-CO_2 emissions, noise reduction and local air quality. The system will be flexible and robust, capable of adjusting to changing traffic levels and supporting an increasingly diverse range of aircraft; all while maintaining the highest standards of safety and security. Air traffic management will also be fully connected with other modes of transport, creating a truly integrated transport network. (European Union, 2025)

5.1. Strategic Deployment Objectives (SDOs)

The focus here is on Europe's deployment priorities, introducing the strategic deployment objectives. These objectives represent a set of high- priority actions, or essential operational changes, that must be implemented between 2025 and 2035. They are crucial for delivering the overall vision and performance targets and are built on SESAR Solutions that are either already mature or expected to reach that level by the next year. (European Union, 2025)

The SDOs were selected following a prioritisation process that evaluated the relevance and readiness of the supporting SESAR Solutions. The selection was then based on four criteria: the critical role they can play in addressing climate-neutral aviation, capacity and scalability, safety criticality and the uptake of innovative air mobility.

- Allerts for reduction of collision risks on taxiways and runways;
- Optimising airport and Terminal Manoeuvring Area, TMA, environmental footprint;
- Dynamic airspace configuration;
- Increased automation support;
- Transformation to Trajectory-based Operations (TBO);
- Virtualisation of operations;
- Transition towards performance of Air- Ground Connectivity (Multilink);
- Service-oriented delivery model (Data- driven and Cloud-based);
- CNS Optimisation, Modernisation and Resilience;
- Enable Innovative Air Mobility (IAM) and drone operations.

Even though all those 10 objectives are equally important, this paper will give more emphasis to the 9th objective due to its topic. The objective itself aims to optimise, modernise and increase the resilience and interoperability of Communication, Navigation and Surveillance in Europe, building on top of ongoing deployment activities, in particular the ones already included in Commission implementing regulations (PBN – Performance-Based Navigation, datalink). (European Union, 2025)

5.2. Infrastructure and how it can be optimized

The objective of deployment is to deliver benefits as soon as possible, while keeping investments smart, cost-effective and well- coordinated. To achieve this, different actors need to align their plans and timing, with support from EU funding to help make that happen. Since automation, integration and harmonisation are central to the future vision, it's important to establish common standards early and involve a wide range of public and private stakeholders from the very beginning - even during the R&D stage (Research and Development stage). This broad collaboration lays the groundwork for a smooth and successful rollout across the entire network. (European Union, 2015)

CNS technologies, both on the ground and onboard aircraft, are a key technical foundation for many of the future operational improvements and new procedures in the ATM system. The performance expectations for these systems are becoming more complex, and they will increasingly be viewed as part of a single, integrated air-and-ground CNS environment. Where it makes sense, different areas communication, navigation and surveillance may move towards shared or common infrastructure components. (European Union, 2015)

At the same time, CNS systems and infrastructure, both airborne and ground-based, will adopt a more business-oriented approach, aiming to use resources more efficiently and deliver the required capabilities in a cost-effective and spectrum-efficient way. These considerations are reflected in the CNS roadmaps, which defines the technologies and infrastructure needed to support the evolution of the SESAR Target Concept. (European Union, 2015) According to the SESAR Master Plan 2025, these are the specific objectives about CNS optimisation and modernisation:

- Implemented a secured surveillance functionality that enables detection and, when possible, mitigation of security threats that could affect the surveillance chain;
- Implement minimum operational work (MON);
- Rationalise ILS and implement efficiency measures/methods for more cost-effective maintenance of ILS, providing a link between ICAO and national CNS provision;
- Optimise surveillance, leveraging terrestrial and space-based information.

5.3. Future of legacy navigation infrastructure

Legacy navigation infrastructure, such as VOR, DME, NDB, and ILS, remain widely used around the world, and most aircraft carry the necessary equipment to use them. Because GNSS signals can be vulnerable to interference, it has been recognized that some traditional radio navigation systems, or an alternative navigation service, must be maintained as a backup to GNSS. (ICAO, 2016)

Managing operations during a GNSS interruption will depend mainly on the use of signals from other constellations or on applying pilot and ATC procedures, supported by onboard inertial systems and selected conventional navigation aids. If a broad GNSS outage occurs in a region, switching back to conventional aids and procedures may reduce airspace capacity or flight efficiency. However, when signal loss affects only one GNSS constellation, switching to another may allow the same PBN performance level to be preserved. (ICAO, 2016)

As PBN becomes the standard for area navigation, DME stands out as the most suitable conventional aid to support these operations (assuming aircraft have onboard DME multilateration capability), as it is already integrated into multi-sensor avionics for this purpose. DME networks and coverage will therefore need to be improved accordingly. Likewise, the continued widespread use of ILS will ensure that, where installed, it remains a viable alternative for approach and landing in the event of a GNSS failure. (ICAO, 2016)

Today's single-frequency GNSS offers the most accurate globally available positioning service. Although it generally delivers very high availability, it still lacks sufficient resilience to certain vulnerabilities - especially radio frequency interference and ionospheric disturbances caused by solar activity. Because a fully resilient solution has not yet been achieved, it remains essential to maintain a terrestrial navigation infrastructure that is robust enough to ensure safe and continuous aircraft operations. (ICAO, 2016)

5.4. Cost-Efficiency Analysis of Legacy Navigation Infrastructure

To assess whether legacy ground-based navigation (GBN) infrastructure should be maintained, rationalized or replaced, a cost-efficiency evaluation was performed using a multi-criteria analytical framework based on three pillars:

- Economic efficiency (CAPEX + OPEX)
- Operational performance (availability, continuity, coverage)
- Resilience contribution (backup capability during GNSS degradation)

The analysis compares:

- ILS vs GNSS/GBAS approaches,
- VOR/DME vs DME/DME positioning networks,
- NDB vs alternative backup solutions.

5.4.1. Cost Structure Definition

(A) Capital Expenditure (CAPEX) Includes:

- Equipment acquisition
- Installation and calibration
- Civil works and site preparation
- Flight inspection certification

(B) Operational Expenditure (OPEX) Includes:

- Preventive maintenance
- Corrective maintenance
- Flight inspection cycles
- Energy consumption
- Spectrum and regulatory compliance

Table 1. Typical ranges (indicative European averages 2015 -2025)

System	CAPEX (approx..)	Annual OPEX
ILS CAT I	1.0 – 1.5 M€	120 – 180 k€
ILS CAT III	2.0 – 3.5 M€	200 – 350 k€
VOR/DME	0.8 – 1.5 M€	80 - 150 k€
Standalone DME	0.4 – 0.6 M€	50 – 100 k€
NDB	0.2 – 0.5 M€	30 – 65 k€
GBAS	2.5 – 4.0 M€	150 – 250 k€

Cost per Operational Benefit Metric (COCU)

$$COCU = \frac{Total\ Lifecycle\ Cost}{Coverage\ area\ x\ Operationa\ Avialibity}$$

Where:

- Lifecycle cost = CAPEX + (OPEX × 20 years)
- Coverage area = effective service radius
- Availability = system availability (e.g., 99.9%)

This enables comparison between:

- Wide-area enroute systems (VOR/DME)
- Precision approach systems (ILS)
- Satellite-based systems

A comparative cost-efficiency assessment indicates that ILS remains operationally indispensable in high-density environments and for CAT II/III precision approaches, where its independence from satellite vulnerability ensures high resilience. However, due to significant lifecycle and maintenance costs, ILS is economically unjustified at low-traffic regional airports. GNSS/GBAS solutions offer greater scalability and lower per-runway infrastructure requirements, yet their exposure to radio frequency interference and jamming limits their suitability as a standalone solution in resilience-critical environments. Regarding en-route navigation, VOR infrastructure is progressively less cost-efficient due to higher maintenance demands and reduced relevance in performance-based navigation (PBN) airspace. In contrast, an optimized DME network provides a more economically sustainable alternative, supporting DME/DME positioning, enhancing spectrum efficiency, and aligning with multi-sensor avionics architectures.

This rationalization approach is consistent with the Minimum Operational Network (MON) concept.

Finally, although NDB systems exhibit low capital and operational costs, their limited accuracy and vulnerability to atmospheric interference render them operationally inefficient within modern PBN frameworks. A gradual phase-out strategy is therefore recommended, retaining installations only where terrain constraints or redundancy requirements justify minimal backup capability.

Overall, a hybrid architecture combining selective ILS retention, DME network optimization, and GNSS-based primary navigation represents the most cost-efficient and resilience-balanced solution.

Resilience Cost Multiplier

A resilience weighting factor (RWF) was introduced:

$$Adjusted\ Cost = \frac{Lifecycle\ Cost}{Resilience\ Contibution\ Score}$$

Where Resilience Contribution Score (1–5) evaluates:

- GNSS independence
- Failure isolation capability
- Capacity preservation during outage

Table 2. Typical scoring for navigation system in Portugal

System	Resilience score
ILS	5
DME	4
VOR	3
VOR/DME	4
NDB	2
GNSS	2 (due to vulnerability)

This demonstrates that although ILS has higher cost, its resilience-adjusted cost becomes competitive.

Considering the specific characteristics of Portuguese airspace—particularly the extensive Santa Maria oceanic FIR, the high operational reliance on GNSS, and the projected growth in traffic density—a balanced and resilience-oriented CNS strategy is required. Maintaining ILS capability at major airports such as Lisbon, Porto, and Faro remains operationally justified due to traffic volume and precision approach requirements. At the same time, the rationalisation of the VOR network and the expansion of DME-based positioning coverage represent cost-efficient measures aligned with modern PBN operations. Preserving a Minimum Operational Network (MON) backbone ensures continuity of operations in the event of a GNSS disruption.

From a purely economic standpoint, maintaining the entire legacy navigation infrastructure is not cost-optimal. However, from a system resilience and safety perspective, selective retention of critical assets is essential. The most efficient long-term solution is therefore a hybrid CNS architecture in which satellite navigation serves as the primary layer, supported by a rationalised DME network, retained ILS precision capability at key airports, a minimal VOR backbone where operationally justified, and the gradual retirement of NDB systems. This approach supports both cost-efficiency and operational robustness, while remaining consistent with SESAR Strategic Deployment Objective 9 and broader European ATM digitalisation goals.

6. Conclusion

Aviation navigation in Portugal has evolved within the broader global transformation of air traffic management, progressing from early non-radio techniques to a complex system of ground-based and satellite-based technologies that sustain operations across both the Lisbon and Santa Maria Flight Information Regions. This evolution reflects not only technological advancement but also Portugal's commitment to maintaining high safety standards within one of Europe's most geographically distinctive airspace structures—characterised by a vast oceanic FIR, significant transatlantic traffic flows, and growing operational density.

Although Global Navigation Satellite Systems (GNSS) constitute the primary navigation source across Portuguese airspace, particularly in the oceanic environment of the Santa Maria FIR, their vulnerability to radio-frequency interference, jamming, and spoofing represents a non-negligible operational risk. In this context, legacy ground-based navigation systems—including ILS, VOR, DME, and, to a lesser extent, NDB—retain strategic importance as resilience layers within the national CNS architecture. Their independence from satellite signals and proven operational continuity during GNSS disruptions provide critical safeguards for both continental and island operations.

The analysis of the Portuguese navigation infrastructure between 2015 and 2025 demonstrates that modernization efforts have not aimed at full replacement of legacy systems, but rather at selective upgrading and rationalisation. ILS installations at major airports such as Lisbon, Porto, and Faro remain operationally justified due to traffic volume and precision approach requirements, while the gradual optimisation of the VOR network and the reinforcement of DME capabilities align with performance-based navigation (PBN) implementation. Within Portugal's specific operational context, maintaining a Minimum Operational Network (MON) backbone is essential to ensure continuity of service during potential GNSS outages, particularly given the strategic relevance of transatlantic routes.

From an economic standpoint, full preservation of all legacy systems across the territory would not be cost-optimal. However, from a safety and resilience perspective—especially considering Portugal's oceanic responsibilities—selective retention and performance-based rationalisation are justified. The most suitable long-term approach for Portugal is therefore a hybrid CNS architecture in which GNSS remains the primary navigation layer, supported by an optimised DME network, strategically retained ILS installations at high-traffic airports, a reduced but functional VOR backbone, and the phased withdrawal of NDB systems.

Such a strategy ensures operational continuity, preserves safety margins, and supports capacity growth while aligning with the European ATM Master Plan and SESAR Strategic Deployment

Objective 9. In the Portuguese context, modernization of legacy navigation infrastructure is not merely a technological choice, but a strategic necessity to safeguard national and transatlantic airspace operations in an increasingly complex and satellite-dependent aviation environment.

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References

Djunaedi 2024. ‘Development study of augmented reality based learning media Very High Frequency OmniDirectional Range (VOR) at Aviation Polytechnic’. Available at: https://www.atlantis-press.com/proceedings/veic-24/126007493

Davis, D. 2021. *Exploring the early history of radio navigation in aviation*. Available at: https://flyingthebeams.com/extra-1/f/exploring-the-early-history-of-radio-navigation-in-aviation

Durgut, M. 2020. *Navigation aids (VOR, DME, NDB...)*. Available at: https://www.aviationfile.com/navigation-aids-vor-dme-ndb-ils-tacan/

European Union 2015. *The roadmap for delivering high performing aviation for Europe: European ATM Master Plan executive view edition 2015*. Available at: https://www.sesarju.eu/sites/default/files/documents/ATM_MasterPlan_web.pdf

European Union 2025. *European ATM Master Plan*. Available at: https://www.sesarju.eu/sites/default/files/documents/reports/SESAR%20Master%20Plan%202025.pdf

Eurocontrol 2005. *LSSIP 2024 – Portugal local single sky implementation*. Available at: https://www.eurocontrol.int/sites/default/files/2025-07/eurocontrol-lssip-2024-portugal.pdf

Moore, R. and Lopes, J. 1999. ‘Paper templates’. In: *Template’06, 1st International Conference on Template Production*. SCITEPRESS.

NAV Portugal 2022. *Online eAIP – NAV Portugal AIS*. Available at: https://ais.nav.pt/online-eaip-en/

NAV Portugal 2024. *Espaço aéreo em Portugal*. Available at: https://www.nav.pt/espaco-aereo/espaco-aereo-em-portugal

Novák, A. 2008. *Communication and navigation*. p. 135. ISBN 978-80-8070-983-9.

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THE CONCEPT OF INTEGRATING UNMANNED AIRCRAFT INTO A SINGLE AIRSPACE WITH MANNED AIRCRAFT

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Abstract

Remotely piloted aviation systems are a new component of the aviation system, which, based on the latest developments in the field of aerospace technologies, open up new and expand existing opportunities for civil/commercial applications, increase the level of flight safety and efficiency of all civil aviation. The safe integration of remotely piloted aviation systems into non-segregated airspace is a lengthy process that requires coordinated action by many stakeholders, each of whom brings their own expertise to the process. Until now, the activities of civil aviation have been based on the concept that a pilot controls an aircraft while on board, and most often with passengers. Flying aircraft without a pilot on board raises a number of important technical and operational issues that are currently being actively studied by the aviation community. The most important task is to ensure that the integration of remotely piloted aircraft into non-segregated airspace and their use at airfields in no way leads to an increased risk to the safety of aircraft with a pilot on board. The paper considers decision-making models for the management of manned and unmanned aircraft in a single airspace, which provides a detailed analysis of the features of human-operator interaction, automated control systems and intelligent algorithms for remotely piloted aircraft systems, limitations caused by flight safety requirements in accordance with ICAO standards and recommended practices, regulatory and legal regulation and high dynamics of air the surroundings. Special attention is paid to methods of situational awareness, conflict forecasting, responsibility allocation between the pilot and automation, as well as adaptive and hybrid decision-making models based on control theory, probabilistic methods and elements of artificial intelligence. The results of the research can be used in the development of promising air traffic control systems and onboard intelligent systems, the development and updating of new flight rules that ensure the safe and effective integration of manned and unmanned aircraft into a single airspace.

Keywords

unmanned aircraft, unified airspace, integration of unmanned aircraft, U-space, air traffic control, urban air mobility, digital ecosystem

1. Introduction

Over the past decade, unmanned aircraft have become a key element in the development of global aviation activities, the use of which has found its relevance in geodesy, logistics, agriculture, energy, nature conservation, medicine and emergency situations. During this time, there has been a tremendous increase in the use of unmanned aircraft system (UAS), both small and large UAS capable of flying hundreds of kilometers, and in 5-10 years it is expected that the commercial use of UAS will exceed the number of commercial flights of small aircraft.

The widespread use of UAS is due to a significant reduction in the cost of technology and the development of autonomous control; high demand for the rapid delivery of various household goods (mail and small cargo delivery, medicines); monitoring of power lines, pipelines and railways; application in the national economy (spraying fields, monitoring forest fires, floods, aerial photography), which requires regular and long-range flights, including beyond the line of sight of the operator of UAS [ICAO 2016].

However, separate airspace is currently being used, where manned aircraft system (MAS) and UAS are controlled separately, which does not fully meet current trends in the development of unmanned aviation and is due to limited airspace use (bans on flights in cities, reservation of airspace zones, insufficient digital management tools) and significantly hinders market development [ICAO 2020, EUROCONTROL 2020]. This circumstance necessitates the transition to an integrated system for the use of airspace, in which UAS perform flights on a common basis with manned aircraft, while ensuring the level of flight safety at all stages, from takeoff to landing.

The integrated airspace management system will create the most favorable conditions for mass commercial services, which will be driven by an increase in the number of operators and manufacturers of UAS and, as a result, the creation of new jobs, which will lead to an influx of large investments into the state. In turn, the relevant government agencies will be able to more quickly and effectively carry out ecosystem monitoring, border protection, fire intelligence, mapping, and emergency support. Commercial organizations and business structures will receive new business developments, which will make it possible to fly without significant restrictions, with uniform standards and regulation of this area of aviation activity [FAA 20204, SASAR 2021].

The modern development of technology, the emergence of UTM/U-Space, the development of collision avoidance systems and next-generation communications provide the foundation for the development of future aviation, in which UAS and MAS will be able to fly together and safely. All these functions are significantly cheaper when using a UAS, but they are impossible without access to large amounts of airspace. Ensuring flight safety is a key aspect of integration, since MAS and UAS already intersect in areas of airports and airfields, at low altitudes in cities and suburban areas, on patrol routes, etc., without common rules, this creates significant risks for all users of airspace, urban infrastructure and third parties [FAA/NASA 2018-2022].

Most of the regulations, especially regarding small UAS, beyond visual line of sight (BVLOS), mass operations and unmanned traffic management (UTM), have not yet been included in formal standards and recommended procedures (SARPs). In practice, States are forced to develop their own rules, which leads to a lack of synchronization of standards, lack of uniformity, and difficulties in international operations. The regulatory framework is not yet fully consistent with the pace of development of unmanned technologies. The main gaps — technical detail, cybersecurity, regulation of massive small UAS and UTM, as well as differences in national implementation — remain a serious obstacle to the full integration of UAS into the airspace. Further harmonization of standards, strengthening of technical requirements and expansion of international cooperation are needed to accelerate the development of the sector [ICA02018-EASA 2019].

Problem description. The development and research of decision-making models for the joint management of MAS and UAS will make it possible to form scientifically sound methods for improving the efficiency and safety of their operation, as well as create the basis for the subsequent implementation of intelligent and adaptive control algorithms in promising aviation complexes, which should formalize the choice of control actions, optimize the allocation of tasks and resources, and coordinate actions in real time, taking into account constraints and risks. When developing decision-making models, it is proposed to use the following methods [RTCA 2020-11- Kuchar J. K., Yang L. C. A 2000].

- system analysis and management theory of complex hierarchical systems with critical infrastructure;
- decision theory, probabilistic methods, and theory of random processes;
- methods of modeling processes in conditions of uncertainty;
- simulation modeling;
- methods of artificial intelligence and intelligent systems;
- analysis of the influence of the human factor on management processes.
- The object of the research is the processes of joint management of MAS and UAS in a single air and information space, which involve the development:
- formalized approach to modeling decision-making processes in the joint management of MAS and UAS taking into account the interaction of a human operator and automated controls;
- decision-making models that integrate levels of strategic, tactical, and operational management in an uncertain and dynamically changing environment;
- methods of coordination and assignment of tasks between MAS and UAS based on criteria of efficiency, safety and resource constraints;
- to formalize the influence of the human factor on the decision-making process in the joint management of aviation systems;

The proposed system has a multi-level structure and includes the following main components [FAA2020, Endsley M. R. 2017, Prescott T. 2024].

1.1. The level of data collection and merging

At this level, information is collected from various sources, including radar facilities, ADS-B systems, airborne UAS telemetry, navigation systems, and meteorological sources. To increase the reliability of information, data fusion is used to form a holistic view of the current air situation.

1.2. Air situation analysis leve

The data obtained is used to evaluate the current parameters of aircraft movement and predict their trajectories in a temporal and spatial context. Predictive models are used to identify potential conflict situations, including violations of minimum separation intervals.

1.3. Decision-making level

The decision-making level implements the formation of recommendations and control actions using rules, optimization methods and intelligent algorithms. Solutions may include changing the route, altitude, or flight speed, as well as reallocating priorities between aircraft. Depending on the level of automation, solutions can be transferred to the dispatcher, pilot, or UAS operator, or applied automatically.

1.4. The level of interaction

This level provides human-machine interaction and information exchange between the system, dispatching personnel and UAS operators. The interfaces are designed taking into account ergonomic requirements and the peculiarities of information perception in conditions of high dynamics of the air situation.

1.5. Features of joint management

Joint management of MAS and UAS is characterized by differences in the levels of autonomy and human responsibility for decision-making. In critical situations, priority is usually reserved for MAS, which should be taken into account when forming control actions. Additional restrictions are imposed by the requirements of certification and regulatory regulation [EASA 2019, Cook A., Tanner G. 2016, Kuchar J. K., Yang L. C. 2000].

1.6. Introductions of integrated decision-making system for joint management of MAS and UAS.

The system is a complex of mathematical models and algorithms that ensure the safe and effective interaction of MAS and UAS in a single airspace.

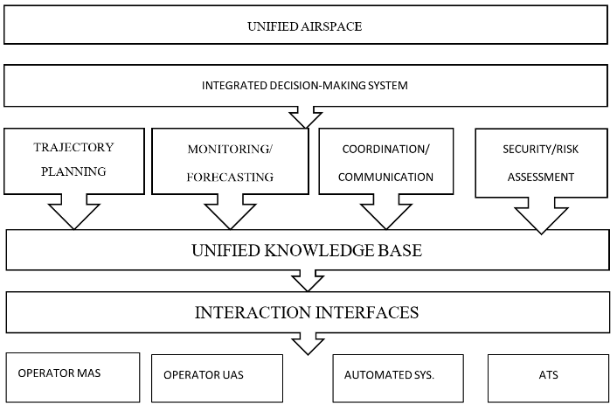


Figure 1. General scheme of Integrated decision-making system for joint management of MAS and UAS.

2. Dynamic air space distribution model.

This model is a functional component of an integrated air traffic control system (ATS) designed to coordinate the use of airspace while simultaneously performing ATS and UAS flights.

The module interacts with classic ATS systems, as well as with UTM systems that provide traffic management for UAS. At the same time, coordination of decisions made by the dispatcher and automated control algorithms is ensured [Bishop C. M. 2006 - Pinto Neto E. C., Baum D. M., Almeida Jr. J. R., Camargo Jr. J. B., Cugnasca P. S. 2022]

The main functions of the dynamic airspace module are:

- formation and modification of space-time zones of airspace in a four-dimensional representation;
- dynamic allocation of corridors and time zones for UAV flights;
- forecasting the trajectories of the MAS and UAS;
- automated detection of potential conflict situations;
- development of recommendations or management actions for their resolution;
- adaptation of the airspace structure to changes in the meteorological and aeronautical situation.

The module supports various levels of UAS control autonomy, from operator control to fully automatic modes.

The input data for the information support module's operation are flight plans for MAS and UAS, surveillance and positioning data, telemetry information, meteorological data, as well as information on time and regulatory restrictions on the use of airspace.

The module results in permits and restrictions on the use of airspace, adjusted flight paths, notifications of conflict situations, and recommendations for air traffic controllers and operators [Kuru K., Pinder J. M., Watkinson B. J., et al. 2023- Kuchar J. K., Yang L. C. 2000].

Dynamic airspace is considered as a four-dimensional area:

$\boldsymbol{\Omega} \subset \boldsymbol{R}^3 \times \boldsymbol{R}$**,** MAS and UAS $i \in 1, \dots N$, described by the state vector

$$\boldsymbol{X_i}(\mathbf{t}) = \begin{bmatrix} \boldsymbol{p_i(t)} \\ \boldsymbol{v_i(t)} \\ \boldsymbol{q_i(t)} \end{bmatrix}, \quad \textbf{(1)}$$

Where

$\boldsymbol{p_i(t)} \in \boldsymbol{R^3}$- position vector,

$\boldsymbol{v_i(t)} \in \boldsymbol{R^3}$- velocity vector,

$\boldsymbol{q_i(t)}$ **–** parameters of flight modes.

The dynamics of motion is described by the equation:

$$\boldsymbol{p_i(t)} = \boldsymbol{v_i(t)}, \boldsymbol{v_i(t)} = \boldsymbol{u_i(t)} \quad \textbf{(2)}$$

The spatial and temporal zones of the unified airspace are represented as:

$\Omega(\boldsymbol{t}) = \boldsymbol{U_{k=1}^M Z_k(t)}, \boldsymbol{Z_k(t)} = \langle \boldsymbol{S_k(t)}, \boldsymbol{T_k}, \boldsymbol{r_k} \rangle$**,** where:

$\boldsymbol{T_k}$ **–** time interval,

$\boldsymbol{r_k}$- priority of flights (UAS or MAS).

The task of the module is to select management decisions and configuration of flight zones in which there is no conflict for all pairs *i* and *j*. The occurrence of a conflict is possible under the condition:

$\exists_t \in [\boldsymbol{t_0}, \boldsymbol{t_0} + \boldsymbol{T_p}]: \|\boldsymbol{p_i(t)} - \boldsymbol{p_j(t)}\| < \boldsymbol{D_{min}}$ **,** where $\boldsymbol{T_p}$ - the forecasting horizon.

Optimization of the use of a single airspace is carried out according to multi-criteria functionality:

$\boldsymbol{J} = \boldsymbol{a_1 J_{safe}} + \boldsymbol{a_2 J_{cap}} + \boldsymbol{a_3 J_{eff}},$

$\boldsymbol{J_{safe}}$- safety indicator,

$\boldsymbol{J_{cap}}$- throughput capacity,

$\boldsymbol{J_{eff}}$ **–** trajectory efficiency,

$\boldsymbol{a_k}$- weight coefficients.

The operation of the model includes the following stages showed in Figures 2-3.

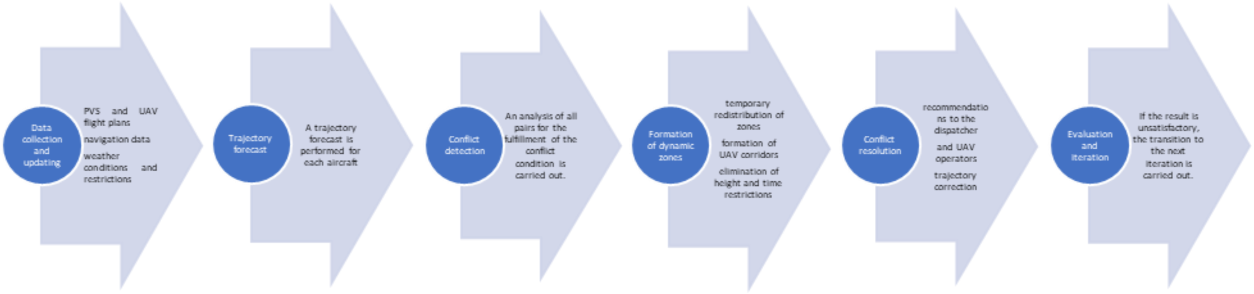


Figure 2. Stages of the model's operation (1)

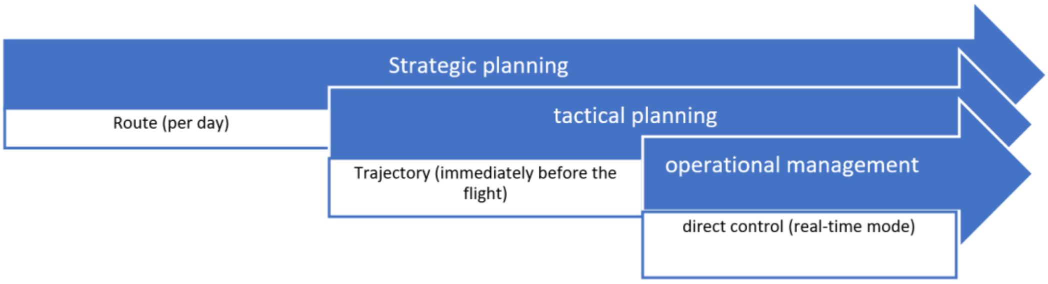


Figure 3. Stages of the model's operation (2)

3. Strategic planning

Strategic planning (Pre-flight) is the coordination of flight plans (including 4D trajectories: 3D+time) between all participants and ATC/UTM services.

The air space model. Lots of aircraft:

$$\boldsymbol{A} = \boldsymbol{A^M} \cup \boldsymbol{A^U}, \boldsymbol{A^M} \qquad (3)$$

controlled by ATS, $\boldsymbol{A^U}$- controlled by U-space serves providers.

The airspace is described by the following expression:

$$\boldsymbol{Z} = \boldsymbol{Z^{ATM}} \cup \boldsymbol{Z^U},$$

where $\boldsymbol{Z^{ATM}}$- controlled airspace,

$\boldsymbol{Z^U}$- U- space airspace volumes,

$\boldsymbol{X_z}\ (\boldsymbol{t})$- Dynamic airspace reconfigurations.

By U-space services described of UAS parameters:

$$\boldsymbol{\alpha} \in \mathrm{A}^{\boldsymbol{U}} \rightarrow \boldsymbol{ID_\alpha}, \boldsymbol{class_\alpha}$$

They are used in separation coefficients and probability constraints.

Flight plan of UAS: $\boldsymbol{\gamma_\alpha} \rightarrow \boldsymbol{UAS\ flight\ plan},$ under restrictions $\boldsymbol{\gamma_\alpha} \in \{\boldsymbol{Z}|\boldsymbol{X_z}(\boldsymbol{t}) = \boldsymbol{1}\}$ corresponds to the validation of trajectories. Conflict situation $\mathrm{C}_{\boldsymbol{\alpha\beta}}(\boldsymbol{z}, \boldsymbol{h}, \boldsymbol{t})$ according services of Strategic conflict Detection and capacity management, under probabilistic constraints $\boldsymbol{P}(\boldsymbol{C_{\alpha\beta}} = \boldsymbol{0}) \geq \boldsymbol{1} - \boldsymbol{\varepsilon}$, optimization $\boldsymbol{minJ}(\boldsymbol{\gamma_\alpha})$.

ATM Flight Plan 4D trajectory Piloted aircraft $\boldsymbol{\gamma_\alpha^{ATM}} = \{(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{h}, \boldsymbol{t})\}_{\boldsymbol{1}}$, agreement of $\boldsymbol{\gamma_\alpha^{ATM}} \cap \boldsymbol{\gamma_\beta^U} = \emptyset_{\boldsymbol{1}}$, bandwidth limitations: $\boldsymbol{\Sigma_{\alpha\epsilon A}I}(\boldsymbol{z}, \boldsymbol{h}, \boldsymbol{t}) \geq \boldsymbol{C_{zb}}$, where $\boldsymbol{C_{zb}}$- declared capacity of sector.

The module operates in discrete time and includes the following steps:

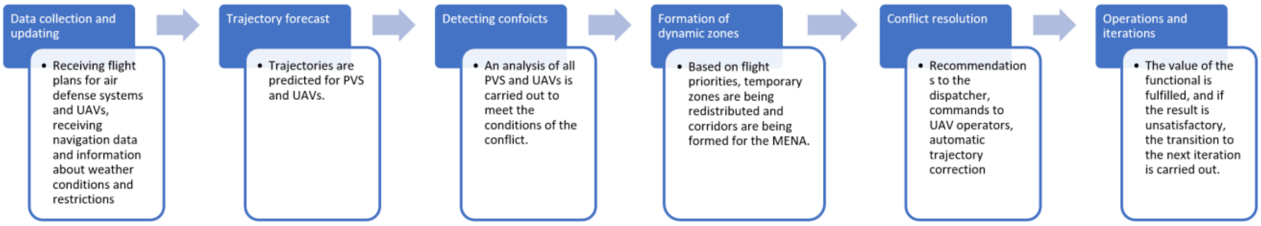


Figure 4. Steps of module operates in discrete time

Tactical planning. Tactical trajectory planning is a level of flight planning focused on the short and medium term (seconds—minutes), the purpose of which is to ensure safe separation of MAS and UAS; adapting trajectories to a dynamically changing environment; performing missions while respecting airspace restrictions and human-machine interaction. Unlike strategic planning (route, trains, schedules), the tactical level works with real time and uncertainties [Austin R. 2010, Valavanis K. P., Vachtsevanos G. J. 2015].

The joint operation of MAS and UAS is characterized by:

- **Asymmetry of management** - the MAS is controlled by a person with high cognitive flexibility; the UAS is an automated system with formalized algorithms.
- **Differences in flight performance** are determined by different restrictions on maneuverability, speed, overloads, as well as different requirements for safe distances.
- **The heterogeneity of the levels of autonomy** UAS appears to be remotely controlled; semi-autonomous; fully autonomous.

The tactical planning model should forecast the movement of UAS and UAS over a limited planning horizon; detect and prevent conflicts (collision avoidance); reschedule trajectories in case of changing weather conditions and failures; coordinate solutions between MAS automation and the actions of the UAS pilot; minimize the load on the pilot and ATS operators [Wooldridge M. 2009, Balas A. V. 2016].

When considering the set of aircraft described in (3), where each aircraft state is determined by the vector described in (2), the dynamics of aircraft movement is described:

$$X_i\ (\boldsymbol{t}) = \boldsymbol{f_i}(X_i\ (\boldsymbol{t}), \boldsymbol{u_i}(\boldsymbol{t}), \boldsymbol{w_i}(\boldsymbol{t}), \qquad \textbf{(4)}$$

where $\boldsymbol{u_i}(\boldsymbol{t})$- controlling influence, $\boldsymbol{w_i}(\boldsymbol{t})$- weather conditions, measurement errors.

Tactical planning is carried out on the final horizon: $\boldsymbol{t} \in [\boldsymbol{t_0}, \boldsymbol{t_0} + \boldsymbol{T}]$ at the trajectory of aircraft $\boldsymbol{\tau_i} = \{\boldsymbol{x_i}(\boldsymbol{t})\}_{\boldsymbol{t}=\boldsymbol{t_0}}^{\boldsymbol{t_0}+\boldsymbol{T}}$, and dynamic restrictions on speed, overload, roll and pitch angles, where for any,

$$\boldsymbol{i}, \boldsymbol{j} \in \boldsymbol{A}, ; \boldsymbol{i} \neq \boldsymbol{j};\ \|\boldsymbol{p_i}(\boldsymbol{t}) - \boldsymbol{p_j}(\boldsymbol{t})\| \geq \boldsymbol{d_{min}}, \forall(\boldsymbol{t}) \in [\boldsymbol{t_{0,}} \boldsymbol{t_0} + \boldsymbol{T}]$$
(5)

Where the airspace restriction is described $\boldsymbol{p_j}(\boldsymbol{t}) \in \boldsymbol{\Theta_k}, \forall \boldsymbol{k}$

Accounting for the human factor fleet for MAS is described by a model of deviation from the recommendations $\boldsymbol{u_t^M}(\boldsymbol{t}) = \boldsymbol{u_i^{rec}} + \boldsymbol{\beta_i}(\boldsymbol{t})$, $\boldsymbol{u_i^{rec}}$ - recommended management, $\boldsymbol{\beta_i}(\boldsymbol{t})$ - a random variable simulating the flight response, with a distribution $\boldsymbol{\beta_i} \sim \boldsymbol{N}(\boldsymbol{0}, \boldsymbol{\Sigma_i})$

For UAS, the task can be solved through game theory with conflicting interests, which results in receiving recommendations for the UAS in the control system, and for the pilot of the UAS in the form of recommendations.

Level 3: Operational control and safety is the process of forming and adjusting flight paths in real or quasi-real time, taking into account: airspace restrictions; weather conditions; aircraft characteristics; control room commands; unpredictable behaviour of other traffic participants.

Automated planning algorithms based on optimization methods, graph theory, Model Predictive Control methods, artificial intelligence [ICAO 2019, EUROCONTROL 2020].

The key problem of joint management is the difference in: the level of autonomy; reaction time; control and communication channels; responsibility for decision-making. MAS rely on a human pilot, while UAS operate on the basis of on-board algorithms, which requires consistent interaction protocols and uniform "detect and avoid" standards.

The safety of trajectory planning models is assessed by guaranteed conflict and collision prevention; resistance to sensor and communication errors; correct operation in case of incomplete or unreliable information; predictability of UAS behaviour for pilots and controllers. Probabilistic risk models; methods of reachability analysis; formal methods of verification and logical proof of properties; scenario modelling and digital twins are used for formal verification of security [7,8].

The model of the dynamics of the armed forces described in expressions (2), (3), and the conflict model (4) defines the task of optimal operational planning with constraints:

$$\boldsymbol{min_u J_i} = \int_{\boldsymbol{t_0}}^{\boldsymbol{t_i}+\boldsymbol{T}} \left(\left\|\boldsymbol{p_i}(\boldsymbol{t}) - \boldsymbol{p_i^{ref}}(\boldsymbol{t})\right\| \boldsymbol{1^2} + \boldsymbol{\lambda}\|\boldsymbol{u_i}(\boldsymbol{t})\|\boldsymbol{1^2}\right) \boldsymbol{dt}$$

And under the conditions:

$$\begin{cases} x_i = f_i(x_i, u_i) \\ x_i(t_0) = x_i^0 \end{cases}, \begin{cases} x_i(t) \notin C_{ij}, \forall_j \neq i) \\ u_i(t_1) \in U_i \end{cases}$$

The condition of other aircraft is known with an error $\boldsymbol{x_j} = \boldsymbol{x_j} + \boldsymbol{\varepsilon_j}, \boldsymbol{\varepsilon_j} \sim \boldsymbol{N}(\boldsymbol{0}, \boldsymbol{\Sigma_j})$, $\boldsymbol{P}(\boldsymbol{d_{ij}}(\boldsymbol{t})\ \geq_{\boldsymbol{1}} \boldsymbol{d_{min}}) \geq \boldsymbol{1} - \boldsymbol{\delta}$, this allows you to take into account ADS-B errors, communication delays, and the human factor.

Based on the above, we will draw up a general flowchart for safe trajectory planning, where the current state is at the input. $x_i(t)$, forecasts of MAS $x_i(t: t + T)$ and the limitations of airspace. Safety is ensured by the invariance and the formal reachability constraint, showed in figure 5.

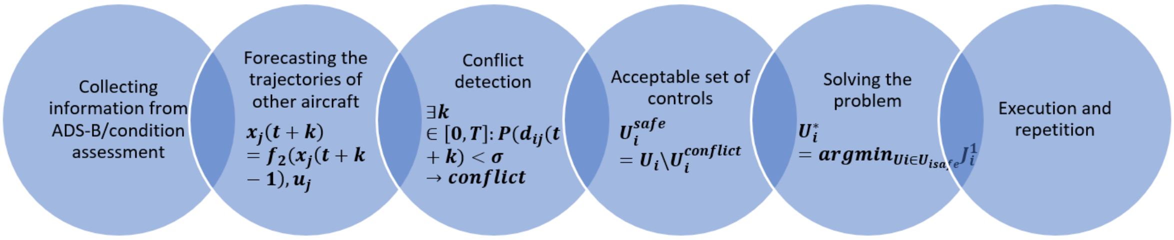


Figure 5. The flowchart for safe trajectory planning

The monitoring and forecasting model is designed for continuous monitoring of the air situation, forecasting is carried out based on the analysis of time series of flight parameters and risk factors using probabilistic and intelligent methods, which makes it possible to assess trends in the state of the system and the likelihood of dangerous situations over a given time horizon.

The results of monitoring and forecasting are used in the decision-making system to generate warnings and corrective control actions that improve flight safety in an uncertain and dynamically changing environment. The model consists of five interconnected levels shown in the figure 6. [ICAO 2019, EASA 2019, Cook A., Tanner G. 2016, Kuchar J. K., Yang L. C. 200]

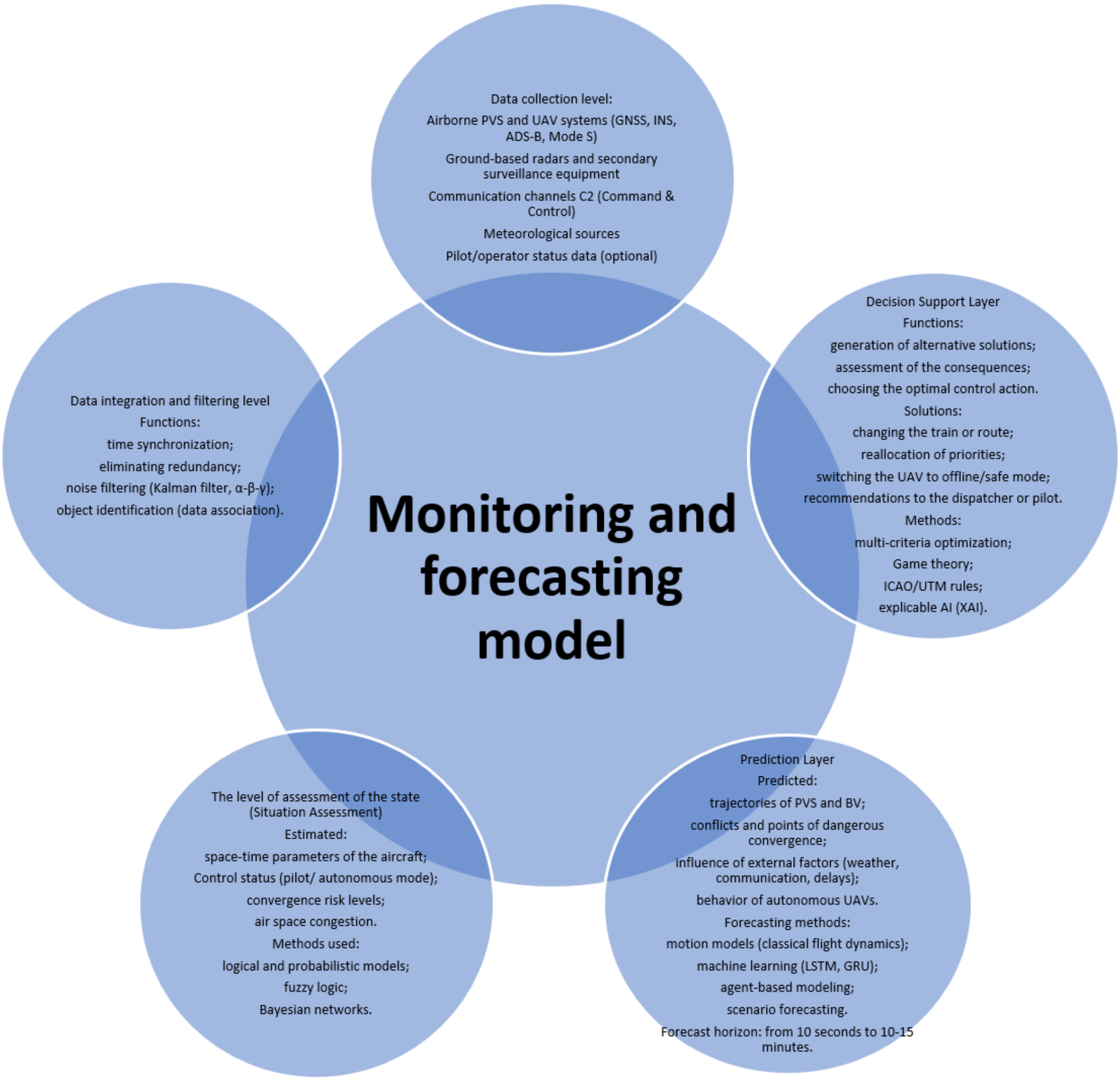


Figure 6. Interconnected levels monitoring and forecasting model.

The general state of the joint management system is described by the expression:

$$\boldsymbol{X(t) = [X_p(t), X_b(t), X_e(t)],}$$

where $X_p(t)$- vectors of the status of manned aircraft, $X_b(t)$- vectors of the state of unmanned aircraft, $X_e(t)$ - the parameters of the external environment.

The expression is valid for manned and unmanned aircraft:

$$X_i(t) = [x_i(t), y_i(t), z_i(t), v_i(t), \psi_i(t), \gamma_i(t)]1^T$$

where, $x_i(t), y_i(t), z_i(t)$ - spatial coordinates, $v_i(t), \psi_i(t), \gamma_i(t)$- speed, course, trajectories.

The dynamics of aircraft movement described in (3) defines the monitoring process, which is described: $y_i(t) = h_i(x_i(t)) + v_i(t)$,

where $y_i(t)$- measurement vector (radar, telemetry, ADS-B), $v_i(t) \sim N(0, R)$- Gaussian measurement noise, where $x_i(t) = E[x_i(t) \vdots Y_i(t)]$- the method of optimal filtering of aircraft states.

The forecast of the conditions of the aircraft in the interval Δt is formed by:

$$x_i(t+\Delta t) = \Phi_i\big((\Delta t)x_i(t)\big) + \int_t^{t+\Delta t} \Phi_i(t-\tau)\, \mathrm{B}_i u_i(\tau) dr,$$

where Φ_i, B_i – state transition and control matrices, where a training model is used for the UAS:

$$x_i(t+\Delta t) = \mathbf{M}_{Mi}(x_i(t), c_i)$$

With the probability of a conflict described in (4), the integral risk level is determined by:

$$R_{ij} = \int_{t_0}^{t_0+T_p} p_{ij}^{conf}(t)dt$$

Accordingly, the decision-making task is formulated as a multi-criteria optimization.:

$$U^* = argmin_{U\epsilon\Omega_1}\{\alpha_1 R_{conf} + \alpha_2 T_{delay} + \alpha_3 C_{load}\}\mathrm{m}$$

$R_{conf}, T_{delay}, C_{load}$- total risk of conflicts, delays, and workload on the dispatcher, α_k- weight coefficients.

The coordination and communication model is designed to ensure coordinated, safe and effective management of MAS and UAS in a dynamically changing environment with limited decision-making time and possible failures of communication channels and data uncertainty.

The model is considered as a multi-level human-machine system, including control subjects (pilots of the air defines system; UAS operators; autopilots, AI modules and control objects (air defines systems and UAS), airspace, weather conditions.

Decision-making is carried out within the framework of a distributed model, where:

- person makes high-level decisions even in critical situations.;
- automated systems perform routine and high-speed operations;
- intelligent agents offer alternatives and forecasts.

The key principle is the adaptive allocation of responsibility between humans and automation, depending on the complexity and risk of the situation [FAA 2020, SASAR 2021].

The model provides for: mechanisms for detecting conflicts and failures; redundancy of communication channels; transition of the UAS to safe autonomous modes; support for situational awareness of operators and pilots.

In general, the model of coordination and communication in the decision-making system for the management of manned and unmanned aircraft is an integrated human-machine architecture that ensures coordinated interaction between humans and automated controls based on continuous information exchange, adaptive distribution of functions and multilevel coordination of actions.

The basic principles are the organization of a single information space, multi-level coordination and adaptive communication.

Security mechanisms are provided by proactive (preliminary modelling of interaction scenarios; allocation of dynamic separation zones, forecasting of conflict situations) and reactive (time and space separation, immediate response protocols, escalation of decision-making in emergency situations

The effectiveness of the model should meet the criteria of reaction time to changes in the air situation, safety indicators (number of conflict situations), the capacity of mixed airspace and the reliability of communication channels.

Figure 7 shows a conceptual diagram of the coordination and communication model, and Figure 8 shows the components of the decision support system [Clothier R., Walker R. 2015, Cummings M. L., Bruni S., Mercier S. 2017].

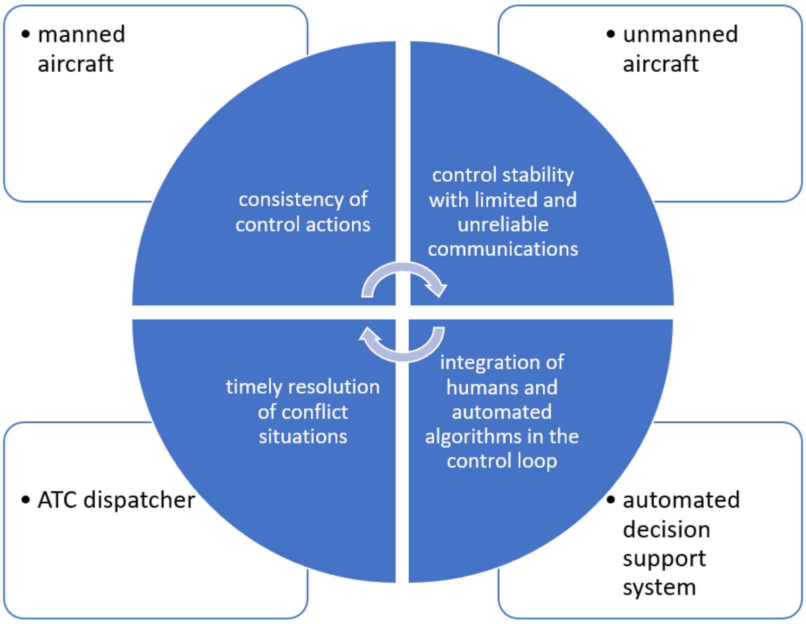


Figure 7. Conceptual diagram of the coordination and communication model

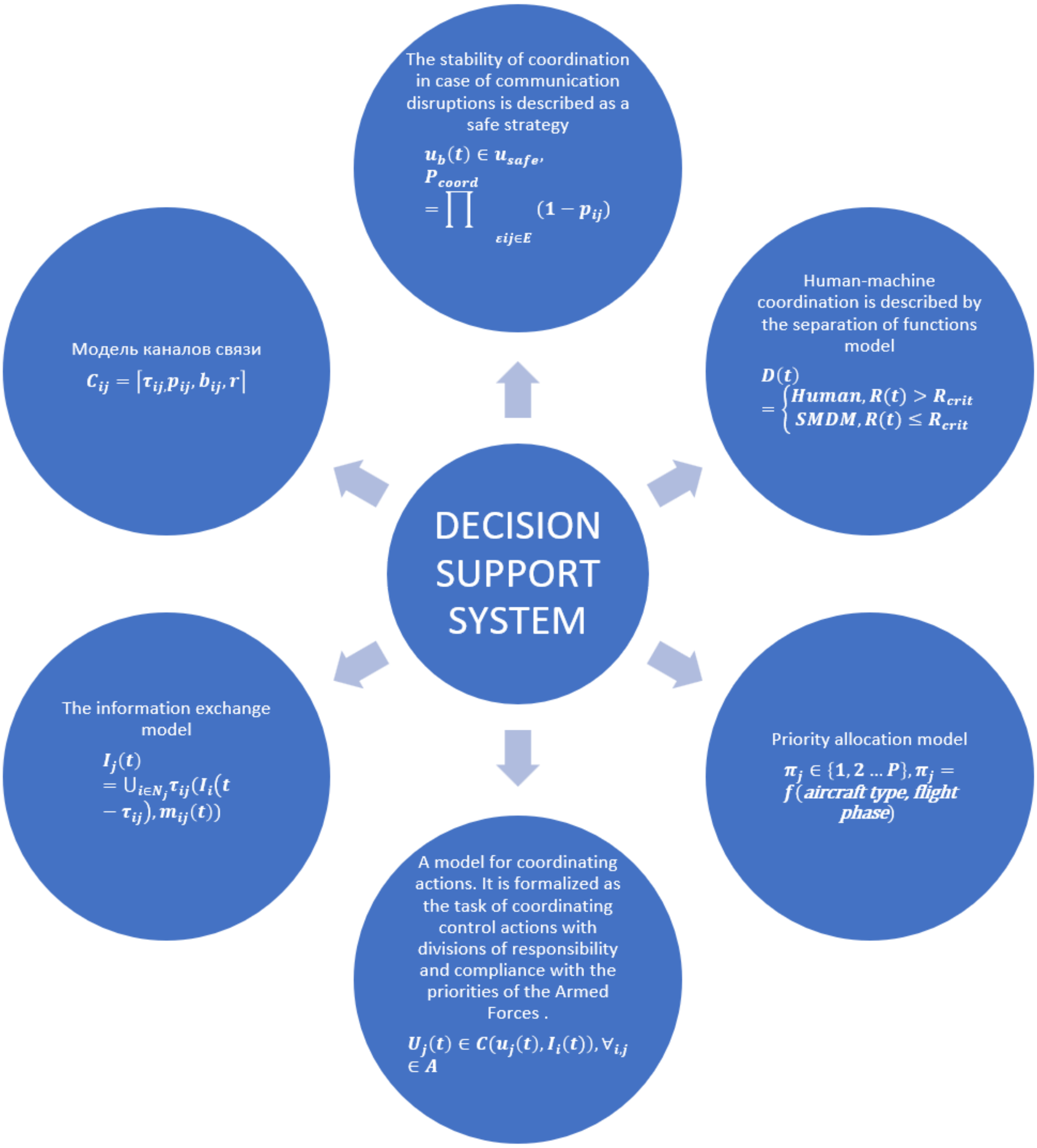


Figure 8. Components of the decision support system

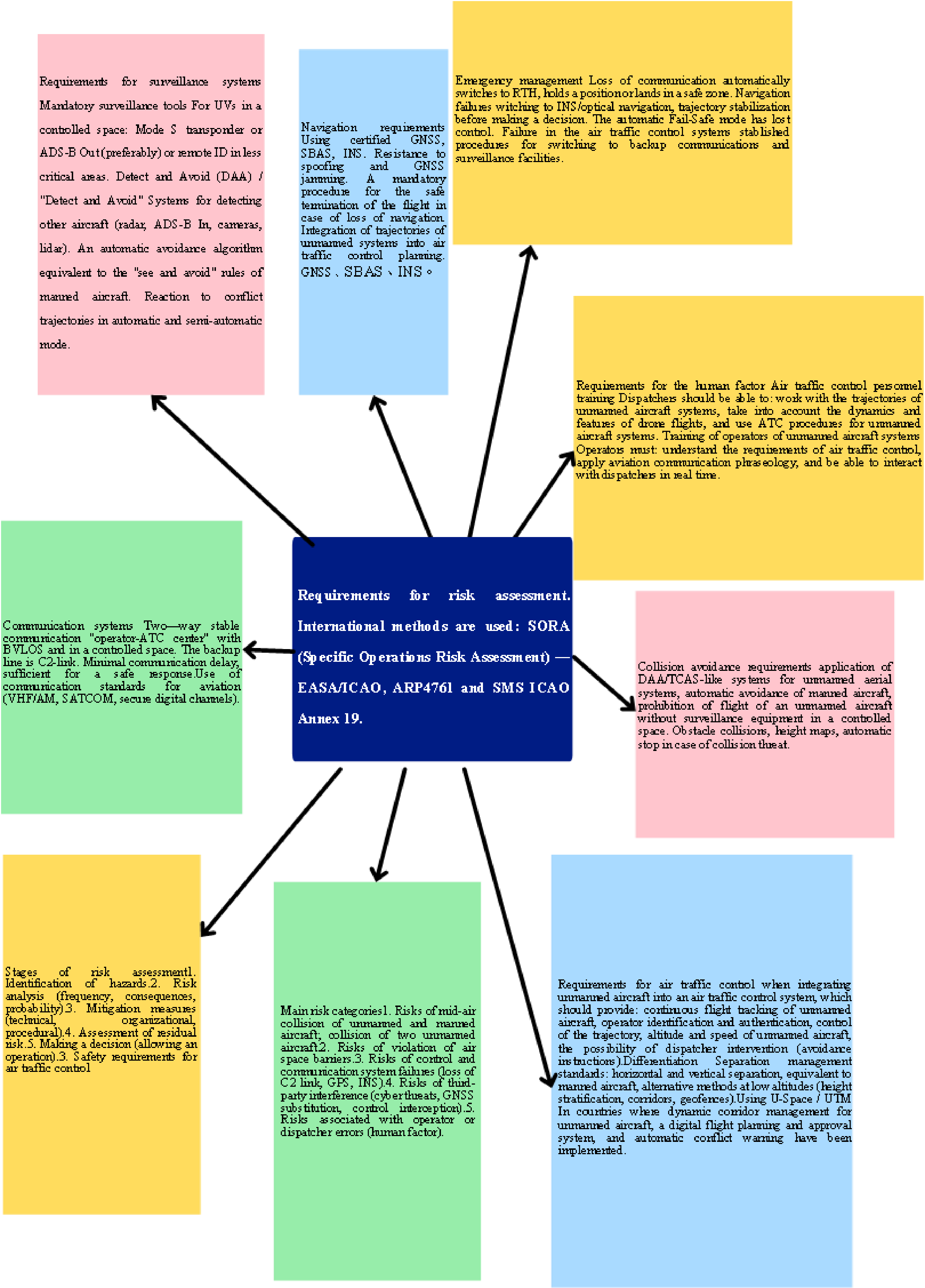
4. Risk assessment model

The task of risk assessment is formulated as determining a quantitative indicator reflecting the likelihood of a dangerous situation and the severity of its consequences under given flight conditions. Based on the obtained risk value, a management solution should be formed aimed at reducing the level of danger to an acceptable value. Improving the flight safety of manned and unmanned aircraft in conditions of increasing air traffic intensity and a more complex operational environment requires the use of intelligent decision-making systems based on a formalized risk assessment. One of the key tasks of such systems is the timely identification and quantification of factors that can lead to dangerous and emergency situations. Depending on the nature of the occurrence and the area of impact, risk factors are grouped into the following groups:

- technical factors characterizing the current state of on-board systems, equipment reliability and stability of control and communication channels;
- the human factor reflecting the level of training, the psychophysiological state and the cognitive load of the pilot or operator of an unmanned aircraft;
- environmental factors, including meteorological conditions, terrain features, and the presence of external disturbing influences;

- operational factors related to flight modes, air traffic density, and airspace restrictions;
- information factors that determine the reliability, completeness and timeliness of data entry into the management system.

This division makes it possible to ensure the modularity of the model and simplify the adaptation of its structure to the specific operating conditions of PVS and UVS. In real-world aircraft operating conditions, the input information about the state of the system and the external environment is incomplete and uncertain. In this regard, the model provides for the use of fuzzy logic methods and probabilistic models that allow for interval and linguistic parameter estimates. The use of these methods increases the model's resistance to measurement errors and provides a more adequate representation of the risk level in conditions of uncertainty. The developed multifactorial risk assessment model is integrated into the decision-making system and is used to predict the development of dangerous situations and the formation of control actions. Depending on the value of the integral risk indicator, the system can issue warnings, limit the permissible flight modes, or initiate a transition to safe or emergency control mode. A special feature of the model's application for unmanned aircraft is the need to take into account delays in communication channels and the level of autonomy of the control system, whereas for manned aircraft the influence of the human factor plays a key role. A multifactorial risk assessment model designed for use in decision-making systems for the management of manned and unmanned aircraft. The model provides a comprehensive account of heterogeneous risk factors and allows you to form informed management decisions in conditions of uncertainty and a dynamically changing environment. For unmanned aircraft, the key factors are the stability of communication channels and the level of autonomy, while for manned aircraft, the main focus is on minimizing the impact of the human factor. The unified structure of the model makes it possible to take these features into account by adaptive adjustment of the weighting coefficients [ICAO 2019, EOROCONTROL 2020, Moiseev N. N. 2014, Kuchar J. K., Yang L. C. 2000].



Requirements for risk assessment. International methods are used: SORA (Specific Operations Risk Assessment) — EASA/ICAO, ARP4761 and SMS ICAO Annex 19.

Requirements for surveillance systems Mandatory surveillance tools For UVs in a controlled space: Mode S transponder or ADS-B Out(preferably) or remote ID in less critical areas. Detect and Avoid (DAA) / "Detect and Avoid" Systems for detecting other aircraft (radar, ADS-B In, cameras, lidar). An automatic avoidance algorithm equivalent to the "see and avoid" rules of manned aircraft. Reaction to conflict trajectories in automatic and semi-automatic mode.

Navigation requirements Using certified GNSS, SBAS, INS. Resistance to spoofing and GNSS jamming. A mandatory procedure for the safe termination of the flight in case of loss of navigation. Integration of trajectories of unmanned systems into air traffic control planning. GNSS、SBAS、INS。

Emergency management Loss of communication automatically switches to RTH, holds a position or lands in a safe zone. Navigation failures witching to INS/optical navigation, trajectory stabilization before making a decision. The automatic Fail-Safe mode has lost control. Failure in the air traffic control systems stablished procedures for switching to backup communications and surveillance facilities.

Requirements for the human factor Air traffic control personnel training Dispatchers should be able to: work with the trajectories of unmanned aircraft systems, take into account the dynamics and features of drone flights, and use ATC procedures for unmanned aircraft systems. Training of operators of unmanned aircraft systems Operators must: understand the requirements of air traffic control, apply aviation communication phraseology, and be able to interact with dispatchers in real time.

Communication systems Two—way stable communication "operator-ATC center" with BVLOS and in a controlled space. The backup line is C2-link. Minimal communication delay, sufficient for a safe response.Use of communication standards for aviation (VHF/AM, SATCOM, secure digital channels).

Collision avoidance requirements application of DAA/TCAS-like systems for unmanned aerial systems, automatic avoidance of manned aircraft, prohibition of flight of an unmanned aircraft without surveillance equipment in a controlled space. Obstacle collisions, height maps, automatic stop in case of collision threat.

Stages of risk assessment1. Identification of hazards.2. Risk analysis (frequency, consequences, probability)3. Mitigation measures (technical, organizational, procedural).4. Assessment of residual risk.5. Making a decision (allowing an operation).3. Safety requirements for air traffic control

Main risk categories1. Risks of mid-air collision of unmanned and manned aircraft; collision of two unmanned aircraft2. Risks of violation of air space barriers.3. Risks of control and communication system failures (loss of C2 link, GPS, INS).4. Risks of third-party interference (cyberthreats, GNSS substitution, control interception).5. Risks associated with operator or dispatcher errors (human factor).

Requirements for air traffic control when integrating unmanned aircraft into an air traffic control system, which should provide: continuous flight tracking of unmanned aircraft, operator identification and authentication, control of the trajectory, altitude and speed of unmanned aircraft, the possibility of dispatcher intervention (avoidance instructions).Differentiation Separation management standards: horizontal and vertical separation, equivalent to manned aircraft, alternative methods at low altitudes (height stratification, corridors, geofences).Using U-Space / UTM In countries where dynamic corridor management for unmanned aircraft, a digital flight planning and approval system, and automatic conflict warning have been implemented.

Figure 10. Risk assessment team

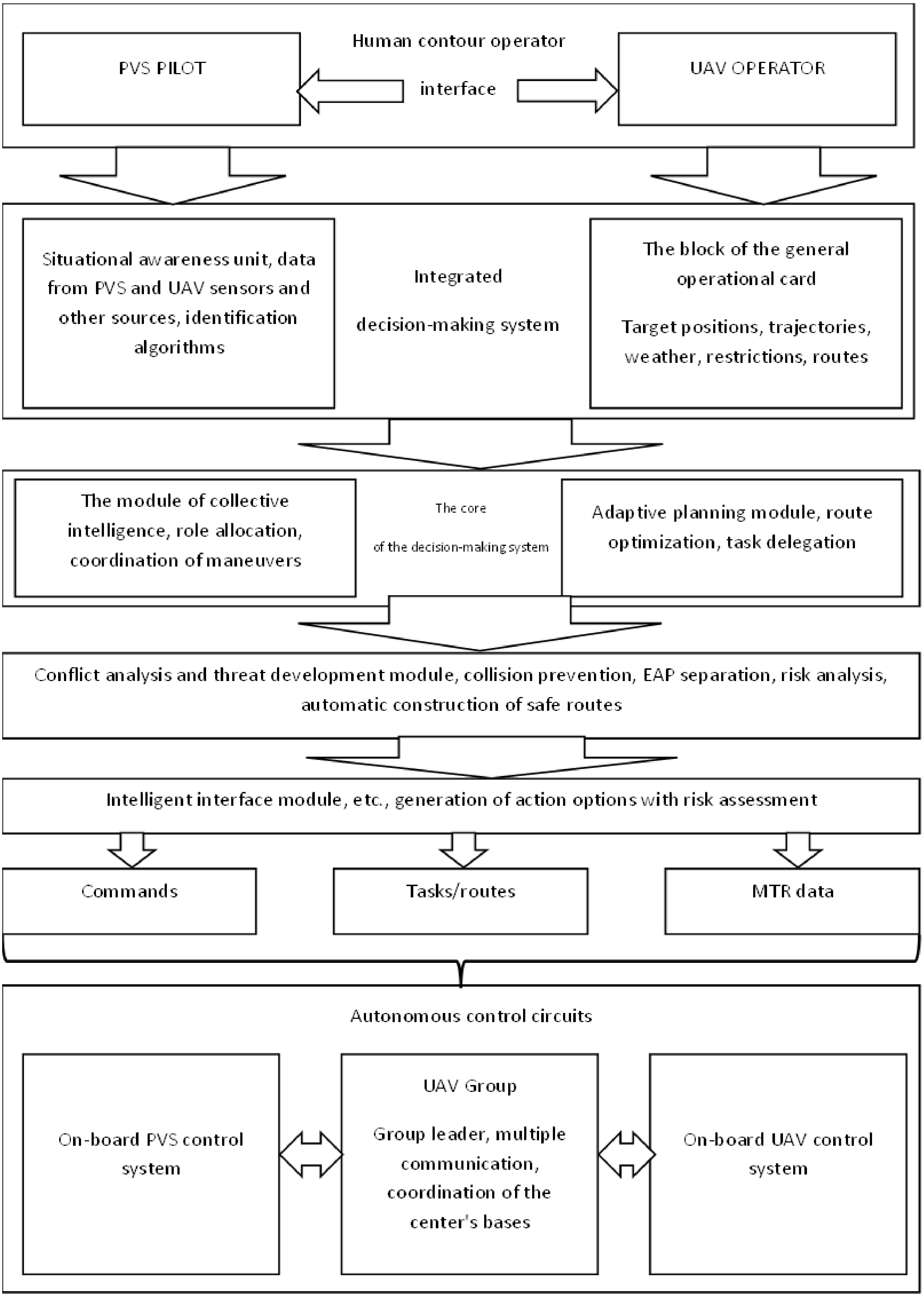


Figure 11. General model of Integrated decision-making system

5. General conclusions

The presented article develops and substantiates a set of interrelated models that form the methodological and algorithmic basis of an intelligent air traffic control system for manned and unmanned aircraft in conditions of high dynamism, uncertainty and heterogeneity of the information environment. The dynamic model of airspace allocation allows for an adaptive approach to managing the structure and parameters of airspace use based on the current and predicted state of the air situation. Unlike traditional static schemes, the proposed model provides a real-time redistribution of airspace, taking into account user priorities, safety constraints and aircraft characteristics, which helps to increase capacity and reduce air traffic conflict. The monitoring and forecasting model ensures the continuous formation of a holistic view of the state of the controlled system and the external environment through the integration of data from on-board, ground and external information sources. The use of predictive assessments allows you to move from reactive to proactive management, providing proactive identification of dangerous trends and increasing the time reserve for making management decisions.

The coordination and communication model formalizes the processes of information interaction between air traffic participants and the elements of the control system. Taking into account data transmission delays, limited bandwidth of communication channels and various levels of autonomy of unmanned aircraft makes it possible to increase the consistency of actions and stability of management in a distributed system architecture. The multifactorial risk assessment model integrates the results of the functioning of airspace allocation, monitoring, forecasting and coordination models, providing a quantitative assessment of the risk level taking into account technical, operational, human, external and informational factors. The use of weighted aggregation and uncertainty accounting methods makes it possible to form sound management decisions in conditions of incompleteness and inconsistency of information. The set of developed models forms a single scientific and methodological platform for intelligent air traffic control, which ensures an increase in the level of safety, adaptability and efficiency of aviation systems. The results obtained create a theoretical and practical basis for the further development of automated and autonomous air traffic control systems in conditions of joint operation of manned and unmanned aircraft [Pinto Neto E. C., Baum D. M., Almeida Jr. J. R., Camargo Jr. J. B., Cugnasca P. S. 2022, Valavanis K. P., Vachtsevanos G. J. 2015, Balas A. V. 2016].

References

Austin, R. 2010. *Unmanned Aircraft Systems: UAVs design, development and deployment*. 2nd ed. Chichester: Wiley.

Balas, A. V. 2016. ‘Smart safety: advanced aviation safety and autonomous airspace management’. *International Journal of Aviation Technology*.

Bishop, C. M. 2006. *Pattern recognition and machine learning*. New York: Springer.

Clothier, R. and Walker, R. 2015. ‘Safety risk management of unmanned aircraft systems’. *Reliability Engineering & System Safety*.

Cook, A. and Tanner, G. 2016. *European air traffic management: principles, practice and research*. London: Routledge.

Cummings, M. L., Bruni, S. and Mercier, S. 2017. ‘Human–automation collaboration in air traffic management’. *Human Factors*.

Endsley, M. R. 1995. ‘Situation awareness in dynamic systems’. *Human Factors*, 37(1), pp. 32–64.

Endsley, M. R. 2017. *Situation awareness analysis and measurement*. Boca Raton: CRC Press.

European Organisation for the Safety of Air Navigation (EUROCONTROL) 2020. *European ATM Master Plan*. Brussels.

European Organisation for the Safety of Air Navigation (EUROCONTROL) 2021. *UAS ATM integration operational concept*. Brussels.

European Union Aviation Safety Agency (EASA) 2019. *U-Space concept of operations*. Cologne.

Federal Aviation Administration (FAA) 2020. *Integration of civil unmanned aircraft systems (UAS) in the national airspace system (NAS) roadmap*. Washington, DC: Federal Aviation Administration.

Federal Aviation Administration (FAA) 2020. *UAS traffic management (UTM) concept of operations v2.0*. Washington, DC.

Fedorov, V. A. and Kiselev, A. N. 2016. *Theory and methods of air traffic control*. Moscow: Mashinostroenie.

Federal Aviation Administration, NASA and Industry UTM Research Transition Team 2022. *Unmanned aircraft system traffic management (UTM) concepts of operation*. FAA/NASA.

International Civil Aviation Organization (ICAO) 2016. *Global air traffic management operational concept*. Montreal: ICAO.

International Civil Aviation Organization (ICAO) 2018. *Remotely piloted aircraft systems (RPAS) manual*. Doc 10019. Montreal: ICAO.

International Civil Aviation Organization (ICAO) 2019. *Manual on air traffic management system requirements*. Doc 9882. Montreal: ICAO.

Klein, M. and Maimon, O. 2024. *Foundations of soft logic*. New York: Springer.

Kuchar, J. K. and Yang, L. C. 2000. ‘A review of conflict detection and resolution modeling methods’. *IEEE Transactions on Intelligent Transportation Systems*, 1(4), pp. 179–189.

Kuru, K., Pinder, J. M., Watkinson, B. J. et al. 2023. ‘Toward collision-free trajectory for autonomous and pilot-controlled unmanned aerial vehicles’. *arXiv preprint*.

Moiseev, N. N. 2014. *Mathematical methods of system analysis*. Moscow: Nauka.

Pinto Neto, E. C., Baum, D. M., Almeida Jr., J. R., Camargo Jr., J. B. and Cugnasca, P. S. 2022. ‘UAS in the airspace: a review on integration, simulation, optimization, and open challenges’. *arXiv preprint*, arXiv:2211.15330.

Prescott, T. 2024. *The psychology of artificial intelligence*. London. Available at: https://doi.org/10.4324/9781003088660.

Rasmussen, J. 1997. ‘Risk management in a dynamic society’. *Safety Science*.

RTCA 2020. *Minimum aviation system performance standards (MASPS) for detect and avoid (DAA) systems for unmanned aircraft systems*. RTCA DO-365.

SESAR Joint Undertaking 2021. *Concept of operations for very large scale UAS integration*. Brussels.

Valavanis, K. P. and Vachtsevanos, G. J. 2015. *Handbook of unmanned aerial vehicles*. Dordrecht: Springer.

Vasiliev, S. N. and Kuznetsov, I. A. 2018. *Intelligent decision support systems*. Moscow: Fizmatlit.

Wooldridge, M. 2009. *An introduction to multiagent systems*. 2nd ed. Chichester: Wiley.

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