

Air Traffic Control Coordination and Monitoring: A Review of European Practices

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Article Info	Abstract
<p>Received: 27.03.2026 Revised: 04.05.2026 Accepted: 05.05.2026 Published: 20.05.2026</p> <p>Keywords: Air Traffic Control, Air Traffic Management, Capacity Management, Air Traffic Flow Management</p> <p>Jel Code: Z00</p> <p>Corresponding Author: Hasan Buğra IŞILAR</p> <p>Research Article https://doi.org/10.5281/zenodo.20297862</p>	<p>Air traffic control (ATC) coordination and supervision are of vital importance for maintaining safe, orderly, and efficient air traffic operations, particularly in areas where traffic density and operational complexity are high. With the continuous growth in global air transport demand, effective coordination mechanisms between countries and regions have become increasingly important. The primary aim of the study is to evaluate the current methods used in the control and management of European airspace and through a literature-based review to provide a general framework explaining existing coordination. To achieve this objective, the study first establishes a conceptual framework for air traffic control based on a comprehensive literature review. It then examines the roles of international and regional aviation organizations, such as ICAO, EUROCONTROL, and IATA, in the coordination and monitoring of airspace operations. Using a descriptive analysis approach, the study reviews current air traffic control services in Europe and evaluates the operational procedures, regulatory frameworks, and technological developments that support air traffic management. Emphasis is placed on key issues such as capacity management, the complexity of air traffic, controllers' workload, and air traffic flow management, digitalization and automation, artificial intelligence and machine learning, Single European Sky, remote/digital towers, UTM integration, green ATM and trajectory-based operations (TBO). Furthermore, recent operational initiatives and technological tools, including the COCA (Complexity and Capacity) project, the CAPAN capacity analysis method, and Airport Collaborative Decision-Making (A-CDM) applications, are addressed. The reviewed literature indicates that increasing traffic demand, system complexity, and air traffic controllers' workload remain the primary challenges in air traffic management. This study contributes to the current literature by offering a thorough and contemporary literature analysis of air traffic control coordination and surveillance techniques in Europe. The findings of this study suggest that the increasing complexity and traffic demand in European airspace require more integrated, adaptive, and technology-driven policy frameworks. From a policy perspective, strengthening coordination mechanisms among national air navigation service providers (ANSPs) should be prioritized to reduce airspace fragmentation and enhance cross-border interoperability. Consequently, technological innovation, collaborative decision-making processes, and coordinated regulatory frameworks are of vital importance to ensure the safe and efficient management of European airspace.</p>

1. Introduction

Air traffic control services are of vital importance for the smooth and safe operation of air traffic. Maintaining the safety of this service necessitates constant coordination through mutual communication. In recent times, research domains within the field of air traffic management have expanded to encompass both established disciplines and novel advancements in science and technology. To maintain a satisfactory level of congruence with such rapid changes, effective communication and coordination between all sections of air traffic management is an essential prerequisite. The increasing demand and air traffic associated with the shift in passenger preferences towards air travel is increasing the workload of air traffic management within the projected timeframe (Nolan, 2011). The commissioning of new airports and increased investment from the Asia-Pacific and Middle East regions to upgrade airports in North America and Europe are also increasing the need for air traffic control. The International Air Transport Association (IATA) has stated that it is anticipated that air passenger traffic will exceed 7 billion by 2035, with an annual growth rate projected to exceed 3.5 percent. In developed regions, airport authorities are concentrating on the modernization of existing airport infrastructure through the introduction of advanced air traffic management systems, with the objective of enhancing the efficiency of air traffic services (IATA, 2019). The increased investment in the enhancement of airport infrastructure within developed regions of North America and Europe is a key factor in the growing demand for effective traffic management solutions. The increase in demand and flight numbers has created a need for investment in new tools and equipment for air traffic management. For instance, in 2017, Seattle-Tacoma Airport in the United States initiated an expansion program with an investment of 1.6 billion US dollars; the airport's systems for managing air traffic accounted for the second-largest share of this expansion (FAA, 2010).

The airport terminal control and ground control systems received approximately one-third of the investment. The lighting and signaling equipment associated with these systems is also included in this category (IATA, 2019).

Current estimations suggest that hardware components will account for in excess of 75% of the air traffic management market by 2025, a development that will be driven by the commissioning of new airports and the increasing digitalization of existing airports. The majority of developed regions, including North America and Europe, are concentrating on the enhancement of existing air traffic management systems with the objective of providing superior air traffic services to airlines (EUROCONTROL, 2000). The field of air traffic management has undergone significant expansion, driven by the development of existing systems and the commissioning of new airports. The increasing use of artificial intelligence in air traffic systems has led to a growing demand for more advanced software (Wickens, Mavor, & McGee, 2013). For instance, in 2019, the Irish Aviation Authority (IAA) utilized Iridium NEXT satellites equipped with Aireon space-based Automatic Dependent Surveillance-Broadcast (ADS-B) payloads (Eurocontrol, 2017). This innovative software facilitates real-time air traffic surveillance and tracking and the provision of air navigation services. Concurrently, air traffic control assumes a pivotal function within the overarching framework of air traffic management, a development primarily attributable to two interrelated factors. Firstly, the escalating volume of passenger traffic, and secondly, the market entry of a multitude of new airlines (Rantanen, 2005). The demand for more advanced communication and navigation systems is driving further growth in the field of air traffic control (ATC). For instance, in January 2019, the National Air Traffic Services (NATS), the body responsible for air traffic management in the United Kingdom, installed an AI-supported digital control tower at Heathrow Airport. The principal objective of the control tower is to minimize delays in flight. The expansion primarily stems from the emergence of remote and virtually controlled towers. For instance, countries such as India and China are providing cost-effective solutions for air traffic management services by focusing on regional connectivity and long-haul flights (IATA, 2019; Sengur, 2022).

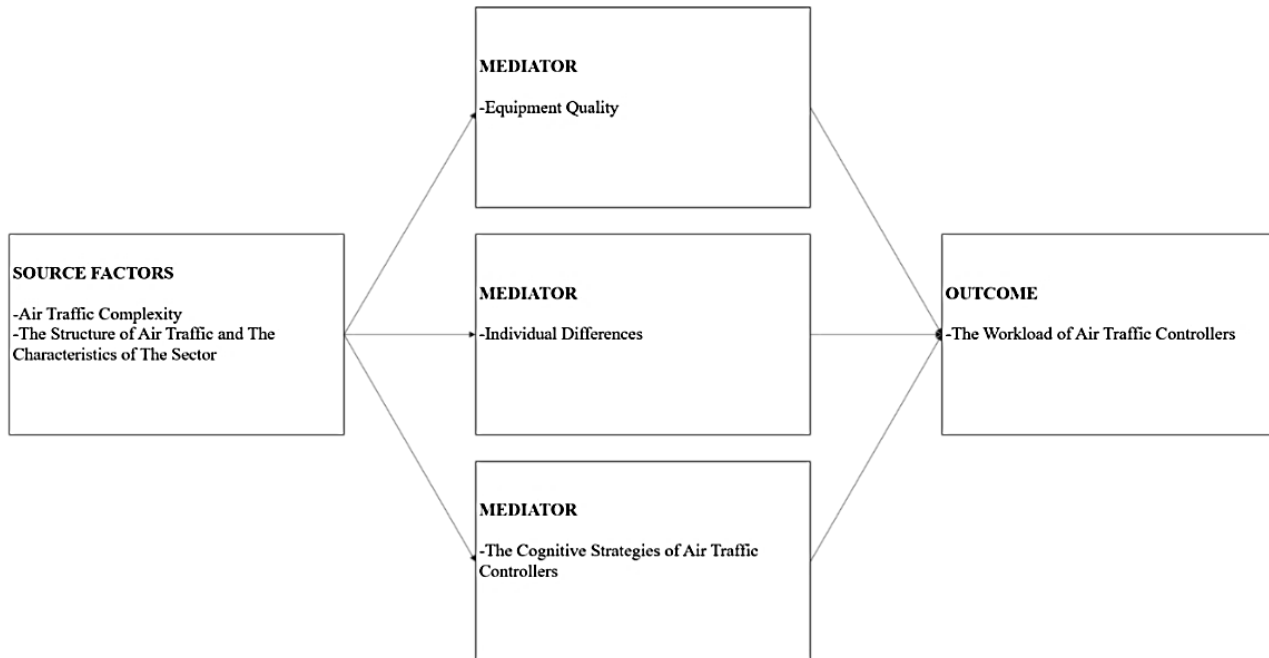
In this context, the study examines how air traffic control in Europe has evolved in response to changing demands and how current practices are being implemented. A plethora of recommendations have been proposed concerning how air traffic control can manage the increasing volume of traffic in an efficient and safe manner. The literature review revealed that a thorough examination of European air traffic management had not been conducted, and existing research was limited to appraisals of the topic. A complete literature review of ATM has not been conducted, and contributions have been made to the literature concerning advancements in the field and potential deficiencies. The study is significant in terms of identifying emerging practices in Europe and their evolution or differentiation.

2. Literature

The study's framework is predicated on government and contractor technical reports, scientific journal articles, book chapters, and operational reviews. The relevant references are primarily drawn from the fields of ATM research, human factors, safety management systems, air traffic control management, and cognitive psychology and computer modeling. While the primary focus is on the examination of practices regarding air traffic control coordination and monitoring, theoretical and empirical studies on workload assessment have also been utilized, given the importance of human factors in ensuring this coordination. The majority of the established factors related to air traffic management have been published by EUROCONTROL, IATA, and ICAO or drawn from the relevant literature. Recently, a series of significant reports and articles on the ATC problem have been published, including various in-depth reviews of the complexity factor literature (Malakis, 2019). Complexity has been defined as a situation or event being complex and incomprehensible, with many parts coming together to form a more complex situation, and furthermore, each unit combining to make the existing situation even more difficult (Cambridge Dictionary, 2020). In the context of air traffic control, however, numerous distinct definitions of complexity have been proposed (Radišić, Andraši, Novak, Juričić, & Antulov-Fantulin, 2020). The most perspicuous definition was provided by Meckiff and colleagues as the difficulty in monitoring and managing a specific air traffic situation (Meckiff, Chone, & Nicolaon, 1998). Air traffic complexity can also be defined as a series of potential aircraft-to-aircraft and aircraft-to-environment interactions occurring within a specific time frame. It is important to note that not all of these interactions require the same level of attention, urgency, or workload (Radišić, Andraši, Novak, Juričić, & Antulov-Fantulin, 2020). It is important to note that complexity does not bear the same significance as air traffic density. The number of aircraft in a sector has been shown to influence complexity; however, treating this number as the sole indicator is not a valid approach, particularly when comparing two different sectors (Kirwan, Scaife, & Kennedy, 2001; Mogford, Guttman, & Morrow, 1995; Athènes, Averty, & Puechmorel, 2002). It is noteworthy that two disparate sectors may exhibit analogous traffic density, yet significantly disparate levels

of complexity. Numerous studies have demonstrated that complexity generally increases workload (Christien, Benkouar, Chaboud, & Loubieres, 2002). Mogford et al. (1995) posited that complexity is a pivotal factor in the workload of controllers (see Figure 1). However, it should be noted that complexity and workload are not directly correlated. A range of mediating factors have been identified, including equipment quality, individual differences, and controllers' cognitive strategies.

Figure 1. Factors affecting controller workload



The study refers to the work of Mogford and colleagues (1993) on the subject of complexity. Given the anticipated increases in traffic, alongside corresponding developments in ATC (Air Traffic Control) procedures and technologies, there is a growing need to understand the capabilities of control systems and controllers and to determine the 'safe' limits of their workload (Schmidt, 1976). In this context, studies on how air traffic control adapts to the increasing demand and traffic have been evaluated in this section. The literature review revealed that issues of capacity and complexity in relation to air traffic are frequently encountered in various studies. Another frequently encountered topic is how EUROCONTROL and various organizations across Europe are responding to the increasing traffic and the projects they have developed for monitoring and coordinating this traffic. It is reported that the greatest limitation of air traffic management lies in the increasingly complex operations (Mogford, Guttman, & Morrow, 1995). It is thought that improved measures to address ATC complexity could provide benefits such as the evaluation of ATM productivity, the comparison of cost-effectiveness, and the assessment of the impact of new tools and procedures (Mills, 1998). In this regard, EUROCONTROL's Network Capacity and Demand (NCD) initiative is implementing the Complexity and Capacity (COCA) project. The primary objective of COCA is to identify, develop, and evaluate factors related to air traffic control complexity; to validate and test complexity factors; and to identify those linked to controller workload and sector capacities. The aim of the application is to create a model of air traffic, compare this model with factors causing complexity in air traffic, design the airspace according to this model to determine the optimum capacity, and apply the existing capacity to sector classification and air traffic flow management (EUROCONTROL, 2000). In the majority of studies conducted to date, attempts have been made to draw conclusions whilst disregarding the cognitive structure of air traffic controllers. However, recent advancements in technology and increasing human-machine interaction have led to little discussion on how to reduce cognitive load, aside from a few studies and reports. It has been observed that with increasing automation technologies, the cognitive load on controllers can be reduced, thereby ensuring a safer air traffic flow. Within the context of the COCA project, EUROCONTROL acknowledges the necessity of incorporating controllers' cognitive aspects into the complexity of air traffic.

Recent advancements in air traffic management (ATM) and air traffic control (ATC) systems have been significantly shaped by rapid technical progress, escalating traffic demand, and the rising complexity of airspace operations. The digital transformation of ATM systems has become a significant trend marked by the integration of automation, data-driven decision-making, and sophisticated decision-support technologies.

ATM systems are progressively integrating artificial intelligence (AI) applications and automation technologies to improve operational efficiency and assist controllers in managing intricate traffic scenarios (Xia et al., 2026; EUROCONTROL, 2020). The SESAR Joint Undertaking emphasizes that the "Digital European Sky" goal is heavily reliant on the deployment of intelligent technology that can provide predictive traffic management and real-time decision assistance which contributes to safe implementation of ATM operations (SESAR JU, 2026).

In this regard, artificial intelligence and machine learning have been employed particularly in domains such as traffic flow forecasting, conflict identification, and workload evaluation. Current advancements focus on a "human-in-the-loop" model, emphasizing the enhancement of human operators rather than their complete replacement, with AI systems serving as assistive tools to supplement human decision-making capabilities (Whig et al., 2024). FAA (2023) underscores that next-generation ATM systems seek to enhance the interplay between automation and human proficiency to guarantee safety and operational resilience.

A significant trend is the heightened emphasis on the intricacies of air traffic and the administration of controller duty. Capacity management now transcends mere traffic volume considerations. Advanced models incorporating complexity measurements and dynamic sectorization tactics are supplanting conventional capacity management. Reports from EUROCONTROL (2006) and CANSO (2022) emphasize the importance of managing controller workload and operational complexity for ensuring safety and efficiency in high-density airspace.

Moreover, collaborative decision-making procedures and network-centric operations have become essential components of contemporary ATM systems. The execution of Airport Collaborative Decision-Making (A-CDM) programs signifies a shift from centralized control systems to coordinated efforts among air navigation service providers, airlines, and airport managers. ICAO (2021) indicates that collaborative frameworks enhance information exchange, augment predictability, and bolster overall system performance.

Significant European-scale modernization initiatives, like the Single European Sky and SESAR programs, play a crucial role in influencing ATM advancements at the European level. These projects seek to diminish airspace fragmentation, enhance interoperability, and establish performance-based management systems. The European Commission and the SESAR Joint Undertaking highlight developments such as Free Route Airspace and trajectory-based operations, which provide more flexible and efficient flight planning (SESAR, 2025).

Technological innovations have facilitated the creation of remote and digital tower concepts, enabling air traffic services to operate independently of the physical location of control towers. This is especially advantageous at low-traffic airports where cost advantages can be achieved without jeopardizing operational safety. Research conducted within the SESAR framework indicates that digital towers are becoming viable and scalable options for the existing air traffic management environment (SESAR JU, 2026; SESAR, 2025).

The incorporation of unmanned aerial vehicles into regulated airspace has generated both obstacles and opportunities for air traffic management. U-Space and unmanned traffic management (UTM) technologies represent a significant advancement in the safe and effective integration of drones into current airspace frameworks. EASA (2021) delineates a legal framework that facilitates this integration, emphasizing the necessity for solutions that are harmonized and scalable (EASA, 2021).

Environmental sustainability is now a crucial catalyst for ATM innovation. The significance of decreasing fuel usage, limiting emissions, and improving flight paths is increasing. Trajectory-based operations and performance-based navigation are essential for attaining these environmental goals (ICAO, 2022). The transition to trajectory-based operations (TBO) in air traffic management represents a significant paradigm shift. TBO is not a conventional sector-based control; rather, it is a four-dimensional aircraft trajectory management system that incorporates time, facilitating more accurate and efficient traffic management. This approach, broadly supported by the International Civil Aviation Organization and the Federal Aviation Administration, is anticipated to serve as the foundation for future ATM systems.

The research indicates that contemporary ATM systems are evolving towards a highly integrated, data-centric, and collaborative framework. Technological innovation, particularly in artificial intelligence and digitalization, alongside coordinated regulatory initiatives and stakeholder collaboration, is essential for tackling the problems posed by increasing traffic demand and operational complexity (ICAO, 2020).

Another issue encountered in the domain of air traffic management pertains to the management of air traffic flow. The flow management system is regarded as one of the most promising short-term approaches for alleviating the serious congestion problems currently affecting the air traffic network across the United States and Europe. As Amedeo (1987) noted, congestion is having a significant impact on air traffic in both the United States and Europe. This situation is still, to a certain extent, limited to the busiest commercial airports and a few 'sectors' of the air traffic control (ATC) network. However, the distribution of traffic is such that the effects are practically felt by passengers using both North American and Northern European air routes (Nolan, 2011).

The increase in demand has resulted in heightened congestion in air traffic, leading to various challenges at several airports. Airlines have asserted that the direct financial burden of airport and air traffic control delays in the United States alone amounts to 2 billion dollars. It is evident that the cost in question represents a significant proportion of the net profit of the US airline industry, which was 26.4 billion dollars in 2019 (United States Department of Transportation, 2019).

Situational awareness is examined as another key factor influencing air traffic control. Situational awareness is recognized as a fundamental element affecting an effective air traffic control system and the decision-making and performance of controllers (Endsley & Rodgers, 1994). Air traffic controllers are responsible for the coordination and monitoring of a large number of aircraft to ensure minimum separation and safe and efficient take-off, en route, and landing operations (Dailey, 1984). The successful execution of this complex and demanding task is contingent upon situational awareness (Endsley & Rodgers, 1994). Controllers must be cognizant of and monitor numerous factors, such as aircraft positions, fuel status, approach and descent procedures, and flight routes (Rodgers, 1993). Despite the plethora of definitions of situational awareness, the most generally applicable definition was provided by Endsley (1987). According to the aforementioned definition, "situational awareness is defined as the perception of elements in the environment within a given time and spatial volume, the understanding of their meanings, and the reflection of their states within an immediate timeframe" (Endsley & Rodgers, 1994). The objective of this study is to identify these elements—including perception, comprehension, and projection—to ensure the safety requirements for air traffic control during flight and to enhance efficiency. The issues engendered by an absence of situational awareness are substantial, not only from a material and financial standpoint but, above all, because human lives are at risk (Dailey, 1984). The potential for errors to arise in practice can be mitigated through the implementation of coordination and monitoring mechanisms supported by technological solutions. Furthermore, the employment of alerts and proactive measures can serve to minimize human error.

3. Methodology

Air traffic control can be defined as an operational element in which the human factor, safety management systems, air traffic management, cognitive psychology, and technical infrastructure interact (Schmidt, 1976). However, analyzing the cause and effect of a specific phenomenon in air traffic control services can be challenging due to the presence of multiple variables where numerous factors interact (Gerede, 2015).

This research employs a structured literature review methodology to analyze air traffic control (ATC) coordination and monitoring practices in Europe. Instead of employing an empirical research design, the study conducts a systematic examination of existing academic and institutional literature to cultivate a thorough grasp of current air traffic management (ATM) systems and their operational dynamics. The review is both narrative and systematic, seeking to synthesize information from various sources within a cohesive analytical framework. This approach is particularly appropriate for topics like ATC coordination, where information is dispersed among scholarly articles, regulatory documents, and technical reports. The aim is to synthesize current research and identify main themes, patterns, and gaps in literature. The literature utilized in this study was gathered from many sources to guarantee academic structure and practical significance. Academic publications were retrieved from prominent scientific databases, including Web of Science, Scopus, and Google Scholar. Moreover, comprehensive evaluations were performed on institutional reports and policy documents from prominent aviation entities, including International Civil Aviation Organization, EUROCONTROL, International Air Transport Association, EASA, CANSO, and SESAR Joint Undertaking. These sources have been selected because of the decisive role they play in shaping global and European air traffic management (ATM) policies and practices. The literature was chosen based on specific inclusion criteria to guarantee both its relevance and quality. Studies were included if they:

- Focus on air traffic control (ATC) or air traffic management (ATM)
- Coordination, capacity, complexity or controller workload,
- Check out European airspace or give ATM insight relevant to the world,
- Published in peer-reviewed journals or by recognized aviation institutions.

Recent advancements in technology and operations, including digitalization, artificial intelligence, and collaborative decision-making procedures, were also taken into consideration. A thematic analysis was performed to analyze the literature collected. An iterative process of reading and coding the selected sources resulted in key themes. This analysis covered four key dimensions: (1) ATC coordination practices, (2) capacity management strategies, (3) air traffic complexity and controller workload, and (4) technological and operational innovations, such as digital ATM systems and collaborative decision-making frameworks.

The study does not present empirical findings but synthesizes insights from the literature to highlight common patterns, emerging trends and areas of convergence and divergence across different sources. This method makes it possible to gain a conceptual understanding of how the ATC coordination is structured and managed in the European context.

The study's most significant limitation is the inaccessibility of primary sources, which hinders the ability to substantiate claims and verify information. In the context of literature review, data obtained from secondary sources is of paramount importance for the accurate observation of the phenomenon under study (Vassala, 2006). The data obtained is based on a comprehensive review of the extant literature, regulatory authorities' guidelines, company reports, and internet data. The capacity of air traffic control to orchestrate air traffic in an orderly and secure manner is predominantly realized through mutual communication and adherence to legislation. The present study examines compliance with regulations and operational procedures to ensure the proper functioning of air traffic management in Europe.

4. Synthesis of Findings from Literature

4.1. Innovation and Technological Developments in ATM; Principles and Improvement Initiatives

The literature on current ATC/ATM advances indicates that European air traffic management is progressing towards a more digital, integrated, and performance-oriented framework. Current research and institutional reports indicate that digitization, automation, artificial intelligence, and data-driven decision-support systems are essential elements of ATM modernization. EUROCONTROL emphasizes the growing utilization of AI-driven applications to improve forecasting, decision-making, resource allocation, and human performance in air traffic management operations (Xia et al., 2026). The SESAR Digital European Sky vision identifies digital transformation as a crucial facilitator for enhancing the safety, security, sustainability, and efficiency of European air traffic management (EUROCONTROL, 2020; SESAR, 2025).

The body of literature also recognizes the increasing importance of trajectory-based operations. Future ATM systems are expected to control aircraft trajectories in four dimensions (including time), as opposed to sector-based control. FAA's NextGen program considers trajectory based operations (TBO) as an important transition in modern air traffic management, where all stakeholders and automation systems share the same understanding of aircraft movement and future trajectory. Though this example is from the United States, it is indicative of the larger trend of predictive ATM based upon data-sharing, worldwide (FAA, 2023).

Recent literature indicates that the ATM domain is expanding beyond conventional manned flight. The advancement of U-space in Europe signifies the increasing necessity to include unmanned aircraft systems into both controlled and uncontrolled airspace. The U-space regulatory framework was implemented in January 2021 to facilitate the safe segregation and effective utilization of airspace between manned and unmanned aircraft, according to EASA. This indicates that future Air Traffic Control coordination will increasingly involve hybrid traffic scenarios, where conventional aircraft, drones, and even sophisticated air mobility vehicles will function inside interconnected airspace systems (EASA, 2021).

Sustainability has finally emerged as a pervasive issue in ATM literature. Digitalization, free-route airspace, performance-based navigation, and trajectory optimization are increasingly being seen not only as efficiency instruments but also as methods to diminish fuel consumption and emissions. The literature generally suggests a transition of European ATM from a fragmented and capacity-limited system to a more collaborative, automated, interoperable, and environmentally conscious system. This transformation introduces new issues in controller workload, AI governance, cybersecurity, human-machine interface, and the regulatory integration of new airspace users.

Air traffic encompasses all aircraft in flight or maneuvering and taxiing at an aerodrome. The Air Traffic Control service is a service provided to prevent collisions between aircraft, to ensure maneuvering clearance between aircraft and obstacles, and to expedite, maintain, and ensure the orderly flow of air traffic (Annex 11). In Annex 11, the objectives of air traffic services are defined as preventing collisions between aircraft, preventing collisions between an aircraft and another aircraft in the maneuvering area, and preventing collisions with objects, bodies, or obstacles on the ground; maintaining air traffic in a swift and orderly manner; providing the necessary information and advice to ensure flights are conducted safely and efficiently; and to inform the relevant authorities and providing support where necessary in emergency situations and when search and rescue operations are required. Air traffic services are divided into sections to ensure these objectives are met. They consist of three sections: Area Control (ACC), Approach Control, and Aerodrome Control. ACC is responsible for controlling air traffic at high altitudes within a specific airspace (FIR) during the period between takeoff and approach. It controls traffic originating from the approach control service. The separation of aircraft is carried out in two different ways: VFR (Visual Flight Rules) and IFR (Instrument

Flight Rules). In addition to flight separation, it transmits various information to aircraft, such as weather conditions, altitude, speed, and no-fly zones. Airspace is divided into classes, with different flight rules applying to each class. Approach Control takes over control once the aircraft has reached a specific altitude, providing control services within a radius ranging from 56 to 93 km. This situation varies depending on the characteristics of the airport (Osamba, 2012). Takeoff control assumes control from the tower once the aircraft has passed an altitude of 500 meters; at this stage, it issues instructions for the aircraft to climb and reach its flight level. Local control, on the other hand, is responsible for the active runways at the airport; landing and takeoff clearances are issued at this stage. Its duties include runway separation, maintaining gaps between flights, and ensuring the maximum utilization of the runways.

The International Civil Aviation Organization (ICAO) has instituted the Global Air Navigation Plan Strategy (GANP) to establish a global air navigation system that is secure, sustainable, efficient, and interoperable. It is primarily grounded in the A-CDM initiatives of IATA and EUROCONTROL. Socio-economic concerns arising from the aviation industry are encountering numerous obstacles due to evolving and escalating demand. Passenger and cargo travel is anticipated to quadruple global aviation traffic within the next 15 years (ICAO, 2020). Over 120,000 flights are conducted safely and securely each day (ATAG, 2018). Projections indicate significant air traffic expansion over the next two decades, attributed to favorable economic, political, and social developments (ICAO, 2018). Simultaneously, emerging demands on the aviation system, advancing technology, novel methodologies, and the expanding role of personnel require not only the resolution of difficulties but also the transformation of the global air navigation system to guarantee the continuity of aviation. The International Civil Aviation Organization (ICAO) has released a framework known as the Global Air Traffic Management Operational Concept (GATMOC, Doc 9854) to facilitate systematic and sustainable oversight of global air traffic.

The International Civil Aviation Organization (ICAO) has released a framework known as the Global Air Traffic Management Operational Concept (GATMOC, Doc 9854) to facilitate the systematic and sustainable oversight of worldwide air traffic. GATMOC establishes the basis for a unified operational framework for an integrated, sustainable, cohesive, and internationally interoperable air traffic management (ATM) system. The operational concept functions autonomously from technology and is characterized as a representation of what is anticipated. The prompt advancement of a sustainable aviation system founded on GATMOC necessitates a cooperative, coordinated, and enduring planning instrument like GANP. Thus, the vision, performance objectives, and conceptual framework outlined in GANP explicitly reference GATMOC. By persistently advancing supplementary guidance documents, such as the Air Traffic Management System Requirements Manual (Doc 9882) and the Global Performance Guide for Air Navigation Systems (Doc 9883), while establishing solid conceptual frameworks and emphasizing an integrated, sustainable, compatible, and globally interoperable air navigation system. ICAO standards predominantly emphasize seven specific components of the ATM procedure. To elucidate the delivery of these services, the seven conceptual components have been summarized in conjunction with conceptual modifications. The initial aspect is to the organization and management of airspace. Airspace organization creates airspace frameworks to facilitate various types of air operations, traffic densities, and service levels.

Airspace management is the procedure by which airspace alternatives are chosen and executed to fulfill ATM requirements. All airspace is under the jurisdiction of air traffic management (ATM) and serves as the foundation of the system. Air traffic management possesses a flexible and dynamic framework to effectively coordinate airspace. Any limits placed on airspaces of a specific volume are regarded as a temporary condition for air traffic management (ATM). Airspace borders ought to be modified in accordance with the density and flow conditions of air traffic; national or procedural limits should not impede the flow.

The second element pertains to airport operations. Airport operators play a crucial role in the air traffic management system. Safety, security, and efficiency are guaranteed under all circumstances, while concurrently aiming to uphold airport capacity at its maximum level. This scope includes services such as lighting, taxiways, exits, runways, and precision ground guiding. The ATM system is tasked with optimizing the utilization of the airport's airside infrastructure capabilities. The primary objectives are to minimize runway occupancy duration, ensure aircraft can maneuver safely in all weather conditions while maintaining capacity, direct aircraft on taxiways, sensitive zones, and transition surfaces under all circumstances, and to accurately ascertain the purpose and location of all vehicles and aircraft in the movement area, disseminating this information to ATM stakeholders.

The third component has been recognized as the equilibrium between demand and capacity. Demand and capacity balancing systematically assesses traffic patterns and airport capabilities throughout the system to mitigate conflicting requirements for airspace and airport resources, while enabling users to decide when, where, and how they will operate. The utilization of data regarding air traffic patterns, meteorological

conditions, and system facilities facilitates the effective management of air traffic flow in collaborative processes. Demand and capacity management establishes a basis for predictable allocation and scheduling by optimizing assets through collaborative decision-making at the strategic level to enhance efficiency. During the pre-tactical phase, collaborative decision-making facilitates adjustments to assets, resource allocations, anticipated trajectories, airspace restrictions, and the scheduling of entry and leave times for airports and airspace volumes to mitigate imbalances whenever feasible. During the tactical phase, efforts encompass adaptive modifications in airspace organization to optimize capacity, real-time alterations in airport and airspace entry/exit timings, and diverse user interventions in the schedule.

The fourth operational component is designated as traffic synchronization. Traffic synchronization refers to the strategic implementation and upkeep of air traffic flow in a secure, systematic, and efficient manner (Pawełek, Lichota, Dalmau, & Prats, 2018). Flight paths are assessed in a clear and unequivocal manner, from multiple dimensions. Narrow bottlenecks causing traffic congestion are detected and eradicated by proactive approaches. Traffic optimization guarantees the enhancement of runway efficiency.

The fifth component is designated as airspace user operations. Airspace user operations pertain to the ATM-related components of flight operations. This scope addresses the synchronization of global practices and criteria to improve safety and efficiency. Relevant ATM data is utilized for an airspace user's general, tactical, and strategic situational awareness and conflict management, while pertinent operational information from the airspace user is sent to the ATM system. Collaborative decision-making seeks to promptly assess the effects of aircraft and airspace user system design on air traffic management (ATM), emphasizing the necessity of evaluating aircraft as a core element within the ATM framework.

The sixth component is identified as conflict management. Conflict management encompasses three tiers: strategic conflict management through airspace organization and administration, demand and capacity equilibrium, and traffic synchronization. Conflict management mitigates the risk of aircraft collisions and hazards to an acceptable threshold. Potential hazards that may jeopardize an aircraft encompass: collision, topography, meteorological conditions, turbulence, conflicting airspace operations, and ground vehicles or other impediments in the apron and maneuvering area during ground operations. Strategic conflict management mitigates risk and alleviates constraints to a certain extent. The notion of conflict can be broadened within the confines of established procedures, safety protocols, and relevant information. Collision avoidance systems are integral to ATM safety management; yet they are excluded from the assessment of the calculated safety level necessary for maintaining separation.

The seventh and concluding component is the management of ATM service delivery. The objective of ATM service provision management is to provide seamless operation from gate to gate across all phases of the flight and among all service providers. The ATM service provision management component governs the equilibrium and integration of decisions from several processes, together with the schedule and criteria for these decisions. Flight trajectories and agreements significantly influence the decision-making processes within Air Traffic Management (Wickens, Mavor, & McGee, 2013). The services offered by the ATM service provision management component are developed according to the ATM system design and are delivered upon request. The design of the ATM system is conducted through collaborative decision-making and the implementation of safety and operational processes throughout the system. The plans established by management include all physical phases of operations, and processes and practices are executed accordingly.

4.2. Capacity Management Approaches

Delays in air transportation result in customer dissatisfaction and substantially impact carriers' financial performance. EUROCONTROL data indicates that the airline industry experiences an annual financial deficit ranging from 1.3 to 1.9 billion Euros attributable to delays (EUROCONTROL, 2003). Airspaces are categorized into distinct portions known as sectors. A sector is a segment of airspace delineated by geographical coordinates and a designated radio frequency, overseen by a control crew. Various sectors converge to establish the FIR (Flight Information Region) line, which denotes the flight information area (EATM, 2004). During peak demand periods, the number of flights operated must not be above the predetermined limit, known as sector capacity. The capacity for managing air traffic refers to the capability of delivering air navigation services to a specific amount of air traffic while maintaining a high safety standard and avoiding substantial operational, economic, or environmental issues under normal circumstances (EUROCONTROL, 2002). Sector capacity refers to the regulation of aircraft within a designated area by a controller, ensuring safety while preventing undue congestion or capacity deficits during a specified timeframe (Jaurena, 2009).

It is essential to assess the increased sector capacities and their effect on controller workload in light of the revised airspace laws, modifications in air traffic control procedures, and the technologies devised to address

the expected rise in air traffic. EUROCONTROL has created the CAPAN (Air Traffic Control Capacity Analyzer Tool) and COCA (Complexity and Capacity) software for this objective. CAPAN is a capacity assessment methodology established by EUROCONTROL (EUROCONTROL, 2006). This approach relies on a simulation engine that assesses the controller's workload and estimates air traffic density for a designated air traffic sample. CAPAN employs two capacity values derived from two methodologies (peak and regression approaches) to predict the controller's workload through simulation (EUROCONTROL, 2006). The ideas of capacity, complexity, and workload are significantly interrelated. The intricacy elevates the controller's workload, whereas the workload constrains capability. Sector capacity encompasses not only the quantity of aircraft within the sector but is also significantly influenced by the interactions among aircraft across several sectors. With the escalation of interconnections, the complexity correspondingly intensifies. Consequently, it is essential to identify the reasons or conditions that complicate controllers' tasks and contribute to an increased workload. The COCA project has defined aims to elucidate the link among complexity, workload, and capacity. These objectives are (EUROCONTROL, 2006);

- The analysis of ATM complexity must encompass both macroscopic and microscopic perspectives, incorporating elements such as route segments, airspace volumes, traffic flows, and converging or crossing locations across several levels, including sector, center, or state.
- The supply of pertinent complexity indicators and capacity evaluators for designated complexity analyses and additional studies has been identified as ATFM (Air Traffic Flow Management), airspace design, ATFM performance and efficiency, and economic studies for ATM, among others.

The COCA project has mostly concentrated on macroscopic analyses and methodological advancement. Throughout the development process, comprehensive procedures and processes were established, and the outcomes were executed extensively in environmental applications, validated by operational experts.

The CAPAN approach is in development as part of the COCA (Complexity and Capacity) project. One of COCA's objectives is to establish a straightforward, rapid, and precise technique for estimating workload and capacity that incorporates complexity as an inherent aspect (Christien, Benkouar, Chaboud, & Loubieres, 2002). The Complexity and Capacity (COCA) project was launched by the EUROCONTROL Experimental Center (EEC) at the conclusion of 2000. The main objective is to delineate the correlation between capacity and complexity using precise performance measurements. The COCA project employs two distinct methodologies: identifying and assessing the elements that contribute to complexity in air traffic control, and verifying, testing, and analyzing the correlation between these complexity factors and controller workload (EUROCONTROL, 2006). The objective of the CAPAN method is to create an effective approach for assessing sector capacity. Efficiency is assessed by three distinct criteria in the air traffic method: compatibility, usability, and precision. For the approach to be effective, specific procedures must be adhered to (Christien, Benkouar, Chaboud, & Loubieres, 2002).

- Calculation of parameters: Air Traffic Flow Management (ATFM), Wide Object-Oriented Data Standard Traffic Observable Complexity Knowledge (WOODSTOCK), ATFM Modeling Capacity Tool (AMOC)
- Classification of sectors according to their complexity level
- Preparation of a large-scale workload model for each classification
- The use of a regression model to predict sector capacities

The workload of controllers refers to the duration required by a controller to accomplish all responsibilities within a designated time period (Majumdar & Ochieng, 2002). Workload assessment necessitates a definition of airspace, pertinent flight plans or radar tracks, aircraft performance data, and the selection of a representative traffic sample. This requires a database encompassing diverse information, including the working conditions and hours of controllers, within the air traffic service system sanctioned by operational specialists. In the CAPAN system, predictions are generated by two methods:

4.2.1. Peak Method

Real-time simulation studies and operational trials have categorized numerical boundary values and their qualitative interpretations as delineated in Table 1 according to the CAPAN methodology (EUROCONTROL, 2006).

Table 1. Peak Method

Boundaries	Workload	Working Hours
%70 and above	Excessive Load	42 min.
%54-%69	High Level Load	32-41 min.
%30-%53	Medium Level Load	18-31 min.
%18-%29	Low Level Load	11-17 min.
%0-%17	Very Low Level Load	0-10 min.

4.2.2. Regression Analysis

An identical quantity of flights can generate varying workloads. In the event that the traffic sector's circumstances have become intricate, the controller's responsibilities for that sector may increase. In the peak method, assessing complexity and workload purely based on the overall time expended by a controller may prove inadequate. The regression model analyzes the distribution of time spent on each flight independently, yielding four distinct scenarios (EUROCONTROL, 2003).

1. Regression analysis indicates that the capacity value typically exceeds the CAPAN capacity value when the sector's peak hour aligns with the most intricate traffic conditions.
2. The regression capacity number is typically inferior to the CAPAN capacity value, establishing a conventional ATC workload when the sector's peak hour aligns with uncomplicated traffic conditions.
3. When the regression capacity number approaches the CAPAN capacity value, it signifies that the sector's peak hour reflects the average traffic complexity for the entire day.
4. If the workload documented throughout the 24-hour simulation is little, the capacity estimate may significantly exceed this regression analysis result. This indicates the presence of surplus capacity.

4.3. A-CDM Implications in Air Traffic Management

The Airport Collaborative Decision Making (A-CDM) function is a component of a broader collaborative decision-making and action-taking framework (ICAO, 2020). The objective of the procedure is to oversee the aircraft's turnaround period, execute it transparently, and enhance service across all pertinent domains. A-CDM was initially introduced in Europe in 2004 in the context of air traffic control, as ATFM (ATM network management) necessitates greater airline involvement for fleet-level management at certain airports. Subsequent to Europe, the FAA (Federal Aviation Administration) started analogous programs targeting more interfaces. Conversely, ICAO has embraced and extended the concept. It has developed applications mostly based on the EUROCONTROL paradigm, including the GANP and Aviation System Block Upgrades (ASBU) (ICAO, 2021). A-CDM primarily focuses on fostering collaborative situational awareness among air traffic management, airlines, and airport operations (IATA, 2018). A-CDM enhances air traffic services through three phases. Initially, in incoming traffic, air traffic management (ATM) notifies Airport Collaborative Decision Making (A-CDM) of the aircraft's arrival and its corresponding time, while ATM supervises the aircraft until control is transferred to apron control or until the aircraft comes to a complete stop. Secondly, during the turnaround phase, A-CDM exercises control over the aircraft. It supplies the requisite information to the ATM for the turnaround. It modifies priorities and procedures in accordance with the stated temporal target information. A-CDM relinquishes control of the aircraft to the ATM when the aircraft is off-block (engine start) or enters the taxiway. During the concluding phase of departing traffic, the ATM supplies the A-CDM with the TSAT (Target Start-up Approval Time) to meet the necessary requirements. TSAT denotes Target Start-up Approval Time. The IATA (2012) defines TOBT (Target Off-Block Time), CTOT (Calculated Take Off Time), and the traffic conditions under which an aircraft anticipates receiving authorization for engine start or pushback as the timeframes issued by ATC. ATM oversees the aircraft's departure procedures from the airport and communicates the projected landing time at the destination. These self-replicating processes facilitate enhanced demand forecasting. Furthermore, the ATM can compute estimated departure and arrival times with enhanced accuracy and precision. In certain tough and atypical circumstances, flexibility is afforded. Upon a re-evaluation and collective request, operations may be reassessed utilizing alternative approaches, including slot modifications and reduced turnaround durations (IATA, 2016).

A-CDM is responsible for coordination both in the control tower and at the airport. It offers services at three distinct tiers. Initially, it executes supportive and implementation duties to enhance efficiency in local airport operations through resource management, particularly by alleviating congestion on airport aprons, taxiways, and runways. ATFM is present at the second level. The ATFM function is executed within the ACC (Area Control Center), necessitating collaboration between A-CDM and ACC. This level monitors and records ATM movement timings and can impose limitations on departures and arrivals if required. Airport operations and the turnaround procedure may also be encompassed within these limitations. At the third and final level, ACC/ATFM communicates with other Flight Information Regions (FIR), ensuring inter-regional cooperation. This stage is designated as the regional ATFM network (EUROCONTROL, 2002). When slot exchanges transpire across regions, alerts are issued, and estimated arrival and departure times are conveyed to the pertinent regions. The airlines' operation control centers (OCC) are increasingly actively engaged in the ATFM processes.

5. Discussion and Result

Air traffic management is facing capacity congestion due to the rising demand for air travel. To address the growing demand and guarantee air transportation, novel technologies are being devised, and infrastructural enhancements are being executed. Projections for future air traffic are crucial for the advancement of these technologies and the establishment of requisite rules (EUROCONTROL, 2000). The factors contributing to the heightened demand, the locations experiencing this rise, and the present condition of air traffic are crucial for formulating precise forecasts. The objective of the study is to investigate and evaluate the existing methods and strategies for managing European airspace within this context and to provide a comprehensive framework. The administration of safe, secure, efficient, and orderly airspace, considering the rising demand and capacity density, has been analyzed through directives, protocols, and newly developed applications. The study assessed the current and evolving practices in Europe and their variations or transformations.

The literature review indicates that air traffic management (ATM) systems in Europe are experiencing a significant shift, stimulated by digitalization, automation, and heightened operational complexity. This study presents an integrated perspective on air traffic control (ATC), indicating that technical innovation, coordination mechanisms, and workload management constitute a complex interconnected framework within a broader systemic transformation, despite prior research concentrating on individual aspects.

A significant finding from the literature is the transition from traditional management, which was sector-oriented and focusing on traffic volume, to a more dynamic and complexity-oriented management approach. This change reflects the inadequacies of traditional capacity models, which are unable to address the growing variability and unpredictability of contemporary air traffic. The emphasis is increasingly on complexity metrics and workload-sensitive instruments. These advancements provide significant operational advantages, while also introducing new obstacles, particularly with human-machine interface and controller adaptability. The reliance on automation and AI-based decision support systems prompts significant inquiries over trust, transparency, and the potential hazards of excessive rely on automated technologies.

A significant topic of discussion is the evolving function of air traffic controllers in progressively automated settings. The literature constantly underscores a "human-in-the-loop" model, contending that complete automation is neither practical nor preferable in the short run. The controllers are intended to serve as supervisors of intricate systems rather than as direct operators. This alteration has significant ramifications for training, skill prerequisites, and cognitive demands. While automation may diminish ordinary tasks, it may concurrently elevate cognitive complexity, necessitating controllers to handle infrequent but significant scenarios. Consequently, next ATM systems must be developed with a robust human-centered approach to ensure that automation enhances rather than undermines operational safety.

The findings emphasize the significance of collaborative and network-centric strategies in the management of European airspace. The instances of Airport Collaborative Decision-Making (A-CDM) and the Single European Sky framework illustrate a distinct transition towards integrated and multi-stakeholder coordination. This move resolves persistent problems associated with airspace fragmentation and inefficiency across national borders. Nonetheless, despite these initiatives, institutional and political impediments continue to pose substantial challenges to complete integration. Nonetheless, the efficacy of pan-European ATM coordination remains constrained by disparities in national regulations, operating protocols, and technology infrastructures.

The emergence of new technology, including unmanned aircraft systems (UAS) and digital towers, presents both opportunities and challenges for air traffic management (ATM) systems. These improvements, although enhancing flexibility and scalability, also contribute to increased system complexity and introduce new safety issues. The research indicates that legislative frameworks are still developing and may not be entirely

congruent with the operational reality of hybrid airspace situations where manned and unmanned aircraft coexist. This indicates the necessity for more adaptable and proactive regulatory strategies.

Environmental sustainability constitutes a significant facet of the discourse. The heightened focus on trajectory-based operations and performance-based navigation signifies a wider movement towards environmentally optimal air traffic management. The literature indicates that technology solutions alone are inadequate for attaining sustainable goals, necessitating coordinated policy frameworks and stakeholder alignment. If they are misaligned, the potential advantages of these innovations may be constrained.

The literature addresses the topic of air traffic management in relation to capacity, complexity, time, and workload. The newly created methodologies and technologies are designed to address issues in these four dimensions, enhance system performance, and augment capacity. The complexity element is identified as the primary issue of ATM service. The complexity of air traffic is determined by the configuration of air traffic and its geographic positioning. The quality of equipment, cultural and individual disparities, and the cognitive constraints of controllers significantly influence the complexity of the issue and, consequently, the workload of the controllers. The research undertaken and the innovative techniques devised seek to diminish complexity and lessen the burden on controllers. EUROCONTROL, IATA, and ICAO have created multiple apps aimed at enhancing capacity and optimizing air traffic management. EUROCONTROL has initiated the Complexity and Capacity (COCA) project, which has produced a suite of software designed to identify the determinants of complexity in air traffic and to facilitate enhancements in this domain. COCA constructs an air traffic model that analyzes various traffic patterns across different sectors based on complexity-inducing elements, and utilizes this model to ascertain the appropriate capacity level. Furthermore, it categorizes capacity by sectors and implements this in air traffic flow management (ATFM). The COCA study indicates that new technology can alleviate the cognitive load on controllers, hence enhancing the safety of air traffic services. EUROCONTROL employs a program named CAPAN (ATC Capacity Analyzer Tool) to assess capacity and workload. Technology employs a simulation method that assesses controller workload and air traffic density. Two distinct methodologies, specifically regression and peak analysis, are employed to assess the controller's workload according to the circumstances and intensity.

ICAO Annex 11 delineates the procedures and implementation methods for air traffic management; however, ICAO is formulating new global norms in response to evolving environmental conditions. ICAO has established a concept identical to the A-CDM implementations executed by IATA and EUROCONTROL, referred to as GANP (Global Air Navigation Strategy). The airport collaborative decision-making function (A-CDM) is an element of a comprehensive collaborative operation and decision-making framework founded on cooperation. Under the GANP, a law known as the Global Air Traffic Management Operational Concept (GATMOC, Doc 9854) has been issued, offering guidelines for the systematic management of global air traffic. The regulation has analyzed the fundamental components necessary for time and capacity management in air traffic control. The analysis indicates that the ICAO standards on air traffic management are found on seven distinct core factors. The components include airspace regulation and management, airport operations, demand and capacity balance, traffic synchronization, airspace user operations, conflict management (complexity), and ATM service provision management. The study finally reveals that the most commonly encountered challenges in air traffic management pertain to constraints regarding capacity, complexity, workload, and time. The paper aims to elucidate the strategies implemented by regulatory authorities and organizations such as ICAO, IATA, and EUROCONTROL to address these restrictions. Due to heightened demand and emerging capacity challenges, along with advancements in technology, various applications may be developed to address this issue. The augmentation of capacity immediately influences the intricacy of air traffic.

The discussion indicates that, despite the shift of European ATM systems to a more integrated, automated, and collaborative architecture, significant obstacles persist. The challenges include escalating system complexity, ensuring efficient human-machine interaction, addressing institutional fragmentation, and integrating new airspace users. Consequently, forthcoming research ought to concentrate on the empirical validation of complexity and workload models, the advancement of human-centered AI systems, and the assessment of regulatory frameworks that facilitate cross-border coordination and technological integration.

In this context, it is essential to develop innovative applications to mitigate complexity. In literature, aside from a few studies, there is a scarcity of research dedicated to developing innovative approaches and technologies to tackle complexity and capacity difficulties; the initiatives of regulatory authorities may be insufficient to identify the principal impacting factors. Thus, upcoming research addressing these concerns will yield benefits for air traffic management and air traffic flow management.

Acknowledgements

I wish to convey my appreciation to the Turkish Aeronautical Association University and Eskişehir Technical University for their steadfast assistance in this study. I extend my gratitude to my respected adviser, Prof. Dr. Ferhan Şengür, for his assistance and criticism during the research.

Author Contributions

Author 1: Conceptualization, Methodology, Formal Analysis, Writing – Original Draft

Author 2: Supervising, Writing – Review & Editing.

Declaration of Interest

Ethical approval

Not applicable.

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