Exploring AI Solutions in Air Traffic Management

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Haaga-Helia University of Applied Sciences
Aviation Business
Thesis
2024

Abstract

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Degree
Bachelor of Business Administration, Aviation Business

Thesis Title
Exploring AI solutions in Air Traffic Management

Number of pages and appendix pages
43 + 0

This thesis explores the possibility of using artificial intelligence tools in air traffic management. It includes a literature review and a case study analysis of five artificial intelligence-based systems, including tools for conflict resolution, weather prediction, reduced separation minima, stream-based management, and automatic speech recognition.

The incentive for the research comes from necessity. The amount of air traffic has grown significantly during the recent history, with the covid pandemic only halting the growth for a short while. At many instances, airspace and airport capacity are already utilized to the maximum. New methods to improve both the efficiency and the safety involved are thus required to make way for further growth in the industry.

The thesis argues that the growing air traffic demands innovative solutions to improve the operational efficiency and safety in air traffic management, while also considering the environmental impact of aviation. Artificial intelligence's capacity for data processing and decision-making support is highlighted as a promising means to address these challenges.

The key findings from the research suggest that artificial intelligence tools can optimize airspace usage and resource allocation, potentially improving operational safety and efficiency through warning systems, reduced controller workload and enhanced situational awareness. However, the feasibility of immediate implementation is inadequate due to potential cyber threats, legal issues, and user acceptance challenges. Future implementation appears promising but requires further research and development.

The thesis is structured into chapters that define the key concepts, present the methodology, conduct a literature review, analyse the cases, and conclude with recommendations for artificial intelligence implementation in air traffic management. It emphasizes the importance of maintaining operational safety as a priority over efficiency gains and suggests that while artificial intelligence systems are not yet ready for direct implementation, they hold significant potential for future use in air traffic management.

The thesis concludes with recommendations for careful implementation, considering safety and user acceptance. It also suggests areas for future research, including artificial intelligence's possible role in dynamic airspace management and real-world pilot projects to gather empirical data on artificial intelligence systems in air traffic management.

Key words
Air traffic management, artificial intelligence, safety, efficiency, air traffic control, implementation

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1 Introduction

In an era defined by unprecedented growth in global air travel, the aviation field is faced with an elaborate web of challenges that demand innovative solutions. The combination of increasing air traffic, finite and already congested airspace, and the growing necessity for sustainable practices demands a re-evaluation of the air traffic management patterns we are used to. This thesis embarks on a journey into the world of artificial intelligence to explore its possible applications and tools in addressing the multifaceted challenges of air traffic management.

1.1 Background and rationale

The rapid growth of air travel over the last decades has strained existing air traffic management systems. This dictates a compelling need for more advanced technologies capable of coordinating the complex air traffic flows in the limited air space and airport capacity available.

Aviation industry hit a wall head on and with full speed with the arrival of the Covid-19 pandemic. The pandemic brought a time of deep uncertainty and stagnation with number of flights dropping to less than half during the initial year of the pandemic (Statista 2024). However, this seems to have been a very temporary setback and even the closure of the Russian airspace seems to have little effect as the year 2024 is already predicted to be another all-time high (The Straits Times 2023). As global air travel keeps growing despite the occasional crises, the ever-growing need for new remedies for congestion and sustainable practices arises again.

Artificial intelligence, with its capacity for adaptive learning, data processing and insightful decision-making, emerges as a promising means for evolving how air traffic is managed, controlled, and optimized. By taking advantage of machine learning, predictive analysis and support systems for decision-making, artificial intelligence could contribute to increased operation efficiency and safety and a more sustainable aviation ecosystem. The rationale for this research is based in the recognition that the successful application of artificial intelligence has the potential to revolutionize air traffic management practices.

1.2 Objective

The objective of the thesis is to assess the effects of artificial intelligence tools on the operational safety and efficiency in air traffic management. Additionally, the feasibility of implementing the artificial intelligence tools from air navigation service providers perspective is looked into.

A literature review will explore the potential uses of artificial intelligence in the various subsections of air traffic management, including air traffic control, air traffic flow and capacity management, air space management and flight planning and routing. The literature review will compare systematically the new artificial intelligence-based applications to the conventional tools, which are used today in air traffic control units. Furthermore, the thesis will explore the environmental and operational benefits of artificial intelligence integration and provide recommendations for implementation and future research in the field.

1.3 Significance

The aviation industry is a significant polluter. The largest contributors for global warming from aviation include the cirrus clouds and carbon-dioxide and nitrogen oxide emissions, caused from the contrails of aircraft engines. The cirrus clouds trap the heat to the atmosphere and the emissions absorb the heat radiation from the earth and reflect it back to earth. (EPA 2023.) It is estimated that aviation is responsible for up to 3.5 percent of the global warming (Lee et al 2020). Thus, even a very small improvement in the efficiency of the tens of thousands of flights, which are flown globally daily could result in a crucial reduction in the negative effects aviation causes to the global environment.

The significance of this research lies with its potential to offer new solutions that transcend the theoretical realm, revealing the recent developments in artificial intelligence technology that could result in practical applications and solutions to the air traffic management and navigation service providers. As the findings unfold, various stakeholders in aviation, including policymakers and researchers could gain valuable insights on the revolutionary role of artificial intelligence in the formation of the future of aviation.

1.4 Relevance

The thesis focuses on building a base for improving decision-making and practices. Aviation industry operates in a very dynamic and complex environment facing challenges with increasing air traffic, consequent congestion, and the need for sustainable practices. The thesis will address the broad challenges faced by aviation and aims to give context for future research. In addition to academic contribution, the emphasis is also on the practical applications of artificial intelligence and their potential to assess find real-word issues. The research focuses on the tangible ways in which artificial intelligence could be applied to improve operational efficiency, optimize routes, or enhance decision making processes. Feasibility of the potential applications is considered to examine if the solutions are viable and practical.

1.5 Structure

Chapter 2 of this thesis will first define the key concepts used later in the literature review. It is essential knowledge to help the reader better understand the deeper analysis presented later. Chapter 3 will discuss the methodology used in the research, present the research questions, and assess the reliability of the sources. Followed by the methodology, chapter 4 presents a comprehensive literature review, which will explore the present landscape of artificial intelligence and air traffic management. Subsequently, chapter 5 will produce a systematic analysis of the cases and compare the conventional methods to the new artificial intelligence-based systems. Finally, chapter 6 will deliver a thorough discussion of the findings and recommendations for implementation of artificial intelligence in the air traffic management practices.

In traversing the following pages, the reader is invited to participate in a dissertation on the fusion of artificial intelligence and air traffic management – a topic that holds potential of transforming the skies we know and providing a more efficient and sustainable future for the global aviation.

2 Key concepts

The following chapter delivers a comprehensive investigation to the key concepts essential to understanding the intersection of artificial intelligence and air traffic management. By clarifying the fundamental principles, theories and methodologies related to artificial intelligence and air traffic management, this chapter sets the foundation for a deeper plunge into the practical cases and applications presented in the subsequent chapters.

The first subchapter will define some of the complex features of artificial intelligence. Artificial intelligence is breaking the barriers we were used to have and define for computers. It represents a comprehensive change in how machines learn, sense, and interact with things. From explainable artificial intelligence to human-machine interactions, the subchapter will deliver a package which elucidates the relevant parts of artificial intelligence for this study.

The number of people, systems, and procedures a single international flight requires is staggering. There is a multitude of critical components in the different operational and technical aspects of air traffic management, which provide for the safe and efficient air travel we enjoy. The second subchapter opens up the relevant parts of air traffic management, which supports the entirety of the global aviation industry.

2.1 Artificial Intelligence

This subchapter will define the key concepts related to artificial intelligence. Artificial intelligence itself derives from two words – ‘artificial’, meaning man-made or synthetic, and ‘intelligence’, which is defined as the capability to acquire and apply knowledge, think, and decide. Combined together, artificial intelligence is described as a computer system endowed with capabilities similar to the human brain, comprising of language comprehension and generation, which resembles human communication, image recognition or creation, data-driven learning and problem-solving. (Cambridge dictionary s.a.)

Explainable artificial intelligence, or XAI, is an artificial intelligence system designed to allow for human oversight. It requires transparency and features which help the human controller to understand what the artificial intelligence system is doing, what data is used and how it is processed, and why the system comes to the solution it provides. It can be done either as a transparent system, which can be constantly monitored and which continuously explains the actions and reasoning, or it can be done as a system which provides the necessary information afterwards to the controller for analysis. (Degas, Islam, Hurter, Barua, Rahman, Poudel, Ruscio, Ahmed, Begum, Rahman, Bonelli, Cartocci, Di Flumeri, Borghini, Babiloni & Arico 2022.)

The three levels of XAI are descriptive, predictive, and prescriptive artificial intelligence. Descriptive XAI system describes the working principles of an artificial intelligence system, or the results it provides, it can be used to analyse situations and explain why there is a need for certain actions. Predictive XAI system predicts the actions of an artificial intelligence system which would results from a certain entered parameter, or a change in a condition and it can provide forecasts of the consequences of actions and thus provide background information for more enlightened decisions. Prescriptive XAI, is a system which distinguishes mistakes or faults in the artificial intelligence system and prescribes ways to fix the problems caused by them. This final level is advanced and requires the system to examine the results and prescribe the necessary changes to the system to remedy the issue, while maintaining understandability to the user. It can consider various different sources of information and predict the suitability of each of them to the problem at hand. (Degas et al 2022.)

Human-machine interactions, or human-machine interface, or HMI. The touchpoint between a human and the artificial intelligence software or system is called human-machine interaction or HMI. It can be any device, system or a feature which enables humans and machines to interact and connect with each other. It could for example be a display system, touchscreen, or a keyboard, or a combination of all these. Complex artificial intelligence systems usually include multiple sophisticated touchpoints, which enable various ways of interaction. (Xie, Pongsakornsathien, Gardi & Sabatini 2021.)

Adaptive automation is a system of which either the user, or the system itself, can change the amount of automation in use real-time. Where in the more traditional system the level of automation is set at a given level by the user and it usually does not change if it is not changed, in the adaptive automation system the system can follow parameters and change the level depending on the situation, with or without user input. The more the automation level is increased, the more the system increases its control and autonomy, resulting in the highest levels making and executing the decisions by itself while only informing the user. (Scerbo 2009.)

2.2 Air Traffic Management

The following subchapter will clarify the key concepts related to the air traffic management. Air Traffic Management, or ATM, itself is the combination of both air and ground services related to the air traffic services, airspace management and air traffic flow management (EC Regulation 549/2004 2004).

Air traffic services in turn are a combination of flight information service, alerting service, air traffic advisory service and air traffic control service (EC Regulation 549/2004 2004). These services are generally provided by air traffic controllers, with the intent of collision avoidance and efficiency of air traffic (SKYbrary s.a. a). Air traffic control is service done by air traffic controllers with the objective of keeping air traffic, which can be both in the air or on the ground, from colliding with each other and limiting delay by maintaining orderliness of the traffic and a rational sequence between them (EC Regulation 549/2004 2004). This is done over voice or datalink communication between the air traffic controller and flight crew and by controlling the aircrafts horizontal flight path, altitude, rate of descent or climb or speed in the air, or pushback directions, taxi routings, clearances to lineup the runway, take-off, or land (SKYbrary s.a. a). Air traffic control is separated to different areas. Firstly, the area control service, which is the service provided in a certain block of airspace, usually at higher altitudes covering sectors or even entire nations. Secondly, approach control service, which is the service provided to the airborne departing and arriving traffic at a certain airport in the so-called terminal area of TMA of the airport. Additionally, the aerodrome control service, which is the service provided to the traffic at and close to the airport. (EC Regulation 549/2004 2004.)

Air traffic flow management, or ATFM, is a service, which aims to promote safe and efficient flow of air traffic by optimizing the capacity and matching the volume of air traffic to the reported capacity of each air traffic control unit (ICAO 2018). It is done in three different phases. The first phase is strategic, which starts already a few months before and covers broader and more time-consuming measures such as rescheduling and increasing the capacity of an air traffic control unit or the investigating the possible need for tactical measures in the near future. The next phase is called pre-tactical planning, which is done daily in regard to the next day and includes for example rerouting on a smaller scale and decisions to use of tactical measures during the upcoming day. The final phase is the tactical phase, which includes the enactment of the measures, such as constraints for the amount of traffic in certain air space blocks or limiting the amount of arriving aircraft to match the lowered runway capacity due to low visibility operations. This is seen as rerouting or the CTOTs, meaning calculated take-off times, which are known commonly also as slots, which are issued to aircraft still on the ground to delay their departures. (SKYbrary s.a. a.)

Airspace management is both the planning and operational function related to allocation and sometimes restriction of airspace to all the various parties which want to use it (EC Regulation 549/2004 2004). The service deals both with the large-scale planning of how airspace is designed and structured, and the daily operation of allocation of airspace blocks, flight levels, flight routes or zones (SKYbrary s.a. a).

Calculated take off time, or **CTOT**, is a certain time which is determined and released by the air traffic flow management unit, as an outcome from their tactical slot allocation procedure with the intent to have the aircraft depart the airport at that time (ICAO 2015). The ATFM departure slots are distributed via the European Network Manager after a request from local flow management positions, which are located at the national area control centres. The local air traffic control units have to then ensure that the aircraft departs within the -5 to +10-minute departure window. (Performance Review Unit s.a.)

Radar display system is the radar image air traffic controllers typically use to present the traffic in their control sector visually on a computer screen in their controller working positions. The data can be derived from multiple sources. The original system, which does not need an input from the aircraft is called primary surveillance radar which detects the aircraft by the reflections of the signal it sends. The most commonly used system is called secondary surveillance radar, which works by interrogation/answer logic, a ground-based interrogator-receiver sends a signal to which the aircrafts transponder replies to, which allows the ground station to determine the distance and direction of the aircraft. Newer secondary surveillance radar systems allow also for data link communications, which allow parameters such as aircraft altitude and selected altitude, track and heading to be transmitted to the ground station. More modern systems called ADS-B, Automatic Dependent Surveillance – Broadcast, works simply by a ground unit receiving data broadcasted by the aircraft constantly. Finally, WAM, or Wide Area Multilateration, is a system which works by many ground stations receiving the aircraft transponders signal and calculating the aircrafts position from the combined information, it works a bit like a reverse GPS system. The radar display system can combine these various information systems and calculate the most likely position of each aircraft. The system is used to maintain required separation between aircraft and plan and execute an efficient and orderly flow of traffic. (ICAO 2007.)

Advanced surface movement guidance and control system, or **A-SMGCS**, is a radar-based system used for ground-based air traffic control. The data, similarly, like the data from secondary surveillance radar or ADS-B system, can be shown visually on a radar display system. It can significantly increase the situational awareness of ground or apron controllers. It may also be equipped with additional tools to help reduce the workload of the controller and add additional safety layers, such as stop bar automation or a red highlight colour for closed runways. (Eurocontrol 2020.) Figure 1 presents an image of a A-SMGCS from Helsinki-Vantaa air traffic control with an aircraft label also visible in blue colour in the middle. The green label is a ground vehicle performing runway inspection.

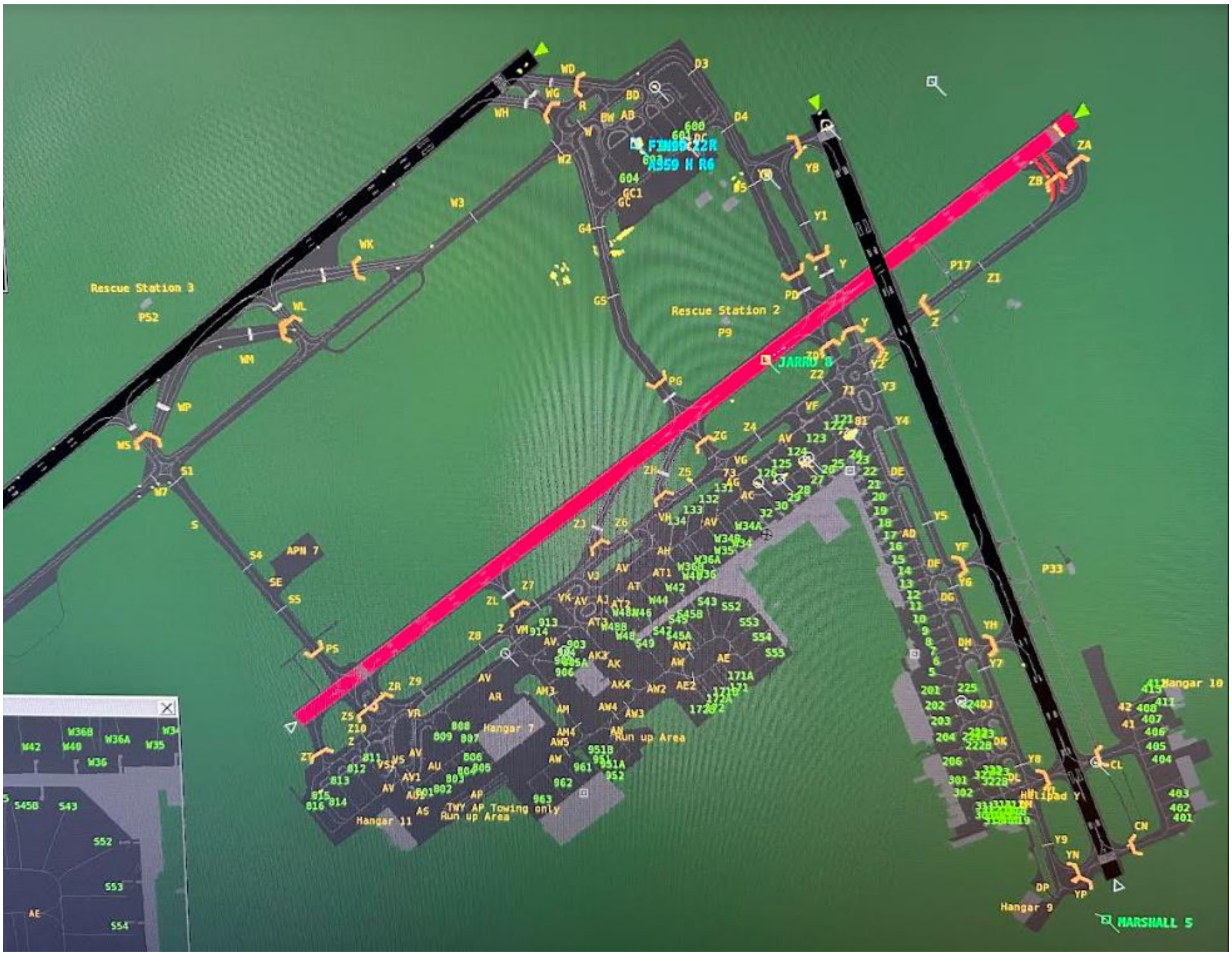


Figure 1. The A-SMGCS image for Helsinki-Vantaa airport.

Aircraft label. The radar display unit is used to show the air traffic controller the information of each aircraft in their sectors and usually also nearby sectors for better situation awareness. The display shows the information of the aircraft as labels, each showing the aircraft callsign, the position derived from the previously mentioned sources, radar, ADS-B or WAM, flight parameters such as altitude, track, speed, aircraft type and weight class. It can also be used to show warnings which require immediate controller input. (Eurocontrol 2017.) Figure 2 shows an aircraft label from Helsinki-Vantaa air traffic control. The information includes among other things the callsign of the aircraft, which sector is controlling it, aircraft type, altitude and cleared flight level and ground speed.

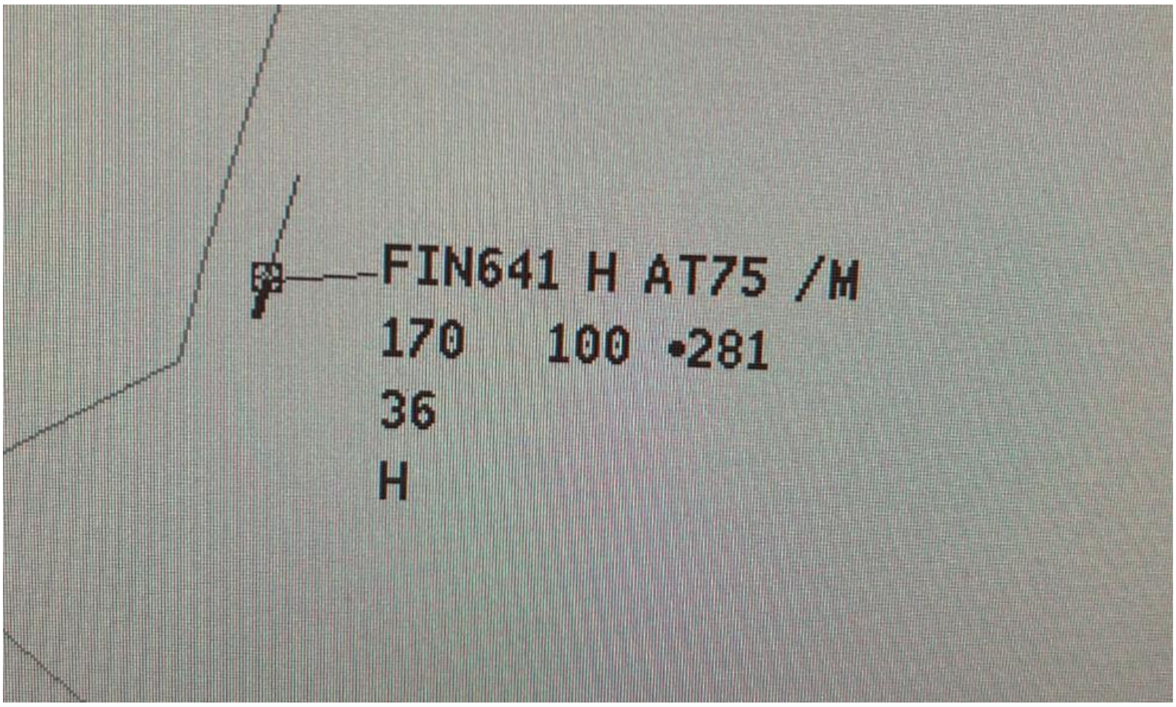


Figure 2. Aircraft label on TopSky -radar display at Helsinki-Vantaa airport.

3 Methodology

The following chapter will present the research questions, objective and methodology used in the thesis. It will additionally describe the processes involved in data collection and evaluate the reliability of the data and sources.

3.1 The research questions

The research question of this thesis is:

How can artificial intelligence tools be used to improve the operational efficiency and safety of air traffic management?

The sub-question is:

Are the artificial intelligence systems analysed feasible for implementation by air navigation service providers?

3.2 Research objective

The main objective of this research is to find and evaluate the different ways to implement artificial intelligence tools to air traffic management and analyse their effects on operational safety and efficiency.

Additionally, the other object for the research is to find out if the tools are feasible for implementation as they are, or possibly in the future in the units providing air navigation services. The assessment of feasibility will be used to provide recommendations for the possible future users of the systems.

Artificial intelligence and systems based on it have become an upcoming megatrend and new systems are being developed widely. This thesis will look into the situation as it is today with a lean towards the economical possibilities for air navigation service providers, airlines and other shareholders while holding onto the very much necessary safety aspects involved. Increased efficiency results also in a reduced impact on the ecological damage aviation industry causes.

3.3 Research methods

The research method used in this thesis is a combination of both quantitative and qualitative methods, resulting in the research being of the mixed method.

Mixed method research is a research method, which integrates properties from both quantitative and qualitative research methods to allow the research to better understand and answer the research questions. The mixed method approach allows the research to build the theory during the research while still answering to the research questions in the same study. It can be argued to fit well in applied research. (Byrne & Humble 2007.)

Applied research is a research approach, which focuses on solving or gaining better understanding to specific real-world problems. It can study the applicability of theories on practical issues and be used to generate new technologies, commodities, or procedures. (Kothari 2004.)

Quantitative research method has a numerical and statistical approach to the research. It is used to test and measure hypotheses and theories objectively with replicable results. Qualitative research is used to summarize, analyse, or categorize more subjective and possibly more complex issues, which require deeper understanding to grasp. It is used to explore ideas or generate theories. (Kothari 2004.)

The reasoning behind the mixed method approach is to better allow the thesis to use both the directly numerical and more subjective data in the research. The mixed research approach explores new ideas, generates theory while also generating results and solves practical problems based on the theory.

The thesis can be argued to have an applied research aspect to it, as it seeks to solve practical problems and studies the applicability of the systems to help solve the problem. The application of artificial intelligence tools for commercial or safety purposes would require the use of new technologies and the application of new procedures from the air navigation service providers.

3.4 Research material and tools

The research gathered data to provide a solid theoretical background for the literature review in chapter 4. The main focus for the sources used in the literature review was on peer-reviewed research articles to provide more reliability, while other sources were used for other chapters, although still being first critically evaluated for reliability and also relevance for this research.

Most of the research data is secondary, pre-existing data from various research articles and publications with research focusing on artificial intelligence or aviation. Publication platform MDPI provided for many of the peer-reviewed research articles. Additionally, statistics and articles were used to provide up-to-date information to base the introduction chapter on. Legal texts and official websites specializing in aviation publications, information and knowledge were used to build chapter 2 and explain the key concepts to the reader.

The data was selected on relevance to the topic and its ability to help in answering the research questions. Artificial intelligence is quite modern subject and had a limited research base from which the studies fitting the research setting were searched for and chosen to be included.

3.5 Data reliability

Although the artificial intelligence is a new research field, nearly all of the studies used were from peer-reviewed publication, which increases data reliability.

The research focused on peer-reviewed publications for the basis of the literature review. Publications from platforms such as MDPI, IEEE Xplore and AHFE International were used, which all publish only peer-reviewed articles. Any articles, which were not accesses through peer-reviewed publication platforms were checked to be peer-reviewed elsewhere, such as the article on stream-based air traffic flow management, which was also published in the International Council of the Aeronautical Sciences.

As the articles are peer-reviewed and go through editorial standards the reliability of them can be considered high. MDPI also has a commitment to open access publishing, which increases data transparency.

Official websites and publications from trusted national and international organizations such as ICAO, Eurocontrol and Traficom were used in writing the background for the thesis. The reliability of data published by ICAO, which is an agency under the United Nations, Eurocontrol, which is an agency under EU and ECAC and Traficom, which is a government agency can be deemed high.

SKYbrary was used for many sections in the key concepts chapter. It utilizes a wiki type approach, but it has a strict content management and control process and restricted access to editing the articles to increase quality and reliability of the data. It was established by Eurocontrol and uses information mainly from trusted sources such as ICAO, EASA, and FAA. Thus, the reliability of the site can be assessed to be medium to high at the minimum.

4 Literature review

The following chapter will delve into a comprehensive examination of existing research related to using artificial intelligence in various aspects of air traffic management. The literature review will function as a basis for deeper understanding of the context, current state, and the future of knowledge in the field.

By analysing the relevant studies and methodologies, the chapter aspires to provide deeper insight and establish the theoretical framework upon which this study is built upon and clarify the complexities inherent in the conjunction of artificial intelligence and air traffic management while contributing to the ongoing dialogue in the field. The literature review is organized into several cases to facilitate a structured exploration of the various themes and findings.

4.1 Background and restrictions in use

The use of artificial intelligence in air traffic management began from programs used to coordinate and enhance the air traffic flows and have since evolved to predict the four-dimensional flight paths (Degas et al 2022). In the air, time and speed play a crucial role in addition to the three-dimensional position of the air traffic.

As aviation is generally considered an extremely safety-critical industry, the artificial intelligence systems so far have not reached wide everyday use in the air traffic control service units. Most of the safety related work is done by trained air traffic controllers, who are responsible for the efficient and safe flow of traffic. (Degas et al 2022.)

The systems at this point cannot take the responsibility for the safety or control of the air traffic but could already be used to enhance the safety by monitoring air traffic controller’s workload, providing alerts if the amount of traffic surpasses the controller’s abilities or capacity. Additionally, in case the air traffic controller becomes incapable of continuing the work due to sickness or being otherwise indisposed, the so-called adaptive automation system could independently start to provide direct actions to ensure the safety of the aircraft. (Degas et al 2022.)

In such safety-critical industry, it is of utmost importance for the person responsible for the air traffic to understand what is happening and to be in control of the situation. The amount of data involved in these artificial intelligence systems can be beyond what humans are capable of process and comprehend. Thus, it is very important that the system’s fundamental principles are understood by the user and the human-machine interface is built in such a way that the human air traffic controller using the system can verify the information when necessary. (Westin, Hilburn, Borst, van Kampen & Bång 2020.)

Explainable artificial intelligence (XAI) plays a vital role in retaining the cognitive supervision over the artificial intelligence systems. As the system simply cannot perform functions which the human in control cannot understand, the applicability of the systems is restricted by the artificial intelligence systems capability to rationalize its actions to the controller in charge – what the system does, how it will do it and why it is done. (Degas et al 2022.)

Few different methods of keeping the controller in the loop have been proposed. The data can be presented to the controller visually or the presented options could be backed by a text. The main purpose of the explainability feature is to provide the air traffic controller the answers to questions what, how and why, in regard to the artificial intelligence systems actions. (Westin et al 2020.)

In the so called black-box model, the air traffic controller does not see the reasoning and information behind the decision and is just presented with the solution. This model is not advisable, as the air traffic controller cannot validate the information used to arrive at this solution, thus they are unable to comprehend the reasoning. Consequently, this lack of understanding could result in partial or total loss of the situational awareness and mistrust towards the system. Additionally, for the retroactive investigations of incidents or accidents, that are very common in aviation, the traceability of the participants, situation and all the decision-making involved is crucial. (Xie, Pongsakornsathien, Gardi & Sabatini 2021.)

The black-box model, even when working properly, is not a valid option. The worst option is of course the system which does wrong things for reasons the controller cannot understand. The black-box model falls in the next bracket, where either the system does the right thing or the functioning principles are understood, but not both. In air traffic management the artificial intelligence systems have to do the right things, while the controller also understands the reasoning behind it. (Westin et al 2020.)

Artificial intelligence systems might function best in the pre-tactical phase of air traffic management. The pre-tactical phase, which focuses mainly on planning and solving compound problems which arise in the future, instead of the fast situations requiring immediate air traffic controller input, for example in the terminal areas of the airports. In the rapid situations the controller does not necessarily have enough time to be able to verify the information and solution presented by the artificial intelligence system. (Cocchioni, Bonelli, Westin, Ferreira & Cavagnetto 2023.)

4.2 Case 1: Conflict resolution

A conventional air traffic control tool Medium Term Conflict Detection, or MTCD, is a system used mainly by area control service units which processes flight data parameters, such as aircraft speed and altitude, and uses them to predict and detect possible conflicts or losses of separation between aircraft. It can also be used safeguard restricted airspace blocks and can calculate the possible conflicts up to 20 minutes into the future. The system calculates the future aircraft position from the flight plan and flight parameters and in case it detects a conflict between two aircraft or an aircraft and a restricted airspace the system is able to alert the controller of the problem arising in the near future. The system does not work like artificial intelligence and thus does not proactively present any solutions to the arising problems, it just points them out. The system also does not consider any additional problems possibly caused by the controller solving the conflict. (SKYbrary, s.a. b.)

In a situation where solving a problem could result in various other problems, the role of artificial intelligence is emphasized as a holistic solution provider. The rest of this subchapter will introduce a synopsis of a situation which could happened in the daily work of an area control air traffic controller. The explainable artificial intelligence models are then reflected on the situation and how they could offer solutions to the problems.

Degas et al (2022) presents a scenario where two aircraft would be in the same position at the same time in the near future and thus the risk of collision or losing the required separation between the aircraft exists. The Medium-Term Conflict Detection system (MTCD), which is already widely used by air traffic control units, would alert the controller of the conflict.

The controller then solves the conflict by changing the flight path or level of one of the aircraft, which results in a change to the arrival time of the aircraft, which in turn might result in the aircraft arriving at the destination at a rush hour. Consequently, the change in arrival time could result in further congestion, delay to other aircraft and increased workload of the combined shareholders including the airlines air and ground staff and air traffic controllers. (Degas et al 2022.)

The following different forms of explainable artificial intelligence could help all the parties involved firstly make an informed decision and illustrate the consequences of it to the parties involved. The three levels of XAI are descriptive, predictive, and prescriptive. (Degas et al 2022.) These artificial intelligence systems are called decision-support systems or DSS. The models can either be naturally comprehensible, meaning they are already understandable during the whole process, or provide a description of reasoning after the process has occurred in the black-box model. The models can be either local, which work inside the different parts of the system or global, which tries to clarify the whole entirety of the operation, possibly without even interpreting anything except for the decision or results. Additionally, the models can also be used simultaneously to offer more insight into the decision-making process inside the black-box model. The models can be used it various different ways. (Xie et al 2021.)

The descriptive XAI could explain why the requirement to alter the flight path or level of the aircraft exists, which is due to the risk of collision. It could also provide information related to the possible bottleneck in the airport capacity at the time of arrival in case the aircraft is late. (Degas et al 2022.)

Predictive XAI could provide the user with the possible end results of the actions, thus informing the controller, airline and airport staff of the congestion caused by the controller’s actions to solve the initial issue. Consequently, the various different stakeholders could react accordingly to the upcoming congestion. (Degas et al 2022.)

Prescriptive XAI would be able to combine the capabilities of the previous two levels, both descriptive and predictive XAI, and in addition to that recommend the most suitable solutions to the problem with reasoning included. It could consider multiple sources of information, such as the amount of traffic at the destination airport, present meteorological conditions, fuel consumption of the aircraft types involved and both pilot and air traffic control workloads. With the capability of use rapidly such vast amount of information in supporting the controller’s decision-making, the provided solution could be applied with minimal contemplation and thus also minimize the impact to the controller’s workload. (Degas et al 2022.)

4.3 Case 2: Weather prediction

The conventional methods used by air traffic control units for weather prediction are built on ground-based weather radar systems. The method of function is somewhat similar to the weather radars used in the aircraft. For air traffic control units, the weather image is however mainly nice-to-know information and cannot be used to accurately predict the weather as the image presents the weather phenomena in a two-dimensional format and the aircraft are on various different altitudes. The weather can be nearly calm and clear at a higher level while a hailstorm rages on at a lower altitude, or vice versa. Two aircraft at the same geographical location, but on different altitudes can thus experience totally different weather conditions and depending on the situation neither, only one or both could ask for different navigational aid in circumnavigation a lightning storm seen on the weather radar display. In addition, the quite colourful clouds and precipitation presented can clutter the radar display and hamper the air traffic controller’s ability to see and utilize the aircraft labels.

Consequently, the weather phenomena are usually not presented on the main radar display. Figure 3 below shows the side weather display from Helsinki-Vantaa air traffic control.

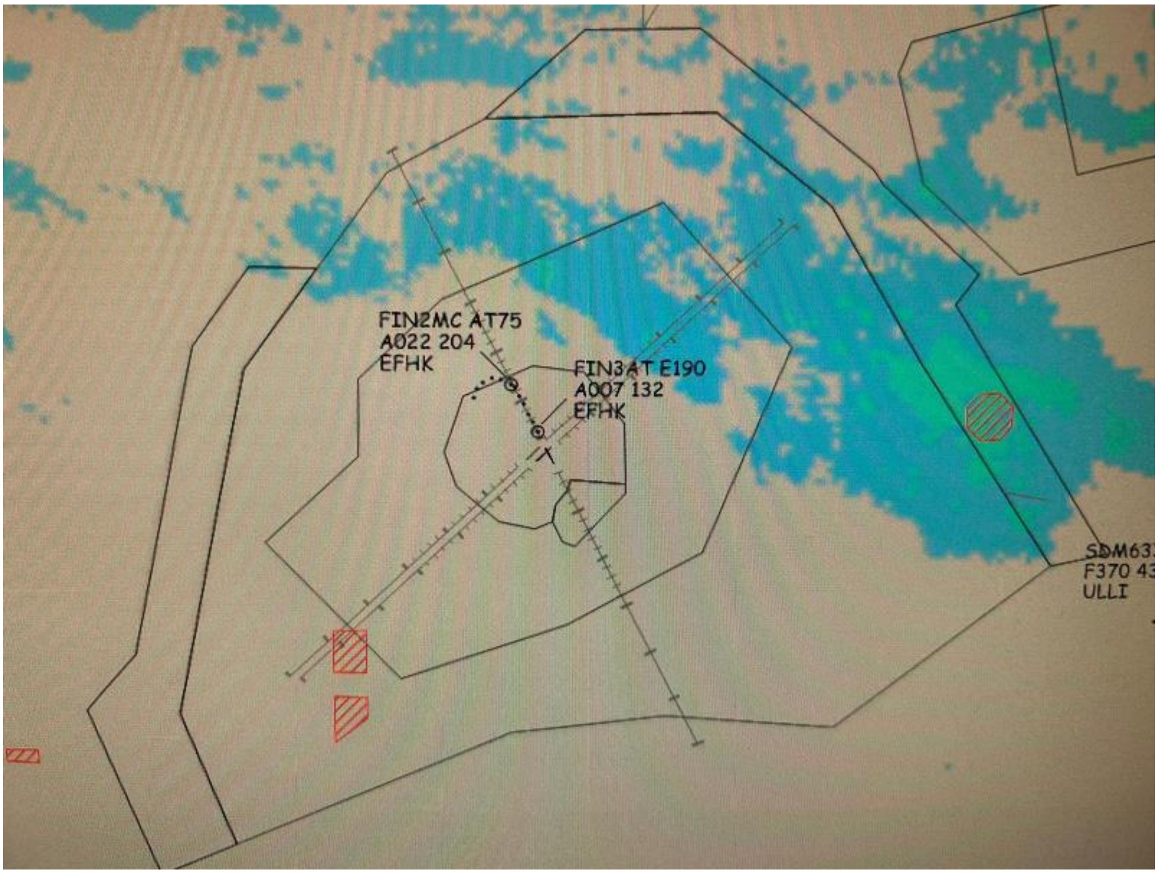
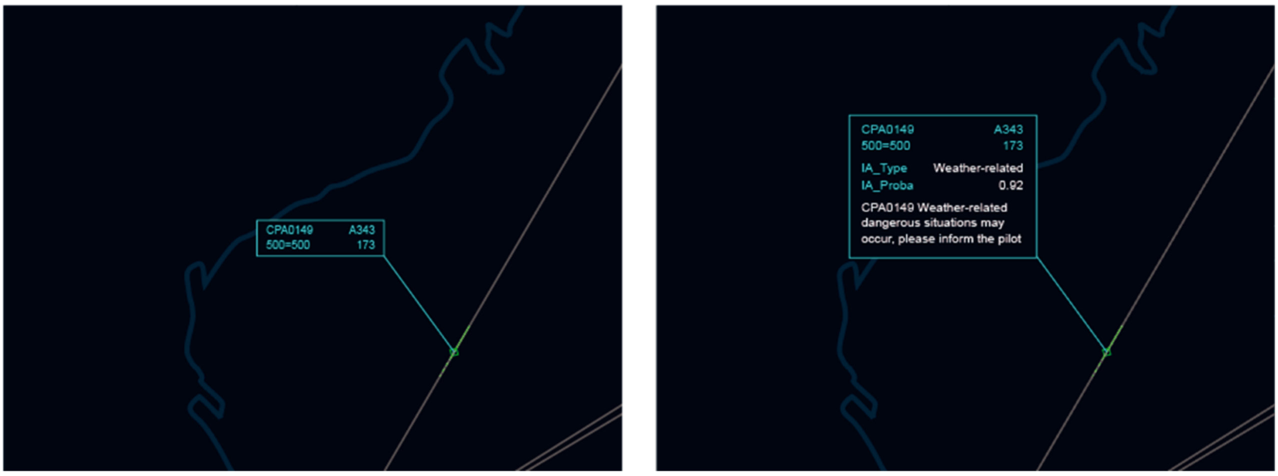


Figure 3. Precipitation presented on a radar display at Helsinki-Vantaa ATC.

A separate side display is often used, which can be checked to gain some kind of idea of the possible weather, while the actually all necessary information in controlling the air traffic is received directly from the pilots over the radio when they ask for headings to avoid certain weather. (SKYbrary, s.a. c.)

Artificial intelligence could be used in weather prediction to estimate the possible threats more accurately to aircraft, even before their own weather radars detect the threats. An XAI model could be a used in system which combines, processes and analyses large quantities of meteorological data in the background and warns the air traffic controller in case the data crosses certain parameters. The decision support systems data and the meteorological status related to the area around each aircraft could be analysed anytime with a prompt from the air traffic controller, but the system would remain otherwise silent unless the predictive model predicts dangerous meteorological conditions and recommends commencing a warning to the aircraft. (Xie et al 2021).

Below, is a visual representation of a radar image from a radar display system. On the left, the XAI system is in silent mode and the system working in the background cannot be seen in any way and the label for CPA0149, Cathay Pacific Airbus343, can be seen presented ordinarily. However, on the right the predictive XAI system is triggered by adverse meteorological conditions reported in the area and the prompt for action can be seen. The warning can subsequently be used by the air traffic controller to check the weather conditions and thereafter warn the pilots of the weather, or if the system is transparent and trusted by the air traffic controller, the pilots can be given the warning directly. Figure 4 below shows the visualisation of the system. (Xie et al 2021).



CPA0149 A343
500=500 173
IA_Type Weather-related
IA_Proba 0.92
CPA0149 Weather-related dangerous situations may occur, please inform the pilot

Figure 4. Silent mode (left) and warning prompt (right) (Xie et al 2021).

4.4 Case 3: Reduced separation minima

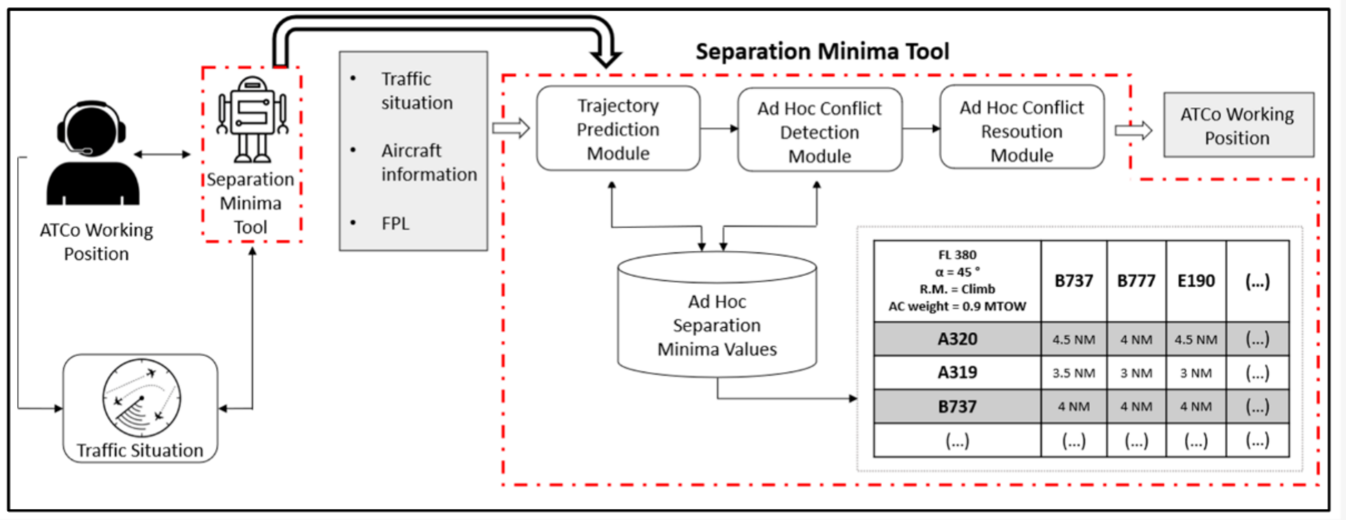
To prevent collisions between aircraft and maintain the necessary safety marginals on top of that there are two main ways of providing a separation between two aircraft, horizontal and vertical and the smallest allowed distance between the aircraft is called a separation minima. Vertical separation is the simpler one, which is generally 1000 feet, or 300 meters. For horizontal separation there are various ways to achieving it, it can be done by referencing the aircraft to different geographical locations, achieving the required angle between the aircraft in reference from or to a navigation aid or it can be time or distance based. Radar display units are commonly used to provide distance based horizontal separation. The usual separation is 5 nautical miles, or 9,3 kilometres, but when certain surveillance equipment parameters are achieved, it can be reduced to 3 nautical miles, or 5,6 kilometres. For successive aircraft following the same approach track within 10 nautical miles of the runway threshold, it can be further reduced to 2,5 nautical miles or 4,6 kilometres. For lighter aircraft which follow heavier aircraft, due to the dangerous vortexes caused by the wings of the heavy aircraft, the separation minima is increased and called wake turbulence separation and it can be as large as 8 nautical miles, or 14,8 kilometres. (Traficom 2018.)

Where it is on the other hand one of the main constraints for airspace usage and ultimately also the hard limit for it, separation minimas are also the very necessary safety barriers between aircraft. The separation minimas used today originate from history and are based on old technology, which was not very accurate or sophisticated (ICAO 2007.)

A recent study looks into the possibility of using artificial intelligence to reduce the minimum separation between certain aircraft to support more efficient airspace usage. As there are a multitude of different combinations and situations, it would be impossible for a human air traffic controller to remember and apply all of them. However, with the help of artificial intelligence, it could be possible. (Serrano-Mira, Sanz, Pérez-Castán, Netjasov, Moreno & Ayra 2023.)

A database would be created which would store the necessary separations between each type of aircraft. The data would combine statistical information of the aircraft, such as weight and wake turbulence profile and situational information, such as the altitude and speed vector of each aircraft and present meteorological information and of course the additional safety margin. (Serrano-Mira et al 2023.)

The so-called Separation Minimum Tool, or SMT, would analyse the situation and compare it to the database. Then, the new, reduced, separation minima would be presented directly to the air traffic controller. As the data is automatically presented to the controller and does not require memorization of numerous different combinations, the separation minima could also include decimals, instead of 4 or 5 nautical miles, a separation of 3.7 nautical miles could be used between certain aircraft. (Serrano-Mira et al 2023.). Figure 5 below shows the working method of the separation minima tool.



FL 380 α = 45 ° R.M. = Climb AC weight = 0.9 MTOW	B737	B777	E190	(...)
A320	4.5 NM	4 NM	4.5 NM	(...)
A319	3.5 NM	3 NM	3 NM	(...)
B737	4 NM	4 NM	4 NM	(...)
(...)	(...)	(...)	(...)	(...)

Figure 5. The working principle of separation minima tool (Serrano-Mira et al 2023).

4.5 Case 4: Stream based management

Air traffic flow management can be used to reduce the concentrated load of airports, but also in congested airspace blocks. The conventional way has been to limit the number of aircraft inside a certain block of airspace, which has its own air traffic controller, called a sector. In case a surplus is detected traffic flow management initiatives are issued to rectify the issue, with the common methods being changes in speed, routing, or extensions in flight path. (Lertworawanich, Pongsakornsathien, Xie, Gardi & Sabatini 2021.)

A new method, which in a way aims to increase the amount traffic inside a certain airspace, instead of proposing new ways to limit the amount of traffic in it. In this method, called stream-based management, artificial intelligence assembles a homogenous set of aircraft with similar routes into a stream. The stream is comprised from aircraft with in-lining routes. Instead of controlling a certain airspace, the air traffic controller would control a stream. (Lertworawanich et al 2021.)

The aircraft in the stream would need to be similar in terms of speed, altitude, and routing. The aircraft would be classified by engine types, being either jet powered, turbo-propeller or propeller aircraft, as propulsion method usually affects the aircraft speed and profile significantly. Furthermore, the present position of the aircraft, the route midpoint and the estimated operation time are also considered. (Lertworawanich et al 2021.)

The stream based artificial intelligence system could propose strategic actions to solve the overload situations, based mainly on speed control of the aircraft, or changes in the flight plan route. The system could also be responsible for the situations where two different streams cross, the control and separation between the streams and the affected aircraft could be given to the automation.

Altogether, the stream-based management system could make a set amount of traffic easier to handle and mitigates the extent of information, allowing for an increased amount of traffic to be handled by a single air traffic controller. (Lertworawanich et al 2021.)

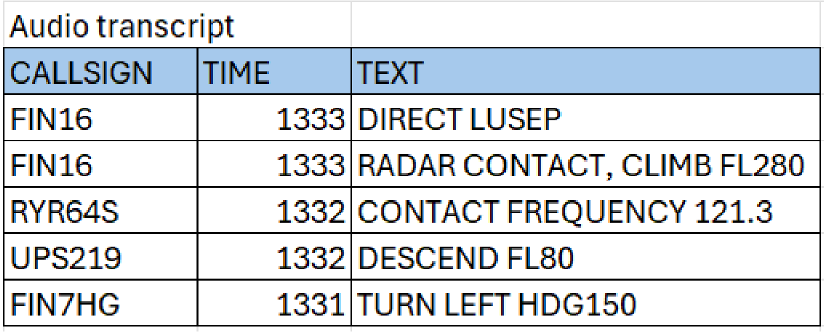
4.6 Case 5: Automatic speech recognition

Speech recognition systems are not yet in use in use in the air traffic control units due to the systems being still too rudimentary to capture the speech with high enough accuracy. Problems arise from technical difficulties in radio channels, the variability of phraseology and speech patterns and accents of different air traffic controllers. (Badrinath & Balakrishnan 2021.)

Thus, the conventional approach has been, instead recognition of speech the recording of speech, consisting of the communications between air traffic control and pilots. It is related more to the investigation of incidents and accidents and is only indirectly related to safety and not an additional safety net in operational use. The communications are investigated during incident investigations to find the possible causes to the incidents which can often be related to misunderstandings or false readbacks. The recordings are, as per just culture principles, not used to find and frame the culprit, but to improve the procedures and related training to improve operational safety in the future. (ICAO 2018.)

Automatic speech recognition, or ASR, is a modern system which can identify and understand air traffic controller's speech and the given clearances over radio. The technology is not yet widely used in the air traffic management units, and it is still in the quite early development and will require to pass the intensive safety and regulatory hurdles the air navigation industry requires, but the rapid evolution of artificial intelligence text models and AI based speech recognition technology could bring new possibilities in the near future. (Pinska-Chauvin, Helmke, Dokic, Hartikainen, Ohneiser & Lasheras 2023.)

The technology itself works in three phases, first the speech is translated into text, for example the voice communication of "Finnair one six, turn left heading 180, climb flight level 280.". Next, in the second phase the system translates the text to concepts which are more easily read by the machine, which would look like this "FIN16, TURN LEFT HDG180, CLIMB FL280". Finally in the third phase the outcome is presented to the air traffic controller in the human-machine interface without needing any manual input from the controller. (Pinka-Chauvin et al 2023.) Below figure 6 presents an image how the visualization of the history of clearances could be shown to the air traffic controller.



Audio transcript

CALLSIGN	TIME	TEXT
FIN16	1333	DIRECT LUSEP
FIN16	1333	RADAR CONTACT, CLIMB FL280
RYR64S	1332	CONTACT FREQUENCY 121.3
UPS219	1332	DESCEND FL80
FIN7HG	1331	TURN LEFT HDG150

Figure 6. How the system could present the communication history to the controller (Imitating Pinka-Chauvin et al 2023).

The purpose of the system is to enhance safety by increasing the situational awareness and productivity of the air traffic controller while also reducing the workload. It could be implemented inside the terminal areas in controlling arriving traffic or in area control units for enroute sectors. The system is able to spot incorrect clearance readbacks by comparing the generated texts from the air traffic controller and the pilot. (Pinka-Chauvin et al 2023.)

A pilot project, called STARFiSH, abbreviated from Safety and Artificial Intelligence Speech Recognition applied artificial intelligence speech recognition to advanced surface movement guidance and control system (A-SMGCS) at Frankfurt Airport. The artificial intelligence system combining the ASR and A-SMGCS could understand the clearances given to pilots by apron controllers and incorporate them into the A-SMGCS system visually for improved situational awareness. (Pinka-Chauvin et al 2023.)

Another study investigated the applicability of automatic speech recognition system highlighting the label of the aircraft by identifying the callsign from pilot radiotelephone messages and combining it with the radar display system. When the callsign was spoken on the frequency, the correct label would be highlighted, which in turn would increase the situational awareness of the air traffic controller. This can help the air traffic controller identify the correct aircraft when it first speaks on the frequency or when it has a request. Conversely, it also provides for another safety layer when the air traffic controller issues a clearance to an aircraft it also highlights the mentioned callsign and label on the display unit, this allows the controller to notice their fault if they actually meant to give the clearance to another aircraft. The visualization of the systems working principle is provided below in figure 7. (Pinka-Chauvin et al 2023.)

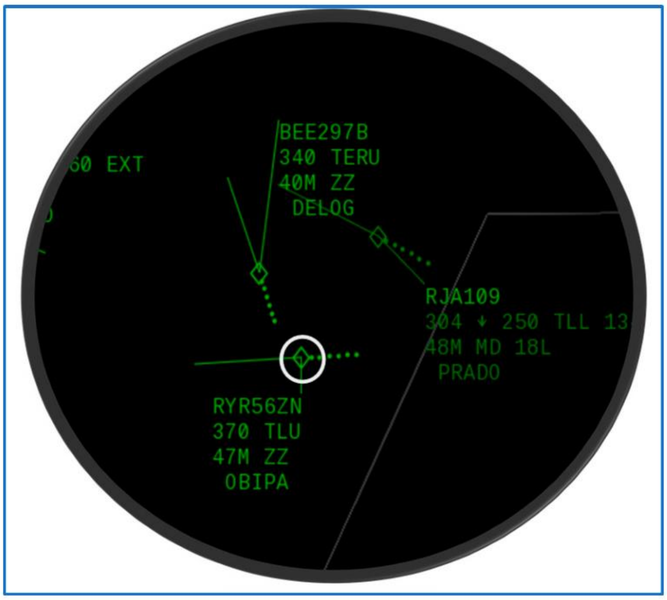


Figure 7. Label highlighted by ASR on radar display (Pinka-Chauvin et al 2023).

5 Case study

This chapter will present a systematic analysis of the cases presented in the previous chapter. Each case will be analysed according to the analysis framework, which is explained in detail below.

5.1 Analysis framework

This subchapter will introduce the analysis framework that guides the systematic examination of the cases presented earlier in the thesis. The analysis framework ensures consistency, structure and comprehensiveness in understanding and interpreting the cases. The main categories analysed are operational efficiency and safety. These categories were chosen due to their direct impact to the stakeholders in aviation and the customers using their services.

Operational efficiency directly affects the costs and expenses of airlines, air traffic control units and the stakeholders related to both services. The improved efficiency results in more optimal resource utilization for both air traffic control units and airlines. In addition, improvements in operational efficiency also reduce the environmental impact of aviation. Improved efficiency can result for example from shorter routes, reduced delays or congestion, more efficient airspace usage or performance optimization.

Aviation is in special spotlight for media outlets and thus operational safety has a major part to play in the quality of the media attention, the general popularity of air travel and the overall safety of the passengers. Subsequently, incident prevention and reputation protection are of major concern to air traffic control units, airlines and other aviation stakeholders. The enhancements in safety can result for example from improved decision-making, more accurate weather predictions, improved situational awareness or reduction in the amount or severity of incidents.

The division of each case to either operational safety or operational efficiency section is shown below in Figure 8. Each case has some effect on both, at least indirectly, but allocation was done based on the main focus of the proposed artificial intelligence system. More thorough analysis of how each case could affect safety and efficiency is done in the subsequent subchapters. Additionally, a SWOT analysis is presented for each case, which is used to assess the feasibility of using the analysed artificial intelligence tool in air traffic management.

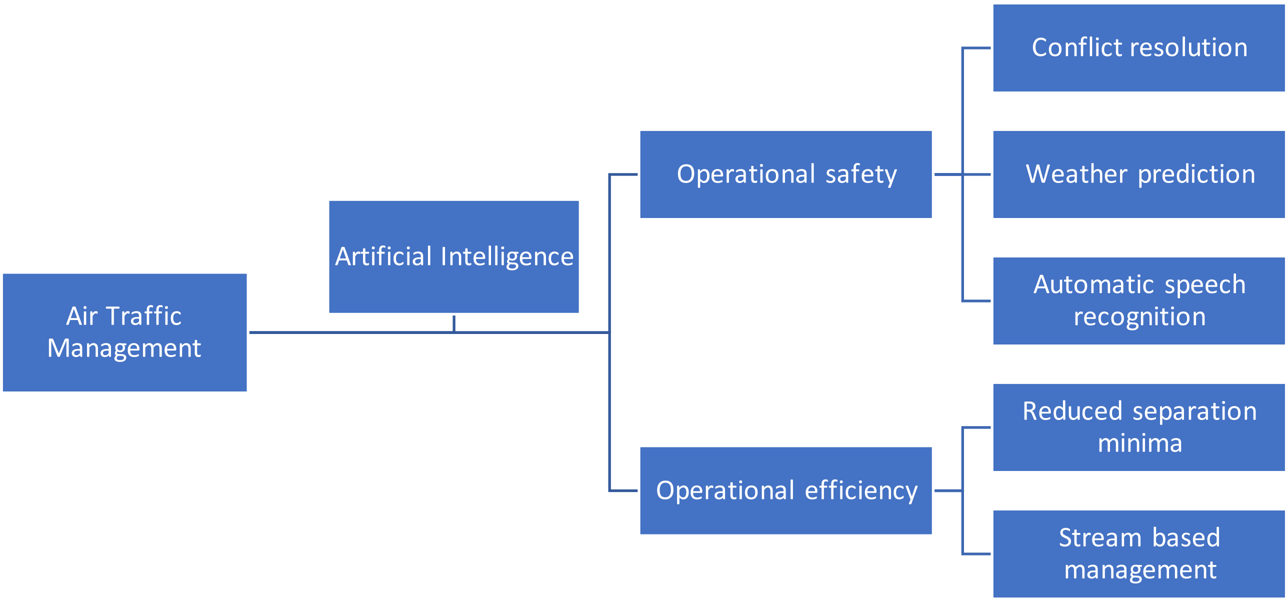


Figure 8. Division of the cases based on their focus operational safety or efficiency.

5.2 Case analysis

The following subchapter will analyse the five cases from chapter 4. Each case will be examined through the analysis framework.

Case 1: Conflict resolution. The explainable artificial intelligence system for conflict resolution proposes improvements for both safety and efficiency. The immediate focus is on safety, but the advanced properties also offer benefits to the efficiency.

Conflict detection tools exist already today, but the conventional systems are not able to offer possible solutions how to solve the conflict. Furthermore, the conventional systems do not offer reasoning or data behind the conflicts, they just point it out. Even the most rudimentary of the three different levels of explainable artificial, each more advanced than the previous one, could offer improvements to the situational awareness of the air traffic controller, which is crucial in the safe control of the traffic. If the system can offer more than one option, the air traffic controller could choose the most suitable one, which could also lessen the traffic complexity and burden of the whole traffic situation in the controlled sector.

The basic levels focus more on the safety while the more advanced levels of artificial intelligence start to lean more also towards the efficiency of the whole chain of stakeholders involved. Especially with more complex issues, the decision support system could propose benefits targeted also to efficiency by also considering the standpoint of stakeholders. If this artificial intelligence tool would offer air traffic control units the possibility to consider the causation their decisions have on their primary customers, the airlines and then further along the line airport staff, they could make more informed decisions. In addition to that, if the system could give the stakeholders associated a heads-up warning of an upcoming congestion, rerouting, or delay, they could better prepare for the immediate and subsequent problems. This would improve cohesive situational awareness, which could result in better profile planning for airlines and better resource allocation for airport operators which could possibly reduce turnaround times, both of which improve efficiency. Below the is the SWOT analysis for case 1.

Strengths

- Holistic decision support: The system's ability to process large amounts of information rapidly could support in making informed decisions, which could also support airport capacity by reducing spot congestion. This could be used to optimize airport capacity.
- Enhanced safety: The operational safety can be increased through the systems proactive conflict resolution. Timely conflict detection and recommendations for solutions, which are explained and based on predictions of the resulting consequences, could allow for improvements in decision making and better consequences for all participants. The amount of data processed could also improve the quality of the predictions from conventional models.
- Reduced controller workload: The artificial intelligence system is able to digest more information than a human controller could and can provide finished solutions, which can be executed fast without using a lot of time for decision making. This also increases operational safety.

Weaknesses

- Implementation: Implementing the artificial intelligence system to the various systems used by air traffic control units could be challenging. Also, the possible black-box model implementations which lack the necessary transparency for air traffic controllers to understand and trust the systems could face opposition.
- Reliance on data quality: The artificial intelligence system relies strongly on the accuracy of the data it analyses. Imprecise data could lead to it giving the air traffic controller recommendations which are based on false data – leading to disastrous consequences.
- Novel situations: Aviation is a very dynamic environment, and the system could face challenges when unforeseen situations arise and the parameters it is presented with do not match the ones it is designed to work with.

Opportunities

- Stakeholder support: Informing other stakeholders involved would allow them to better prepare and plan for the upcoming situations, including congestions and delays.

- Stakeholder engagement: Implementing strategies to involve the stakeholders in the development and implementation process could allow the system to provide targeted solutions to the varying needs of the parties involved.
- Higher levels safety and efficiency: The artificial intelligence system allows for a possibility to both reduce incidents and improve efficiency with the possibility of constant development of additional features.

Threats

- Information overload: Too many options with too much information might cause indecisiveness. Focusing too much on end of the line stakeholders instead of solving the conflict at hand could actually cause safety issues if the decision is delayed.
- Danger of automation bias: Overreliance on the artificial intelligence system could result in situations, where the controller trusts the options presented by the system blindly without evaluating them. Lack of overlook or critical thinking could result in safety issues.
- Regulatory standards: Possible problems with implementation could arise from regulatory issues related to the necessary regulatory approvals and certifications to ensure compliance with safety standards and operational regulation.
- User acceptance: Possible problems with implementation could arise from the air traffic controller workforce which might resist implementation of novel artificial intelligence systems.
- Cyber threats: The artificial intelligence system which relies on vast amounts of data and needs to be connected to highly safety critical air traffic control systems could impose new system vulnerabilities.

Case 2: Weather prediction. The artificial intelligence tool for weather prediction focuses solely on the operational safety aspect. The conventional system used today are not very practical to use or even very accurate. The reliance is on hearing the necessary information from the pilots or the meteorological units. The systems do not analyse the data or generate any direct warnings and only the precipitation and clouds are shown.

The possibilities in a system which processes and analyses the data would allow for integration of more data sources. The system could combine the information from several different observation stations and actually also the aircraft. Already today the weather information can be received from the aircraft via the ADS-B system. If the artificial intelligence system could be fed with the data from the hundreds and thousands of flights equipped with ADS-B, it could find patterns and even generate highly accurate weather models of an extremely large area. The predictive weather warnings could be issued to aircraft more accurately and in a timely manner and the aircraft could possibly avoid turbulence or other adverse weather conditions more effectively.

As the new system is also usually in silent mode and alerts the air traffic controller only in case of weather alerts, it could also be integrated to the main radar displays without cluttering the radar image.

Strengths

- Enhanced safety: Early warnings could allow the aircraft to circumnavigate adverse weather phenomena and the hazards associated with them, which would have a direct impact on flight safety and reduce the number of aircraft damaged by hail or turbulence. The warnings could improve the situational awareness of both the air traffic controllers and the pilots.
- Accuracy and rapidity: Automated analysis process could provide real-time data and alerts to the air traffic controller’s main display, which the air traffic controller could relay to the pilots quickly giving them more time to react to the issue. The warnings could also augment the capabilities of the aircrafts weather radar and allow for more informed decision-making for the pilots.

Weaknesses

- Transparency issues: The amount of the data processed by the system would be quite vast and the properties of it are of meteorological nature, which could only be understood by a trained meteorological officer. Thus, it could be very challenging to generate a system with principles of operating that can be understood at the air traffic control working position. Consequently, the reliability of the warnings can be impossible to verify resulting in trust issues.
- Reliance on data quality: The artificial intelligence system relies strongly on the accuracy of the data it analyses. Imprecise data could lead to it giving the air traffic controller recommendations which are based on false data – leading to disastrous consequences.

Opportunities

- Development and integration opportunities: The system could be used to integrate existing infrastructure including the weather observation stations on the ground and the constantly moving observation stations in the air – the aircraft themselves. This could result in massive amounts of real-time data for very accurate weather models.
- Interdisciplinary development opportunities: Weather predictions as used broadly across multiple different regimens and industries. Collaboration with research institutions, meteorological agencies, or various other lines of business could facilitate in rapid developments of the system and new development possibilities in other areas as well.

Threats

- Hardware requirements: The necessary data processing and transmitting capabilities could be very high as the amount of data can prove to be massive if large areas are covered at once and the weather information from hundreds or even thousands of aircraft is used simultaneously.
- Necessity for automation bias: As the controller has no way to verify the data of the system, there is no other way, but to trust the system blindly. This could result in false alerts or the more dangerous missed alerts, where controllers and pilots rely on the system to alert in case of adverse weather, but for some reason it does not.
- Regulatory standards: Possible problems with implementation could arise from regulatory issues related to the necessary regulatory approvals and certifications to ensure compliance with safety standards and operational regulation.
- Cyber threats: The artificial intelligence system which relies on vast amounts of data and needs to be connected to highly safety critical air traffic control systems could impose new system vulnerabilities.

Case 3: Reduced separation minima. The artificial intelligence -based system, Separation Minimum Tool, has total focus in just the operational efficiency. The conventional method of 5 nautical miles between aircraft is universal and used with few exceptions on all aircraft regardless of weight or speed. Reducing the smallest allowed distance between two aircraft has no benefits what-so-ever to safety and could possibly even affect it negatively. However, if it functions as intended, it could allow for significant improvements in efficiency, while also maintaining the adequate and necessary level of safety.

Minimum separation between aircraft is the main limiting factor in air space capacity and if it could be reduced, the air space could be utilized more optimally. If the example used in the introduction of the case, where 3.7 nautical miles could be used instead of 5 nautical miles as the minimum separation between aircraft, would be generalized for a whole air space block, it would increase the maximum capacity of the block by 26%. The minimum separation is of course rarely used and is considered to be more the hard boundary before loss of separation. Reducing the minimum separation would still allow for more room when working close to the boundary.

The reduction in the separation minima has to be inspected also through the operational safety aspect. The safe implementation and operation of the system would require heavy testing and calculations related to the wake turbulence effects of each aircraft type with all the possible weights within the allowed maximum take-off weights. There are many safety aspects related to the caricature example used in last paragraph where the maximum capacity of an air space block was increased by 26%. Firstly, even though the minimum separation between aircraft is reduced, the workload of a single air traffic controller is not reduced or optimized in anyway and the system proposes no help to the controller workflow. In a busy sector an increase in traffic of over 20 percent could prove to be impossible for the air traffic controller to handle in a safe manner. Secondly, the 5 nautical mile separation between aircraft is quite universal and works in nearly all cases. In case the new system is not adapted homogenously in all adjacent air traffic control units, transferring the air traffic control responsibility between sectors could require additional procedures. Some of the sectors involved could use the new reduced separation minimum tool, and some might not, which would require additional letters of agreement between the air traffic control units.

Strengths

- Flexibility: Unlike the traditional separation minimas, which are constant, the separation minimum tool could allow for dynamic separation based on the situation and aircraft types involved.
- Increased efficiency: Through the dynamic new separation minimas, the separation minimum tool could reduce the necessary separation between certain types of aircraft, which would directly increase the capacity of many air space blocks.
- Contained system: External data input is not necessary in this case, as all the data needed is already in the radar systems. This limits the cyber threat level significantly.

Weaknesses

- Testing requirements: Changing fixed separation minimas would require heavy inspection of the aerodynamic properties of the various aircraft types before it could be reliable implemented. Implementation could be quite straightforward once all the testing is done.

Opportunities

- Development and integration opportunities: The system offers possibilities for continuous evolvement and applications to other parts of the industry as well. One possible application could be using the same kind of system in terminal area control for flights in the final approach phase. Reduction in the necessary separation minima there could also improve airport capacity, in addition to the proposed enroute efficiency.
- Reduced operational costs: Increased efficiency and capacity utilization could generate valuable reductions in the costs for airlines.

Threats

- Regulatory standards: Possible problems with implementation could arise from regulatory issues related to the necessary regulatory approvals and certifications to ensure compliance with safety standards and operational regulation.

- Possibly reduced safety: Increase in airspace capacity could result also in increased air traffic controller workload when utilized to the new maximum and requirement for new procedural requirements between air traffic control units.
- User acceptance: Further challenges with the implementation of a reduced safety margin could arise from both the air traffic controller and pilot workforce, which might challenge the implementation of the reduced separation minima tool.

Case 4: Stream-based management. Stream-based management is a novel way proposed to control the air traffic. The ideological change to the conventional approach is quite large, changing from controlling air space blocks to aircraft streams.

The reasoning behind the system is focused on operational efficiency, but if implemented well, it does not necessarily affect operational in a negative way and the results could even be positive. However, as the proposed change in thinking is so fundamental, the training associated with the change would require to be heavy to cater for the new operational procedures related to the new system.

The improvements in efficiency are notable, when the controller could control several clustered aircraft instead of many single aircraft. This could result is both increased efficiency in air space utilization as well as reduced workload for the air traffic controller, which in turn could actually increase the operational safety.

As the system could be also given the responsibility for the control of the controlled aircrafts the requirement of transparency is foundational. For the air traffic controller to relinquish the control of the traffic to the artificial intelligence system the system has to be absolutely trusted, and for it to be trusted, the controller has to understand the functioning mechanisms in a very thorough way. This sets a strong necessity for a transparent mode of operation for the system. Additionally, as aircraft tend to have different destinations the system would have to be very adaptable to cater for aircraft leaving the stream as well as allowing new aircraft to enter an existing stream.

Strengths

- Increased efficiency: Stream-based management method could allow for more optimized air space utilization allowing more aircraft in the same airspace. Additionally, as the system is able to dynamically control the streams speed and routes, it could adjust to the possible overload situations better and reduce congestion.
- Possibly enhanced safety: If executed well, the system could optimize controller workload and reduce the cognitive load of the air traffic controller. The system is also planned to be responsible for the safe separation of the streams, which could result in enhanced safety by eliminating the

possibility to human error. The decisions made by the system could be based on all the data of multiple sectors and predictions of future, resulting also in proactive conflict resolution.

Weaknesses

- Transparency requirements: As the system is planned to control the air traffic directly, the need for thorough transparency is essential.
- Danger of automation bias: Overreliance on the artificial intelligence system could result in situations, where the controller trusts the options presented by the system blindly without evaluating them. Lack of overlook or critical thinking could result in safety issues.
- Reliance on data quality: The artificial intelligence system relies strongly on the accuracy of the data it analyses. Imprecise data could lead to it combining the streams incorrectly or even controlling the streams based on false assumptions, which could lead to disastrous consequences.
- Complexity of implementation: The fundamental changes in procedures and systems the stream-based management requires could propose many challenges in integration and retraining.

Opportunities

- Possibility for global adaption: The fundamental change presents challenges, but also opportunities. If the new method is more efficient and is also deemed to be adequately safe, it could result in widespread change in the procedures in the air traffic control units all around the globe. Collaboration between international aviation authorities could speed up the process.
- Development and integration opportunities: As per the other cases, this system could also be developed further, and the future systems could be used in integration. For example, the separation minimum tool presented in the earlier case could possibly be used together with the stream-based air traffic management, which could possibly result it compound interests.

Threats

- Regulatory standards: Possible problems with implementation could arise from regulatory issues related to the necessary regulatory approvals and certifications to ensure compliance with safety standards and operational regulation.
- User acceptance: Further challenges with the implementation of a totally new way of controlling the traffic could arise from the air traffic controller workforce, which might challenge the implementation stream-based management.
- Cyber threats: The artificial intelligence system which relies on vast amounts of data and needs to be connected to highly safety critical air traffic control systems could impose new system vulnerabilities. Additional, even larger threats arise as the system would directly control the aircraft instead of just proposing options for the air traffic controller.

Case 5: Automatic speech recognition. The automatic speech recognition systems proposed in case 5 offer a primary focus in the operational safety, with only marginal effects on efficiency. The systems are novel as conventional systems do not exist yet and the voice today is only recorded for incident and accident investigations.

The systems effects to safety could be significant. The ability to see and verify the uttered callsigns and clearances would present an additional safety net. It would also allow for quick way to double check the clearance given to an aircraft a while ago, as the clearance history is visible for the last few clearances.

Highlighting the aircraft callsign on the radar display when the controller, or the aircraft mentions it would also increase the situational awareness of the air traffic controller, resulting in direct improvement in the operational safety. Similarly, but on the ground control, the STARFiSH system used to augment the visual display of A-SMGCS with the uttered clearances and taxi routes could produce enhanced situational awareness in the apron control positions.

The proposed changes are quite small, including the clearance history display, the highlighting of the callsign and the visualization of the given clearances on the ground radar display. This could help with the implementation, but all of the effects are still quite distinct.

Strengths

- Enhanced safety: The improvements in the various different systems for situational awareness and error detection result in a direct improvement in operational safety. The controller is able to better track his own speech, correct call signs and readbacks, compliance with the clearances given and the ground radar system also helps the controller visualize the near future. The visualization of the given clearances on the A-SMGCS display might also help the controller detect his own errors.

Weaknesses

- Technical limitations with data quality: As the air traffic controllers and pilots around the globe, regardless of the global attempt to unify the phraseology, use various different speech patterns and accents the automatic speech recognition system might not be able to understand them all. In addition, distorted radio transmitters might cause misinterpretations or reduced reliability in the system.

Opportunities

- Development and integration opportunities: The system offers possibilities for continuous evolvement and applications to other parts of the industry as well. As artificial intelligence systems are becoming more advanced, the speech recognition capabilities are also improving. Furthermore, the technology could be used also in safety investigations and air traffic controller or pilot training.

Threats

- Cyber threats: The artificial intelligence system which relies on vast amounts of data and needs to be connected to highly safety critical air traffic control systems could impose new system vulnerabilities.
- Radio interference: As the system relies on clear radio channels, it could possibly be disrupted by even cheap handheld radio transmitters.
- User acceptance: Possible problems with implementation, caused by new ways to record and store the communications by air traffic controllers and pilots, could arise from the air traffic controller workforce.
- Regulatory standards: Further obstacles with implementation could arise from regulatory issues related to the recording and storing the communication, or from receiving the necessary compliance approvals related to the safety of the system.

6 Conclusion

This final chapter of the thesis will first provide conclusions based on the literature review and discuss the significance of the results and applicability of them. The relationship between operational safety and efficiency is further discussed based on the results. The chapter will also answer the research questions and provide recommendations in the use of artificial intelligence for organizations working in air traffic management. Possibilities for future research are also considered.

The objective of the thesis was to explore the artificial intelligence applications for air traffic management and assess if and how they can improve the operational safety and efficiency in it. Based on the case analysis, the artificial intelligence systems can be deemed to be able to provide improvements in both sections of air traffic management. The methods of improvement are through the systems applications of technology integration to improve the performance of the procedures, managements systems or controllers, or to overcome existing problems in them. The methods are discussed further in the subsequent subchapters.

One of the major strengths of the artificial intelligence systems compared to the conventional methods can be noted to be the ability to process vast amounts of data and provide solutions based on it. Additionally, it is able to monitor the chosen parameters tirelessly without breaks. Both of these can be used to help in decision-making.

6.1 Operational safety

The artificial intelligence can be found to improve operational safety in air traffic management. Three of the five cases propose direct and distinct improvements to operational safety, with one of them, stream-based management, allows for a possible improvement to it in case it is integrated well. The reduced separation minima from case 3 could actually degrade operational safety if it is implemented without the necessary safety assessment and procedures involved. The improvements in operational safety result from improved decision-making, situational awareness, reduced workload, error detection, early warnings of hazards of conflicts, reduction in the possibility of human error, more accurate prediction models and proactive conflict resolution. Table 1 below will help visualize which case uses which methods to improve the operational safety.

Table 1. Summary of the methods which improve operational safety.

Method of improvement	Case 1	Case 2	Case 3	Case 4	Case 5
Improved decision-making	x	x			
Improved situational awareness	x	x			x
Reduced workload	x			x	
Error detection					x
Early warnings of hazards or conflicts	x	x			
Reduction in human error				x	x
More accurate prediction models	x	x			
Proactive conflict resolution	x			x	

As can be seen from the table, the proposed artificial intelligence systems use quite varying ways to improve operational safety. Improved situational awareness is the most prevailing method, with the conflict resolution tool (case 1), the weather prediction system (case 2) and automatic speech recognition system (case 5) applying it. All other methods are used by two different systems. The conflict resolution tool from case 1 uses most different ways, six out of eight, trying to improve operational safety.

There are nevertheless also some possible threats to operational safety as well. As noted earlier, Case 3 - the reduced separation minima tool does not improve safety in any of the methods. As mentioned, the proposed system could actually reduce operational safety, due to increased controller workload. For case 3 there are however no other safety threats. For the other cases safety issues could also arise from cyberthreats, which is a major concern in all of the systems. Data quality is another very safety critical aspect and plays a key role in all cases except for case 3. Case 3, being a contained system, has certain safety benefits compared to systems which rely on integration with and data from other systems. The possible threats to operational safety are summarized in table 2 below.

Table 2. Summary of the possible threats associated with the systems.

Possible threats to safety	Case 1	Case 2	Case 3	Case 4	Case 5
Cyber threats	x	x		x	x
Increased workload			x		x
Information overload	x				
Automation bias	x	x		x	
Radio interference					x
Reliance on data quality	x	x		x	x
Limited adaptability	x				
Transparency issues	x	x		x	

Although case 1 had the most varying ways to improve operational safety, it also has more possible threats associated with it than the other cases. Transparency issues and automation bias are both involved in three of the five cases. Radio interference is possibly the most challenging issue to solve, but the associated risk is quite low as the possibility to change radio frequencies to deliver clearances exists already.

All of these threats are less distinct than the methods used to improve safety. Additionally, and more importantly, most of them can be circumnavigated or nullified with appropriate development of the systems or procedures and with thorough implementation and training involved. Altogether the systems can be concluded to offer direct improvements to operational safety in air traffic management with preventable risks involved, with the methods presented in the tables above.

6.2 Operational efficiency

The operational efficiency could be improved by the artificial intelligence systems analysed. As the profit margins in aviation are so narrow, even small improvements can result in large cost reductions. The cases 3 and 4, as in the reduced separation minima and stream-based management, focus more on improving the operational efficiency. Both of them target to increase the capacity of airspace, allowing for more traffic in a certain volume of airspace. The example used in the case 3, which was 3.7 nautical miles instead of 5, would be a 26 % improvement in the maximum capacity of the sector. This cannot naturally be applied to the maximum directly, but the optimizations could result in direct reduction in costs.

From the three other cases only case 1 with the conflict resolution tool can offer some indirect improvements in efficiency. The improvement is a result of the increased situational awareness and heads up warnings it is able to provide to the stakeholders involved. With the systems help airlines are able to optimize their flights altitude profiles more accurately and airports can better allocate their resources to match the demand.

Consequently, it can be said that artificial intelligence systems can be used to improve operational efficiency in air traffic management. The methods of improvement were mainly through optimization from increased capacity or more accurate prediction tools for planning or resource allocation.

6.3 Implementation and development

The implementation challenges involved with the artificial intelligence systems are complex. Problems with integration to existing systems could arise and the integration could require very large changes to the infrastructure or procedures that are applied today. Regulation and the cyber security requirements could hinder the progress significantly.

As aviation has very strict and complex safety and legal requirements, the regulatory standards involved in the implementation of the system are a major factor in all the cases. User acceptance is another challenge, which needs to be addressed. Aviation is heavily unionized industry, and the strong unions can thwart the implementation significantly, if they deem the systems are either not safety enough or the implementation could result in the reduction in the number of workers needed. Thus, user acceptance plays a key role in all the cases except for the weather prediction tool.

Integration to existing systems could pose challenges in all the cases except for the simpler reduced separation minima tool. Technical and hardware requirements play a large role in the weather prediction tool and automatic speech recognition system.

The development possibilities for the systems are monumental. The possibilities for exponential growth are vast as the systems could be built on top of each other and used in the development of additional future systems. Most notably the same data that is used for the weather prediction tool could be applied even globally to build circumambient weather prediction models which could be applied across multiple different industries.

As can be noted from the analysis, there are still plenty of hurdles to jump before the systems are applicable for implementation in air traffic management organizations. Technical, safety and legal issues are the biggest threats to consider in the development of the systems. However, the issues found slowing the implementation are still only merely speed bumps on the way, not roadblocks halting the process. Altogether, it can be summarized that the systems analysed in the cases are not quite yet ready for implementation directly by air navigation service providers, but it is highly likely that they will be in the near future once the arising issues are catered for.

6.4 Recommendations for implementation

As we can notice in the previous subchapter, there are plenty of risks and threats to identify and mitigate before the systems are ready to be implemented in the operational air traffic management. Thorough risk analysis is required in both the systems focusing on operational safety and especially in the systems which focus on operational efficiency. Increased operational efficiency is naturally a very important part when conducting air operations, but it cannot be at the cost of operational safety.

As can be seen from the reduced separation tool in case 3 and the stream-based management in case 4, increased efficiency could in the worst case degrade operational safety. Thus, the utmost care must be used during the development and integration of the systems to maintain the operational safety intact, as it is always the first priority in aviation. The acquisition and implementation of the systems should never be done lightly without strict analysis of the possible implications to operational safety and operational efficiency should not be prioritized over the operational safety.

As user acceptance is such an important factor in the implementation of the systems, it should be considered thoroughly in both the development and implementation of the systems. The end users will be the actual operators for the systems and also have the latest and most applicable first-hand knowledge and experience of the operational factors related to air traffic management. This more silent and easily hidden knowledge should be taken advantage of and used to develop and integrate the systems to the operational environment with the help and cooperation of workers and unions. This will help to develop the systems to be more user friendly and to implement them in such a manner that the end user is satisfied to use them.

6.5 Future research

As artificial intelligence is an arising megatrend, research related to it is also conducted on an accelerating pace. Focus on the research could be targeted to varying sectors. The few regular issues that arose multiple from this research include cyber threats and user acceptance. As the new systems might even directly control the aircraft, evaluation of vulnerabilities and new threat mitigation strategies are required to ensure the operational safety involved.

Additionally, as user acceptance is such a key factor in the implementation of the systems, in-depth studies to it and the human factors involved could provide valuable insight to the development of the systems to allow for a smoother transition to the new upcoming era involving artificial intelligence systems in air traffic management. The human factors aspect could help the system developers understand better how human controllers interact with the artificial intelligence tools, the workload in the varying dynamic situations and the decision-making progress involved. The insight could be also used to improve the training and education of both experienced and new air traffic controllers, including new simulation tools and training methodologies which could also focus on improving the proficiency in the usage of the artificial intelligence tools and address issues related to the trust and transparency of them.

Another possibility for future research is the use of artificial intelligence in the airspace management to allow for more dynamic use. Constantly activating and deactivating military training areas and glider areas is already very frequent and customary in Finland (Traficom 2021). The newest aspect of it include requires airspace for also unmanned aircraft systems, or drones, which brings totally new characteristics to it. Research on if artificial intelligence could possibly be utilized in the distribution of airspace could bring new insights into the matter.

Future research should be conducted in real-world situations to gain more insight into the actual operations, which can be quite more dynamic than the controlled environment in simulations. This could provide more concrete information related to their performance related to actual real-world operational safety and efficiency. Pilot projects including real air navigation service providers could help gather empirical data and validate the benefits of using the artificial intelligence systems, while also bringing forth the possible problems from real-world integration.

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