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THE IMPACT OF MATHEMATICAL MODELING ON AIR TRAFFIC CONTROL EFFICIENCY: A COMPREHENSIVE STRUCTURED REVIEW

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Abstract:

Air travel is crucial for global connectivity, yet it faces increasing challenges due to rising air traffic volumes and complex operational demands. Mathematical modeling has emerged as a transformative solution in air traffic control (ATC), enhancing efficiency and safety across the aviation sector. This review delves into the application and outcomes of mathematical models in ATC by analyzing recent literature that incorporates various computational techniques for optimizing air traffic flow, predicting and mitigating conflicts, and improving decision-making processes. In order to attain this, we thoroughly searched scholarly articles from well-known databases, for instance, Scopus as well as IEEE articles published in the last decade, focusing on studies that demonstrated clear numerical results regarding the effectiveness of mathematical modeling in ATC operations. The flow of the study is based on the PRISMA framework. By analyzing a comprehensive selection using an advanced searching approach on Scopus and IEEE database found (n=22), the final primary data was analyzed. The review highlights significant

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advancements, such as the development of algorithms capable of optimizing flight paths, reducing airspace congestion, and enhancing fuel efficiency, which collectively contributes to more sustainable aviation practices. The findings are divided into four themes, which are (1) optimization of ATC operations, (2) route and flight scheduling optimization, (3) resilience and robustness in atm systems, and (4) technological advances and their integration in air traffic management (ATM). Conclusively, mathematical models have proven indispensable for maximizing ATC efficiency and are pivotal in guiding strategic planning and policy-making to accommodate future air traffic growth while maintaining high safety standards.

Keywords:

Mathematical Model, Airspace, Air Traffic Control

Introduction

In the global economy, air travel is essential for facilitating the movement of people and goods over great distances. As air traffic continues to increase, so too does the complexity of managing it efficiently and safely (Guo et al., 2022; Jo & Chang, 2023; Standfuss et al., 2024). In this era of rapid technological advancement, mathematical modeling emerges as a powerful tool in the realm of air traffic control (ATC), offering sophisticated solutions to optimize operations and enhance overall efficiency. The intricate web of factors influencing air traffic—ranging from weather patterns and airspace congestion to aircraft performance and fuel consumption—presents a formidable challenge to traditional ATC systems. Historically, ATC relied heavily on human controllers making real-time decisions based on limited information, leading to inevitable bottlenecks, delays, and inefficiencies. However, the advent of mathematical modeling has revolutionized the landscape of air traffic management (ATM) by providing decision-makers with data-driven insights and predictive capabilities (Nasution et al., 2023). At its core, mathematical modeling in ATC involves the creation of computational algorithms and models that simulate various aspects of air traffic dynamics. These models leverage principles from mathematics, computer science, and operations research to analyze complex interactions and optimize outcomes. By integrating vast amounts of data, including flight trajectories, weather forecasts, airport capacities, and airspace configurations, mathematical models empower ATC authorities to make informed decisions in real time. Among the main advantages of mathematical modeling in ATC is its capacity to anticipate as well as mitigate potential conflicts before they arise. Through advanced algorithms, models can forecast airspace congestion, identify optimal routing strategies, and anticipate adverse weather conditions, enabling controllers to proactively adjust flight paths and schedules to minimize disruptions (Malozyomov et al., 2024; Oshodi, 2022). Additionally, mathematical models facilitate the optimization of fuel consumption and emissions by optimizing aircraft trajectories and minimizing unnecessary deviations (Singh & Sharma, 2015). Furthermore, mathematical modeling enhances safety within the airspace system by providing insights into potential risks and vulnerabilities. By simulating various scenarios and analyzing potential outcomes, models enable ATC authorities to recognize possible safety risks and take appropriate action before they become serious incidents. Risk management must be done proactively in order to guarantee the safety of passengers, crew, and ground personnel. Moreover, the impact of mathematical modeling extends beyond operational efficiency to encompass strategic planning and policy development (Abdelmoula et al., 2022). By simulating long-term trends and evaluating the implications of different regulatory frameworks, models assist policymakers in designing robust strategies to accommodate future growth while maintaining safety and sustainability standards. In conclusion, the integration of mathematical modeling into ATC represents a paradigm shift in the way we manage the skies. By harnessing the power of data and algorithms, mathematical models offer unprecedented opportunities to optimize efficiency, enhance safety, and shape the future of air travel. This article explores the multifaceted impact of mathematical modeling on ATC efficiency, examining its applications, benefits, and implications for the aviation industry and society at large.

Literature Review

In recent years, the integration of mathematical modeling in ATC has garnered significant attention for its potential to enhance efficiency as well as safety pertaining to air travel. A systematic literature review (SLR) by (Emha Abdillah et al., 2024) emphasizes the pivotal role of Artificial Intelligence (AI) in improving ATC operations. The study highlights how AI can predict weather patterns, identify conflicts, and recommend optimal routes, showcasing the growing dependence of ATC on AI and machine learning. Furthermore, (Estrova, 2023) delves into the complexity of ATC training, emphasizing the critical role of efficient learning processes in shaping the proficiency of aviation personnel. By analyzing training programs, simulator training, and instructor competence, this research underscores the importance of human factors in optimizing ATC efficiency through mathematical modeling. Moreover, it will provide insights into air traffic conflict detection and resolution (CDR) from an ergonomics perspective (Hamdan et al., 2022a). The study presents an SLR on CDR processes in ATC, highlighting key aspects of ATC as a sociotechnical system. By developing a framework for CDR, this research aims to enhance air traffic safety and efficiency by addressing the bounce-back of air traffic density post-pandemic. These findings underscore the significance of considering humans, environment, interface/system, and task design in ATC operations, showcasing the potential for mathematical modeling to revolutionize conflict resolution processes in ATM (Hamdan et al., 2022a). Additionally, by outlining a unified perspective that integrates reinforcement learning as well as model predictive control techniques for adaptive traffic signal control, a critical review of traffic signal control methodologies is then presented (Wang et al., n.d.). This study bridges the gap between different optimization and control algorithms, aiming to advance transportation network efficiency. By applying the mathematical language of the Markov decision process, this research identifies common ground and shortcomings in existing methodologies, paving the way for cross-fertilization and advancements in adaptive traffic signal control. These insights contribute to the broader discourse on leveraging mathematical modeling to optimize traffic control systems for enhanced efficiency and performance. Mathematical modeling has become an indispensable tool in improving ATC systems' efficacy and efficiency by facilitating sophisticated simulations and optimizations. Several studies have illustrated how mathematical modeling is applied in various facets of ATMs, highlighting its impact on operational efficiency, strategic planning, and safety enhancements. Firstly, integrating mathematical models in air traffic flow management is well illustrated by Hamdan et al. (2021), who present an optimization model that includes path rerouting and diversion strategies. This model is designed to improve decision-making under the control of a central authority, which, as demonstrated, leads to significant reductions in delays and cancellations. This approach contrasts with traditional methods, where decisions are distributed across various authorities and stakeholders, often resulting in less coordinated actions (Hamdan et al., 2022b). Furthermore, the application of mathematical modeling in airport connectivity optimization involves using advanced

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algorithms to manage the increasing complexity of air traffic and the need for robust communication networks (Al-Rubaye & Tsourdos, 2020). Their study focuses on the implementation of 5G technologies in airport environments, ensuring that connectivity is maintained efficiently amidst high traffic demands. The mathematical models they propose are used to optimize network coverage and capacity, taking into account dynamic traffic conditions and minimizing power consumption while maximizing throughput. In addition to operational and technological aspects, mathematical modeling also plays a critical role in managing the cognitive workload of air traffic controllers, a key factor in maintaining operational safety and efficiency. Ahlstrom and Friedman-Berg (2006) highlight how cognitive workload can be assessed through eye movement metrics, providing a direct measure of the mental strain placed on controllers during high-traffic periods (Ahlstrom & Friedman-Berg, 2006). Similarly, Schmidt (1976) addresses workload modeling related to sector capacity, offering a methodology to evaluate and optimize controller workloads to prevent fatigue and errors (Schmidt, 1976). These studies collectively underline the profound impact of mathematical modeling pertaining to efficiency, safety, as well as sustainability with regard to ATC systems. By leveraging sophisticated simulations, optimizations, and real-time data analysis, ATC systems can not only handle increasing traffic volumes but also improve overall airspace management and safety protocols, ensuring that air travel remains one of the safest modes of transportation (Ahlstrom & Friedman-Berg, 2006; Schmidt, 1976). Mathematical modeling has fundamentally transformed ATC systems, enhancing efficiency and facilitating effective management of airspaces. Research like that of Hamdan et al. (2021) demonstrates the utility of centralized models in air traffic flow management (ATFM), which optimize rerouting and diversion strategies to significantly reduce delays and cancellations. This approach streamlines decision-making processes, allowing for quicker and more efficient responses to disruptions (Boujarif et al., 2021). The cognitive workload of air traffic controllers is another critical aspect profoundly impacted by mathematical modeling, directly influencing operational safety and efficiency. Ahlstrom and Friedman-Berg (2006) illustrate how real-time eye movement metrics can offer a sensitive assessment of cognitive load, providing information that can help adjust operational practices to enhance controller performance and safety (Ahlstrom & Friedman-Berg, 2006). Similarly, Schmidt (1976) provides a semi-empirical model for evaluating and optimizing controller workloads across different ATC sectors (Schmidt, 1976). These models are crucial for maintaining high safety standards, preventing controller fatigue, and ensuring that workload distribution is both practical and sustainable. Looking forward, the integration of advanced technologies and mathematical modeling in ATC is set to grow. Adelantado et al. (2004) discuss the role of distributed simulation in testing and implementing new airport operational concepts and technologies. Such advancements are vital as they prepare ATC systems to meet future demands and global traffic increases, ensuring the continued evolution of ATM towards greater efficiency and enhanced safety. All of these research initiatives demonstrate how important mathematical modeling is to managing the complexity of air traffic today and setting the stage for future advancements in the field (Adelantado et al., 2004).

Material And Methods

Identification

An extensive number of pertinent papers were selected for this investigation using three key stages of the systematic review process. In the first stage, dictionaries, thesauruses, encyclopedias, as well as previous research were consulted in order to identify synonymous terms in addition to selecting relevant keywords. We chose all pertinent terms after creating

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search strings for the IEEE and Scopus databases (see Table 1). During the first phase through the systematic review process, 628 articles were obtained for the current research project from both databases.

Table 1: The Search String

Scopus	TITLE-ABS-KEY ("mathematical model" AND ("air traffic control" OR atc) AND (efficiency OR competence OR capability OR performance)) AND (LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA, "MATH")) AND (LIMIT-TO (PUBSTAGE, "final")) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "English")) **Date of Access: May 2024**
IEEE	"mathematical model" AND ("air traffic control" OR atc) AND (efficiency OR competence OR capability OR performance) **Date of Access: May 2024**

Screening

In the screening process, a set of potentially pertinent research items is examined to determine whether or not their content is in line with the designated research question(s). Research topics are frequently chosen according to how mathematical modeling affects ATC efficiency during the screening stage. Duplicate papers will now be removed from the list of documents that have been searched. Four hundred ninety-five articles were eliminated in the initial screening stage of the procedure. During the second phase, 133 papers were assessed using specific criteria for inclusion and exclusion, as shown in Table 2. Additionally, the literature, for instance, research articles, was selected to be the first criterion due to its status as the main source of practical advice. Additionally, it includes evaluations, meta-syntheses, chapters, books, meta-analyses, book series, as well as conference proceedings that were not incorporated in the most recent study. Furthermore, only English-language articles were included in the assessment. It is important to remember that the plan was only intended to cover the years 2014 through 2024. Three papers in total were eliminated because they met the duplicate criteria.

Table 2: The Selection Criterion of Searching

Criterion	Inclusion	Exclusion
Language	English	Non-English
Timeline	2014-2024	< 2014
Literature type	Journal (Article)	Conference, Book, Review
Publication Stage	Final	In Press
Subject Area	Engineering, Mathematics	Others

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Eligibility

Once all the requirements for inclusion and exclusion criteria have been met, the final review sample is generated. A thorough disclosure of every research item in the sample's inventory is required because readers would otherwise be unaware of the specific research things that serve as the basis for the study's findings. There are a total of 130 items in the third level: eligibility. Pertaining to this juncture, thorough scrutiny was conducted on all article titles and substantial material to verify adherence to the inclusion requirements and applicability to the current study's research objectives. Consequently, 108 articles were eliminated because, based on empirical data, their abstracts, as well as titles, had little bearing on the objective of the study. In the end, 22 articles were made available for evaluation.

Data Abstraction and Analysis

The present investigation examined and synthesized a range of research designs (quantitative methods) using an integrative analysis as among the assessment strategies. The competent study's aim was to pinpoint pertinent subjects and subtopics. The initial phase of the theme's development was the data collection phase. Figure 2 demonstrates the authors' meticulous examination of a compilation of 22 publications for assertions or information pertinent to the study's topic. The authors next reviewed important recent research on the mathematical model employed in the ATC system. Investigations are being conducted into the research findings and the methodology applied in all of the research. The author then worked with other co-authors to create themes based on the data in the background of this research. Throughout the data analysis process, analyses, opinions, riddles, as well as additional ideas pertinent to the interpretation of the data were recorded in a log. In order to determine whether the theme design process was inconsistent in any way, the authors finally compared the outcomes. It is important to note that the authors address any differences in opinion among the concepts with one another. Eventually, the generated themes were adjusted to guarantee consistency. Two experts participated in the analysis selection, one in the engineering department (Nawal Aswan Abdul Jalil—expert in system engineering) and the other in the civil aviation authority (Muhammad Firdaus Ismail—expert in ATC system management), to ascertain the problem's validity. By determining the domain validity, the expert review phase guarantees each subtheme's significance, clarity, as well as suitability. This research employed an integrative analysis as among the examination approaches to analyze as well as synthesize various research designs (qualitative, quantitative, along with mixed methods). Expert research focused on creating relevant topics as well as subtopics. The process of gathering data was the first stage in the theme's development. The authors meticulously examined a set of 22 publications in search of remarks or details to answer inquiries from the present study. The effect of mathematical modeling on ATC efficiency is then analyzed by the authors and experts, and relevant groups are formed. The approach yielded four primary themes: i) optimization of ATC operations, ii) route and flight scheduling optimization, iii) resilience and robustness in atm systems and technological advances, and iv) their integration into ATM. From this point on, the authors continued developing each theme, including any related themes, concepts, or ideas. The corresponding author collaborated with other co-authors within the parameters of this study to develop themes based on the results. In this instance, a log was kept throughout the data analysis procedure to record any analysis, viewpoints, conundrums, or other concepts pertinent to the interpretation of the data. To address any disparities in the theme-creation procedure, the authors also compared their findings. It should be noted that the authors discuss any discrepancies that may have emerged regarding the themes. Ultimately, minor adjustments were made to the established themes to guarantee consistency. Two experts, one specializing

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in system engineering and the other in ATC, examined the problems to verify their validity. By demonstrating domain validity, the expert review stage contributed to ensuring the sufficiency, clarity, as well as significance of each sub-theme. The author executed changes at their discretion in response to expert comments as well as feedback. The questions are as follows:

1. What are the effective methods to optimize system efficiency in air traffic control, considering different airspace structures and traffic densities?
2. How can air traffic management be adjusted to enhance environmental sustainability and reduce energy consumption?
3. In what ways can air traffic systems be made more resilient to disruptions and maintain efficient operations under varying conditions?
4. What technological innovations and methodologies are transforming air traffic management, and how do they integrate with existing systems to improve performance and safety?

Result and Finding

Optimization of ATC Operations

The significance of mathematical modeling in enhancing ATC efficiency is well recognized in recent research, providing substantial benefits in managing airspace and optimizing flight routes. Through the application of various mathematical techniques and models, the field has witnessed improvements in fatigue management, route optimization, traffic system operations, and terminal airspace capacity management. Yan et al. (Yan et al., 2021) contributed significantly to this field by developing an improved compressed sensing method for selecting speech features, specifically aimed at detecting fatigue in air traffic controllers. This approach notably improved the precision of fatigue detection, a critical factor in making sure that ATC operations are both safe as well as effective (Yan et al., 2021). Similarly, Han et al. (Han et al., 2017) utilized a max-plus-linear model to optimize the flow of aircraft within the traffic system, focusing on minimizing system delays and effectively managing the inflow of aircraft into the system (Han et al., 2017). On route and airspace management, Aydoğan and Cetek (Aydoğan & Cetek, 2023) implemented a simulated annealing method to optimize aircraft routes across mixed airspace structures. Their methodology aimed at reducing overall operational costs while ensuring conflict-free routing, highlighting the model's ability to handle complex airspace utilization scenarios (Aydoğan & Cetek, 2023). Additionally, Zhang et al. (Zhang et al., 2016) developed a dynamic model for estimating terminal airspace sector capacity, which facilitates better management of airspace resources and supports the efficiency of ATM systems (Zhang et al., 2016). Cecen (Cecen, 2021) introduced a multi-objective approach using the point merge system to manage terminal maneuver areas (TMAs). This method significantly reduced aircraft delays as well as the number of conflict resolution maneuvers, showcasing how sophisticated mathematical modeling can directly enhance operational efficiency in congested areas (Cecen, 2021). These studies collectively demonstrate the transformative impact of mathematical modeling on the efficiency of ATC operations. By integrating sophisticated mathematical approaches, researchers and practitioners are able to address complex challenges in ATC, leading to safer and more efficient ATM.

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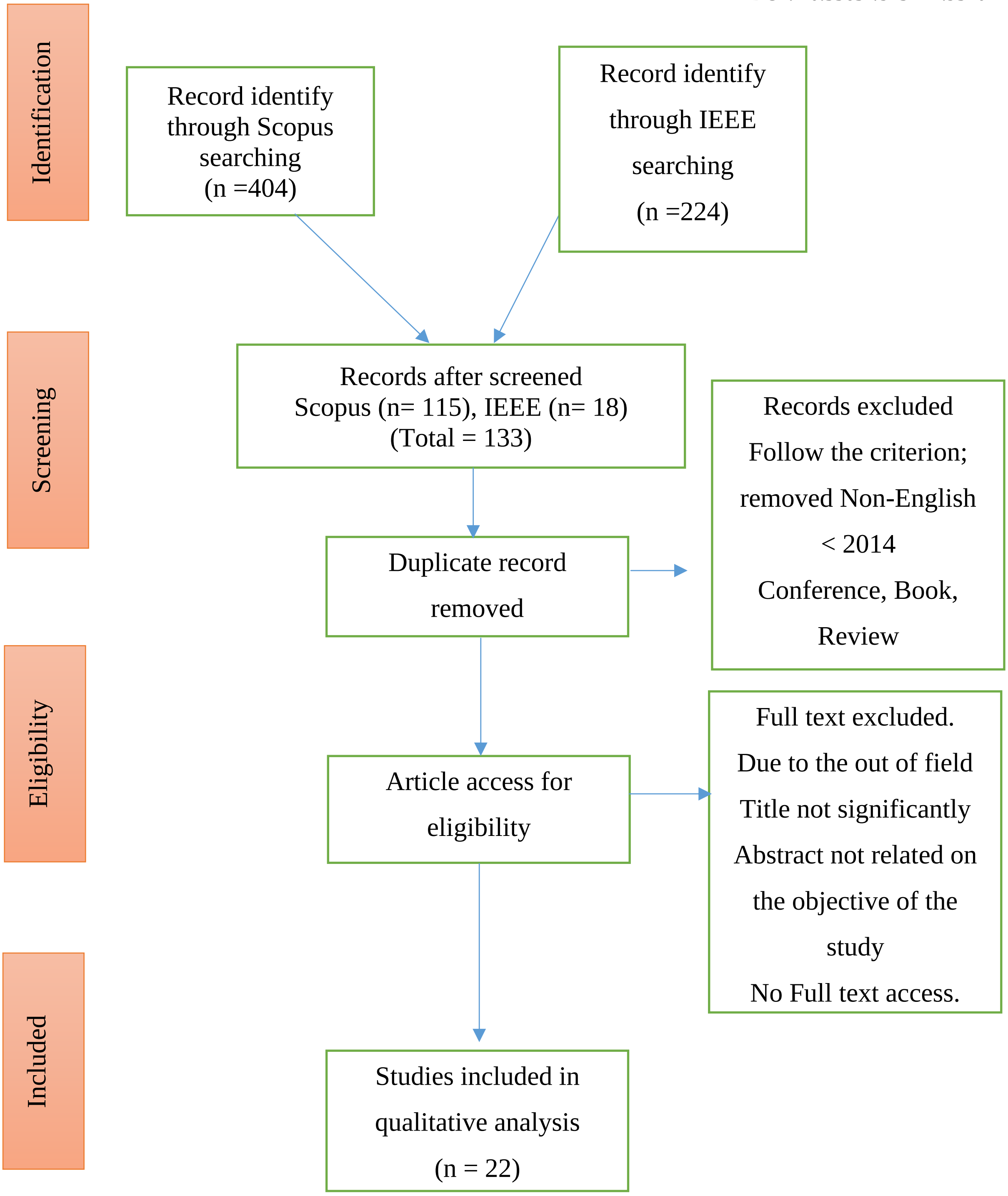

Fig.1. Flow Diagram Of The Proposed Searching Study (Moher D, Liberati A, Tetzlaff J, 2009)

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Route and Flight Scheduling Optimization

Mathematical modeling has transformed ATC by enhancing efficiency and energy management, as seen in recent advances in route and flight scheduling optimization. Researchers like Coletsos, Ntakolia, and Caceres have explored innovative methods that rethink traditional ATC frameworks, moving towards more flexible, efficient, and environmentally friendly systems (Coletsos & Ntakolia, 2017). The adoption of the 'free flight' concept, as discussed by Coletsos and Ntakolia (Coletsos & Ntakolia, 2017) represents a significant shift from airport-centric to airplane-centric management. This shift is essential as it directly contributes to the reduction of ground-holding and air delays, optimizing the use of airspace, and minimizing air traffic controllers' workload. Their research suggests a mathematical framework that deconstructs the complex problem of air traffic flow management into more manageable sub-problems, enhancing the overall flexibility and efficiency of the system (Coletsos & Ntakolia, 2017). Further expanding on this concept, Ntakolia, Caceres, and Coletsos (Ntakolia et al., 2020) introduce a dynamic integer programming model that incorporates 4D trajectories to manage the flow of air traffic more effectively. This model is designed to address the burgeoning demands on air transport systems by optimizing capacity and safety, aligning with broader environmental objectives set by governing bodies like EUROCONTROL. Their model prioritizes reducing energy costs and environmental impact, focusing on variables such as flight duration, speed deviations, and the timing of flights to optimize both safety and efficiency (Ntakolia et al., 2020). These models not only support current air traffic demands but also provide a scalable solution that can adapt to future increases in air traffic. By using mathematical modeling to predict and manage air traffic flows, these researchers contribute significantly to the field's ongoing efforts to improve ATC systems' responsiveness and resilience to fluctuating traffic patterns and environmental considerations.

Resilience and Robustness in ATM Systems

Pertaining to ATM, employing mathematical modeling significantly enhances the robustness and resilience of systems, particularly in managing gate assignments, scheduling flights, and optimizing arrival strategies in complex airspace. Researchers have developed various models to address these challenges, focusing on minimizing disruptions and improving efficiency and safety. Yu, Zhang, and Lau (Yu et al., 2017) introduced an adaptive large neighborhood search heuristic specific for robust gate assignment problems at airports, confronting the challenge posed by frequent gate conflicts due to tight scheduling. This model effectively balances traditional operational costs with the need for resilience against disturbances, ensuring smoother airport surface operations and providing a framework that can adapt to real-time issues (Yu et al., 2017). Simultaneously, Şimşek and Aktürk (Şimşek & Aktürk, 2022) explored resilient scheduling for airlines, which is crucial for minimizing the operational impacts of unexpected disruptions. Their development of a bi-criteria nonlinear mixed integer mathematical model assists in creating schedules that are not only cost-efficient but also robust against delays and cancellations, enhancing overall airline reliability (Şimşek & Aktürk, 2022). Liu, Delahaye, Zhao, and Notry (Liu et al., 2023) contributed by integrating meteorological data into the scheduling process at terminal maneuvering areas (TMAs). Their model uses wind networking to inform flight scheduling, reducing uncertainty in arrival times caused by variable wind conditions. This approach significantly decreases the potential for conflicts and delays, making the air traffic system more predictable and robust under fluctuating environmental conditions (Liu et al., 2023). These studies collectively highlight the crucial role with respect to advanced mathematical modeling in improving the ATC system's resilience. By addressing

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both planned schedules and real-time operational adjustments, these models provide a foundation for more reliable and efficient ATM.

Technological Advances and Their Integration in Air Traffic Management

The integration of technological advances in ATM has seen significant strides in enhancing efficiency through various mathematical modeling approaches. Researchers have focused on multiple aspects including aircraft sequencing and scheduling, noise management near airports, as well as the development of flow management for air traffic to address current challenges and future demands. Dönmez (Dönmez, 2023) explored the performance pertaining to multi-objective scalarization methods in aircraft sequencing as well as scheduling, highlighting the effectiveness of these methods in reducing delays and optimizing operational efficiency in ATM systems. These methods, such as the weighted sum and ε-constraint methods, have been crucial in handling the complex variables and objectives involved in ATC, leading to more streamlined and efficient operations (Dönmez, 2023). Chatelain and Van Vyve (Chatelain & Van Vyve, 2018) presented a model focusing on minimizing aircraft noise in the vicinity of airports. Their approach not only addresses environmental and social concerns but also integrates fairness in traffic assignment, which is pivotal in managing the increasing air traffic around urban centers. Their work emphasizes the dual objectives of operational efficiency and community welfare, using mathematical models to balance these aspects effectively (Chatelain & Van Vyve, 2018). On a different front, Akgunduz and Kazerooni (Akgunduz & Kazerooni, 2018) established a non-time segmented modeling strategy that included speed-dependent fuel consumption to manage air traffic flow. This model enhances the realism of air traffic simulations by allowing for adjustments based on real-time weather conditions and operational demands, thus improving the safety and efficiency of air traffic networks (Akgunduz & Kazerooni, 2018). These studies collectively demonstrate the critical role of advanced mathematical modeling in solving contemporary challenges in ATM. By leveraging these sophisticated models, stakeholders can address the multifaceted aspects of ATC, from environmental concerns to operational efficiency and fairness in resource allocation.

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Table 4: The Research Article Findings Based on The Proposed Searching Criterion

No.	Author Name and Year	Objectives	Methodologies	Findings	Conclusion & Future Research
1	Yan Y., et al. (2021)	Develop a high-efficiency fatigued speech feature selection method for ATC based on improved compressed sensing.	Improved compressed sensing, support vector machine classifier	The method improved the precision of fatigue detection, demonstrating significant advancements over current methods.	Suggests further adaptation and refinement of compressed sensing techniques in ATC operations for enhanced fatigue detection.
2	Aydoğan E., Cetek C. (2023)	Optimize aircraft routes to minimize total cost in mixed airspace structures.	Simulated annealing, mathematical modeling	Achieved cost reduction and efficiency improvements in flight route planning.	Recommends incorporation of wind conditions in future models for more accurate optimization of flight routes.
3	Han Y.-X., et al. (2017)	Optimize air traffic system operation by incorporating buffer size using max-plus-linear modeling.	Max-plus algebra, simulation	Demonstrated effective control of system delays and optimized resource allocation.	Encourages further exploration of max-plus algebra in different operational scenarios within ATC.
4	Zhang M., et al. (2016)	Estimate terminal airspace sector capacity and manage ATC and airspace resources effectively.	Dynamical modeling, multiple linear regression analysis	Found correlations between controller actions and sector capacity, verifying model feasibility.	Highlights the need for continuous improvement and validation of dynamical models in ATC for enhanced accuracy in capacity estimation.
5	Adewolu B.O., Saha A.K. (2020)	Enhance Available Transfer Capability (ATC) in	Sensitivity analysis, ACPTDF method	Enhanced ATC by over 60%, improved bus	Suggests further studies on FACTS device placement and

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No.	Author Name and Year	Objectives	Methodologies	Findings	Conclusion & Future Research
		deregulated power networks using FACTS devices.		voltage, and reduced power losses.	optimization in different network conditions for improved performance.
6	Cecen R.K. (2021)	Optimize terminal maneuver area (TMA) management using point merge systems and other techniques.	Mixed integer linear programming (MILP), ε-constraint method	Reduced aircraft delays and conflict resolution maneuvers, showing the efficacy of the optimization approach.	Proposes broader application of MILP models in ATC and emphasizes the integration of multiple objectives for holistic traffic management.
7	Yu C., et al. (2017)	To solve a robust gate assignment problem considering both traditional costs and robustness to disturbances.	Adaptive large neighborhood search (ALNS) heuristic, mathematical modeling	The ALNS algorithm outperformed benchmark algorithms in solving gate assignment issues effectively.	Suggests integrating the ALNS into existing expert systems to assist airport managers in decision-making processes.
8	Coletsos J., Ntakolia C. (2017)	Transform ATM from an airport-centered to an airplane-centered system to increase safety, efficiency, and capacity.	Mathematical modeling, two-level problem approach	Developed a support system to assist the free flight concept, aiming to improve flexibility and reduce air traffic flow management complexity.	Recommends further development and testing of the two-level approach to fully support the free flight scenario.
9	Dönmez K. (2023)	Evaluate the performance of various multi-objective programming scalarization	Mixed-integer programming, multi-criteria decision-	Identified augmented weighted Tchebycheff as the most effective method for optimizing	Encourages future research to explore other multi-objective optimization methods in ATM,

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No.	Author Name and Year	Objectives	Methodologies	Findings	Conclusion & Future Research
		methods for aircraft sequencing and scheduling.	making (MCDM) methods	aircraft sequencing and scheduling.	considering various stakeholders.
10	Chatelain P., Van Vyve M. (2018)	Model air traffic assignment near airports to minimize noise annoyance and achieve fairness in aircraft operation distribution.	Mathematical modeling, α-fairness Social Welfare Function (SWF)	Developed and validated a new model for fair air traffic assignment that reduces total annoyance and achieves fairness.	Suggest utilizing the model as a decision support tool by CDMs to balance efficiency and fairness in air traffic assignments.
11	Akgunduz A., Kazerooni H. (2018)	To address congestion and safety risks in air-traffic by introducing a non-time segmented flight plan formulation with rerouting options.	Non-time segmented mathematical modeling, sequential solution heuristics	Demonstrated the efficacy pertaining to the model through various test cases, integrating dynamic sector capacity and speed dependent fuel consumption.	Suggests further exploration of sequential heuristics for real-world application scalability.
12	Krasnyanskiy M.N., et al. (2020)	Optimize adaptive training complexes (ATC) for professional ergatic systems, enhancing economic efficiency and quality of training.	Mathematical modeling based on set theory, optimization of learning process	Presented a model capable of adapting training processes to individual characteristics, improving both speed and quality of training.	Proposes using the model for further development of simulator complexes tailored to the psychophysical traits of trainees.
13	Ntakolia C., et al. (2020)	Address capacity and safety challenges in air transport	Dynamic integer programming, energy	Developed a mathematical model that	Encourages further refinement and application of the model to

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No.	Author Name and Year	Objectives	Methodologies	Findings	Conclusion & Future Research
		by developing new procedures for free flight in a unified airspace.	efficiency analysis in ATM	minimizes energy costs and optimizes ATM performance, tested through simulation case studies.	real-world ATM scenarios for better energy efficiency and capacity handling.
14	Keskin M., Zografos K.G. (2023)	Address network-wide slot allocation problems considering airport connectivity and fairness.	Bi-objective mathematical models, ε-constraint method, network analysis	The models successfully demonstrated the trade-offs between schedule efficiency and fairness, influenced by airport connectivity indices.	Recommends further exploration of connectivity measures to improve fairness in slot allocations across congested airports.
15	Krasnyanskiy M., et al. (2018)	Increase the effectiveness of training in ATCs through individualization and optimization of the learning process.	Mathematical modeling, optimization of training systems	Developed a model that adjusts training to individual learner features, enhancing training effectiveness.	Suggests that the model could be used to design more effective and adaptable training systems in professional settings.
16	Şimşek D., Aktürk M.S. (2022)	Minimize delay risks in airline scheduling by integrating resilience in schedule design.	Bi-criteria nonlinear mixed integer model, second-order conic inequalities	Developed resilient schedules that handle disruptions better than minimum cost schedules.	Suggests further development of resilient scheduling models that can adapt dynamically to disruptions.
17	Liu W., et al. (2023)	Improve safety and efficiency in TMA by integrating wind	Mathematical modeling, simulated annealing algorithm, ADS-B data integration	Demonstrated how reducing possible conflicts as well as flight delays can be achieved	Recommends expanding the utilization of wind networking and ADS-B data to enhance TMA operations.

No.	Author Name and Year	Objectives	Methodologies	Findings	Conclusion & Future Research
		networking into aircraft arrival scheduling.		through wind networking.	
18	Akgunduz A., et al. (2018)	Minimize costs and enhance safety in en-route flight planning in constrained airspace.	3D mesh network modeling, multiple solution strategies, including centralized and decentralized approaches	Developed a model that effectively handles mid-air conflicts and optimizes fuel consumption.	Encourages applying these modeling techniques to larger networks and exploring further decentralized solutions.
19	Jiang H., et al. (2021)	Systematically address the joint scheduling of arrival and departure flights in various traffic scenarios.	Bi-level programming model, elitism genetic algorithm	Improved fairness and efficiency in scheduling under different traffic conditions.	Suggests continued development of bi-level programming models to handle increasingly complex traffic scenarios.
20	Mortazavi M.R., Naghash A. (2018)	Design pitch and flight path controller for F-16 aircraft using LQR and EA techniques.	Linear quadratic regulator, evolutionary algorithms, step-by-step design algorithm	Developed a controller that effectively manages flight path and pitch, achieving desired robustness.	Proposes the application of this controller design methodology to other aircraft types for enhanced performance.
21	Vishnyakova L.V., Popov A.S. (2021)	Optimize airspace structure and aerodrome infrastructure during modernization.	Mathematical modeling, multidimensional conditional optimization, simulation modeling	Provided a methodology to select the best options for AS structure and aerodrome infrastructure using computer modeling.	Recommends further application of these models to evaluate and optimize additional airport and airspace configurations.

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No.	Author Name and Year	Objectives	Methodologies	Findings	Conclusion & Future Research
22	Mitici M., Blom H.A.P. (2019)	Estimate air traffic conflict and collision probabilities to evaluate and design future ATM systems.	Comparative mathematical modeling, unified mathematical framework	Outlined a comparative evaluation of models for estimating conflict and collision probabilities.	Encourages the development of more unified frameworks to better evaluate and design future ATM systems.

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Discussion and Conclusion

The significance of mathematical modeling is improving ATC efficiency. Various mathematical techniques and models have been applied to enhance fatigue management, route optimization, traffic system operations, and terminal airspace capacity management. These studies demonstrate the transformative impact of mathematical modeling on ATC operations' safety as well as efficiency. Mathematical modeling has revolutionized ATC by introducing more flexible and efficient systems that prioritize reducing ground-holding and air delays, optimizing airspace usage, and minimizing air traffic controllers' workload. These models additionally tackle the increasing demands on air transport systems and aim to optimize capacity, safety, and environmental impact, making them adaptable to future increases in air traffic. Furthermore, the use of advanced mathematical modeling allows for better decision-making processes, leading to more effective resource allocation and optimization of air traffic flow. This ultimately results in cost savings for airlines, reduced fuel consumption, and minimized environmental impact. Overall, the integration of advanced mathematical modeling in ATM systems is essential for satisfying the aviation sector's expanding demands and guaranteeing air travel's efficiency as well as safety. By enhancing and perfecting these models over time, we may strive towards a more sustainable and resilient air transportation system for the future. The integration of advanced mathematical modeling in ATM has proven to be crucial in addressing various challenges such as aircraft sequencing and scheduling, noise management, and air-traffic flow management. These models have significantly improved operational efficiency, reduced delays, minimized aircraft noise, and balanced environmental concerns with community welfare, ultimately enhancing the safety as well as efficiency pertaining to the air traffic networks. The reviewed articles demonstrate significant advancements in ATC via mathematical modeling implementation, addressing safety, efficiency, and resource optimization. Safety enhancements are evident in the development of sophisticated models for detecting controller fatigue—a major risk factor in air traffic incidents. Techniques such as fatigued speech recognition allow for early detection and intervention, significantly mitigating risks associated with human factors in ATC operations. Additionally, advancements in scheduling and sequencing have refined the handling of air traffic flow, effectively reducing potential conflicts and enhancing overall air safety. In terms of operational efficiency, mathematical models have proven essential in optimizing flight routes and managing airspace. The utilization of algorithms such as simulated annealing and dynamic integer programming facilitates the complex task of airspace management, allowing for more efficient routing and scheduling of flights. This not only reduces fuel consumption and delays but also cuts operational costs significantly. Such improvements are crucial in responding to the increasing demands of air travel, ensuring that air traffic systems are both responsive and robust. Resource optimization also benefits from the strategic application of mathematical models, particularly in the allocation and management of both human and physical ATC resources. For instance, models have been employed to strategically place FACTS devices in power networks, enhancing their performance and efficiency. Similarly, the optimization of terminal maneuver areas and airport slots ensures better utilization of existing resources, accommodating the rising air traffic volumes without compromising service quality or safety. Overall, the integration of mathematical modeling into ATC practices marks a transformative step towards a more sophisticated, safe, as well as efficient ATM. Since air travel keeps increasing, these models provide the necessary foundation to adapt to and efficiently manage future challenges, ensuring the smooth functioning of global air travel networks.

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