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EDITOR-IN-CHIEF'S WORD

Continuing the constant support of the presentation of scientific achievements of Croatian scientists, members of our Croatian Academy of Engineering, this issue is dedicated to the presentation of some research work in the field of aviation.

The guest editor of this issue is Prof. Doris Novak, PhD, full professor at the Faculty of Transport and Traffic Sciences, University of Zagreb and head of the Department of Aeronautics, who presents in several articles some results of research projects of the mentioned department.

I believe that every reader will gain new useful insights.

Editor-in-Chief
Vladimir Andročec, President of the Croatian Academy of Engineering

EDITOR'S WORD

Dear readers,

In the context of the global economy, air transport is an important factor in achieving growth and economic development, not only globally but also at regional and national level. In order to meet numerous challenges in providing safe and reliable air transport services in populated areas, air traffic management is constantly being improved by implementing new technologies and developing new practices and monitoring procedures.

To this end, we are glad to present in this issue of Academy's Bulletin Engineering Power a number of research projects conducted at the Department of Aeronautics of the Faculty of Traffic and Transport Sciences of the University of Zagreb.

Guest-Editor is Doris Novak, associate member of the Academy in the Department of Transport.

Editor
Zdravko Terze, Vice-President of the Croatian Academy of Engineering

FOREWORD

Air traffic has been continuously increasing, giving rise to many challenges, especially in increasing the airspace and sector capacity. By reducing the fragmentation of airspace, an attempt is made to increase the efficiency of the air traffic management system and the provision of air traffic services. This is the core idea of the Single European Sky, a project of modernising European air traffic management system since 2004 in areas of safety, capacity, environment and cost-efficiency. In this regard, one of the major challenges is to reduce flight delays according to pre-planned navigation routes. The concept of free flight or free routes aims to shorten the flight path from departure to destination, which has a positive effect on reducing delays by shorter flight times. In addition, the fuel consumption during the short flight is less, which has a positive effect on the economy of the flight, but also on the reduction of aircraft emissions in the atmosphere. The workload of an air traffic controller has also an impact on the airspace capacity in which it is necessary to provide greater flow of aircraft to reduce delays. With appropriate design of training syllabus, and with acquisition of practical skills in provision of air traffic control service, it is possible to directly increase the capacity of a given airspace and reduce aircraft fuel consumption. In addition, it is possible to predict or calculate under conditions when unexpected storm clouds occur in the atmosphere, which require aircraft to safely avoid them. Finally, automated systems in air traffic management that use artificial intelligence in prediction tools should assist air traffic controllers to have good situational awareness of aircraft position and other data that may adversely affect flight safety. All these concepts are being developed within the framework of research projects at the Department of Aeronautics of the Faculty of Traffic and Transport Sciences at the University of Zagreb in cooperation with other partner universities and European air navigation service providers. We hope that by reviewing our research below we will stimulate interest in the field of air traffic management and in our research.

Guest-Editor
Doris Novak, University of Zagreb, Faculty of Traffic and Transport Sciences

CONTENT

Editors' Words ... 1
Project ATCOSIMA – Air traffic Control Simulations at the Faculty of Transport and Traffic Sciences ... 2
Free Route Airspace for Efficient Air Traffic Management ... 10
Methodology for Predicting Sector Capacity in Convective Weather Conditions ... 18
The Proposal of a Concept of Artificial Situational Awareness in ATC ... 23

Biljana Juričić[1], Bruno Antulov-Fantulin[1], Tea Rogošić[1]

Project ATCOSIMA – Air traffic Control Simulations at the Faculty of Transport and Traffic Sciences

[1]Faculty of Transport and Traffic Sciences, University of Zagreb, Croatia

Abstract

Air traffic controller training is a highly regulated sector. It is prescribed by international rules and requirements. The important segment of training is the provision of practical exercises on air traffic control simulators. Although regulations prescribe required performance objectives for initial training, they do not set any assessment criteria on how to assess the candidates, nor do they consider any flight efficiency indicators. In this paper, an overview of the objectives of the ATCOSIMA project is presented. Baseline air traffic simulations performed at the Faculty of Transport and Traffic Sciences of the University of Zagreb were analysed in more detail explaining exercises, assessment criteria description, as well as the achieved candidates' scores.

Keywords: *simulation, air traffic control, air traffic controller, training, assessment, candidate, score*

1. Introduction

Air Traffic Controllers (ATCOs) are highly qualified professionals that provide air traffic control (ATC) service (and maintain safe, orderly and expeditious air traffic within the area of their responsibility. Their primary objective is to separate flights at the safe distance in the air and to separate flights on the manoeuvring area of an aerodrome. While doing that service, they prove different air traffic controller tasks such as: controlling and monitoring aircraft movement, planning, coordination, communicating with pilots using radio or data link, conflict search and detection and, finally, conflict resolution tasks in the airspace of their responsibility.

Since their job directly influences safety of air traffic, they have to be highly trained and skilled to acquire adequate competency for the provision of air traffic control. That is the reason why ATCO training is strictly prescribed by the international rules and regulations. At the global level, International Civil Aviation Organisation (ICAO) defines minimum standards and recommends practices for ATCO training in Annex I – Personnel Licensing [1] while at the European level, ATCO training is regulated by the EU Regulation 340/2015 [2]. This regulation prescribes ATCO training requirements and conditions for acquiring ATCO license.

According to these regulations, ATCO training is defined with strict and serious requirements. Every candidate has to successfully finish two phases of ATCO training: initial and unit training [2].

Initial training includes basic and rating training. Basic training is defined as theoretical and practical training designed to impart fundamental knowledge and practical skills related to basic operational procedures [2], while Rating Training provides knowledge and skills related to a job category and appropriate to the discipline to be pursued in the ATS environment [2]. After finishing initial training, candidates acquire Student ATCO License which is a prerequisite for starting unit training.

The Unit Training leads to the issue of air traffic controller licence and includes operational procedures, training of specific tasks, abnormal and emergency procedures and human factors issues [2]. After successful completion of unit training, candidates finally acquire an ATCO License that gives them a privilege to provide air traffic control service within specific airspace and to work with real air traffic.

The high level of ATCO knowledge and competences was a major purpose for development and implementation of a new more detailed uniform European standards of initial training comparing to the previous requirements [3]. This resulted in the development of the common core content for initial training which defines subjects, topics, taxonomy level and training methods [4].

Also, European regulation defines examination and assessment performance objectives for basic training and rating training.

Since ATCO has to be highly competent, skilled and trained to cope with the high traffic demand and possible unusual traffic situations, their training must impart theoretical knowledge and practical skills for all three types of air traffic control: aerodrome, approach and area control. Practical skills are trained and performed on the synthetic training device (STD) such as simulators and part-task trainers. Simulators are real-time human-in-the-loop computer-based devices that simulate important functions of the real situation of ATCO working positions, airspace, procedures, flight trajectories, while part-task trainers only enable simulation of partial ATCO functions. The main functionalities and requirements for acquisition or development of air traffic control simulators are researched in studies [5] and [6].

Despite the uniform standards of initial training, there are still differences in the training process, duration, organisation of courses, number of theoretical lessons, etc. Furthermore, there is neither a requirement for a minimum number of practical exercises on the simulator nor commonly defined assessment criteria for evaluating the candidate's performance during practical exercises.

There are not many previous studies on the training requirements of ATCOs and on how to evaluate the assessment of ATCOs. One of the studies proposed basic principles for evaluation during simulation exercises that assess candidates' performance in relation to safety indicators and workload, such as:air traffic separation, decision making implementation of ATC procedures, equipment usage, communication and coordination [7]. The other study proposed a candidate's performance measurement by counting mistakes and actions. [8].

There is some research on the training requirements under future conditions when the role of the ATCO changes due to technological improvements in the Air Traffic Management (ATM) system, such as increased automation [9]. None of these studies take into account the development of training assessment criteria.

Although ICAO and EU ATCO regulations define types of training, content, performance objectives, they do not define any standard assessment scoring and criteria to be used for ATCO performance and competency evaluation. [5].

On the other hand, Single European Sky (SES) regulations deal with the development of air traffic management in the coming years and take into consideration the continuous growth in air traffic, as well as its influence on the safety, capacity, environment and service costs. SES prescribes high-level targets and measurable indicators regarding flight efficiency and economics [10]. Although the importance of saving flight costs is enormous, these indicators are neither prescribed for ATCO training nor translated into evaluation criteria.

Taking these two arguments into consideration, Project Development of Common ATC Simulation Training Assessment Criteria Based on Future Pan European Single-Sky Targets (ATCOSIMA) is defined. It deals with the development of an innovative method for measuring ATCO candidate's performance during practical exercises in the simulated environment regarding safety and flight efficiency. This paper presents the project overview with the analysis of the simulator facilities and simulations done at the Faculty of Transport and Traffic Science of the University of Zagreb.

2. Project overview

Project ATCOSIMA is funded by the Erasmus+ Program/KA2 Cooperation Innovation and the Exchange of Good Practices/KA203 Strategic Partnership for Higher Education. Three European higher education institutions are participating within the project: Faculty of Aeronautics and Astronautics of Eskisehir Technical University (ESTU) as a coordinating organisation, Faculty of Transport and Traffic Sciences of University of Zagreb (ZFOT) and Institute of Flight Guidance of Technische Universität Braunschweig (TUBS) as partner organisations.

The main goal of ATCOSIMA project is to develop common assessment criteria to evaluate student performance during simulation exercises within ATCO basic training. The new assessment criteria should involve new indicators and metrics based on future Pan-European Single European Sky targets on flight efficiency.

The benefits of the new assessment criteria should be: more objective way to evaluate candidate's performance and skills during simulator exercises, shorter time for adaptation to new operational environment, shorter time and costs of rating and unit training, improved competences for provision of air traffic services in the future Pan-European air traffic management system, harmonization of training process etc.

The overview of the project methodology is given in Fig. 1. The project includes two important parts: first, a baseline simulations and analysis for evaluation of ATCO performance using current assessment criteria and training techniques and, second, development of the new assessment criteria which incorporates flight efficiency indicators based on the Pan-European Single European

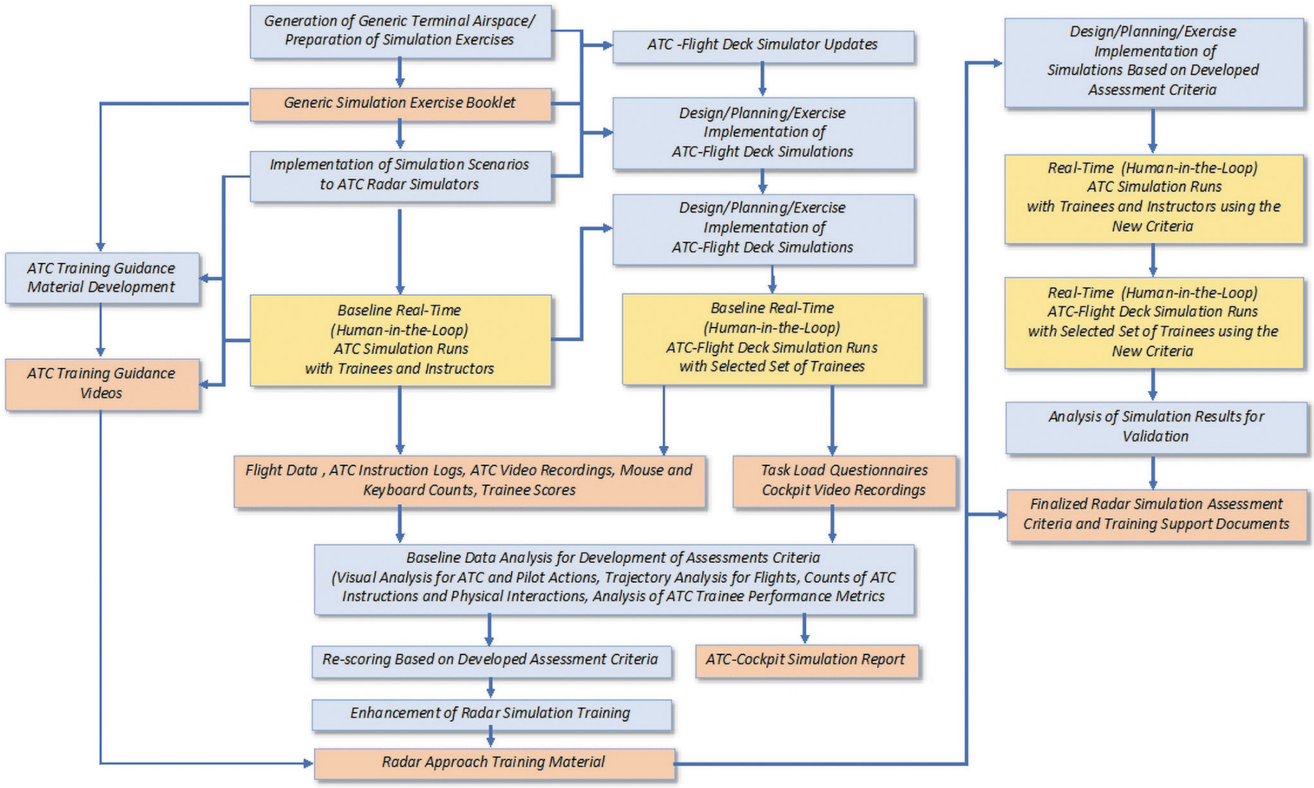

Fig. 1. Overview of the ATCOSIMA project methodology [11]

Sky targets, simulation and evaluation of ATCO performance using these new criteria.

Each project part consists of a set of planning, design, preparation and analysis task (marked by blue blocks), two types of the real time ATC human-in-the loop simulations (marked by yellow blocks) and five outputs that include results of planning and preparation tasks and analysis of collected and post-processed data (marked by red blocks) [11].

As can be seen from the project methodology, the crucial activities are human-in-the-loop simulations. There are two types of simulations to be done: the first one is performed at ATC Radar simulator while the other one is performed at integrated ATC Radar and Flight cockpit simulators. To put it more clearly, the first step simulations will be done at the ATC Radar simulator at the ESTU and ZFOT facilities. Both institutions have the same air traffic control simulator facility and educate future air traffic controllers within undergraduate study of aeronautics. That was a common baseline for the project implementation. The ATC simulator used for this project is Micronav ltd. BEST (Beginning to End for Simulation and Training) Radar Simulator used for air traffic control human-in-the-loop simulations.

The integrated ATC Radar and Flight cockpit simulator within TUBS's facilities enables ATCO human-in-the-loop real-time simulations and human-in-the-loop real time simulations in the A320 flight simulator. There are several output data to be collected from both simulation experiments: flight data logs, video replay files, ATC instructions, ATC voice recordings, mouse and keyboard count and assessment scores. Integrated ATC Radar and Flight cockpit simulations enable additional output data from the pilot's perspective such as: task load questionnaire and cockpit video recordings. [11].

3. Simulator facility at ZFOT

Faculty of Transport and Traffic Sciences owns a permanent license for BEST Radar Simulator from 2013. The simulator is a part of Laboratory for Air Traffic Control at the Department of Aeronautics. It consists of the software and hardware facilities. Hardware is PC based and gathers two ATCO working positions, one pseudo-pilot working position and one system manager working position which can be also used as a pseudo-pilot working position. The user interface is similar to the real ATC working environment. Each ATCO working position has a radar display, an auxiliary display, a voice communication interface display, a keyboard, a mouse, two sets of headphones and several communication switches (Fig. 2).

BEST Radar Simulator software enables simulations of area and approach radar air traffic control service, simulations of flight movement, flight data preparations, airspace design, exercise and scenario development, self-teach facilities etc. Flight movement is simulated according to the Base of aircraft data (BADA) performance model [12]. Simulator system manager enables recording and replay activities of the exercises, so every

Fig. 2. The ATCO working position of the BEST Radar Simulator at the Faculty of Transport and Traffic Sciences

recorded exercise can be played back. A replay of files can be paused at any time so candidates could be briefed about their performances [12].

The training process and the roles of all persons involved in practical simulation training and their interactions are shown in Fig. 3 [13].

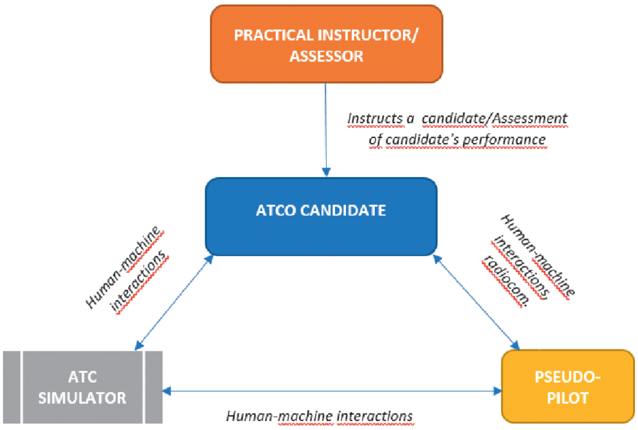

Fig. 3. Persons involved in the process of ATC simulations [13]

There are three persons involved in the simulations: ATCO candidate, pseudo-pilot and practical instructor/ assessor. As it can be seen, there are constant HMI (Human-Machine Interface) interactions and relation of ATC Simulator-ATCO candidate, ATC Simulator-pseudo-pilot and ATCO candidates and pseudo-pilots when using radiotelephony communication. ATCO candidate monitors the radar display of ATC simulator, observes and analyses traffic situations according to traffic data and using adequate software tools to find a potential conflict and resolve it in a safe, accurate and expeditious way.

A candidate has to process a range of information and make a quick decision on what instructions to give to an aircraft. This process is a continuous process due to the simulated aircraft movement within the defined airspace.

Depending on traffic situations and traffic interactions, these tasks can vary from low to high complexity and stress, allowing candidates to manage, develop and improve their skills and attitudes.

Every change in a flight plan, every clearance or instruction given to the aircraft, ATCO candidate needs to mark in the flight strip. Flight strip is a specified form that has an important aircraft flight plan data (call-sign, level, entry point, exit point, heading, and speed) with the empty fields to be fulfilled with the ATCO markings. A flight strip can be an interactive electronic strip marked by mouse or keyboard or it can be a paper strip which is placed in the strip holder and marked with a pencil (Fig. 4).

Fig. 4. Paper flight strips used in simulations

Like ATC working position, the pseudo-pilot working position consists of the same hardware facilities. The pseudo-pilot working position is operated by a trained pseudo-pilot. This person knows how to run the simulation system, how to input data and how to communicate using appropriate radiotelephony communication.

Pseudo-pilot guides aircraft through defined airspace using human-machine interface and makes changes in progress of flight's trajectories according to the clearances and instructions given by ATCO or instructor. The pseudo-pilot inputs (using a keyboard or a mouse) different data given by the ATCO candidate regarding the flight trajectory such as: level changes, heading instructions, speed adaptation, flight plan data etc. One pseudo-pilot can run several aircraft per exercise.

Practical instructor is a person certified and authorized to instruct and train ATCO candidates during practical exercises through five phases presented at Fig. 4.

Explanation of the phases:
- group briefing – briefing of the exercise requirements and objectives with the group of candidates that will take the same exercises,
- individual briefing – briefing with one ATCO candidate on the controller working position before exercise starts,
- observation of candidate's work during the exercise run (knowledge, skills, attitude) and giving instruction, advice and tuition if necessary,
- individual de-briefing – briefing with comments and markings on the candidates' performance, weaknesses and strengths, and
- group de-briefing – briefing and pointing out progress and limitation of all candidates within the group [13].

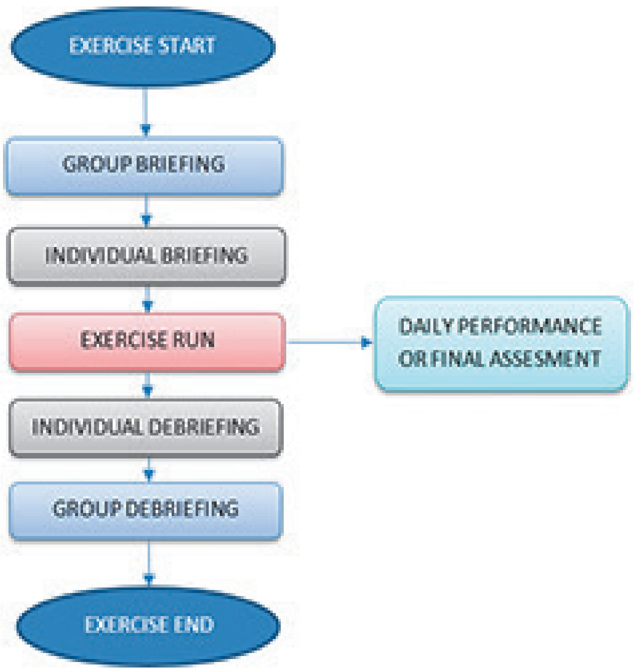

Fig. 5. Simulation activities [13]

The assessor assesses the candidate's performance during the last exercise or the last simulation runs.

The candidate receives an assessment score which is determined according to the defined assessment criteria.

The same person can be an assessor and a practical instructor if he/she fulfils necessary requirements for both roles.

4. Baseline project simulations

For the project needs, the baseline simulations were coordinated between ESTU and ZFOT institutions and executed between February and April of 2018 according to the project schedule.

ATCO candidates were selected from students enrolled into the study of aeronautics at both institutions. These students had passed basic radar approach exercises earlier as the main prerequisite.

There were 19 ATCO candidates participating on the simulation runs among which 14 candidates were students from ZFOT, while 5 were from ESTU.

To avoid possible incorrect assessment and bias caused by previously gained knowledge and adaptation to familiar airspace, a generic airspace was developed for this project and designed on the BEST simulators. This generic airspace is based on the real airspace data of the Frankfurt Terminal Area (TMA) (Fig. 6).

Frankfurt TMA is a controlled airspace within which approach control service is provided. It surrounds Frankfurt Airport and is indicated by point FFM VOR (VHF

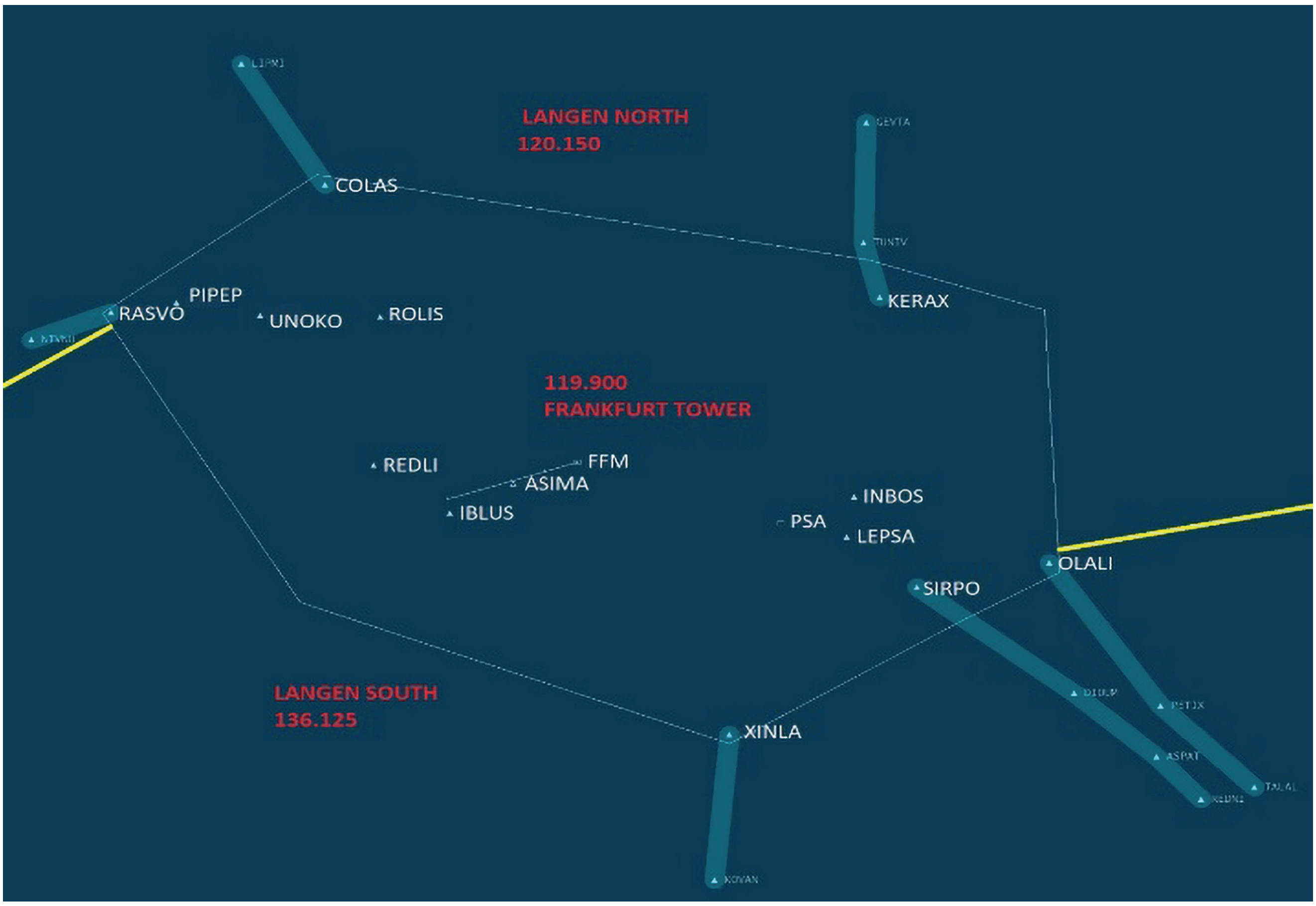

Fig. 6. Simulated airspace of Frankfurt TMA [11]

Omnidirectional Radio Range) in Fig. 6. Although Frankfurt Airport has four runways, for the purposes of the project all simulations used only runway 07C for both approach operations – arrivals and departures. The shape of the designed airspace (convex airspace) and the size (146 NM and 82 NM of maximum and minimum distances between boundary point) is easy to adopt and suitable for practicing and improvement of candidates' skills in provision of basic radar approach air traffic control service [11].

The general objective of all exercises is that the ATCO candidate maintains separation of arriving and departing aircraft in a safe, orderly and expeditious way by using standard radar separation of 1000 ft vertically and 5 NM horizontally and to assist arriving aircraft in approach to land and to assist departing aircraft in climb to a certain level and point. To be successful in these objectives, the ATCO candidate has to efficiently perform specified ATCO tasks: communication, conflict detection, radar vectoring, speed control, level change, strip marking, approach sequencing, use of HMI tools etc.

In the developed exercises, arriving aircraft gets into the Frankfurt TMA at the entry points (RASVO, COLAS, XINLA, KERAX, OLALI and XINLA) that are on the airspace boundary [13]. ATCO candidate has to direct arriving aircraft for landing at Frankfurt Airport from these points to the instrument landing system (ILS) course before point ASIMA and then to transfer aircraft to the Frankfurt Aerodrome Control Tower using radio-communication on frequency 119.000 MHz.

In the developed exercises, the same entry points are also exit points for departing aircraft. To separate traffic at these points, vertical separation minima must be applied for arriving and departing traffic flows. Departing aircraft from the Frankfurt Airport are transferred to Frankfurt TMA 10 NM from point FFM VOR and have to be directed to planned exit points. The departures have to be transferred to the next air traffic control centre, in this case it can be one of the following Area Control Centres: Langen North (on frequency 120.150 MHz) or Langen South (on frequency 136.125 MHz) and climbed to FL250.

Ten different exercises were developed to provide a human-in-the-loop radar approach control simulation with varying levels of difficulty determined by the number of flights to be controlled and by the complexity metrics, such as: number of conflicts between aircraft, mix of departure and arrival traffic, initial separation between successive departures, initial distances of arriving aircraft from the ILS course. The level of difficulty rises with the progress of exercises – the last exercises have higher difficulty, while during the first few exercises, candidates have to familiarize with the human-machine interface, practice communication skills and adapt to the airspace characteristics (Table 1).

In the last exercises, candidates have to be able to quickly process different information and make adequate decisions, to have advanced skills in communication, conflict detection, radar vectoring, speed control and level change as a measure of conflict resolution and approach sequencing [11].

Table 1. Exercises description [11]

	Number of aircraft			Exercise characteristics	
Exercise number	**Arr.**	**Dep.**	**Tot.**	**Duration (min)**	**Difficulty level**
1	5	0	5	24	1
2	6	2	8	26	2
3	6	3	9	25	3
4	6	4	10	26	4
5	7	3	10	27	4
6	7	4	11	28	6
7	8	3	11	28	8
8	8	4	12	30	9
9	9	3	12	31	9
10	9	4	13	30	8

Every student had to run all 10 exercises with the briefing and debriefing procedures done by the instructors. A total of 140 exercises were therefore carried out in the ZFOT during this phase of the project. During and at the end of the exercises, instructors assessed candidate's air traffic control performance at the simulator and marked it in the specified form according to the earlier defined assessment criteria (over-the-shoulder method). After finishing the exercise and error deduction, every candidate was given an assessment score per exercise (Table 2).

The criteria were applied as a percentage deduction from the exercise. Each exercise started with 100% and a certain percentage was deducted for the types of errors such as: collision (30 %), separation loss (30 %), descending aircraft under specified level (30 %), unsafe clearance (10 %), graver mistake in vectoring (5%), greater mistake in communication (3%) etc. By score, the most successful candidate was candidate number 6, while the least successful candidate was candidate number 12.

As it can be noticed, these explained criteria count errors regarding the safety issues. There isn't any indicator dealing with flight efficiency targets.

In all exercises only one aircraft type was used in simulations and that was Airbus A320 as the most frequently used aircraft type with a 16.6% share in the European scheduled flights [15]. The simulated trajectory calculation is based on the Base of Aircraft Data (BADA) [16, 17].

After the simulation provided at ZFOT, a great amount of data was available for collecting and analysis. Simulation circuit with hardware facilities and outputs of air

Table 2. Candidates' scores per exercises [14]

Ex. num.	Candidate number														Average score per ex.
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
1.	85	87	87	86	80	87	92	88	96	85	91	97	92	80	88,1
2.	95	94	97	94	92	93	96	96	100	91	93	94	100	90	94,6
3.	97	91	88	97	92	96	84	87	90	95	90	90	85	95	91,2
4.	92	93	87	98	94	91	95	90	90	82	96	89	90	89	91,1
5.	94	94	87	74	73	93	60	81	79	83	32	65	64	76	75,4
6.	90	92	95	93	94	98	88	93	94	96	75	92	92	89	91,5
7.	97	90	89	94	97	97	96	80	97	95	96	88	87	90	92,4
8.	96	94	95	97	95	95	89	93	97	81	96	93	89	85	92,5
9.	97	92	93	99	100	94	95	96	97	95	97	94	65	88	93
10.	90	80	81	90	82	90	75	81	91	90	75	83	90	84	84,4
Av. score per can.	93,3	90,7	89,9	92,2	89,9	93,4	87	88,5	93,1	89,3	84,1	88,5	85,4	86,6	

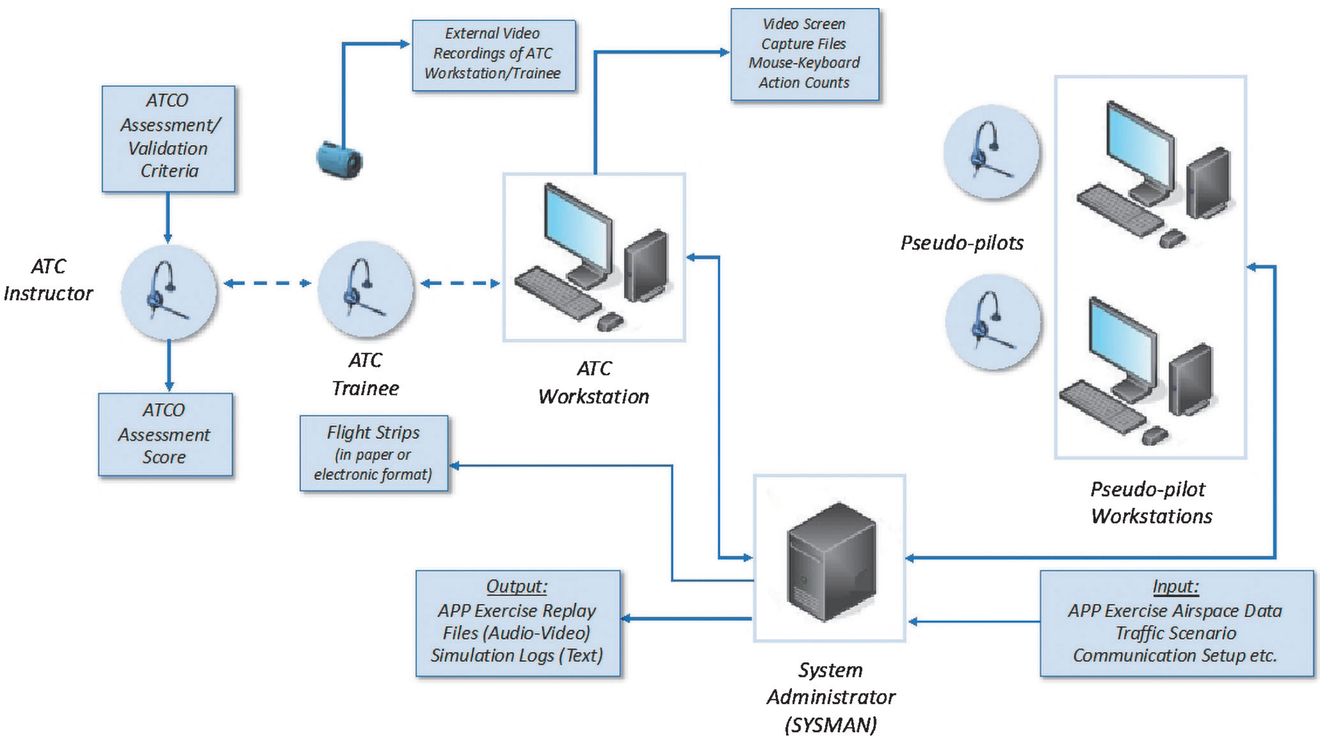

Fig. 7. Simulation data collection [11]

traffic control simulations, as well as data to be collected is presented in Fig. 7.

All simulator facilities are connected to the system manager (sysman) working position in which all airspace flight data and communication are stored as inputs. During the exercises, sysman records exercise replay files and simulation logs which can be later used for assessment evaluation, saving individual data and flight path information [11]. Also, captures of video replay files and candidate's mouse and keyboard interactions are collected to evaluate the candidate's workload.

The second part of the first stage simulations was conducted at TUBS and it incorporated ATC and flight simulation exercises on the A320 simulator. Five out of 14 ZFOT students were selected to run ATC simulations. Assessment scores of the students were taken into consideration for statistical analysis and correlation research of the following metrics: flight efficiency, number of instructions, task count, flight duration, distance flown etc. The results of the first stage simulations are published in the scientific paper 'Project ATCOSIMA: Preliminary Results and Analysis of Real-Time ATC and Flight Cockpit Simulations' [18].

5. Conclusion

Project ATCOSIMA, funded by ERASMUS+, works on the improvement of air traffic controller training and overall competencies of future air traffic controllers. One of three institutions participating in the project is the ZFOT. The project is structured in several stages with the main aim – development of the new assessment criteria to be used in simulation exercises that students complete during the basic training which is integrated into the undergraduate study of aeronautics. In order to achieve its goal, the project has two stages of real-time human-in-the-loop simulations the simulation using

current and two stages of real-time simulation of human-in-the-loop simulations the simulation using newly developed assessment criteria.

In this paper, baseline real time human in the loop simulations with the current criteria assessment at ZFOT are presented with the experiment settings and features.

Acknowledgements

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Bruno Antulov-Fantulin[1]*, Biljana Juričić*[1]*, Tomislav Radišić*[1]*, Tea Rogošić*[1]

Free Route Airspace for Efficient Air Traffic Management

[1]University of Zagreb, Faculty of Transport and Traffic Sciences, Zagreb, Croatia.

Abstract

Free route airspace is a new concept in airspace management that has emerged from the Single European Sky ATM Research program. The goal is to allow aircraft companies to freely plan their routes between predefined points, rather than force them to follow conventional pre-established routes. This mode of airspace management can shorten trajectories, reducing fuel consumption and environmental impact. However, intersection points in a free route airspace are "invisible" at a strategic level, which can increase traffic complexity, increase the workload on air traffic controllers under certain conditions, and indirectly affect flight safety and efficiency of air traffic management. This review examines the implementation of free route airspace and its effects on air traffic management efficiency, leading to suggestions for future research.

Keywords: *free route airspace, air traffic management, flight efficiency, workload, sectors, traffic complexity*

1. Introduction

The development of air traffic management in Europe is a constant process aimed at increasing air traffic and satisfying user demands for airspace while maintaining satisfactory levels of safety and flight efficiency. The trend of growing air traffic in the EUROCONTROL zone since 2013 continued in 2016, after a few years of stagnation caused by the global economic crisis. The number of flights based on instrument flight rules grew by 2.4% on average from the number in 2015. The main driver of air traffic growth in 2016 was the growth in the European low-cost air travel segment. Air traffic growth is even larger in terms of passenger numbers than in terms of flights (+5.1% compared to 2015), which is also the case in preceding years [1]. This growth continued in the first trimester of 2017, with the number of controlled flights in the EUROCONTROL zone increasing by 3.9% on average, corresponding to 907 flights daily [2].

This growth in traffic demand can produce negative consequences such as congestion in parts of airspace, flight delays, flight inefficiency due to excessively long routes, greater fuel consumption, and therefore greater flight costs and environmental impact. Traffic growth can also compromise air safety by increasing the workload on air traffic controllers as a result of more complex traffic situations and possible loss of situational awareness.

A sophisticated air traffic management system based on the concept of a Single European Sky (SES) promises to increase flight safety and efficiency as well as reduce the negative consequences of increased air traffic demand. The strategic long-term goals of SES are to triple capacity, reduce emissions by 10%, reduce flight costs by 50% and increase safety by a factor of 10. To achieve these goals, the SES air traffic management research (SESAR) program brings together the entire air traffic management community, including air navigation service providers, airports, civil and military aircraft users, aircraft manufacturers, airlines as well as European Commission and EUROCONTROL, in order to catalyze research, development and innovation in the air traffic management system. Since its establishment in 2007, SESAR has issued recommendations about new or improved processes and technologies aimed at modernizing the European as well as global system of air traffic management. Each recommendation is accompanied by documentation that includes operational services, environmental reports, efficiency and operability, technical specifications, safety and security assessments, and reports on human and environmental performance. SESAR reflects a strategy of aviation development aimed at creating European economic growth, stimulating innovation as well as offering passengers better connections and safer, less expensive, lower-emissions flights.

Free route airspace (FRA) is one of the technologies that has emerged from SESAR. This novel method for organizing airspace is meant to allow users (airlines) to plan flights via desired routes between predefined points, which represents flexible and optimal resource planning. This should translate to shorter flight trajectories and savings on fuel and other expenses [3]. While FRA can increase traffic flows and reduce the environmental impact per flight, the fact that users are free to select their routes affects air traffic management and the complexity of traffic situations. Conflict detection methods in FRA differ from those in the current system based on air traffic service (ATS) routes and significant points (waypoints). In FRA, aircraft intersection points are "invisible" at the strategic level, which can make air traffic controllers' work more difficult under certain conditions and indirectly affect traffic safety. For this reason, research on FRA implementation and its effects on efficient air traffic management is essential.

2. The FRA concept and its characteristics

FRA is a specific airspace in which users can freely plan their route between entry and exit points without reference to conventional ATS routes (Figure 1) [4,5]. In FRA, all aircraft are subject to air traffic control.

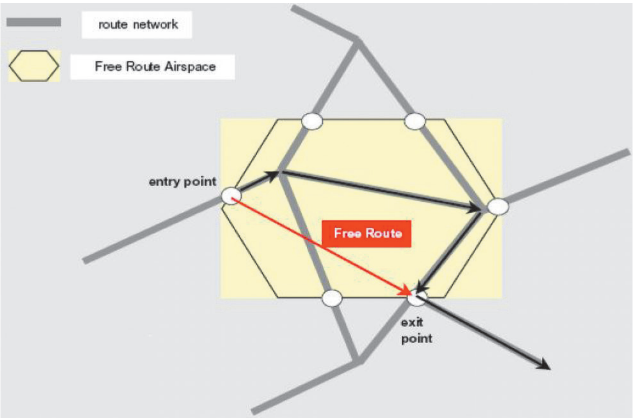

Fig. 1. Illustration of how FRA can lead to shorter flight paths. The conventional ATS route is shown with black arrows, while a possible free route is shown with a red arrow. Adapted from ref. [6]

Currently, FRA in Croatia is implemented at the highest airspace level (FL325-FL660), above the airspace governed by conventional ATS routes (Figure 2) [7].

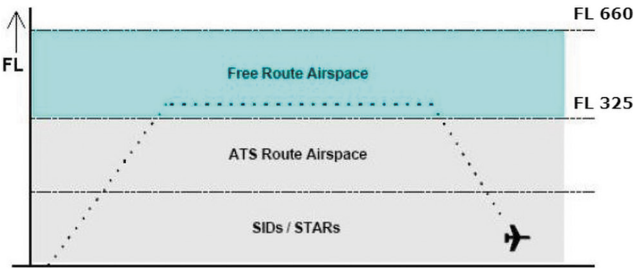

Fig. 2. Illustration of the FRA in Croatia and its relationship to ATS-governed airspace. Adapted from ref. [6]

In 2008, EUROCONTROL began the coordinated development and implementation of FRA in collaboration with civil and military experts in air traffic design, member states of the European Civil Aviation Conference, service providers, airspace users, flight planning organizations and other international bodies. The shift away from conventional routes to free routes opens up new possibilities for airspace users and promises to save up to 25,000 nautical miles per day in the EUROCONTROL zone [3]. It could reduce flight distances by 7.5 million nautical miles per year, which amounts to savings of 45,000 tons of fuel, 150,000 tons of emissions, and 37 million EUR [3]. By 2020, a reduction in flight distances of approximately 4 million nautical miles per year is expected [8]. Airspace users are gradually adapting their flight planning systems to completely implement the potential of FRA, which is fully compatible with current navigation technology.

As network manager, EUROCONTROL is responsible for implementing advanced operation concepts including FRA. European Commission Directive 677/2011 and the amending Directive 691/2010 establish rules for implementing the air traffic management network. Appendix 1 of the former Directive describes European Route Network Design (ERND) and the European Route Network Improvement Plan (ERNIP), which involves an agreed European route network and, where feasible, free route airspace structure designed to meet all ser requirements" [4]. The network manager of ERNIP develops and maintains the following documents [4]:

- Part 1 of ERNIP: European Airspace Design Methodology. General principles, guidelines and technical specifications for airspace design, including the FRA concept.
- Part 2 of ERNIP: European ATS Route Network. This includes all FRA projects scheduled for development and implementation over the 5-year development period.
- Part 3 of ERNIP: Airspace Management Handbook. This covers all civil and military aspects related to FRA.
- Part 4 of ERNIP: Route Availability Document. This includes route orientation and flight planning to facilitate FRA implementation.

These documents were created to enable all EUROCONTROL members to implement FRA precisely and efficiently. Part 1 of ERNIP states that it may be necessary to restructure the current airspace sectorization scheme in order to accommodate existing and future traffic within FRA. Airspace sectorization will have to respond to this challenge while also becoming more flexible. For example, Part 1 of ERNIP stipulates that in FRA, sectorization should not be limited by the flight information region, upper information region or national borders [5], which is a substantial break from the current sectorization scheme. This new approach to sectorization has been called flexible and dynamic adaptation of sector configuration.

By the end of 2016, 48 area control centers had partly or completely implemented FRA, surpassing the goal of 35 centers stipulated in the network manager's roll-out plan. FRA should be implemented in most of European airspace by the end of 2019, and in the rest of relevant airspace around Europe by 2021-2022 (Figure 3). This achievement is the result of extremely close collaboration among network managers, air traffic service providers, military partners and airspace users.

Although flight efficiency initiatives exist in various forms in North America, Australia and other parts of the world, Europe is the first region in the world to implement FRA in its entirety.

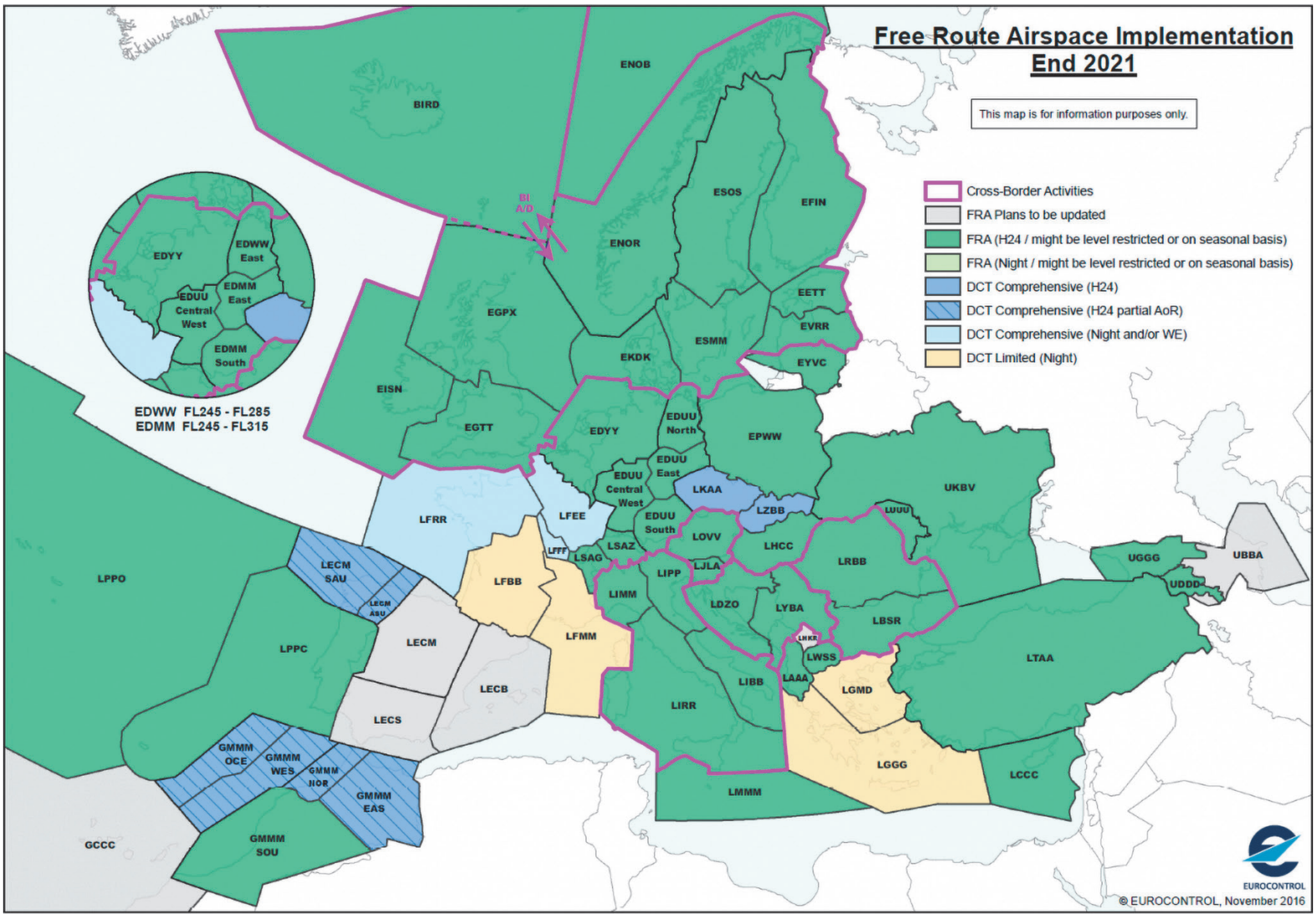

Fig. 3. Implementation of FRA by 2021. Adapted from ref. [4]

3. Air traffic efficiency in Europe

Despite a slight decrease in flight efficiency at the system level in 2016, FRA implementation has already generated visible benefits in fuel, emissions and cost reductions in several member states of EUROCONTROL. Flight efficiency is an average of 1.6 percentage points better in member states where FRA is completely implemented all day, and real trajectories are significantly closer to executed flight plans [1].

The innovative program SESAR 2020 provides the framework for current research in the field of air traffic management in Europe in order to find high-efficiency operational and technological solutions. SESAR 2020 supports SES and an EU aviation strategy aimed at stimulating growth of European trade and innovation as well as providing passengers better flight connections and safer, less expensive, and lower-emissions flights. The SESAR Joint Undertaking is a public-private partnership that manages SESAR 2020 and that involves the European Union and EUROCONTROL as founders as well as 19 members that represent airports, aviation service providers, manufacturers and the scientific community. To enable a comprehensive research program, the SESAR Joint Undertaking also collaborates with airspace users, including airlines, regulatory agencies, normalizing agencies, flight staff professional organizations and global partners. Guided by the European Air Traffic Management Master Plan, SESAR 2020 focuses on transforming the European air traffic management system into a modular automated system that exploits the advantages of new digital and virtual technologies. SESAR 2020 directs a budget of 1.6 billion EUR towards the development of solutions in four key areas: airport operations, network operations, air traffic services and technology development by 2024 [9]. Research is categorized into three areas: theoretical research, commercial research and validation and demonstration on large samples. The three areas are designed to compose an “innovation pipeline” in which ideas develop into effective solutions for commercialization. The following discussion focuses on FRA as one area of SESAR solutions.

Given the number of large projects slated for implementation in the coming years, it is important to bear in mind the message from the 2016 Performance Review Report by EUROCONTROL. This Report emphasizes the need for aviation service providers to efficiently coordinate and implement all air traffic management changes that may hinder operations [1]. The report of the Performance Review Commission identifies some areas for improvement, which are related to a lack of clear strategic goals and the inability of current traffic management algorithms to deal with limited/segregated airspace [1]. Better civil-military collaboration is an important factor in improving flight capacity and efficiency.

In contrast to continuous improvements in the last few years, the horizontal flight efficiency in the EUROCONTROL zone fell from 95.5% in 2015 to 95.4% in 2016 (based on executed flight plans). Over the same period, actual trajectory fell from 97.3% to 97.1% (Figure 4, left panel). Closer analysis of efficiency throughout 2016 (Figure 4, right panel) shows large negative peaks caused by air traffic control strikes. Removing those dates from the analysis leads to an improvement in horizontal flight efficiency of 0.03 percentage points [1].

In SES and EUROCONTROL reports, flight performance is assessed in terms of two horizontal flight efficiency indicators: the key performance environment indicator based on last filed flight plan (KEP), and the key performance environment indicator based on actual trajectory (KEA). These indicators measure the average en route additional distance with respect to the great circle distance. They take into account all segments of the flight during its passage through airspace based on planned distance (KEP) or actual distance (KEA), shown in (1) [10]:

$$HFE_j = \frac{\sum L_{fjp} - \sum H_{fjp}}{\sum H_{fjp}} \% = \left(\frac{\sum L_{fjp}}{\sum H_{fjp}} - 1 \right) \% \quad (1)$$

where L is trajectory length; H, achieved distance; f, flight; j, airspace; and p is the part under analysis. The result is additional distance expressed as a percentage of actual distance. Both indicators are calculated in the same way, except that KEP is calculated based on the last filed flight plan, while KEA is based on real trajectory from radar data. It is important to note that calculation of KEP and KEA for flights within the EUROCONTROL zone takes into account the distances of all flight segments except segments through airspace closer than 40 nautical miles from the take-off and landing airports. Table 1 shows a more detailed view of KEP and KEA calculation for various types of flight.

Table 1. Description of parameters for measuring KEP and KEA distances for different flight types [10]

Flight type	Start point	Flight segments measured		Destination
		Measurement start	Measurement end	
Internal (within EUROCONTROL zone)	Airport	40 NM	40 NM	Airport
Arriving (from outside EUROCONTROL zone)	Border	40 NM	Airport	
Departing (to outside EUROCONTROL zone)	Airport	40 NM	Border	
Overflying EUROCONTROL zone	Border	Border		

In addition to these indicators of horizontal efficiency, air traffic flow management delay is used to describe the state of air traffic in Europe. Substantial increases in traffic have reduced overall service quality in some areas. The percentage of flights arriving within 15 minutes of the scheduled time fell by 1.6 points to 81.5% in 2016. In that year, delays increased by 21% relative to 2015, and the percentage of en-route flights showing delays increased from 3.9% in 2015 to 4.8% in 2016 [1].

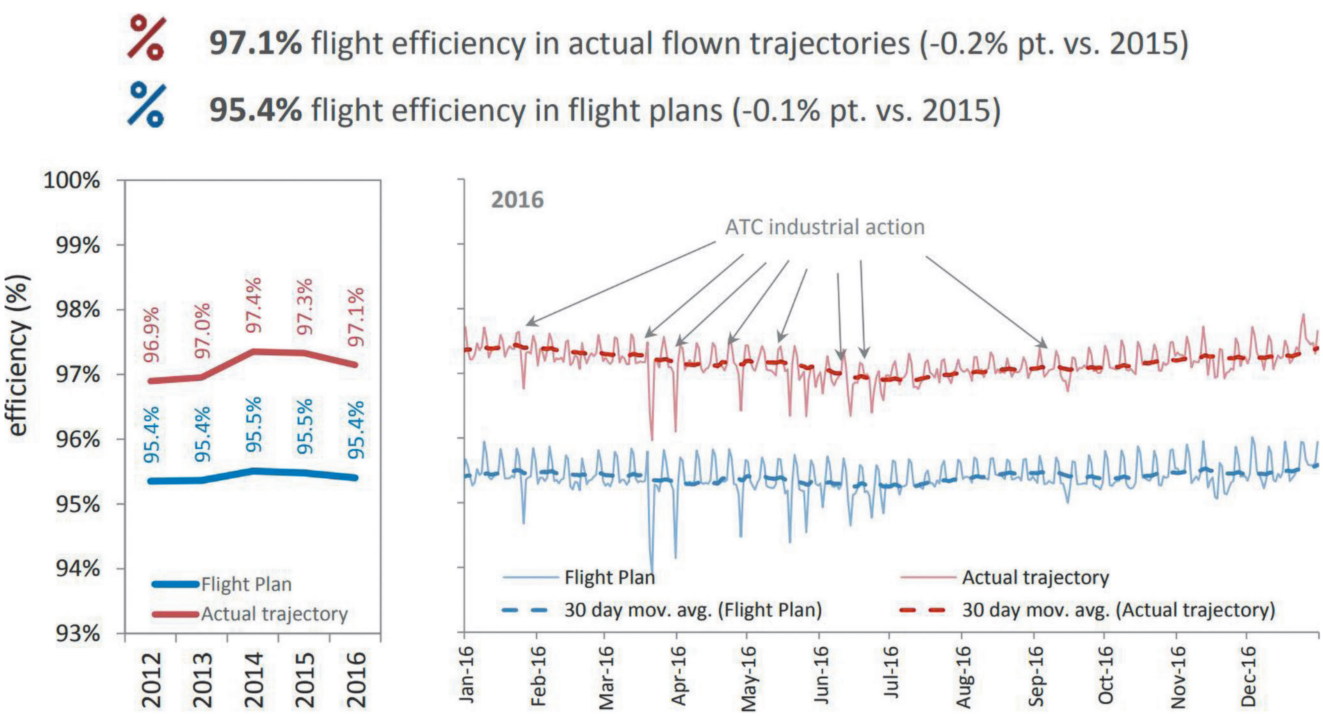

Fig. 4. Horizontal flight efficiency in the EUROCONTROL zone [1]

The factor most frequently contributing to air traffic management delays is the link between air traffic control capacity and staff (55.3%), followed by time limitations (18.3%), air traffic control interruptions or strikes (12.3%) and constraints caused by unusual events (9.1%), which include delays due to upgrades of the air traffic control system.

4. Current state of research and perspectives on future research

This section reviews more important research advances in the field of FRA. One is a study by Kodera et al. [11] in which the authors examine changes in flight planning caused by FRA implementation, and they propose measures to ensure that military and civilian airspace will remain segregated like today. One proposal is that a pilot submits a flight plan for validation through a non-operational tool such as the IFPUV, and if the aircraft is passing through a forbidden area, the flight plan is rejected and a plan that bypasses the forbidden area is offered to the pilot (Figure 5).

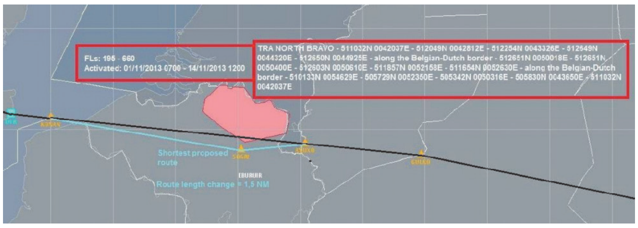

Fig. 5. Illustration of a non-operational tool for flight plan validation, which in this case is suggesting a new route. Adapted from ref. [11]

Future work should develop a proactive system for the network manager and operators that would transmit data about the airspace and propose routes adjusted for weather conditions and operator demands.

Bentrup and Hoffmann [12] examine the advantages of FRA in Europe from the standpoint of airspace users. They draw on large flight datasets for their analysis, which focuses primarily on cost reductions but also on fuel savings. Their analysis suggests that FRA has significant potential to bring savings and advantages over current conventional routes. The potential fuel savings should reduce overall operational costs and greenhouse gas emissions. These benefits indicate why the FRA is an important step for the future of the European aviation industry.

In 2008, EUROCONTROL launched the development and implementation of FRA in Europe, which it continues to coordinate. This implementation forms part of the shared flight efficiency plan developed by a collaboration of EUROCONTROL, the International Air Transport Association, and the Civil Air Navigation Services Organization [12]. Table 2 provides an overview of completed FRA projects according to the functional airspace block [12]. Intensified collaboration across national borders within each block is expected to reduce safety risks and costs while increasing capacity and efficiency.

Table 2. Summary of FRA projects by functional airspace block [12]

Functional airspace block	Member state	Main project
South West Spain (SW FAB)		Partial implementation of direct routes (DCT)
	Portugal	FRA completely implemented
	Spain	Additional FRA projects needed
UK – Ireland (UK/IE FAB)		Project without airspace borders
	Ireland	FRA completely implemented
	Scotland UIR	FL255+
		Phase 3 FRA at Prestwick ACC FL255+
Europe Central (FAB EC)		Southeast and central west projects
		FRA FABEC X-borders 365+
Blue MED FAB		FRAIT – IT Phase 3 (FRA FL 365+)
	Malta	FRA FL105+
	Greece	FRA FL315+
	Italy	FRA FL305+
Central Europe (FAB CE)	Stepwise FRA implementation between 2014 and 2020	
Danube FAB		Cross-border FRA at night
		Cross-border FRA FL105+
Baltic FAB		FRA FL105+
Northern Europe (NE FAB)		NEFRA project
Denmark/Sweden (DK/DE FAB)		Cross-border FRA completed
		Cross-border DK/SE FAB, NE FAB and NEFRA project

Bentrup and Hoffmann demonstrate that using FRA can substantially reduce overall flight costs, fuel consumption and gas emissions, thereby significantly reducing harmful environmental impact. They also consider how FRA technology may alter air traffic and the work of air traffic controllers, and they include the possibility of implementing certain restrictions. They leave these questions for future research.

Krzyżanowski [13] explores an algorithm for calculating optimal flight paths and capacity in upper airspace. The FRA involves greater freedom of movement because aircraft do not have to follow conventional ATS routes, which means that congestion around high-traffic ATS waypoints disappears. In FRA, a larger number of transiently overloaded waypoints will occur, linked to certain flight profiles. To avoid traffic conflicts, flight paths need to be predicted.

Krzyżanowski proposes a simulation model of FRA that depicts the airspace as a cylinder of radius R. One assumption is that traffic moves at various flight levels Hi, and each flight at those levels must adhere to vertical separation conditions (2):

$$\bigwedge_{t_{kj}} \bigwedge_{j} \bigwedge_{m \neq j} O_{Vjm}\left(t_{kj}\right) \geq SV \tag{2}$$

Where

t_{kj} – k moment of aircraft j position inside the airspace

$t_{kj} = t_{k-lj} + \Delta t,\quad k = 1, 2, \ldots, n$

O_{Vjm} – vertical distance between aircraft j and aircraft m

SV – required vertical separation

In addition, all flights in the airspace must satisfy the horizontal separation conditions (3):

$$\bigwedge_{t_{kj}} \bigwedge_{j} \bigwedge_{m \neq j} O_{Hjm}\left(t_{kj}\right) \geq SH \tag{3}$$

Where

t_{kj} – k moment of aircraft j position inside the airspace

$t_{kj} = t_{k+lj} + \Delta t,\quad k = 1, 2, \ldots, n$

O_{Hjm} – horizontal distance between aircraft j and aircraft m

SH – required horizontal separation

Krzyżanowski then proposes the following function (4) for calculating the optimal path for a given flight in the simulated airspace [13]:

$$Q = \left[c_1 + a \cdot \left(L - L_{ek}\right)^2\right] \cdot \left[c_2 + b \cdot \left(H - H_{ek}\right)^2\right] \cdot \left[c_3 + d \cdot \left(V - V_{ek}\right)^2\right] \tag{4}$$

$$L = \sum_{i=1}^{N} \sqrt{\left(x_i - x_{i-1}\right)^2 + \left(y_i - y_{i-1}\right)^2} \tag{5}$$

$$L_{ek} = \sqrt{\left(x_N - x_0\right)^2 + \left(y_N - y_0\right)^2} \tag{6}$$

Where

$i = 1, 2, \ldots, N$ $\quad N$ – aircraft type index

c_1, c_2, c_3 – constant

L – real distance

L_e – enty and exit point distance

H – real altitude of aircraft

H_{ek} – economical altitude of aircraft

V – real speed of aircraft

V_{ek} – economical speed of aircraft

a – distance weighting ratio

b – altitude weighting ratio

d – speed weighting ratio

Applying this algorithm to predict flight paths, Krzyżanowski concludes that FRA significantly increases capacity and may, therefore, help controllers predict conflicts, thereby reducing their workload.

Nava-Gaxiola [14] investigated the FRA in what would become the southwestern (Spain-Portugal) functional airspace block. At that time, nine functional airspace blocks were planned in the whole of Europe. Nava-Gaxiola explores the implementation of the southwestern airspace block by analyzing traffic predictions in this block using Network Strategic Tool (NEST) software. He concludes that the route changes in FRA do not jeopardize safety nor increase the sector load above the level with current conventional routes. However, air traffic controllers indicate that the current conflict resolution tools are inadequate for predicting incoming traffic, although they believe that tools developed as part of SESAR solutions can increase traffic predictability and thereby ease controller workload.

Pereira [15] performs analysis to optimize routes passing through two FRAs in Portuguese airspace. This analysis suggests that combining the two FRAs would save nearly 500,000 nautical miles per year, or an average of 7 nautical miles per aircraft. Combining these two FRAs with the airspace of Morocco and the province of Asturias in Spain would save more than 2,000,000 nautical miles per year, substantially reducing airline expenditures as well as harmful gas emissions [15]. This work leaves open the question of air traffic controller workload, which Pereira expects to increase as traffic and route complexity increases.

Given that complete FRA implementation requires dynamic airspace sectorization, Gerdes et al. [16] investigate a new approach to such sectorization based on air traffic controllers' tasks and workload. They combine "soft" clustering, Voronoi diagrams and evolutionary algorithms to achieve adaptable, time-responsive sectorization as well as harmonized controller workload [16]. Sergeeva et al. [17] take a different approach to airspace sectorization based on evolutionary algorithms. Sequences of sector configurations are generated from two airspace components: shareable airspace modules and sector building blocks. In the same study the authors developed an algorithm that manages the major characteristics of the dynamic sector configuration, including criteria for sector design. The algorithm is modelled and the proposed solutions are compared with existing technical solutions. The results indicate that the algorithm can satisfy the demands of the dynamic airspace configuration (DAC) concept and that its solutions can surpass those based on workload minimization, sector load balance, or transit flight re-entry, at least in the case of DAC levels 1 and 2. The algorithm does not function well at DAC level 3, because such high numbers of shareable airspace modules and sector building blocks impose geometric limitations on sector shape, leading to a convex "balcony" form. The authors highlight the need for further validation and development of the algorithm to make it compatible with DAC level 3 [17].

Improving airspace sectorization to be more dynamic is one of the goals of SESAR, which aims to generalize and harmonize air traffic management solutions across Europe. Dubot et al. [18] present optimization and simulation techniques for generating and evaluating sector configuration plans as well as a decision-making tool to facilitate flow management position tasks. When air traffic controller workload is higher, airspace sectors are usually divided up, whereas they are merged when workload is lower. The division of one sector into two sectors during higher controller workload should reduce this workload and increase capacity (Figure 6).

Figure 6 shows that opening a new sector reduces workload and creates free capacity. However, it can lead to the problem of unused air traffic controller capacity. To avoid this problem, the SESAR program implements flexible, modular dynamic airspace configurations so that large blocks of airspace are divided into many small-

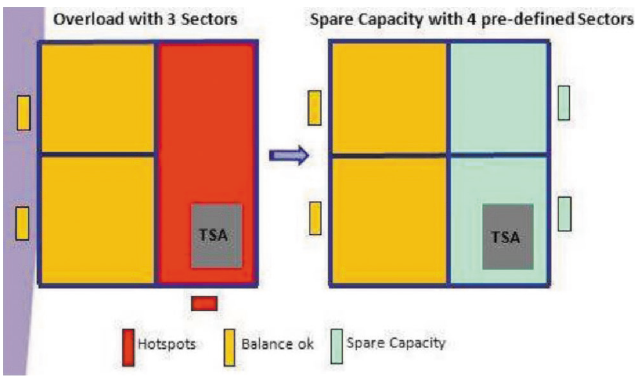

Fig. 6. Illustration of sector division during increased workload. Adapted from ref. [18]

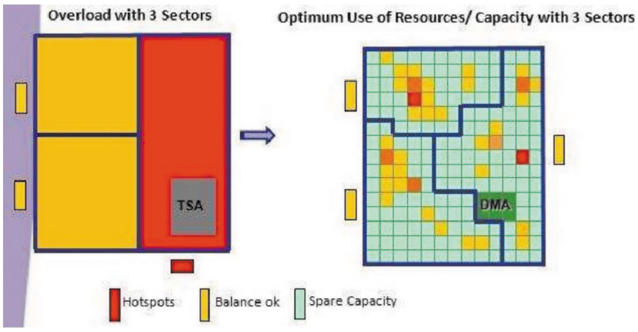

Fig. 7. Illustration of airspace allocation to many smaller blocks, which are grouped within larger control sectors. Adapted from ref. [18]

er blocks. These smaller blocks, which are not necessarily controlled, are grouped into control sectors called "controlled airspace blocks". Control sectors adapt to the specificities of air traffic: the boundaries of these sectors can be adjusted to respond to the problem of "hot points" without increasing the total number of sectors, thereby maintaining a balanced workload allocation among air traffic controllers (Figure 7).

Initial results from qualitative and quantitative analyses are promising: sector configuration plans created using an optimization algorithm and flow management position expertise can allocate workload among air traffic controllers [18]. Further studies should analyze how such novel approaches can be integrated into existing tools for flow management position.

In their review Flener and Pearson [19] analyze optimization methods for sectorizing airspace based on different constraints, such as geometry, workload, and peak traffic. Algorithm-based optimization can improve airspace sectorization, but it also requires re-training of air traffic controllers. The authors' analysis clarifies the need to apply constraints directly to sector optimization rather than applying them when validating optimization results obtained without constraints.

Few studies have examined how FRA affects traffic complexity and therefore the workload of air traffic controllers. One of the more important studies in this area focuses on the effects of trajectory-based operations and their relationship to traffic complexity and controller workload [20]. The authors of this paper succeeded in demonstrating that trajectory-based operations can substantially reduce traffic complexity as perceived by controllers. Versteegt and Visser [21] develop algorithms to identify and resolve traffic conflicts in FRA in order to reduce traffic complexity.

FRA implementation replaces the well-defined structure of conventional ATS routes with diverse traffic networks, making traffic prediction difficult. This creates the risk of conflict situations at diverse locations, whereas such conflicts are usually confined to predictable high-traffic routes in ATS-defined airspace. As a result, the detection of conflicts in FRA is much more difficult than in the airspace defined by ATS. A survey of air traffic controllers showed that they perceive aircraft to enter FRA "from all sides" rather than follow pre-defined entry points and routes as in ATS-defined airspace [22]. In addition, controllers reported feeling that they have fewer options available for resolving traffic conflicts in FRA [22]. This may be due in part to the fact that under the conventional ATS system controllers can direct aircraft onto predefined direct routes, whereas aircraft in FRA already fly direct paths and so controllers must respond differently. The researchers who analysed the survey results concluded that the FRA presents challenges in identifying conflict situations and finding appropriate options for their resolution.This further highlights the need for future research to clarify the effects of FRA on air traffic complexity.

Some papers suggest that FRA does not place additional burdens on air traffic controllers [23], while other papers suggest the opposite [24]. Nevertheless, experts agree that controllers need better tools to detect and resolve conflicts in FRA [14,22–24].

5. Conclusions

Implementing new SESAR technology is essential to increase the efficiency of air traffic management and to ensure safety despite the growing demand for traffic in the coming years.

One such technology is FRA, which allows airspace users to plan their flight paths based on desirable shorter trajectories rather than on pre-defined ATS routes, which can lead to lower fuel consumption, lower costs and reduced environmental impact. This review presents the basic concepts of FRA and provides an overview of the most important research work on the implementation of the FRA. Available evidence suggests that the FRA should increase traffic flow and capacity, which is important to meet the increased demand. Studies also point to the need to move from static to dynamic airspace sectorization in order to respond to the dynamics of traffic flows in FRA. Intersection points and aircraft interactions in FRA are variable, dynamic and difficult to predict. Future research is therefore needed to understand how FRA affects traffic complexity and the workload air traffic controllers.

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Petar Andraši[1], Tomislav Radišić[1], Bruno Antulov-Fantulin[1], Doris Novak[1]

Methodology for Predicting Sector Capacity in Convective Weather Conditions

[1]University of Zagreb, Faculty of Transport and Traffic Sciences, Zagreb, Croatia

Abstract

Convective weather conditions limit airspace capacity and increase the complexity of air traffic. Currently, air navigation service providers calculate sector capacity using air traffic controller workload as reference. The aim of the research is to propose a method for predicting sector capacity in convective weather using air traffic complexity model. In this proposal existing air traffic complexity model should be remodeled to enable finer resolution of complexity results. Also, the model should be upgraded with a new type of indicator showing aircraft-weather interactions. The adopted air traffic complexity model, in combination with the trajectory prediction model and the Weather Ensemble Forecast, should be able to provide a statistical characterisation of sector capacity under impending convective weather conditions.

Keywords: *convective weather, air traffic complexity, sector capacity*

1. Introduction

One of the main goals of air traffic development in Europe is to increase capacity in order to meet traffic demand while maintaining the necessary levels of safety and efficiency. In the second quarter of 2018, traffic growth of 3.5% was recorded, which is considered a high growth rate [1][2]. Up to 2040, traffic growth of 1.9% per year is forecasted for a regulated growth scenario, while the global growth scenario forecasts growth of 2.7% per year [3].

In order to meet the traffic demand, it is necessary to increase the airspace capacity. Reducing the air traffic complexity is one of the ways of increasing airspace capacity. The first published papers researching air traffic complexity date from 1960s [4] when Davis et al. studied effect of traffic density, traffic mixture and number of terminal areas on air traffic controller. Since the concept of air traffic complexity has not been clearly defined until recent years, most of early research is based on controller workload. It is important to emphasize that air traffic complexity is not the same as air traffic controller workload: rather, these concepts are closely related and directly interdependent. Schmidt [5] approached the problem of complexity from the perspective of controller workload. He created the control difficulty index, which can be calculated as a weighted sum of the expected frequency of occurrence of events that affect controller workload. Each event is given a different weight determined by the time the controller needed to perform the task. Hurst and Rose [6] calculated the correlation between workload and traffic density and proved that only 53% of the variance in reported workload ratings can be explained by traffic density. Stein [7] used Air Traffic Workload Input Technique (ATWIT), in which controllers reported workload levels during the simulation to determine which of the workload variables mostly affected the workload. Regression analysis proved that out of five starting variables, four variables (localized traffic density, number of handoffs outbound, total amount of traffic, number of handoffs inbound) could explain 67% of variance in ATWIT scores. These variables are also the first defined complexity indicators in literature. In further research, the number of indicators only increased. Kopardekar et al. [8] successfully validated additional 35 indicators, and the same group of researchers demonstrated that only 17 indicators were statistically significant for the calculation of complexity [9]. Masalonis et al. [10] reduced the number of indicators to 12 by referring to probability, predictability, and validity of the given indicator. Klein et al. [11] selected only seven from those 12 indicators by weighting them and using linear regression.

EUROCONTROL experimental center published a detailed complexity study of the Maastricht upper airspace centre [12] in which various complexity indicators were analyzed. Also, in 2006, the EUROCONTROL Performance Review Commission published a final report defining complexity metrics for air navigation service providers benchmarking [13]. In concept of dynamic demand capacity balancing it is suggested that short-term air traffic flow and capacity measures (short-term ATFCM measures) can be used to influence complexity [14]. The proposed short-term ATFCM measures include short notice ground regulations, ground delay, Take Off Not Before, Take Off Not After, re-routing, change in standard instrument departure, flight level reassignment/ level capping, and speed regulation. EUROCONTROL continues further exploration of the complexity through the SESAR PJ.09 project and the first phase will end by the end of October 2019.

So far only Krozel et al. [15] have carried out research on the impact of convective weather on the air traffic complexity. In their research traffic complexity is expressed as a function of velocity variance and traffic density. However, there are many studies that explore the impact of convective weather on flight trajectory, air traffic controller workload, airspace sectorization and air traffic capacity, which is essentially the core of air traffic complexity and complexity reduction measures. Nilim et al. [16] were one of the first to describe the impact of convective weather on the aircraft using Markov decision process and dynamic programming to minimize fuel burn and trip cost or to maximize profit and safety. DeLaura et al. [17] used trajectory data of aircraft flown through convective weather to develop a model for predicting pilot decisions and aircraft trajectories in the three-dimensional space. McNally et al. [18] proposed a weather avoidance system for near-term trajectory-based operations. Considering the shortcomings of previous research, Hentzen et al. [19] proposed a method for modelling the uncertain development of thunderstorms and combined the developed method with an optimal trajectory planning algorithm based on the reach-avoid method. Although all studies on controller workload indicate that with degrading weather, workload increases, Cho et al. [20] were the first to use regression analysis for developing a model which calculates airspace capacity based on controller workload during convective weather. Welch et al. [21] upgraded the controller workload calculation model and repeated the regression process on a new set of data. The result of the regression process is more accurate capacity prediction in all sectors and under all-weather conditions.

Hadley and Sollenberger [22] were the first to combine dynamic sectorization and convective weather by designing by designing a convective weather scenario in their study of the effects of dynamic rectorization on air traffic controllers. Klein et al. [23] demonstrated that dynamic sectorization, together with rerouting can evenly distribute sector occupancy and reduce its peak load. In all previous research dynamic sectorization was applied to two-dimensional space, i.e. the horizontal plane. Klein et al. [24] published a method of dynamic sectorization in three-dimensional space.

Even though Schmidt [5] tried to determine the capacity of airspace through the controller workload, Mitchell at al. [25] were the first to determine the distribution of potential airspace capacity with given probabilistic weather forecast. Krozel et al. [15] published a comprehensive survey assessing airspace capacity in convective weather. In their paper four specific types of traffic flows were considered passing through defined airspace in two operational concepts (free flights and centralized packing systems).

2. Air traffic complexity

Meckiff et al. defined air traffic complexity as a difficulty of monitoring and managing a specific air traffic situation [26]. Complexity is not synonymous with workload, although it has been proven on several occasions that increasing complexity leads to an increase in workload, which in turn limits the capacity of the airspace sector.

Since complexity is a psychological construct, the best estimate of complexity in any traffic situation is the value given by the air traffic controller. By observing traffic data the air traffic controller can evaluate and determine if the traffic situation is complex or not. The main problem with expert-based evaluation is inconsistency between assessors. Different assessors can give different complexity values for the same traffic scenario. This is the main reason why new methods for complexity estimation are developed without human input. Such methods should be validated by comparing them with the experts.

There are three main groups of methods for determining air traffic complexity:

- Expert-based air traffic complexity estimation – as mentioned above, it is a method where experts, in most cases an air traffic controller, gives their estimate of air traffic complexity.
- Indicator-based air traffic complexity estimation – it is method were air traffic complexity is determined using a set of indicators derived from air traffic data.
- Interaction-based air traffic estimation – it is a method where air traffic complexity is described as number of interactions between different aircraft within given airspace cell (this method could also be defined as a very narrow indicator-based air traffic complexity estimation where complexity is estimated using a very small number of indicators).

It further explains only the interaction-based air traffic estimation, as this method is also used by the EUROCONTROL Performance Review Unit (PRU).

3. Interaction-based air traffic complexity model

As already mentioned, interaction-based air traffic estimation is a method that attempts to enumerate all aircraft to aircraft interactions in the defined airspace. The interactions are sorted according to the complexity dimensions that they attempt to describe. This method was proposed in 2006 by EUROCONTROL Performance Review Commission in the final report defining complexity metrics for air navigation service providers benchmarking [13]. The developed method is used by the PRU to calculate the complexity for each air navigation service provider (ANSP) on annual basis and it is one of the indicators for evaluating the effectiveness of ANSPs.

3.1. PRU complexity model

In order to quantify complexity, the EUROCONTROLs working group has defined complexity dimensions that separately describe the characteristics of an air traffic management system, and to the greatest extent affect the complexity experienced by the controller. The complexity dimensions are classified into three groups; traffic characteristics, airspace and external constraints. Each dimension of complexity is described by a set of indicators. The working group extracted four dimensions from the identified complexity dimensions and indicators, each with one indicator. Selected dimensions and indicators have the greatest influence on the route complexity. Complexity dimensions and their indicators are listed in Table 1.

Table 1. Different microreactor types based on specific characteristics

Complexity Dimension	Complexity Indicator
Traffic density	Adjusted density
Traffic in evolution	Potential vertical interactions (VDIF)
Flow structure	Potential horizontal interactions (HDIF)
Traffic mix	Potential speed interactions (SDIF)

Complexity indicators were calculated using a grid of identical 4D cells laid over the desired airspace. As shown in Figure 1, each 4D cell is 20 [nm] wide, 20 [nm] long and 3000 [ft] high, and within the cell there is flight movement data for 60 minutes. The time interval of the data is one day, which means that each day has 24 data sets for each cell (one set for each hour).

Due to the different overlap limits of different airspaces and cell boundaries, a boundary effect occurs where some aircraft are not taken into account in the complexity calculation. To avoid the border effect associated with using the grid, the grid is moved four times horizontally and three times vertically. The horizontal shift is by 10 [nm] and the vertical shift is by 1000 [ft].

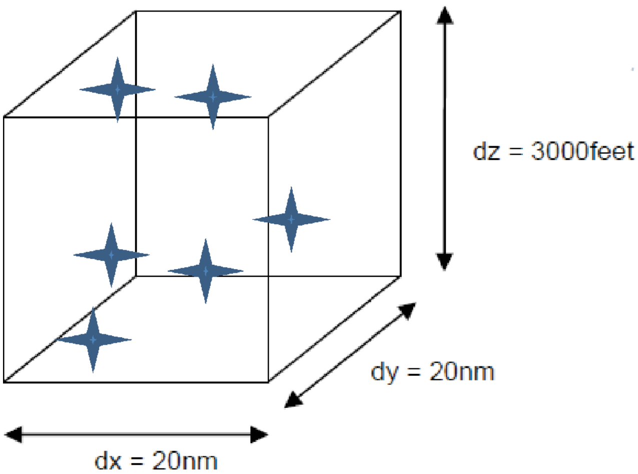

Fig. 1. Cell dimensions

Aircraft interaction is the interaction of two aircraft in a single cell. Each pair of planes in a cell forms two interactions. Therefore, when two planes are in a cell, there are two interactions in a cell, but when three planes are in a cell, then there are six interactions in that cell. As indicated in Table 1, there are three types of interaction.

Potential vertical interactions (rVdif) – It is expressed as the duration of potential vertical interactions (in hours) per flight hour. Two aircraft are considered to interact vertically if both are present in the same cell and have different flight phases (one is in climbing and the other is in cruise or any other combination of climbing, descending and cruising). Flight phase of each aircraft is determined when aircraft enters the cell, an aircraft is considered to be in a descending or climbing phase if its rate of change is greater than 500 feet per minute.

Potential horizontal interactions (rHdif) – It is expressed as the duration of potential horizontal interactions (in hours) per flight hour. Two aircraft are considered to interact horizontally if both are present in the same cell and their flight direction differs by more than 20 °.

Potential speed interactions (rSdif) – It is expressed as the duration of potential velocity interactions (in hours) per flight hour. Two aircraft are considered to be in speed interaction if both are present in the same cell and have a difference in speeds greater than 35 knots. Cruise speeds for each aircraft were taken from the EUROCONTROL Base of Aircraft Data (BADA) aviation database.

Forth indicator is *Adjusted density* – the adjusted density is defined as the ratio of sum of aircraft interaction time and sum of aircraft flight time.

Air traffic complexity is the product of adjusted density and the sum of potential vertical, horizontal and speed interactions. The calculation of air traffic complexity is given in equation 1.

$$Complexity = Adjusted\ density * \left(rVdif + rHdif + rSdif\right) \tag{1}$$

3.2. Model improvements

The current PRU complexity model was developed for the macroscopic evaluation of various ANSPs. As such it is not precise enough for the microscopic evaluation of different sectors within an airspace. To adopt the current PRU model for microscopic complexity calculations, the following changes must be made:

- Resizing of cell dimensions
- Shortening time window

As the PRU complexity model was developed to calculate air traffic complexity across the European airspace, the cell size (20 x 20 [nm]) was designed to reduce the calculation time. Smaller countries, such as Croatia, cover a relatively small volume of airspace. If the current model were applied to calculate the complexity of sectors in such an airspace, some sectors would have a small number of cells. A small number of cells is not sufficient to locate traffic hotspots within the sector or to calculate the weather effect. To allow a better spatial resolution of the complexity measurement, the horizontal dimensions of cells will be reduced. Further research will investigate the reduction of the cell size to 5 by 5, 7 by 7, 10 by 10 and 15 by 15 [nm].

Convective weather conditions are of short duration. On average, life cycle of cumulonimbus (CB) is 30 minutes. Considering that time frame of PRU complexity model is one hour, a CB cloud could form and dissipate within a time frame. To allow a better temporal resolution, the time frame should be shortened. According to EUROCONTROL [13] in their sensitivity analysis, different time frames had very little effect on the ranking of the centers. The smaller time frames also increased the required computation time. But for microscopic analysis, smaller time frames should allow the localization of peaks in the complexity of air traffic and the possible localization of convective weather.

Even though some indicators are affected by convective weather, e.g. rHdif will increase due to weather avoiding, impact of convective weather on complexity is much higher than indicated by rHdif. To determine the complexity of convective weather conditions, model should be upgraded with another indicator which would relate to aircraft-weather interactions. The weather interaction indicator can be expressed as the ratio of the duration of weather interaction and flight time. Aircraft would be considered for weather interaction if it is in convective weather occupied cell or it is flying in close proximity.

4. Capacity prediction

The calculation of sector capacity is currently based on air traffic controller (ATCO) workload. At sector level, capacity is obtained by measuring or calculating how much time ATCO has actively worked in one hour. Due to safety concerns the maximum allowable workload of ATCO is 70% of the calculated workload. According to Mogford et al. [27] complexity is a source factor for controller workload. However, complexity and workload are not directly linked. Their relationship is mediated by several other factors, such as equipment quality, individual differences, and controller cognitive strategies. If all mediating factors remain constant, complexity can be used as proxy measure of workload or capacity. Under such conditions, traffic situations of higher complexity will have a higher workload than traffic situations of lower complexity. Sector capacity in convective weather conditions is even harder to calculate due to uncertainties caused by constantly changing weather and mitigating measures taken by pilots. As mentioned in the introduction, DeLaura et al. [17] developed a model that predicts pilots' mitigating actions in convective weather conditions. In their work they proposed a set of weather-based indicators upon which the model determines pilot actions. Since their work is based on historic traffic data in the USA from 2000s it is recommendable to recalculate the indicators in future research. The indicators should be recalculated in the light of advances in aircraft avionics and weather radar, as pilots' actions may not be the same as at the time of data recording. In order to ensure safe separation from other aircraft, the ATCOs must give each pilot permission to avoid action. To allow pilots to avoid action, ATCO must evaluate pilots desired trajectory and confirm that it doesn't create conflict with other aircraft. Such tasks require a lot of time, so that the workload of the ATCOs is significantly increased and the capacity reduced.

Sector capacity in convective weather conditions should be predicted using Ensemble Weather Forecasts (EWF). EWF is a set of forecasts created with multiple weather simulations where each simulation has slight variation of its initial conditions. Sector capacity should be calculated for each weather forecast in EWF and the calculation of sector capacity should employ the above-mentioned trajectory prediction model and the improved complexity prediction model in its calculation method. All results from capacity calculation should be statistically characterized (Fig. 2).

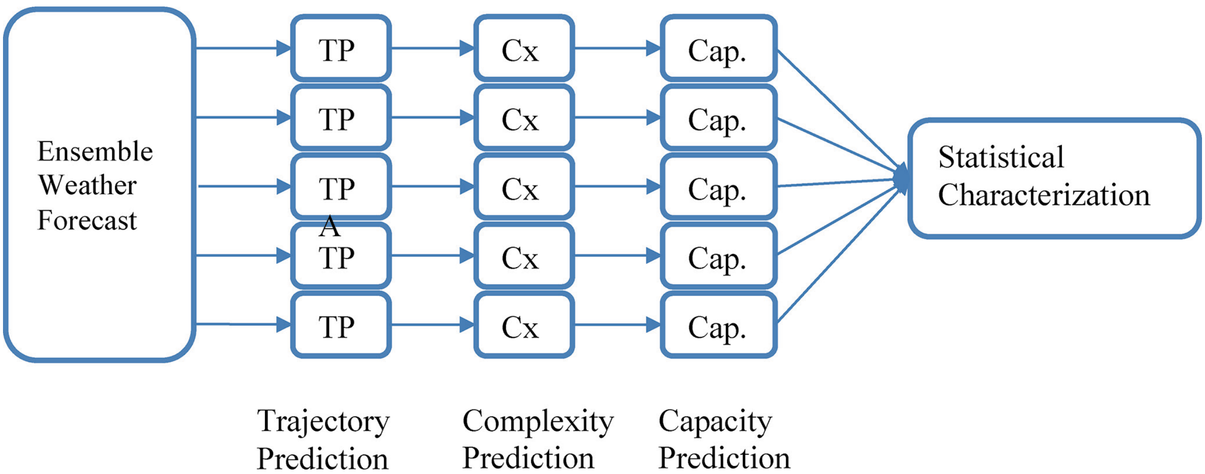

Fig. 2. Sector capacity prediction

5. Conclusions

By applying an improved air traffic complexity assessment method to the current trajectory prediction model, it is possible to increase the reliability of sector capacity prediction. Using such a method with Ensemble Weather Forecast will allow statistical characterization of predicted capacity in uncertain convective weather conditions.

To enable such a prediction, the current air traffic complexity model should be modified to calculate complexity at microscopic level with finer spatial and temporal resolution. Also, air traffic complexity model needs to be improved with a new indicator that will enable quantification of aircraft-weather interaction.

In further development, the developed method for calculating sector capacity will be used to optimize the sector opening scheme. For each forecast given by EWF it is possible to propose ideal sector opening schemes. With such a set of data Flow Manager Position (PMF) will be given prepared opening schemes for the person who created the forecast. Such information enables him to be better prepared for the upcoming traffic flow. Such information will enable him to be more prepared for the upcoming traffic flow.

Another application of predicted sector capacity is to help FMP decide which measures to apply to balance demand capacity. Demand capacity balancing measures are actions implemented by the FMP to reduce or balance workload of ATC. The proposed method can be used to determine which measure would have the minimum impact on aircraft operating costs and the environment in order to maintain maximum traffic flow in a given airspace.. The most commonly used measures are sectorisation and changes in sector configuration, as the addition of more ATC does not have a negative impact on aircraft. But in situations where resources are limited, FMPs use measures such as short term air traffic flow and capacity management measures (STAM). As stated in the introduction STAM measures include short notice ground regulations, ground delay, Take Off Not Before, Take Off Not After, re-routing, change in standard instrument departure, flight level reassignment, level capping, and speed regulations. The complexity model can be used to determine the effect of various measures on air traffic complexity. With such calculations it is possible to determine an almost optimal set of measures to reduce the initial complexity and thus help FMT to increase or balance the capacity.

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Tomislav Radišić[1], Petar Andraši[1], Doris Novak[1], Tea Rogošić[1]

The Proposal of a Concept of Artificial Situational Awareness in ATC

[1]University of Zagreb, Faculty of Transport and Traffic Sciences, Zagreb, Croatia

Abstract

Automation is one of the most promising solutions to the airspace capacity problem. However, we believe that in order to safely implement advanced automation concepts in air traffic control, it is necessary for AI and humans to share situational awareness. One of the main objectives of this concept proposal is to explore the effects and possibilities of distributed human-machine situational awareness in en-route air traffic control operations. Instead of automating isolated individual tasks, such as conflict detection or coordination, we propose to create a basis for automation by developing an intelligent situation-aware system. The sharing of the same situational awareness between the members of the air traffic controller team and AI enables the automated system to reach the same conclusions as air traffic controllers when faced with the same problem and to be able to explain the reasons for these conclusions. Machine learning can be used to predict, estimate and filter at the level of individual probabilistic events, an area in which it has shown great ability so far, whereas the reasoning engine can be used to represent knowledge and draw conclusions based on all the available data and explain the reasons for these conclusions. In this way, the artificial situational awareness system will pave the way for future advanced automation based on machine learning. Here, we will explore which technologies and concepts are useful in building the artificial situational awareness system and propose the methodology for testing the AI situational awareness.

Keywords: *Air traffic control, artificial intelligence, situational awareness, concept proposal*

1. Introduction

The air traffic controller's job will be very different in the future; it will have to be adapted to new circumstances.

The growth in air traffic in Europe is already putting a strain on the European air traffic management system. In 2018, delays in en-route air traffic management (ATFM) increased by 104%, while traffic increased by only 3.8% in the same period. As in previous years, the main cause of ATFM delays on routes was the lack of air traffic control (ATC) capacity (34%) [1]. The current air traffic throughput for a given sector is constrained by air traffic controller (ATCO) workload. The growing number of aircraft means that the workload of air traffic controllers is increasing to such an extent that it is possible for the ATCO to lose situational awareness (SA), leading to unsafe operations. Demand capacity balancing (DCB) measures are then employed to reduce the workload of individual ATCOs and ATFM delay is thus created.

Automation is one of the most promising solutions to the capacity problem, but it is clearly stated in the SESAR

Single Programming document for 2019-2021 that the human should be kept in the loop in order to ensure safety:

> *Automation could provide the key to significant performance improvements across many aspects of ATM. On the other hand, human cognitive abilities, especially in safety-critical situations, can have positive benefits and provide strong arguments against full autonomy in certain situations. The challenge is therefore to propose solutions with automation levels or autonomy that have the capability to provide substantial and verifiable performance benefits whilst fully addressing safety [2].*

Therefore, we believe that to implement advanced automation concepts it is required that the artificial intelligence (AI) and human are able to share the SA. Exploring the effects and possibilities of distributed human-machine situational awareness in en-route operations is one of the main objectives of the methodology presented here. Instead of automating isolated individual tasks, such as conflict detection or coordination, we propose to create a basis for automation by developing an intelligent situation-aware system. Sharing the same team situational awareness (TSA) between ATCO team members and AI (Figure 1) will allow the automated system to reach the same conclusions as ATCOs when confronted with the same problem and explain the reasoning behind those conclusions.

Previous research has shown that SA will actually improve in systems with greater automation as long as it was applied to information acquisition and action implementation, as compared to automation of cognitive functions, specifically information analysis [3]. This means that automation will provide the greatest benefit if it replaces monitoring tasks instead of automating the higher-level decision tasks.

Other studies have shown that automation can be beneficial to maintaining the situational awareness, even at intermediate levels of automation [3,4]. On the other hand, it was found that monitoring automation involves considerable workload [5,6], therefore, self-monitoring automation with graceful degradation characteristics should be employed to the greatest degree possible.

ATCOs work in teams and they share a common SA, often called team SA (TSA). Automation tools are mostly focused on supporting the individual ATCO whereas many of the air traffic control (ATC) functions are a team effort [7,8]. Higher cognitive functions, such as managing team task load or anticipating team member's reactions and capabilities, are very difficult to automate [7]. For this reason, automation must be able to share the same TSA as the rest of the team.

In previous SESAR Exploratory Research project BEST, ATM-specific ontology was developed for data handling in support of SWIM [9]. Guidelines (aimed at practitioners) were developed on how ontologies can be used flexibly to describe metadata and how they can be used in innovative yet scalable ways. We are trying to integrate ideas and conclusions of the BEST project with advances in AI and ML in order to allow AI to partake in team situational awareness. The ontologies developed in BEST will be used as a basis for development of knowledge graphs (KG) used by the reasoning engine.

In other industries, ontologies were used in combination with reasoning engines to achieve a level of situational awareness, e.g. in SAPPHIRE (Situational Awareness and Preparedness for Public Health Incidences and Reasoning Engines) project [10], which shows that reasoning engines using domain-specific ontologies are able to participate in TSA.

Operators, such as ATCOs, working in environment with high level of automation show signs of out-of-the-loop (OOTL) effect [11–13]. SESAR Exploratory Research (ER) project MINIMA has shown that OOTL effect can be mitigated by varying the level of automation [14]. To mitigate the problem, SESAR ER project AUTOPACE proposes improvement in training with emphasis on preparing ATCOs for potential system failures and for recovering control [15]. While these mitigation measures might bear fruit, it is inevitable that OOTL effect will always be present at higher levels of automation which makes TSA even more important.

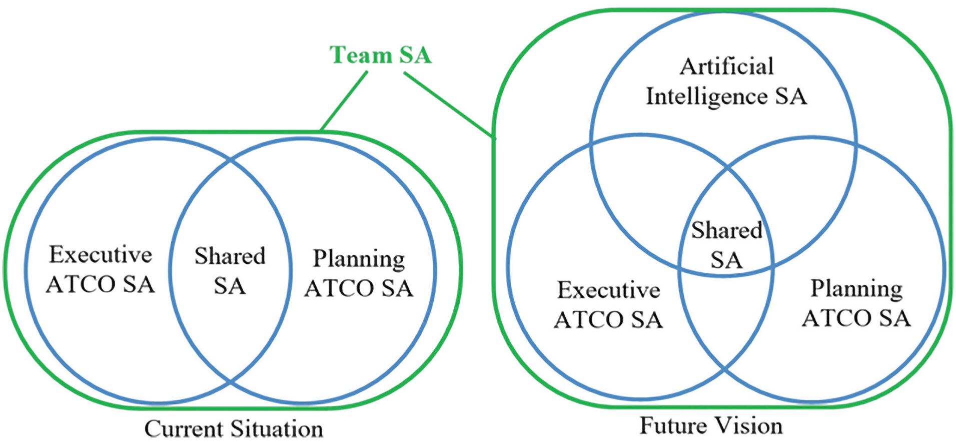

Fig. 1. Concept of Distributed Situational Awareness for Future Automated Systems

2. Vision of AI Situational Awareness

Researchers from different fields have for some time realized that a sense of "awareness" of many systems' own situation is an enabler for robust and dependable behavior even when undergoing radical changes in the environment and drastically diminished capabilities. This insight has recently led to a proliferation of work on self-awareness and other system properties such as self-organization, self-configuration, self-optimization, self-protection, self-healing, etc., which are sometimes subsumed under the term "self-*" [16].

Achieving low-level situational awareness is trivial, any PID controller for example can be considered to have some sort of situational awareness (Level 1 in framework proposed by [16]). However, to achieve higher levels of SA, the system needs to make meaningful observations, make robust semantic interpretation and meaningful attribution, it needs to have an appropriate reaction and be aware of its own goals and history thereof. Semantic web approach (ontologies + rules) to achieving situational awareness is not a novel idea, it has been attempted in different forms and in different fields. In [17], the authors propose a "Situation Awareness Assistant (SAWA) based on Semantic Web technologies that facilitates the development of user-defined domain knowledge in the form of formal ontologies and rule sets and then permits the application of the domain knowledge to the monitoring of relevant relations as they occur in situations". Artificial situation awareness was explored in a narrow scope in embedded systems for healthcare [18], and in a much wider scope in the defence industry for battlefield management [19]. This type of broader situational awareness comes closest to the function of the system as we propose it, which can be found in the literature.

On the other hand, semantic webs and knowledge engineering in general have been present in the field of ATM for some time. The authors in [20]an approach for runtime analysis and automated knowledge-based IT management is presented and applied to the example of an Air Traffic Control (ATC propose an approach for knowledge-based IT management of air traffic control systems which combines the strengths of formal ontologies and Complex Event Processing. Further application of knowledge graphs, semantic web, and ontologies in ATM can be found in [21–24]. None of these, however, address the application of such technologies for achieving artificial situational awareness or ensuring transparency of the machine-learning systems.

In current ATC operations each human team member, executive or planner ATCO, is aware of:

- traffic situation (by looking at the radar screen),
- their own state (e.g. feeling rested or tired),
- other team member state (by verbal/non-verbal communication), and
- system state (by inspecting the error messages, warning lights etc).

On the other hand, the system is unaware of the state of the ATCOs, it is unaware of the traffic situation, and it has very limited awareness of its own state.

Our vision for the future automation concept of en-route ATC operations includes human-machine distributed team SA (TSA) with sector team consisting of executive ATCO, planning ATCO, and AI (actors). Actors will be able to continually monitor each-other states, with AI being aware of the probable human actors' states via analysis of traffic situation. Tasks will be allocated dynamically according to actor states, including graceful degradation of automation ensuring business continuity. According to current task analysis [25], the following monitoring tasks could be automated just by introducing the AI SA into the TSA:

- Monitoring incoming traffic and projecting future flight states.
- Identifying, analysing, and solving entry/transit/exit problems, including climbs/descents, with ability to explain solution to ATCO in natural or coded language on request; warn of unsolved problems.
- Requesting information from, and providing it to, aircraft; maintaining up to date intent information for each aircraft.
- Monitoring conformance of aircraft to planned trajectory.
- Identifying conflicts, detecting ATCO's actions related to conflict solving, and monitoring evolution of conflict solution; alert if solution applied by ATCO does not lead to conflict resolution and explain the reasoning.
- Identifying opportunities for improvement of quality of service.
- Monitoring adverse weather areas and restricted airspace; projecting their evolution.

Also, this system could be an automated proxy between the sector team and the supervisors by including team state reporting, sector state reporting, alerting, and coordination on traffic de-complexing.

Assumptions and key enabling technologies for successful development of such a system are:

- TSA must represent the complete situation with all interactions among aircraft, humans and systems, including accurate representation of system and human states.
- Essential component of TSA is the ability to project future states from current ones.
- A single actor (machine or human) does not have to have complete SA; in this way SA is only partial for each actor.
- Individual SA should overlap to the extent that makes the operations safe and practicable.
- TSA should be distributed among actors in a way that favours individual strengths.
- Data sources and communication infrastructure, including datalink, are available.

3. AI Situational Awareness Methodology Concept

Our approach combines reasoning engine employing predicate logic (first-order logic) based on an ATC knowledge graph system (including rule-based reasoning) with a machine learning (ML) approach for prediction and estimation. ML will be used at a lower level to predict individual probabilistic events (e.g. estimated time over waypoint) whereas the reasoning engine is used at a higher level to draw conclusions from the system state. By combining the reasoning engine with ML, we believe that it will be possible for AI to be ‘aware’ of the situation in a manner similar to a human, that is, AI will be able to assess complex interactions between objects, draw conclusions, explain the reasoning behind those conclusions, and predict future system states.

To enable exploration of the effect of human-machine distributed situational awareness a framework for ATC-specific knowledge representation (i.e. a domain-specific knowledge graph system) should first be developed. In this context knowledge graph should not be considered just as another form of data encoding but, by representing all relevant object attributes, rules, relations, axioms etc. in ATC domain, as a basis for inferring new knowledge and drawing conclusions about the state of the system, both at the level of individual components and at the global level. While ATM-specific ontologies have been used for data encoding and translation in recent years, our approach to automation, combining ML with knowledge graph system (including the rule-based reasoning engine) for AI situational awareness is completely novel.

To feed the data into the knowledge graph, a set of translators from aeronautical data standards to Resource Description Framework (RDF) format will be developed or reused from previous projects (e.g. BEST project in SESAR ER). Other attributes, relations, rules and axioms will be encoded to RDF in cooperation with ATCO experts.

Reasoning can be done by automatic inference, which is a process for filling the gaps in the ontology, or by running a query to answer a specific question. Queries will be developed in cooperation with ATCO experts for each of the monitoring tasks to be automated. By performing these queries at short intervals, continuous monitoring will be achieved. Running queries over large stores of triples can be time consuming, so optimization techniques will be employed to reduce the number of triples, and hardware will be adapted for the purpose (large memory and multiple cores).

4. Concept Assessment

To assess the concept, it will be necessary to determine whether the developed system possesses a quality comparable to human situational awareness. Certainly, artificial SA will not be nearly as comprehensive as human, but we expect that reaching partial SA will be enough to prove the feasibility of the concept. The baseline for a comparison will first have to be developed by assessing ATCO’s SA in a set of given air traffic situations.

Human SA

There are several SA assessment tools, which have been developed over the years. According to [17] the measures can be grouped into three categories:

a) query techniques, in which the subjects are asked directly about their perception of certain aspects of the situation: Situation Awareness Global Assessment Technique (SAGAT), Situation Present Assessment Method (SPAM), Situation Awareness bei Fluglotsen der Langstreckenkontrolle im Kontext von Automatisierung (SALSA), Situation Awareness Probe S (SPAPS),

b) rating techniques, in which either the subjects themselves or observers of the subjects are asked to rate SA along a number of dimensions, typically presented in a series of scales: Situation Awareness Rating Technique (SART), Cranfield Situation Awareness Scale (C-SAS), Situation Awareness Linked Indicators Adapted to Novel Tasks (SALIANT), Situation Awareness Behaviorally Anchored Rating Scale (SA/BARS), and

c) performance-based techniques, in which the level of SA is inferred from the level of performance. The rationale underlying this technique is that a good SA is needed to achieve good performance. This might be the use of objective measurement tools techniques like eye tracking.

Taking into account the previous existing SA measurement tools, [17] two specific kinds of measurement tools have been developed to assess ATCO`s SA in Air Traffic Management (ATM):

1) SA for Shape on-Line (SASHA_L), which is a query technique based on existing measure, especially SPAM. The new component of this SA assessment tool is that the queries are formulated by a subject matter expert (SME) in real-time, taking into account the real scenario as it unfolds. Thus, the SME asks a question if he/she decides that it is appropriate to do so.

2) SA for SHAPE Questionnaire (SASHA_Q) – a questionnaire technique using carefully chosen questions that focus on key elements of SA which controllers have identified themselves. The SASHA_Q is a post-exercise self-rating technique. It consists of ten questions that were especially designed by taking into account the views of controllers themselves about SA and its indicators. Both measures are primarily concerned with controllers` SA when using computer-assistance tools and other forms of automation support.

By assessing SA in ATCO's it seems reasonable and useful to use different kinds of measurement tools as proposed by [17]. The use of SASHA_L and SASHA-Q in combination with an objective measurement tool like eye tracking (to assess perception modes) seems appropriate when studying SA in the mentioned context of the herein proposed research.

Artificial SA

To assess the artificial SA, we formulate our framework according to Jantsch and Tammemäe [16]. We shall define the system aware of certain characteristics of the environment, if three conditions are met:

1. The data interpretation is meaningful;
2. The drawn conclusions are robust; and
3. The reaction of the system is appropriate. [16]

Based on these three rules, we can define five conditions for being aware of the environment and two conditions for being aware of itself. For property P we define the following conditions related to the awareness of the said property by the system [16]:

I. The system performs physical measurements or observations based on the received measurement that are used to derive the values of P by means of a meaningful semantic interpretation.

II. The semantic interpretation is robust.

III. There is a semantic attribution which is meaningful.

IV. The system's reaction to its perception of P is appropriate.

V. A history of the evolution of the property over time is maintained, in particular of the increasing or decreasing deviations over time.

As mentioned previously, we also define two conditions for being aware of itself [16]:

A. The system can assess how well it meets all its goals, thus it has an understanding which goals should be achieved and to which extent they are achieved.

B. The system can assess how well the goals are achieved over time and when its performance improves or deteriorates.

The assessment of the SA level can be performed by writing SPARQL queries designed to elicit the same information as that requested by the ATCO in SASHA_L/Q. These queries will be focused on analyzing the traffic situation in en-route ATC. Additional queries will be designed to elicit information about other members of the team. The purpose of these queries will be to determine whether the system can gain insights into the extent of team SA and the state of other actors. Overall, this methodology and the concept itself were only applied when so many questions remained unanswered**.**

This framework enables us now to define six levels of SA, Table 1.

SA Level	Description
0	A functional system instinctively reacts to a given input always in the same manner; its output is a mathematical function of its input. If it also fulfills the conditions I – IV, we define it to be at Level 0.
1	An adaptive subject tries to minimize the difference between input values and corresponding reference values. If it also meets conditions I – IV it is aware at level 1.
2	A self-aware system 1. is aware of at least one system property and one environment property according to conditions I – IV and condition A, 2. it contains an inspection engine that periodically derives one integrated attribution of the system, and 3. it computes its actions based on (a) the monitored and attributed properties of the system and of the environment; (b) the attributed expectations on the system and on the environment; (c) the set of goals set for the system and the environment.
3	A history sensitive self-aware system fulfills all requirements of Level 2 and, in addition, fulfills the history conditions V and B (thus satisfying all seven conditions).
4	A predictive system is a history sensitive self-aware system of Level 3 and, in addition, its decision-making process involves a simulation engine that can simulate the effects of actions on the environment and on the system, thereby predicting future states and behaviors of both the system and its environment.
5	In addition to self-awareness, group awareness means that the system distinguishes between itself, the environment and the peer group. The latter is treated differently by associating it with peer group specific expectations and goals.

5. Conclusion

We have presented here a concept for the development of the artificial situational awareness system in ATC based on combining machine learning modules and reasoning over knowledge graphs. The expected benefits of such a system are the ability to integrate and cross-check other sources of information, detect erroneous information, and automate some of the monitoring tasks.

The remaining research questions are numerous.To what extent are human and artificial SA even comparable? What is the maximum level of SA that can be obtained with KGs and/or reasoning engines? Does the complexity of knowledge engineering make benefits of artificial SA system irrelevant? How feasible is it to encode all required semantics for ATC en-route operations? Is first-order logic powerful enough for all types of queries that will be needed? Is it safe to include AI situational awareness in conjunction with ATCOs in TSA?

In our future work we hope to answer these questions and to find out whether the concept of artificial situational awareness is feasible in air traffic control.

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