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Development Tendencies in Air Traffic Management

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Abstract
This paper investigates the evolution of research themes in Air Traffic Management (ATM) between 2014 and 2024 using keyword co-occurrence analysis. Five dominant clusters—safety and human factors, capacity and airspace efficiency, automation and digitalisation, trajectory-based operations, and sustainability—are identified and interpreted through a socio-technical lens. Beyond describing clusters, the study examines inter-cluster dynamics and situates findings within the policy frameworks of the ICAO Global Air Navigation Plan (GANP) and the European SESAR ATM Master Plan. The use of explicit criteria for keyword normalisation, clustering parameters, and validation metrics enhances methodological transparency. The paper proposes a targeted research agenda for underexplored areas, such as the practical integration of UAS and real-time machine learning in ATC operations. Finally, it outlines practical implications for regulators, ANSPs, technology developers, and training programs, and recommends methodological innovations.

Keywords:
Air Traffic Management; VOSviewer; Bibliometric Analysis; Safety; Capacity Management; Sustainability; Trajectory-Based Operations; Automation.

1. Introduction

Air Traffic Management (ATM) is the cornerstone of the current airspace system. It handles the efficient flow of aircraft through congested airspace (Dmochowski, 2017; Madhwal, 2017, Chen, et al., 2025). However, the continuing increase in global traffic flow means that the requirement for effective ATM solutions has also been on the rise (Gu & Wan, 2020; Esteve & Zanin, 2025). This is in addition to the inherent challenges in the field of ATM. These areas include sector saturation, workload, weather-related disruptions, capacity constraints, and the impact on emissions (Skorupski, 2017; Socha, 2020; Hamdan, 2022). Thus, the field of ATM is beyond the purely technological. While many research works focus on specific aspects of the ATM system, such as conflict resolution, delay propagation mechanisms, or the safety aspect of the system, the research landscape in the ATM system does not provide an integrated overview of the broader framework of research work carried out over the past ten years 4. To achieve the aforementioned research objectives, the proposed research focused on the bibliometric analysis of 50 carefully selected research articles on ATM from 2014 to 2024 through VOSviewer. The research questions of this paper are:

- What are the prominent themes and clusters in ATM research?
- How do the themes link to technology, operations, and the environment?
- Which fields of research are being developed further, and in what areas lies the untapped potential

The map (Fig. 1) displays the main keywords appearing in ATM research and their relations.

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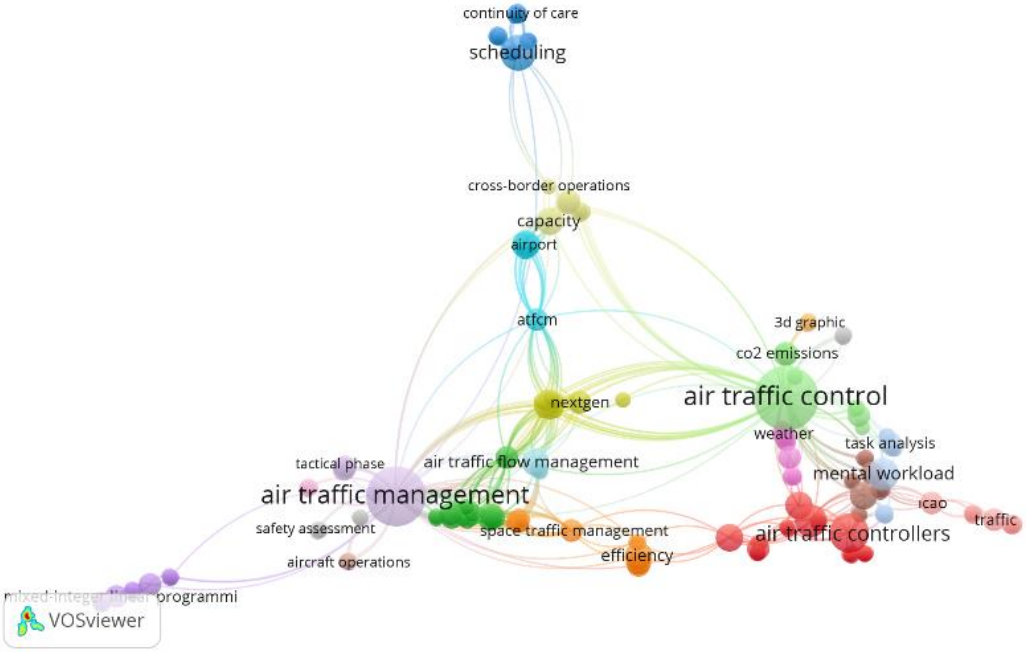

Figure 1. Keyword Network Map Generated with VOSviewer
(source: own compilation)

Larger bubbles visualise more frequent keywords, while colours correspond to the main research clusters: safety, capacity, automation, trajectory-based operations, and sustainability. Based on this, the following hypotheses were formulated:

H_1: The research on Air Traffic Management (ATM) from 2014 until 2024 is organised around five prominent research themes, including the areas of safety and human factors, capacity and airspace efficiency, automation and digitalisation, trajectory-based operations, and sustainability and environmental impacts, which are determined by means of bibliometric cluster analysis.

H_2: Automation, machine learning, and UAS integration are the keywords, and there is a marked corresponding increased importance in the research on ATM in the latter years of the 2014-2024 decade.

This study primarily focused on grasping the major research topics of ATM within a ten-year timeframe (2014-2024) and explaining the relationships among these research topics. Hence, a bibliometric approach was used by analysing 50 peer-reviewed articles in ATM using VOSviewer. The steps involved in keyword cleaning, cluster creation, and keyword network visualisation are explained. The structure of the paper is as follows: the literature review, including research trends, cluster explanations, and gaps, is presented in Section 2. Section 3 describes the methodology. Section 4 then displays the analysis results. Section 5 discusses the findings, while Section 6 describes the practical implications. Section 7 concludes the study.

2. Literature Review

2.1. General Trends in Air Traffic Management Research in the Last Ten Years

We interpret the ATM research landscape as a socio-technical system wherein human actors, technologies, procedures, and regulations co-evolve. Drawing on innovation diffusion perspectives, automation and digitalisation are framed as enabling innovations whose adoption depends on perceived performance gains, compatibility with existing operations, and regulatory support (Torres, 2012; Standfuss, 2024). At the policy level, the ICAO Global Air Navigation Plan (GANP) and the European SESAR ATM Master Plan define capability sets and deployment priorities that directly motivate research in safety enhancement, capacity optimisation, performance-based operations, and environmental sustainability. Overall, ATM research has been growing

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steadily between 2014 and 2024 (Bowman, 2025; Balta, 2024; Brangier, 1990). Increased traffic volume, capacity constraints, safety requirements, and environmental concerns primarily drive this growth. During the early years, from 2014 to 2017, most research focused on safety issues, collision risk models, controller workload, and traditional air traffic control operations. After 2018, the research topics began to shift. Research began to focus more on digitalisation, automation, data-driven decision-making, machine learning, sustainability, and the enhancement of flight trajectories (Jimenez, M. A., Tello, F., & Mateos, A. 2020; Standfuss, 2024; Torres, 2012). In recent years, the integration of unmanned aircraft systems -also referred to as drones- modern ATC technologies, and new communication and navigation systems has also become a leading topic.

In total, over the past ten years, a trend from classic ATC procedures towards more modern, technology-supported, and environmentally aware ATM practices has become obvious:

- Lowercasing and lemmatisation of keywords (e.g., 'models'→'model').
- Acronym consolidation (e.g., 'ATC' merged with 'air traffic control').
- Synonym merging (e.g., 'UAS' and 'drones').
- Removal of stopwords and non-informative terms (e.g., 'study', 'approach').
- Minimum occurrence threshold: ≥3 across the corpus.
- Co-occurrence window: article-level (keywords appearing within the same article).

2.2. Cluster Analysis

The keyword-based cluster analysis aimed at identifying the thematic structure of ATM research published over the period 2014-2024. The analysis utilised the VOSviewer software to conduct a keyword co-occurrence analysis, determining the frequency with which a given term appears in conjunction with other terms throughout the selected articles. Keywords were automatically grouped into clusters based on the strength of these co-occurrence relationships, which represent different thematic dimensions of research within the ATM literature. This type of clustering enables the systematic exploration of the relationships that exist among the various topics covered by research, providing an overview of how the ATM research area has evolved. Overall, the performed analysis identified five major research clusters that are representative of the dominant thematic areas shaping ATM studies during the analysed period. To enhance rigour and reproducibility, the keyword handling and clustering parameters are specified below, along with the corresponding validation procedures (Dmochowski, 2017).

2.2.1. Cluster 1: Safety and Risk Management

This cluster encompasses studies assessing safety, collision risk analysis, human error, and workload of sectors within Air Traffic Management systems. Safety has always been a key domain in research on ATM, particularly due to increased traffic density and a rise in operational complexity. Various previous studies have extensively examined methods for reducing collision risk, improving situational awareness, and enhancing the performance of air traffic controllers under high-workload conditions (Skorupski, 2017; Socha, 2020; Suárez, 2024; Dönmez, Çetek, Kaya, 2022; Stamenić et al., 2025; Vrancken, Cabon, Frantz, 2025).

The strong concentration of safety-related keywords within this cluster confirms that safety and human factors remain a primary pillar of ATM regulations. That is, operational safety and controller workload management remain central challenges in air traffic systems (Philippe, 2025).

2.2.2. Cluster 2: Capacity and Airspace Efficiency

The following cluster covers research related to capacity improvement, airspace design, sector configuration, and delay management in Air Traffic Management systems. The studies within this cluster address the challenges of increasing traffic demand through more efficient airspace structuring and capacity optimisation, while maintaining the required level of safety (Reva, Borsuk, 2015; Shamsiev, 2022). Earlier, several studies have focused on the strategies for airspace sectoring, managing traffic flow, and finding optimisation-based approaches to balance demand and capacity in strongly congested airspace environments. (Edwards, et al., 2016; Dmochowski, 2017; Madhwal, 2017; Hilton et al., 2019; Edwards et al., 2023; Standfuss, 2024, Dhief, et al., 2025; Reynolds 2014; Weigang, 2021; Zombré et al., 2025).

This cluster being most prominent makes clear that capacity and airspace efficiency are the critical operational bottlenecks in research within ATM. The results reveal that optimising airspace structure and traffic flow has

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been the primary key interest for sustaining system performance under increasing traffic volume (Jou, Kuo, Tang, 2013; Pacaux-Lemoine, Debernard, 2000; Pang et al., 2023; Pavlović, Jovanović, Stanojević, 2023; Pavlović, Stanojević, Jovanović, 2025).

2.2.3. Cluster 3: Automation and Digitalisation

This cluster encompasses studies on automation aid tools, machine learning methodologies, and decision support systems designed to enable data-driven operations within the domain of Air Traffic Management. The studies included in this cluster focus on the growing importance of algorithms and computational approaches in supporting air traffic controllers in making more informed decisions. Recent studies on this topic have demonstrated the use of machine learning and optimisation algorithms in handling complex air traffic scenarios and facilitating real-time decision-making in air traffic management systems (Jasek, 1995; Jimenez, Tello, Mateos, 2020; Standfuss, 2024; Torres, 2012; Tafur et al., 2024).

The density of automation- and digital transformation-related keywords in this cluster suggests a notable trend in the direction of ATM research. This establishes that the theme of automation is fast becoming a force that will shape the future of ATM systems.

2.2.4. Cluster 4: Trajectory-Based Operations

This research focuses on management-related studies in flight trajectory planning, conflict resolution, and the optimisation of Air Traffic Management. This research conducts studies on how to increase traffic performance in the airspace environment by improving the predictability of flight trajectories, minimising delays, reducing fuel consumption, and improving traffic flow. Recent studies have explored trajectory planning algorithms, conflict resolution algorithms, and optimisation algorithms to enhance airspace efficiency and reduce its environmental impact (Dmochowski, 2017; Madhwal, 2017; Oehme, 2010; Guo, Bard, 2024; Rosenow, Fricke, 2019).

The presence of trajectory-based operations in this group highlights a significant research focus on performance and predictive approaches for air traffic management. These results indicate a key link between trajectory-based optimisation and integrating established air traffic control procedures with optimised approaches (Louie, Tai, Liem, 2025; Luu, et al., 2021; Sheeja Rani, Aburukba, 2025).

2.2.5. Cluster 5: Sustainability and Environmental Impact

This cluster includes fuel consumption, emissions, noise reduction, and green ATM strategies. In fact, most current ATM studies focus on how air traffic operations can be made more sustainable due to growing environmental concerns worldwide (Pongsakornsathien, et al., 2025; Salmon, 2025).

The cluster analysis indicates the emerging role of sustainability and environmental factors in the context of air traffic management studies. The evidence suggests an increased interest in sustainable ATMs from an environmental sustainability perspective, with sustainability now strongly associated with optimisation and the long-term efficiency of the system (Rezo et al., 2023).

2.3. Keyword Network

The keyword network developed with VOSviewer visualises the connectivity of the main topics of ATM research. Each bubble in the bubble map represents a keyword, and the frequency of occurrence of the keyword in the articles determines the size of the bubble. Keywords that are closely related have stronger connections.

In the map, five major colour groups related to factors such as safety, capacity, automation, trajectory-based operations, and sustainability can be identified. Central keywords, including "air traffic control," "safety," and "capacity," form the largest bubbles, indicating that these words are of great importance in the field. Newer topics, such as "machine learning" and "UAS," also appear, indicating a growing focus on technology and innovation.

2.4. Research Gaps

Although ATM research has grown significantly within the last decade, several gaps remain. Most studies have focused on the areas of safety and capacity, whereas fewer works have been conducted on how automation and

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machine learning can be applied in practical, real-world operations. Similarly, few studies have touched on the integration of UAS in controlled airspace. Only a few studies focus on environmental impacts and/or sustainable ATM strategies. These gaps indicate that there is still a need for more modern, technology-based, and environmentally focused research in the field of Air Traffic Management.

3. Methodology

Table 1. Summary of the Methodology

Step	Description
Data Source	50 ATM articles collected from ScienceDirect and Web of Science
Analysis Tool	VOSviewer is used for keyword co-occurrence and network visualisation.
Procedure	Data extracted → keywords cleaned → VOSviewer → 5 clusters identified.

(source: own compilation)

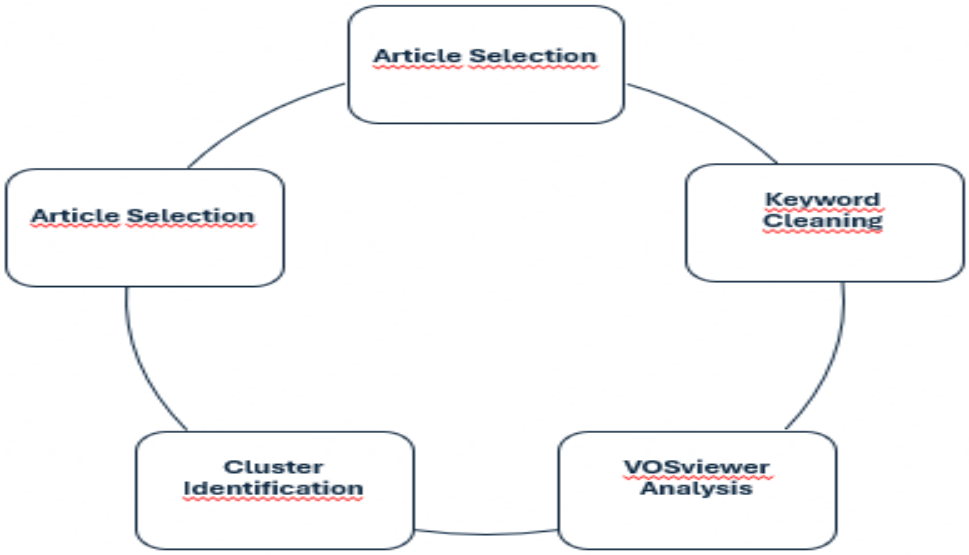

Figure 2. Methodological flowchart of the bibliometric analysis process
(source: own compilation)

4. Results

The keyword co-occurrence analysis of the 50 ATM-related articles produced a dense network of interconnected research themes. As can be seen from the VOSviewer map, this is a highly clustered structure, where particular concepts tend to group naturally into clusters due to their frequency and co-occurrence in the literature. Five big research clusters were identified that corresponded to the dominant subject areas in the 2014–2024 ATM landscape. With respect to the original analysis, the augmented corpus reveals a more intricate and interconnected keyword relationship structure, as well as a clear strengthening of relationships in the areas of air traffic control, air traffic flow management, and human factors.

4.1. Overall Network Structure

Figure 3 represents a highly clustered map, where core terms such as air traffic control, air traffic flow management, airspace sectoring, algorithm, capacity, and safety are located at the centre of the network. These keywords serve as hubs in connecting operational, technological, and environmental research directions.

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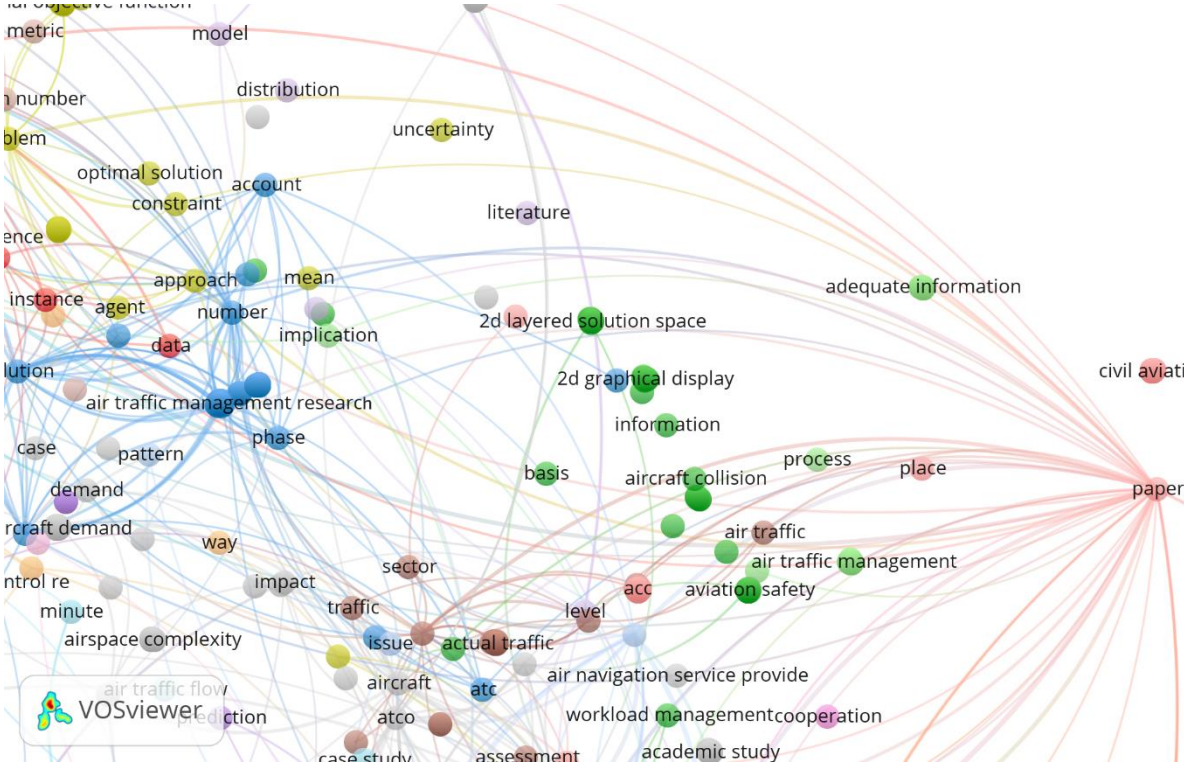

Figure 3. *Keyword co-occurrence network in Air Traffic Management literature, illustrating the relationships and interactions between core research themes and highlighting the interconnected structure of operational, safety, and management-related concepts. (source: own compilation)*

In the keyword co-occurrence network map, each bubble represents a keyword identified in the analysed ATM articles, and the size of each bubble shows how often this keyword appears in the current body of literature. Accordingly, larger bubbles represent keywords with higher usage in ATM research. The position of each bubble also indicates how closely they relate to each other, as keywords that appear together in ATM research are positioned closer together. The links in this visualisation represent the relationship of keyword co-occurrence.

Different colours in the network map denote different research groups identified by VOSviewer. Although each cluster is designated to a particular field of study, it is crucial to realise that links exist between clusters, showing the interdisciplinary nature of ATM research. It should be noted that, for example, strong connections between safety-related and capacity-related clusters demonstrate the close relationship between operational safety and efficient airspace utilisation within modern Air Traffic Management systems.

Network density shows that research in ATM is concentrated around four key areas of interest:

- air traffic flow / ATFM
- sector configuration and capacity
- Algorithmic methods and optimisation.
- safety-related keywords included collision risk, information accuracy, and cognitive load.

These dense regions reflect the most active areas of ATM research between 2014 and 2024.

4.2. Identification of the Five Clusters

4.2.1. Cluster 1 – Safety and Human Factors

The findings of Cluster 1 bear a direct relation to the literature review in Section 2.2.1 and the significance of safety and human factors in Air Traffic Management studies. Various studies have highlighted the paramount aspects of controller workload and its critical influence on operational safety in a complex airspace environment, based on factors such as cognitive processes and human error (Skorupski, 2017; Socha, 2020; Suárez et al., 2024).

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The high co-occurrence of safety-related keywords in this cluster highlights these aspects and their prevalence in ATM studies within the current context.

Within this cluster, the keywords used include aircraft collision, aviation safety, adequate information, cognitive load, and decision-making. The strong internal linkage among these terms indicates that research has consistently emphasised the safety-critical aspects of ATM. Many of these works focus on mitigating human error, enhancing situational awareness, and supporting air traffic controllers during high workload conditions.

Safety remains the primary pillar of ATM research, as human factors continue to influence operational performance.

4.2.2. Cluster 2 – Capacity and Airspace Efficiency

Results from Cluster 2 closely relate to the literature on capacity and efficiency focus discussed in Section 2.2.2 above. In literature, airspace sectoring, traffic flow management, and balancing demand and capacity are recognised as playing major roles in mitigating congestion and delay in high-density airspace environments (Dmochowski, 2017; Madhwal, 2017; Standfuss, 2024). The dominance of terms characteristic of airspace configuration and traffic characteristics in this cluster indicates that optimising capacity is a major concern for research in ATM environments that are under increasing demand pressure related to traffic volume.

This cluster is characterised by terms such as airspace sectoring, configuration, air traffic flow, pattern, and demand. These keywords represent research into the challenges posed by increasing traffic volume, sector capacity limitations, and the structural redesign of airspace. Various investigations aim to optimise sector configuration to reduce delays while balancing demand with available capacity. Since capacity constraints remain an important operational constraint, efficiency-focused research is essential (Martin et al., 2020).

4.2.3. Cluster 3 – Automation, Algorithms, and Digitalisation

The findings of Cluster 3 open up new avenues of discussion, which were initiated in Section 2.2.3. It has been proven in previous research that algorithmic models, machine learning, and data-driven decision support systems play a major role in traffic flow optimisation, accuracy improvement, and workload reduction in traffic centres (Torres, 2012; Standfuss, 2024; Jimenez, M. A., Tello, F., & Mateos, A. 2020). The density of computational/automation keywords in Cluster 3 verifies the widespread use of advanced technologies in efficiency-oriented ATM research.

The cluster is dominated by such keywords as algorithm, model, data, optimal solution, and new methodology. This categorisation mirrors the increasing trend toward computation-based methods, machine learning, data-driven operations, and automated decision-support tools. These works aim to enhance accuracy, reduce controller workload, and improve prediction and optimisation capabilities within ATM (Mirchi et al., 2015).

Automation is the transformative factor in ATM, increasingly shaping the design of the future operational system (Standfuss, 2024; Jakšić & Janić, 2020).

4.2.4. Cluster 4 – Trajectory-Based Operations and Operational Planning

This cluster includes terms like 2D graphical display, information, process, air operation, and aircraft skip.

Keywords include the optimisation of flight trajectories, conflict detection, route planning, and visualisation systems supporting controllers and pilots. These studies focus on improving airspace performance through better trajectory management.

Trajectory-based operations form a bridge between traditional air traffic control and emerging performance-based navigation concepts (Dmochowski, P. A. 2017).

4.2.5. Clusters 5 – Sustainability and Environmental Impact

The last cluster features words like SAF, or sustainable aviation fuel, emission, carbon price, fuel cost, and ATFM performance.

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This cluster highlights the increasing importance of environmental aspects in ATM research, particularly in light of stricter emission targets and higher expectations for the sustainability of the aviation sector. Sustainability has become a core research theme, pointing towards environmentally conscious ATM strategies (Mangav, D., McDermott, O., & Trubetskaya, A. 2026).

4.3. Central Keywords and Link Strength

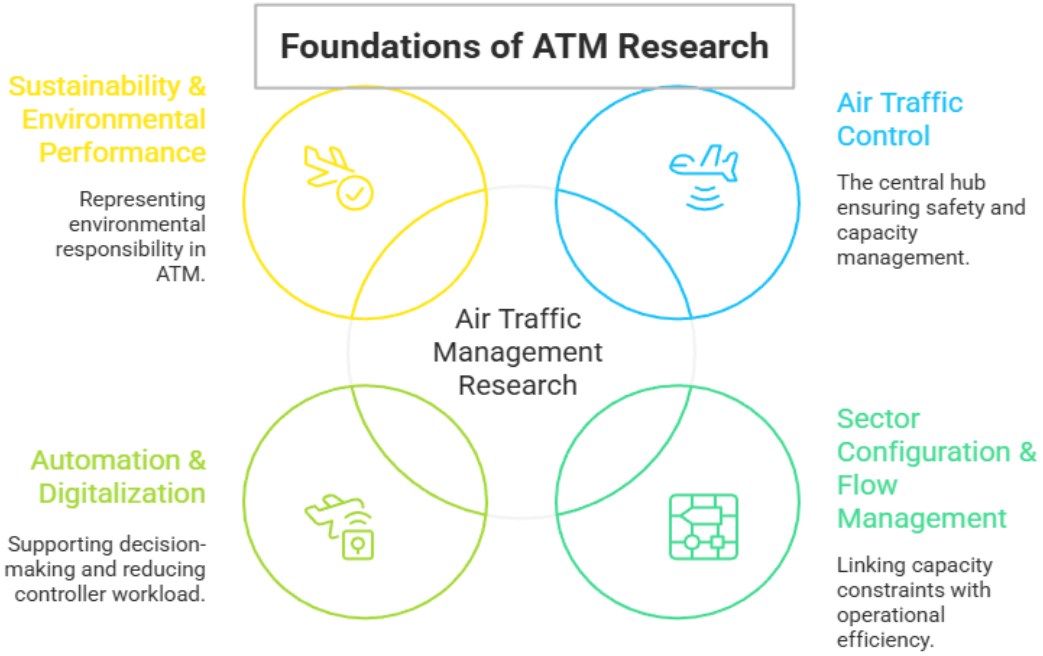

Figure 4. Visualisation of central keywords and their relationships in ATM research
(generated using napkin.ai)

The following keywords serve as central hubs within the entire map, as indicated by the co-occurrence network. They are characterised by high link strength, since they frequently appear together with more clusters; thus, they bridge major research themes.

The most dominant keyword is "air traffic control", located near the centre of the network. Its strong links to the terms related to both safety and capacity suggest that it remains the core element of ATM research and operations (Dmochowski, 2017; Skorupski, 2017).

Additionally, "sector configuration" and "air traffic flow management" exhibit high centrality, linking capacity management to operational efficiency. These also often co-occur with topics such as delay, workload, and airspace structure, reflecting the system-wide importance of capacity balancing.

The core of the automation and digitalisation cluster is represented by keywords like "algorithm," "model," and "data"; their strong link strength suggests a growing research focus on computational methods, machine learning, and optimisation-based decision-support tools, which demonstrate the ongoing shift toward data-driven ATM operations.

Among the sustainable cluster, terms like "SAF," "emission," "fuel cost," and "carbon price" are highly internally connected. The fact that these terms are so closely related shows how environmental performance and policy-driven operations are increasingly being emphasised.

Overall, the central keywords suggest that four interacting forces have driven ATM research in the period 2014–2024:

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•operational safety,
•sector and capacity constraints,
•automation and digitalisation, and
•Sustainability requirements.

These hubs constitute the structural backbone of the ATM research landscape (Jakšić & Janić, Esteve & Zanin, 2025).

4.4. Density Map Interpretation

This density visualisation offers further insight into where research activity has been most focused within the ATM landscape. From this density map, regions in yellow correspond to a higher frequency of the keywords and stronger co-occurrence relationships, while areas in darker tints correspond to less frequently studied topics.

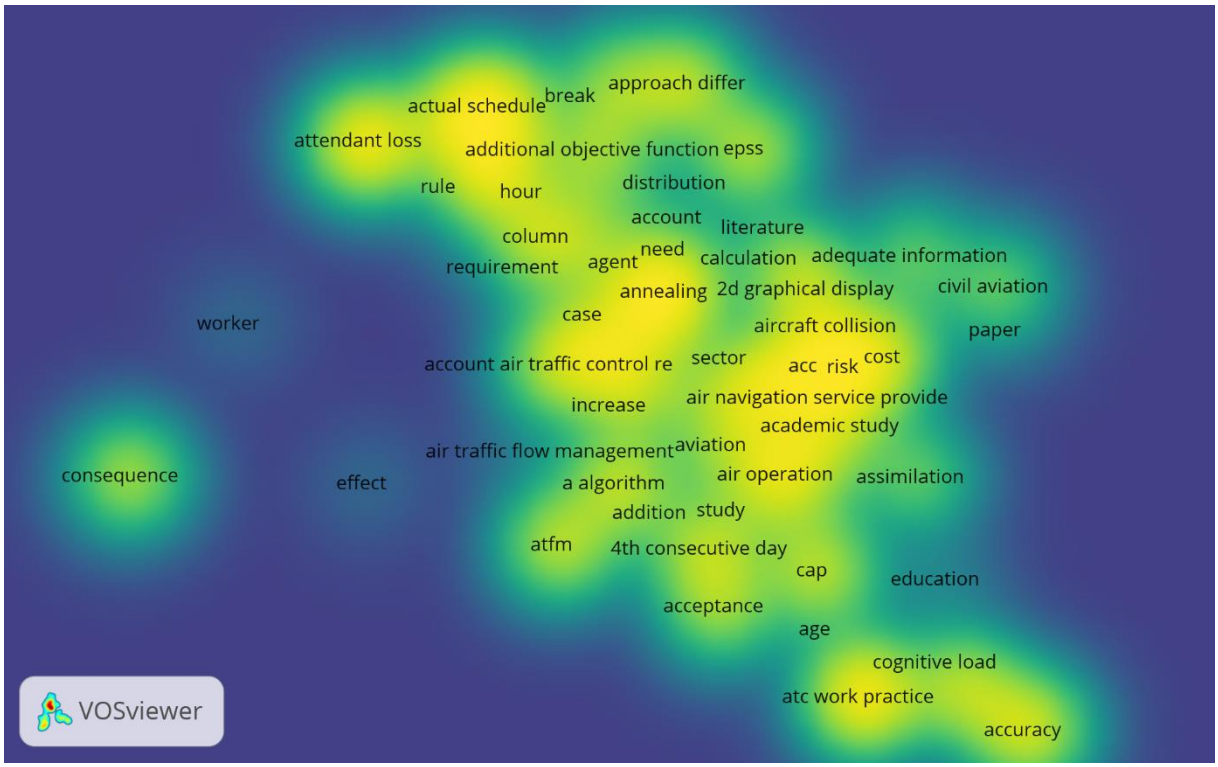

Figure 5. Density map of keyword co-occurrence in Air Traffic Management literature
(source: own compilation)

The brightest regions in the map correspond to keywords related to:

• air traffic flow / ATFM,
• airspace sectoring and configuration.
• Algorithmic and optimisation-based approaches, and
• safety-related concepts such as collision risk and information accuracy.

These areas emphasise the dominant research focus on managing traffic growth, sector efficiency, and the safety of increasingly complex operations.

Another catch is the high-density zone around keywords related to environmental performance, such as emissions, fuel costs, carbon prices, and SAF (Hamdan, 2022). This indicates that sustainability has become a major research priority, aligned with global environmental policies and the aviation industry's move towards greener operational strategies.

The density map reinforces the cluster analysis's observation that ATM research between the years 2014 and 2024 has concentrated on four major areas:

• operational safety,
• capacity and airspace efficiency,
• automation and digitalisation, and
• environmental sustainability. These dense regions represent the areas where ATM research has evolved over the last ten

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years and indicate the direction of scholarly attention.

5. Discussion

Table 2. Summary of the Five ATM Research Clusters

Cluster	Main Focus	Key Insight
Safety & Human Factors	Collision risk, workload, human performance	Safety remains the priority in ATM research
Capacity & Airspace Efficiency	Sectoring, ATFM, demand- capacity balance	Airspace efficiency is essential due to increasing traffic
Automation & Digitalization	Algorithms, ML, decision-support tools	Research trends indicate a clear shift toward data-driven ATMs.
Trajectory-Based Operations	Trajectory optimisation, conflict detection	Modern ATM shift toward performance-based operations
Sustainability & Environment	Emissions, SAF, carbon pricing	Environmental concerns increasingly shape ATM studies

(source: own compilation)

Specific findings from the keyword network and cluster analysis reveal that between 2014 and 2024, the dominant themes in ATM research centred on safety, capacity, automation, trajectory-based operations, and sustainability. The consistency of these themes in the literature, along with the trend from traditional ATC-focused studies toward more technology-driven and environmentally oriented research directions, is evident.

5.1. Safety and Human Factors

Safety is the most prominent theme identified within ATM. The interlinked nature of keywords such as "collision risk," "workload," "information accuracy," and "human performance" confirms previous conclusions drawn within the ATM body of knowledge (Skorupski, 2017; Socha, 2020), which states that the greatest influence on controller workload is, in fact, the density of air traffic. This confirms ATM safety-oriented research as the first pillar within ATM.

5.2. Capacity and Airspace Efficiency

Capacity and airspace efficiency are another essential area being researched in ATM. The way the keywords are grouped in the form of a cluster, with references related to airspace sectorization, traffic flow, and demand, signifies the ongoing attempt to reduce the effects of congestion and increasing volumes (Torres, 2012). In synchrony with earlier research efforts in this area, capacity limitations have been identified once again as a crucial barrier for ATM.

5.3. Automation and Digitalisation

The emphasis on keywords such as algorithms, data models, and decision support systems is indicative of the growing importance given to automation and digitalisation in modern ATM technology. It is in line with the overall digital evolution taking place in the aviation industry, with predictive analytics, machine learning, and optimisation increasingly being adopted to improve the accuracy of decisions and minimise the efforts of air traffic controllers. It is evident from the study that automation is emerging as a paradigm-shaping technology in future ATM systems (Jimenez, M. A., Tello, F., & Mateos, A. 2020; Standfuss, 2024; Dmochowski, 2017).

5.4. Trajectory-Based Operations

Trajectory-Based Operations are described by their strong focus on performance-driven ATM concepts. Trajectory-related keywords, focusing on planning, collision detection, and the predictability of operations, reflect a strong interest within the research community to address issues of delay, fuel burn, and airspace efficiency. These observations reinforce the sector's shift toward performance-driven navigation and flow management, highlighting Trajectory-Based Operations as key to Next Generation ATM Systems (Torres, 2012; Kistan, T., Gardi, A., Sabatini, R., Ramasamy, S., & Batuwangala, E. 2017; Jakšić & janić, 2020).

5.5. Sustainability and Environmental Impact

The increasing presence of sustainability-related terms, including emissions, sustainable aviation fuel, carbon pricing, and fuel costs, within the search data demonstrates that sustainability-related issues are becoming an

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increasingly integral part of ATM-related research. These findings are consistent with the global aviation plans to operate in a more environmentally sustainable manner. Sustainability-related matters are now increasingly being incorporated within the ATM-related research agenda, rather than being relegated to the margins (Hamdan, 2022; Jakšić & janić, 2020; Mangav, 2026).

5.6. General Interpret

On the whole, the evidence suggests a paradigm shift in the study of ATM, where the more traditional air traffic control-oriented paradigm is now being supplemented by, and in some cases, progressively supplanted by more technology-centric, performance-related, and environmentally sensitive paradigms. Safety and capacity remain, of course, the cornerstones, but the rising importance of automation, trajectory-related operations, and environmental considerations can only serve to underscore the primacy of new priorities in contemporary ATM. Nevertheless, the extension of the dataset to encompass 50 articles serves to support further this paradigm shift, where clearer patterns emerge regarding the relationship between safety, capacity, automation, and sustainability (Dmochowski, 2017; Jakšić & Janić, 2020; Esteve, P., & Zanin, M. 2025).

Table 3. Drivers and Barriers by Theme

Theme	Key Drivers	Key Barriers
Safety & Human Factors	Traffic density, operational complexity, resilience requirements	Cognitive load; human error; limited decision-support adoption
Capacity & Airspace Efficiency	Demand growth; network performance targets	Sector constraints, coordination overhead, and regulatory harmonisation
Automation & Digitalization	Data availability; ML/optimisation advances; performance-based ambitions	Certification/trust; interoperability; cyber-security risks
Trajectory-based Operations	Predictability; performance-based navigation; FOC-ATC integration	Legacy procedures; tooling maturity; cross-border coordination
Sustainability & Environment	Emission targets; carbon pricing; SAF initiatives	Measurement granularity; operational trade-offs; policy fragmentation

Source: Own compilation

6. Practical Implications

The findings of this study have significant implications for multiple stakeholder groups involved in the evolution of Air Traffic Management (ATM). Translating these insights into actionable strategies can accelerate the transition toward safer, more efficient, and environmentally sustainable airspace operations.

6.1. Regulators and Policy-makers

Regulators should align deployment roadmaps with measurable targets that simultaneously address safety, capacity, and environmental performance objectives. This alignment ensures that modernisation efforts do not prioritise one dimension at the expense of others. Furthermore, policy-makers need to incentivise data sharing and interoperability for automation tools by establishing robust standards and governance frameworks. Such measures will facilitate seamless integration of advanced technologies across jurisdictions. In addition, regulators should develop certification pathways for machine learning–enabled decision-support systems, specifying clear evidence requirements related to robustness, explainability, and latency. These pathways will help overcome trust and compliance barriers that currently hinder the adoption of AI-driven solutions.

6.2. Air Navigation Service Providers (ANSPs)

ANSPs should prioritise the implementation of trajectory-based operations that demonstrably reduce delays and fuel consumption while maintaining controller workload within acceptable limits. Investments in resilience—such as contingency procedures and cross-border coordination—must be informed by network-level analytics to ensure operational continuity under disruptive conditions. Moreover, ANSPs should establish human-in-the-loop evaluations for automation tools during trial phases. These evaluations will enable continuous monitoring of

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workload, situational awareness, and mode awareness, thereby mitigating risks associated with automation bias and unexpected system behaviours.

6.3. Technology Developers and Integrators

Technology developers must design interoperable, standards-compliant APIs and data models to facilitate integration with legacy ATM systems. Embedding human factors and explainability features into machine learning tools is crucial for fostering controller trust and encouraging adoption. Additionally, developers should provide uncertainty-aware optimisation capabilities that account for variables such as weather and demand fluctuations. These capabilities should be complemented by performance trade-off dashboards, enabling operational decision-makers to balance efficiency, safety, and sustainability objectives in real time.

6.4. Training and Human Factors

Training programs should be updated to incorporate modules on human–AI teaming, mode awareness, and strategies for mitigating automation bias. Scenario-based training exercises that expose controllers to varying traffic regimes and levels of automation will enhance adaptability and preparedness for future operational environments. Continuous monitoring of cognitive workload using validated measures should inform rostering decisions and the deployment of support tools. This proactive approach will help maintain controller performance and well-being in increasingly automated and data-driven ATM systems.

7. Conclusion

This paper conducted a bibliometric analysis of Air Traffic Management (ATM) from 2014 to 2024, aiming to highlight important themes and intersecting concepts within the body of knowledge. Utilising analysis software VOSviewer on keyword matrices reveals five critical groups of themes: safety and human factors, capacity and airspace efficiency, automation and digitalisation, trajectory-based operations, and sustainability and the environment.

It is evident from the results that the backbone of ATM studies remains safety and capacity management. This highlights continued operational concerns regarding increased traffic density values. However, a trend is emerging towards automation, decision support systems based on data, and operational strategies based on trajectory, which indicate progress towards a performance-oriented ATM framework that employs technological support. Additionally, the emergence of sustainability topics suggests an increase in concerns and intentions related to the environment in current ATM studies.

From a scholarly perspective, this study makes several contributions by providing a clear roadmap of the shifts in ATM research topics over the last decade, with a clear linkage of relationships between these topics. From a practical perspective, this study presents concrete policy implications for policy-makers, air navigation service providers, and system developers by identifying key areas for shaping the future of ATM systems.

Nevertheless, the study also has certain limitations. The paper relied on a finite number of articles and presented a basic analysis of the mentioned keywords in the study, which may not be entirely accurate due to the conceptual and methodological divergences in the papers used. The next study could utilise a more extensive number of publications and employ multiple databases, in addition to using citation analysis to identify the themes of ATM papers. Another study could also observe the change in themes of ATM over a period of time to identify emerging themes.

The findings suggest a consensus that the current trend in ATM research is toward an integrated approach that balances safety, efficiency, technological innovation, and environmental sustainability. This holistic view will likely be crucial in the coming years for developing a resilient, efficient, and sustainable air traffic management system.

Through the expansion of the dataset and the strengthening of the keyword network, this research offers a more robust and comprehensive understanding of the ever-evolving paradigm of ATM research.

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