Study of a Full Implementation of Free Route in the European Airspace*

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***Abstract* — Free route airspace permits users to freely plan a route between defined entry and exit waypoints, with the possibility of routing via intermediate points. Flights flying in a free route area remain subject to air traffic control (ATC) for separation provision. This research evaluates an extreme future scenario of free route implementation across Europe. We consider the complete upper airspace of the European Civil Aviation Conference (ECAC) area as a unique airspace block configured with free route. The paper is centered in investigating the benefits for the airspace users, and in the study of possible increments of complexity of such configuration. In this research, fast time simulations are carrying out to discover how much flight time, fuel and distance aircraft can save with this free route configuration. In the other side, the paper explains the evolution of conflicts derived from potential separation losses between aircraft in this new environment. Separation losses in free route can emerge at any point of the airspace, which can require greater effort for solving them in comparison with fixed airways configuration, where conflicts are usually found in well-known airways intersections. The airspace configurations modelled in this study are the fixed airways structure, named as Current, and the future scenario, named as EUROFRA, where new navigation points are added. This research studies the advantages and difficulties that a large scale application of the free route concept can bring to the European airspace.**

Keywords— free route airspace, aircraft conflicts, complexity, flight efficiency, SESAR.

I. INTRODUCTION

Free route is a concept that was first proposed in 2008 by EUROCONTROL, in cooperation with civil and military experts in airspace design, member states, airspace users, flight planning organizations and other international stakeholders. It consists on eliminating the fixed airways structure from an airspace block and substituting the airways by a set of defined fixes of type Entry, Exit, Intermediate, Arrival or Departure (or a combination of them). Airspace users can freely plan a route without reference to the airways network just following very simple flight rules: Flights shall enter the free route area using an Entry or a Departure fix; and Flights shall exit the free route area using an Exit or an Arrival fix. Intermediate fixes can be used to avoid non-flight zones or to follow the flight plan definition rules. Fig. 1 shows an example of the concept of a free route area extracted from [1].

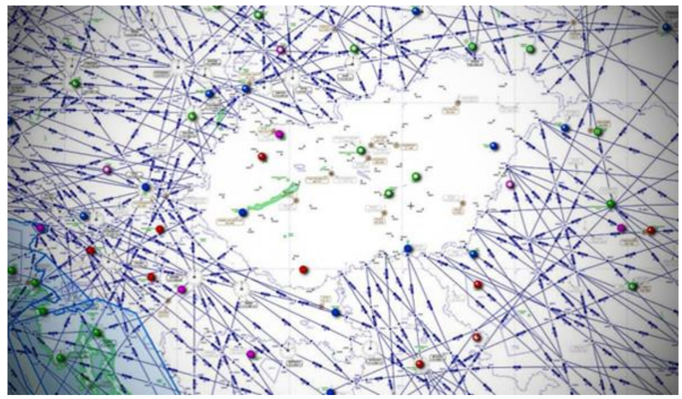

Fig. 1. Example of a free route area connected current airspace structure, based in fix navigation points and airways [1]

In coordination with EUROCONTROL, the European Air Navigation Service Providers (ANSP) are moving from the current airspace structure, based in fix navigation points and airways, to free route operations. The activation of free route is established on principles exposed in EC 677/2011 and, at the end of the year 2014, almost half of the European airspace (30 ACCs out the 64) had implemented various steps of free route. In some cases this implementations are limited to low traffic situations (nights and/or weekends) but there are several areas where free route is open 24 hours. Fig. 2 shows the plans for 2022, where free route are also planned to join the areas of several neighbor ANSP [2].

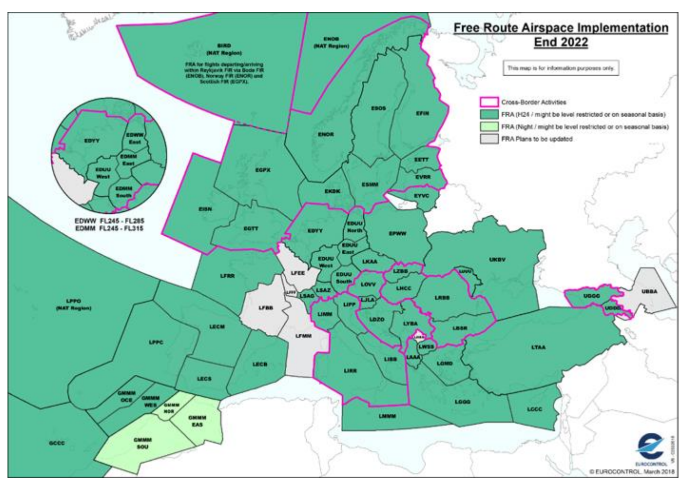

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Fig. 2. European plan for free route airspace implementation [2]

The overall benefits of free route operations are the savings of flight distance by allowing more direct routes. Savings on flight distance derives in savings also of flight time, fuel consumption and a notable reduction of jet engine emissions, which benefits to the end-users and to the environment [3-4]. These benefits can be very important for the society, with studies that showed cost reductions up to 3.8% and maximum potential reduction of emissions near 300 tons of CO2 and 1.4 tons of per year [5]. Some current deployments of free route in Europe showed to save around 25,000 NM flight distance per day (between 2-3.5% of flight distance) [6].

In this paper we design a unique free route airspace block for all the ECAC, joining all current ACCs in Europe. We study the impact of such extreme approach from three different perspectives: end-users and environmental, safety and complexity.

The paper is organized as follows: section II presents the tools used in this study and the EUROFRA design options, then section III presents the metrics to be used in the study. Section IV contains the core of the study with the simulation results. Finally Section V provides the conclusions and the future work.

II. DESIGN OF THE EUROFRA

Fig. 3 shows the ECAC area extension over a map. This border has been obtained using the internal shape files of the Network Strategy Tool (NEST) [7], a simulation tool from EUROCONTROL used mainly in the validation of new concepts related to airspace design and traffic forecast. A shape file is a text file containing the sequence of points (latitude, longitude) that define the 2-dimension limits of the area.

Using the actual airspace blocks of the AIRAC 1707 (June-July 2017) we have extracted the points which had not repetitions on any other block, meaning that they are not internal borders points, but external. Then, we concatenated the sequence of external points from one block with the correct next block until we obtain the actual shape of the ECAC.

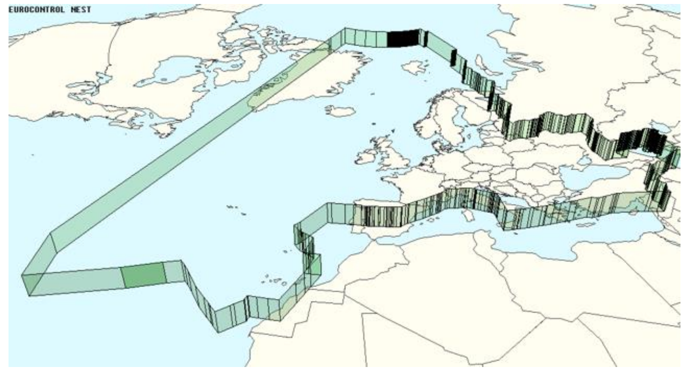

Fig. 3. ECAC shape used to define the EUROFRA area

The EUROFRA is defined as a unique airspace block for the vertical levels from FL250 to FL660. Bellow FL250 the existing airports have to be connected with the free route fixes. This was done with the creation of the Arrival/Departure fixes connecting each of the standard instrument departure (SID) and standard terminal arrival route (STAR). No approximation procedures were simulated for simplicity reasons.

On the West of the ECAC we found that current airspace was already defined as a 24 hours free route airspace. In such cases we have used the existing fixes as fixes of the EUROFRA, but converting the Entry/Exit fixes not located in the border into Intermediate fixes.

New intermediate fixes need to be defined for the rest of the EUROFRA area. They were defined using a uniform waypoint network of 2600 Intermediate fixes. The points were located every one degree apart in Latitude and two degrees apart in Longitude, which in the worst case was a distance around 60 NM. Which such configuration, the segments of a flight plan defined over this grid will be always below the 200 NM limit set by ICAO Doc 4444 for the maximum distance of a leg [8]. Fig. 4 (a) shows the design of the border (Entry/Exit) fixes and the Intermediate fixes of the designed EUROFRA.

Once the airspace was defined we imported the description files into NEST and simulated the full set of flight trajectories of one day. Fig. 4 (b) shows in red color the resulting routes for EUROFRA. Visually, one can observe how the flights are very straight. The study following aims to determine the magnitude of the benefits, but also how complex may result this new airspace structure.

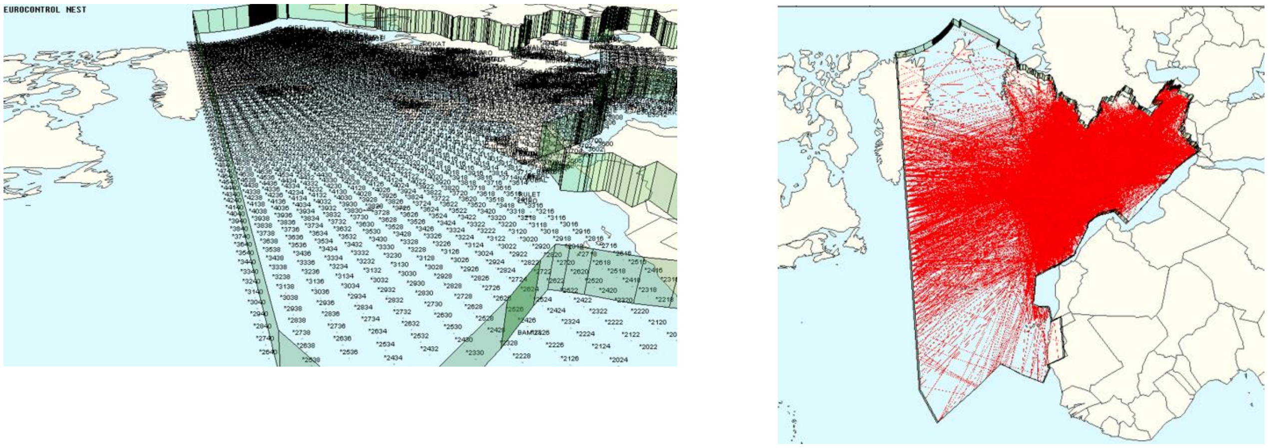

Fig. 4. EUROFRA design. On the left (a) Intermediate fixes of the EUROFRA, on the right (b) Traffic routes simulated by NEST.

III. MATERAILS AND METHODS

The research in air traffic metrics has been historically done in two main areas: safety and capacity. The potential conflicts and of the complexity of the traffic flows have a direct impact in the two areas, been both very related. In Europe the limitation of the capacity of the airspace is a safety measure applied at the strategical level. Capacity is mainly determined by the controllers' workload [9], because, despite the upgrades in the onboard systems, humans still constitute the core of the ATM system [10].

With the constant increase of the air traffic demand, the Single European Sky ATM Research (SESAR) initiative is moving towards a modernization of the airspace with directs benefits for the airspace users. An important target goal of SESAR is the increase of the airspace cost-efficiency. Free route is a concept which directly addresses this target.

A. Route inefficiency

The free route approaches the ideal air transportation system, where all aircraft could fly their optimal trajectories between airports. In 2 dimensions this is the most direct route (not considering wind conditions) from origin to destination. This optimum route will also reduce time and/or fuel proportionally. However, real world constraints such as route structure lead to aircraft flying less efficient trajectories. Reference [11] studies the sources of flight inefficiencies and presents several metrics for measuring them.

Although a free route implementation does not necessarily derives to the most direct and optimum route, it facilitates a closer approach. Compared with a structured airspace the number of re-routings is lower. Fig. 5 shows graphically the flight efficiency gain from a structured airspace to a full free route capability. Nevertheless the benefits of free route have several limitations due to the actual implementation [12]. For instance structural limitations, such as the national borders, or opening schemes, found in the current implementation of free route in Europe today limit the benefits. With the proposal of EUROFRA, where no borders, timing or flow restrictions, we aim to overcome the major part of these limitations.

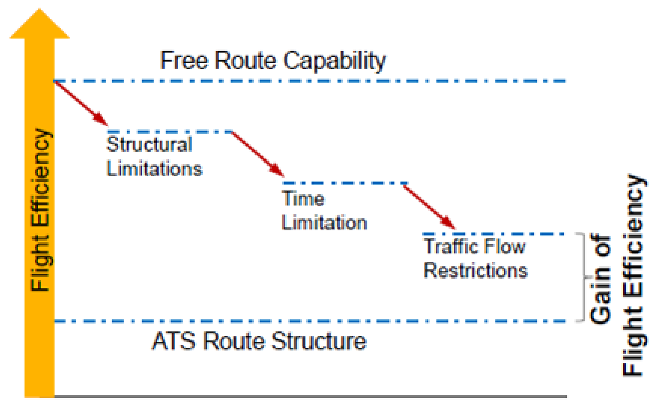

Fig. 5. Sources of route inefficiency [12]

We measure the benefits of free route in terms of distance reduction (and time, fuel and emissions) for a deeper understanding of the consequences of a complete European airspace design. Aircraft conflicts

B. Aircraft conflicts

An aircraft conflict can be defined as a "predicted violation of separation of assurance standard". In the managed airspace a conflict is produced when two or more aircrafts occupy the same altitude, within 1000 feet of one another, and come within a distance of less than 5 NM (nautical miles) of each other. Conflict detection process can be thought as the process for predicting trajectories, detecting loss of separation and deciding when action should be considered [13-14].

Conflicts are calculated for traffic cruising the EUROFRA and using the separation distances given above. We run 10 fast-time simulations adding some uncertainty on the time of the route. The first run was set to the actual departure time, whereas in the nine subsequent runs we changed the departure time of the aircraft along a Gaussian function with an average of 120 seconds and standard deviation of 120 seconds. The process first simulated the trajectory in steps of 10 seconds and then looked for possible separation losses, their duration, and the aircraft involved and the closest distance of the conflict.

The indicator used is the number of separation losses averaged for all runs. It reflects the number of traffic separation infringements that the air traffic controlled in due could managed.

C. Traffic complexity

Given that the number of conflicts do not completely figure the overall complexity of a sector, aviation communities have been very interested in developing quantifiable metrics, not only limited to potential conflicts, but affecting air traffic controller workload [15]. The notion of air traffic complexity has been introduced as '*a measure of the difficulty that a particular traffic situation will present to an air traffic controller*' [16]. Complexity of a sector is determined by the numbers of flights within it, near its border, and on non-level segments within it faces [17].

Traffic density has been the main measure of complexity for many years. Still today the comparison between aircraft entry rate and capacity is used to detect when a sector becomes overloaded [18]. Traffic density is the simplest way to measure the amount of aircraft that the air traffic controllers must keep track of and to anticipate how saturated the airspace will be. But it is well known that traffic density, by itself, is an insufficient indicator of the difficulty a controller faces.

Reference [19] proposes two types of complexity that are related with airspace and ATC systems: inherent and apparent. The inherent complexity is related with affecting factors such as weather, terrain, airspace restrictions, traffic density, traffic flows, aircraft performance characteristics, abnormal events, etc. Inherent complexity is limited to the characteristics of the traffic situation itself, and it is thus considered as a factor causing workload. Factors used to calculate inherent complexity include aircraft proximity to each other, but also to sector boundary. They also consider geometry, such as aircraft headings and aircraft speed differences, weather conditions, number of near aircraft, etc. In the other side, the apparent complexity is related with qualities of the interfaces of the controller's tools, such as mono-color and multi-color displays, touch screens, physical arrangements of displays or consoles, control room layout, software used to display information, etc. Reference [20] exposes the relation between the apparent complexity with the metrics of different performance areas such as air traffic controllers' productivity, benchmarking, cost effectiveness, new procedures impact and airspace redesign assessment.

In [21] a detailed set of metrics was proposed for a more accurate approach of the airspace situation and complexity. The authors defined the dynamic density metric, which tries to capture the complexity or difficulty of a traffic situation by considering the collective effect of all factors that contribute ATC complexity at the sector level and at any specific time.

Future refinements of the complexity calculation will depend very much on the availability of more accurate data. For that reason some new approaches consider 4D trajectories instead of linear vectors. The Trajectory-Based complexity (TBX) metric, proposed in [22] is a modified aircraft counter. Opposite dynamic density, the TBX metric can be computed easily and thus communicated in real-time, which makes it more appropriate to predict sector complexity under the business trajectory SESAR concept.

The report in [23] presents the complexity metrics used in this work, the complexity score. Two indicators define the complexity score: the adjusted density and the structural index. Both metrics are derived from measures of the traffic density, the potential number conflicts, and the specific type of potential conflict, non-exclusively classified as vertical, horizontal and/or speed interactions. Table I summarizes the dimensions they address: density, evolution, flow structure and mix of aircraft performances.

The potential interactions are given for each pair of aircraft that flight in a same three dimensions (3D) square cell of 20 NM side, and from each aircraft's point-of-view. For instance, if there are 2 aircraft in a same 3D cell, it will have a total of 2 interactions (each of the 2 aircraft present interact with the other aircraft); While a 3D cell with 3 aircraft will generate 6 interactions (each of the 3 aircraft will interact with the other 2 aircraft).

TABLE I. COMPLEXITY INDEX DIMENSIONS

Dimension	Indicator	Description
Traffic density	Adjusted density	Potential number of interactions per volume of airspace.
Traffic evolution	Potential vertical interactions (VDIF)	Potential interactions between climbing, cruising and descending aircraft (dif. 500ft).
Flow structure	Potential horizontal interactions (HDIF)	Potential interactions based on the aircraft headings (dif.30°).
Traffic mix	Potential speed interactions (SDIF)	Potential interactions based on the aircraft (dif. 30kt).

The **adjusted density** is defined as the quotient of potential interactions and flight hours, see equation (1).

$$\textit{Adjusted density} = \textit{duration of potential interactions} / \textit{FT} \quad (1)$$

where: FT is the total flight hours controlled in a cell

The duration of a potential interaction (in hours) is calculated as the total number of potential interactions multiplied by the time inside the 3D cell of each involved aircraft. The total flight hours is the sum of all the aircraft flying in the cell during the 1 hour period.

Finally, the adjusted density of a 3D cell computed for every hour is averaged, and same is done for all the 3D cells of the FRA.

The **structural index** provides a macroscopic view of the complexity of a set of traffic flows by considering the three last dimensions of the traffic: the traffic in evolution, the flow structure and the mix of speeds. It is calculated with (2):

$$\text{Structural index} = (\text{Vdif} + \text{Hdif} + \text{Sdif}) / \textit{Adjusted density} \quad (2)$$

The three components are is calculated using (3), substituting X by V/Vertical, H/Horizontal or S/Speed:

$$Xdif = \text{duration of potential x interactions} / FT \quad (3)$$

Vertical interactions are given when at least one of the aircraft is climbing or descending phase during the interaction and the vertical speeds have more than 500 fpm of difference. The horizontal interactions account for pair of aircraft with a difference of headings above 30°. Finally, the potential speed interaction takes into account only the interactions from two aircrafts crossing a cell with a speed differences greater than 35 kt.

The structural index is normalized with the adjusted density and thus has no dimension. It can be interpreted as the percentage of time a pair of flights might have potential interactions relative to the flight time. An interaction can be classified in more than one type, thus the sum of the three metrics can be greater than 1.

Finally, if the structural index and adjusted density are combined, we obtain a generic aggregation called **complexity score** (4):

$$\text{Complexity score} = \text{Adjusted density} * \text{Structural index} \quad (9)$$

The Complexity score brings a general overview of complexity in a particular airspace and traffic conditions, by considering the main two issues affecting complexity: the number of aircraft and their diversity.

IV. EUROFRA Simulation and Results

In this study one traffic sample was selected from a summer day in AIRAC 1707. In total 24,876 flight trajectories crossing the area in study were extracted from the Demand Data Repository (DDR2) [7]. These files contain the trajectories in 4D and the aircraft type, which allows to obtain time, position and nominal cruise speed for our study. The selected day is busy normal operational day without relevant contingencies, such as strikes, weather incidents, military restrictions, volcanic ashes, etc.

The results compare these flights for two configurations of the airspace: the current structured route configuration (named as Current) and the free route airspace configuration (denoted as EUROFRA). The Current results are obtained from the actual trajectories (or M3 traffic files) of DDR2. Be aware that at the selected date a number of free route airspace are already implemented across Europe, thus some benefits of free route are already included. The EUROFRA results are obtained after simulating the same trajectories in NEST using the complete European free route airspace presented in Section II. For the simulation NEST only uses the following data of the traffic sample: the origin airport, the destination airport, the desired cruise flight level and the aircraft type. With these data NEST creates the routes that optimize the distance of the flights.

In the following subsections give results of three metrics: route inefficiency, potential conflicts and complexity score. For all the charts the blue color will be used for the EUROFRA results and the green color for the Current results.

A. *Flight inefficiency*

The total length of the flights under study was reduced in 383,621 NM when comparing Current with EUROFRA, which represents a 2.2% of reduction of the route distances. This reduction can be approached to 5,274 tons of fuel, that converted to Euros (using 605 €/ton from IATA values for July 31st) represents a cost reduction of 3.19 million Euros per day.

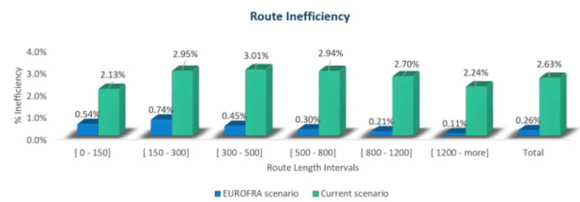

Fig. 6. Comparison of Route Inefficiency

Fig. 6 shows in more detail the comparison of both scenarios. Inefficiency is measured as the additional distance with respect to the minimal orthodromic distance that the route. Data are showed separately by route length intervals. EUROFRA inefficiencies are between 0.11% and 0.74%, always below 1%, while Current is always above 2%, reaching in some intervals more than a 3% of inefficiency. Observe that for the longest routes EUROFRA approaches very close to the optimal route, but with shorter routes the inefficiency is a little higher. Probably a thicker network of Intermediate fixes could improve those cases. Nevertheless, the values of inefficiency of EUROFRA are 4 to 20 times better than in Current.

B. *Aircraft conflicts*

Since using the actual traffic (M3 files) may seem not adequate, because it includes the air traffic controllers' actions which have ensured the separation of all aircraft, we have made the traffic more generic by introducing a variability in the departure times of the flights before calculating the aircraft conflicts. Results of both scenarios are shown in Fig. 7. Notice that the reduction of conflicts is a significant 14% from the structured airspace situation.

Fig. 7. Total number of conflicts

By looking at Fig. 8 we can observe another relevant detail. The distribution of the conflict types in EUROFRA increases for the cruise-cruise conflicts, but reduces significantly for evolving-cruise conflicts. Conflicts involving aircraft in evolutions (ascending or descending) are considered more difficult to detect, and thus their reduction can be considered as a beneficial effect of the free route airspace.

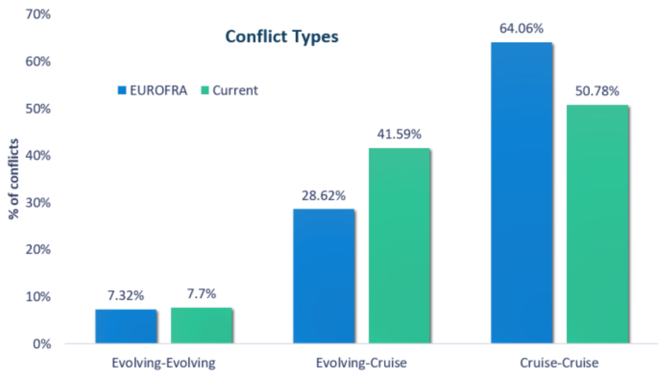

Fig. 8. Aircraft conflicts distribution according to the type of conflicts

In comparison with structured airspace, where conflicts are normally found in known merge navigation fixes or in airways crossing points, in free route the separation losses between aircrafts can emerge in any point of the airspace. As a drawback, this unexpected distribution of the conflicts may require a greater effort for solving them than in structured airspace.

C. Complexity

The general results for complexity are exposed in Fig. 9. The figure shows that the values of the complexity score are exactly the same for EUROFRA and for Current, which can be understood as no benefits and no inconvenient. But observing its two subcomponents (the second and third plots in the chart) we see that this result comes from two contrary updates.

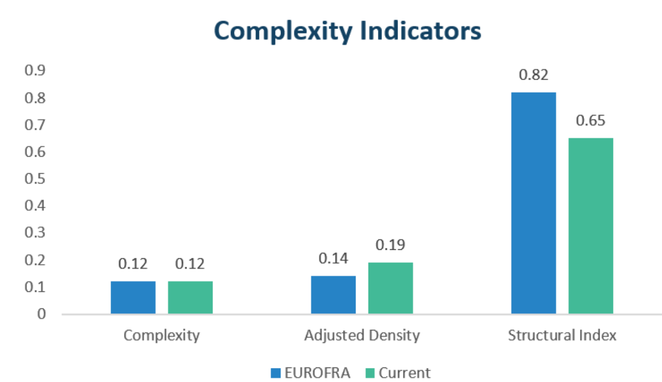

Fig. 9. Complexity indicators

First, observe that the adjusted density of EUROFRA has decreased. This is due to the wider distribution of the aircraft across the airspace, avoiding the aggregation of aircraft that happens when the airways routes are mandatory as in Current.

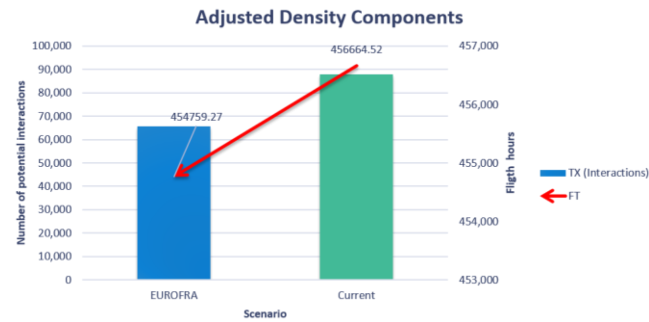

Fig. 10. Adjusted density details

Moreover, observing the values of the individual two components of the adjusted density (see Fig. 10) we find that both components have decreased. Previous results on route distance already showed the decrease of the FT (flight time), but together with this comes that the time of potential interactions has also decreased, and it has decreased in a larger rate. Again the distribution of the flights across the free route area seems to be the reason of this interactions decreasing magnitude.

Going back again to Fig. 9 we observe that the structural index has increase with EUROFRA, opposite but in the same magnitude that the adjusted density has decreased. This seems to point that the main drawback of the free route is in the interactions complexity. For this reason we conduct a closer analysis of the type of interactions as shown in Fig. 11 with the normalized Xdif metrics, this is, after dividing each of them by the adjusted density.

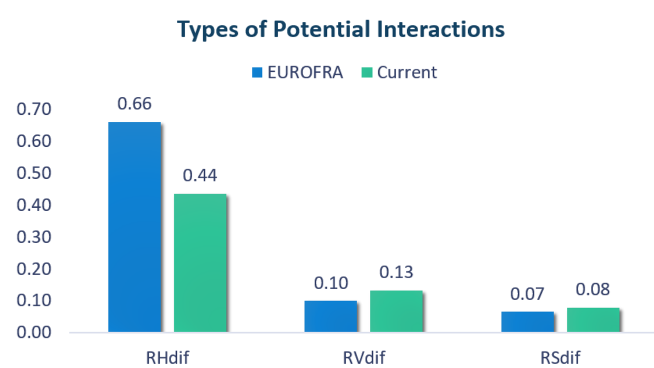

Fig. 11. Types of potential interactions

We observe, as in the conflicts analysis, that the main increments is given in the horizontal plane, while the vertical interactions decrease and the speed interactions are maintained equal. Considering that the vertical interactions are the most difficult to solve by the air traffic controllers we could conclude that the increment of the structural index is not a major drawback for the studied scenario.

V. Conclusions

Europe is progressing in the implementation of new free route areas under the SESAR program. Currently, the situation is that several free route areas are active, although some of them have limitations in the opening time. The maximum futuristic implementation would joint all state members' airspace into a unique free route area, avoiding structural limitations such as national borders. This paper simulates this futuristic implementation, named as EUROFRA, and shows that there is still room for benefits to the airspace users in terms of shorter routes.

Simulations also show that EUROFRA maintains safety and complexity indicators with values similar to the Current scenario. The results show that a full free route airspace does not increase neither the complexity values nor the number of aircraft conflicts, but EUROFRA has a potential impact in the type of traffic conflicts, which number is reduced in the vertical plane, while increases in the horizontal plane.

The work is not addressing the management issues derived from a supra-national airspace organization. Important issues arise when dealing with such large area. For instance the sectorization of the airspace to be able to assign air traffic controllers according to the expectations of the traffic demand is a very challenging problem that benefits from the divided current situation. New assignment methods aircraft-controller could be envision in a situation like EUROFRA.

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