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Free Route Airspace for Efficient Air Traffic Management

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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.

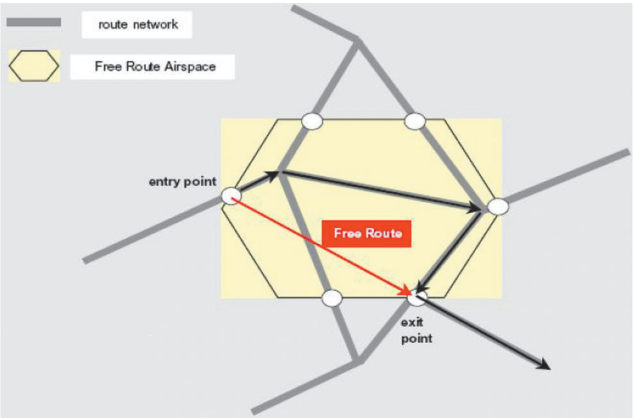

Fig. 1. Illustration of how FRA can lead to shorter flight paths. The conventional ATS route is shown with black arrows, while a possible free route is shown with a red arrow. Adapted from ref. [6]

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

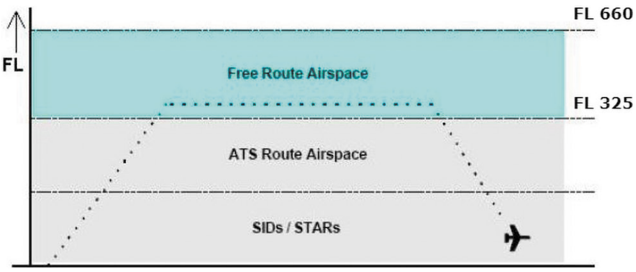

Fig. 2. Illustration of the FRA in Croatia and its relationship to ATS-governed airspace. Adapted from ref. [6]

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.

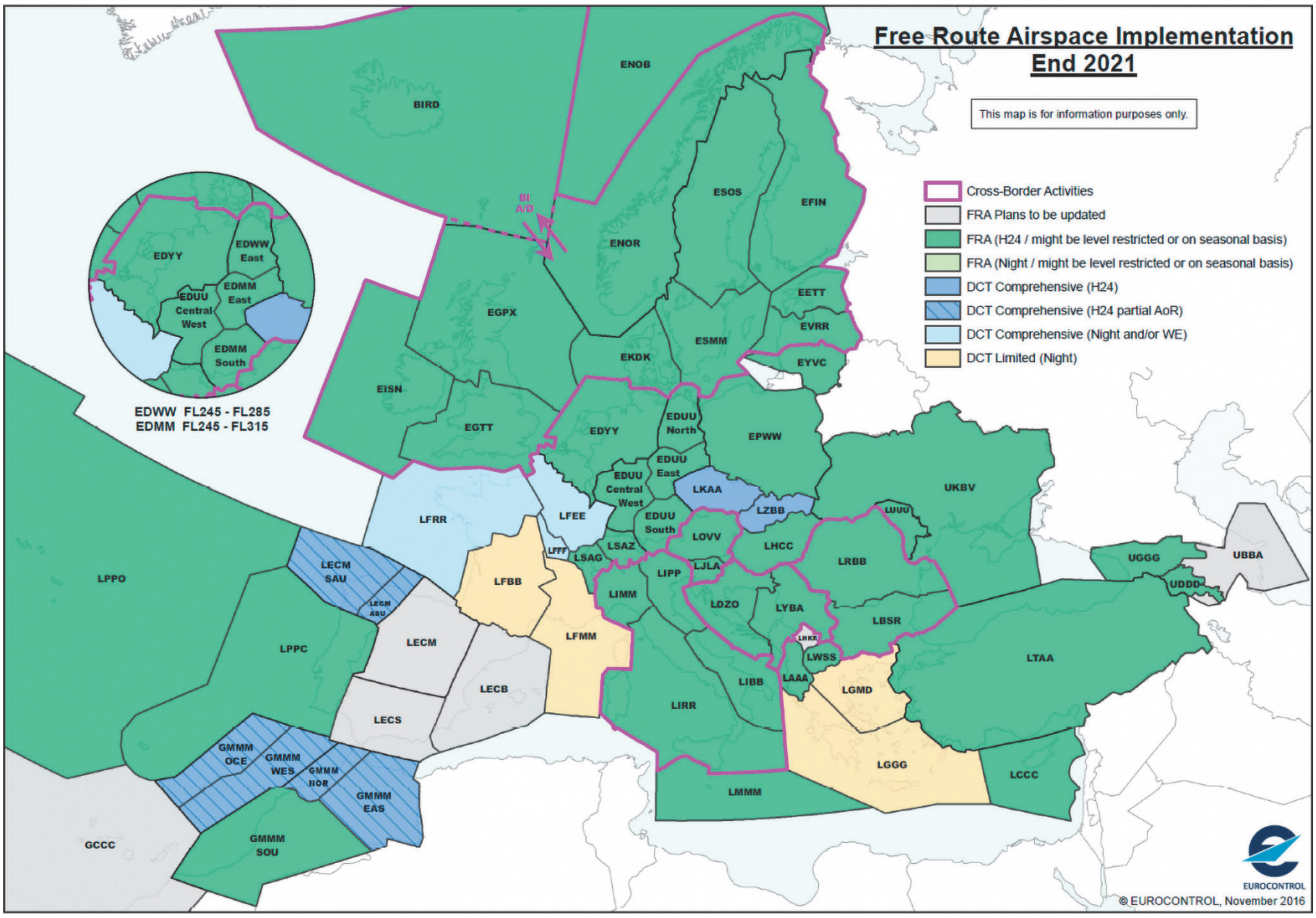

Fig. 3. Implementation of FRA by 2021. Adapted from ref. [4]

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].

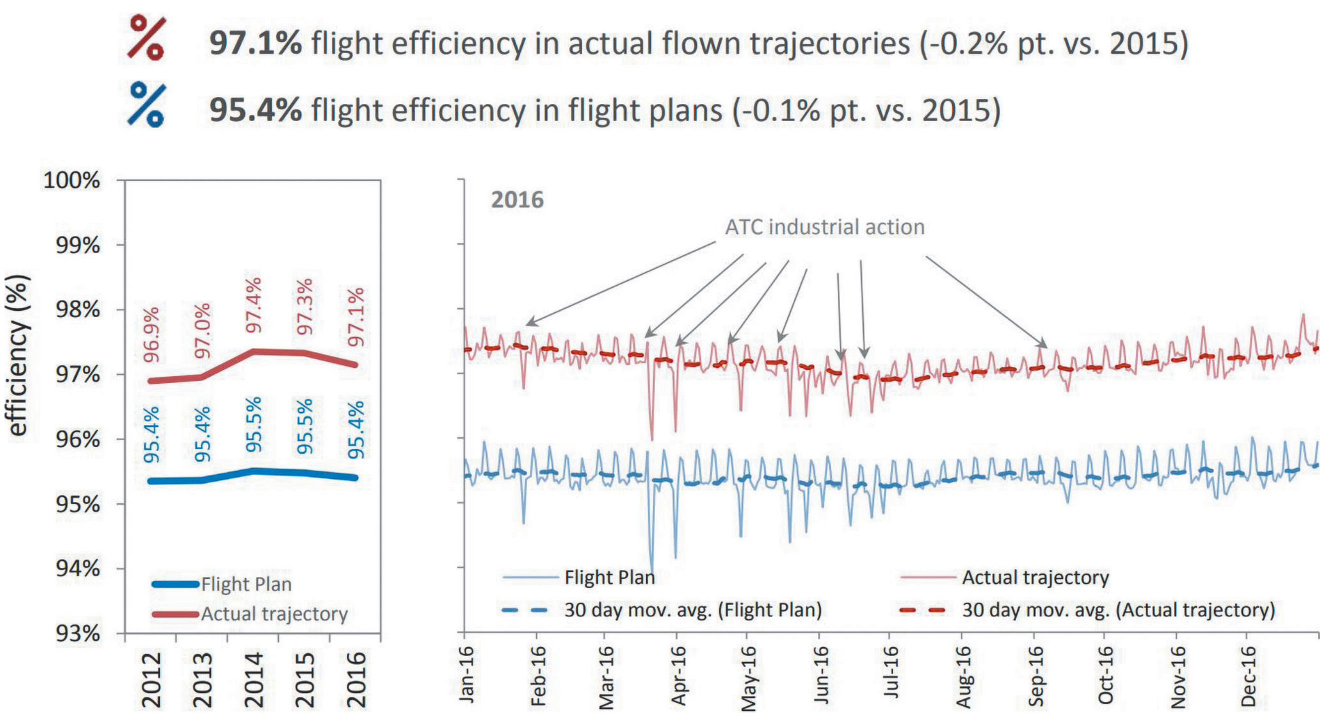

Fig. 4. Horizontal flight efficiency in the EUROCONTROL zone [1]

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).

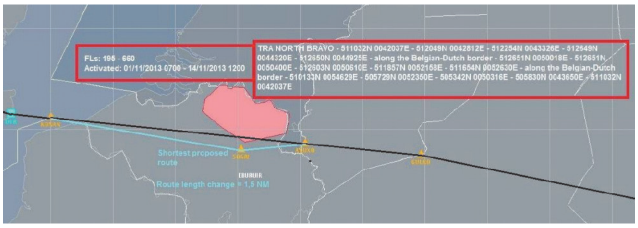

Fig. 5. Illustration of a non-operational tool for flight plan validation, which in this case is suggesting a new route. Adapted from ref. [11]

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 smaller 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).

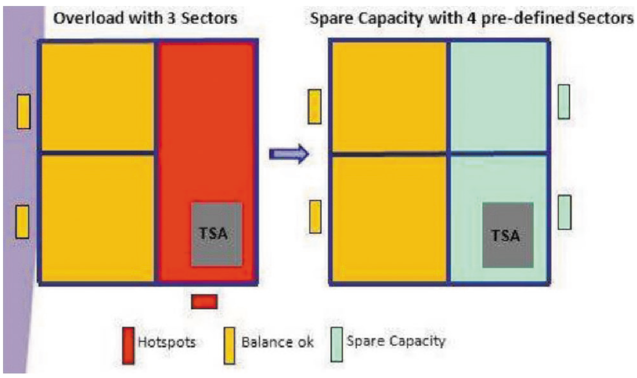

Fig. 6. Illustration of sector division during increased workload. Adapted from ref. [18]

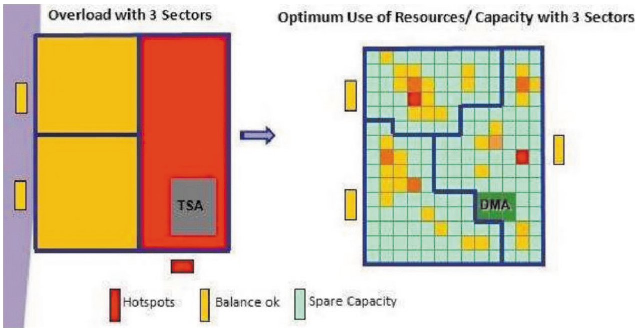

Fig. 7. Illustration of airspace allocation to many smaller blocks, which are grouped within larger control sectors. Adapted from ref. [18]

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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