ASSESSMENT OF THE NORTH EUROPEAN FREE ROUTE AIRSPACE DEPLOYMENT

***Abstract*— Free Route Airspace is an operational concept for the modernization of the airspace, addressed to improving the efficiency of the flights. It also aims at the environmental friendly performance area by reducing the emissions from fuel burnt. But these benefits should not derive in a loss of safety. Several areas are introducing free route as part of the Single European Sky Airspace Research programme (SESAR). This paper assesses the Northern Europe Free Route Airspace deployment, where two SESAR solutions are combined: the Free Route Airspace and the Functional Airspace Blocks. This assessment is produced using fast-time simulations and presented from a safety perspective using two indicator sets: the aircraft loss of separation and the airspace complexity. The number of potential separation losses, together with complexity metrics, such as adjusted density, potential horizontal, vertical and/or speed interactions, are presented for different free route deployment status. Results reflect that from the safety perspective the free route deployment in North Europe did not present notable changes in terms of the selected indicators, despite of the increase of traffic of last years.**

Keywords—free route airspace, separation loss, air traffic complexity, functional airspace block, performance indicators

INTRODUCTION

The air traffic forecast indicates an increase of approximately 2.2% per year, reaching a European sky with 11.2 million operations in 2021 (19% more than the 2014) (Eurocontrol, 2015). This is a challenge for the safety and for the en-route sectors capacity. The implementation of two new operational concepts, the Free Route Airspace (FRA) and Functional Airspace Block (FAB), is part of the path to an efficient European airspace. Both can be considered as relevant intermediate steps on the road to the Single European Sky Airspace Research programme (SESAR) to facilitate the implementation of business trajectories and fuel-efficient 4D profiles. The SESAR Joint Undertaking (SJU) is leading the implementation and deployment several FABs in Europe with the aim to improve the air navigation services performance (ACE, 2006), but with unequal results (Button and Neiva, 2013). According to the first an 11% of the en-route flight inefficiency are attributable to the fragmentation of airways between states within each FAB; and an additional 25% are attributable of the fragmentation between FABs.

In coordination with Eurocontrol and the Air Navigation Service Providers (ANSP), the European airspace is, at the same time, moving from the current airspace structure, based in fix navigation points and airways, to a new airspace structure oriented to free route operations. The activation of FRA is established on principles exposed in EC 677/2011 and, at the end of the year 2014, almost half of the European airspace (30 Area Control Centers out the 64) had implemented various steps of free route. The overall benefits of free route operations are distance and flight time savings, deriving in less fuel consumption and a notable reduction of jet engine emissions which benefits the environment (Aneeka and Zhong, 2016). These benefits are important for the society, but very relevant for the airspace users, reaching a cost reduction up to 3.8% if applied to full Europe (Bentrup and Hoffmann, 2016). Specific FRA partial deployments allowed to save around 25,000 NM flight distance per day (between 2-3.5% of flight distance) (Nava-Gaxiola and Barrado, 2016).

In a FRA airspace users freely plan a route between the defined Entry and Exit fixes, with the possibility of routing via Intermediate points. A FRA has also Arrival and Departure fixes available, but does not have airways. The free route flights remain subject to air traffic control (ATC) for the separation provision and flight level change authorizations. With the combination of the two concepts (FAB and FRA) the air traffic controllers are assuming important modifications on their day-to-day activity. To assess the new concepts the Air Traffic Management system (ATM), ICAO proposes the use of Performance Indicators. In Europe, the Commission Regulation No 691/2010 defines its own Performance Framework, being the safety performance area of main interest. Safety performance indicators include concepts such as compliance and maturity, but also number of airspace events per flight. In particular, the number of occurrences of Separation Minima Infringements at en-route is used with some limitations. Since separation incidents are very infrequent and they can be produced by a number of external factors during the tactical phase, in this paper we propose the use of the potential separation infringements found in the pre-tactical trajectories as a proxy for the airspace safety. Moreover, the complexity of the traffic flows are used as a second safety proxy indicator.

In this paper is assessed one of the largest FRA in Europe, the Northern Europe Free Route Airspace (NEFRA). NEFRA is formed by two FABs: the North European FAB (NEFAB) and Danish-Swedish FAB (DK/SE FAB); and six countries: Norway, Finland, Estonia and Latvia from NEFAB, and Sweden and Denmark from DK/SE FAB (also known as NUAC). The evaluation aims to provide the evolution of safety by determining how complex this airspace evolves while the FAB and the FRA concepts are combined and operating together. As an added value with respect to previous studies, the paper shows for the first time some joined results of the FRA deployment in two interacting FABs.

The structure of the paper is the following: Section 2 exposes the research of the literature related with conflict detection and with complexity. The third section describes the metrics and the traffic data used for the assessment. Then, the section 4 presents the simulation results. Finally, in section 5 conclusions and future work are exposed.

RELATED WORK

The research in air traffic metrics has been historically done in two main areas: safety and capacity, both very interrelated. In the safety area, the main indicators are the number of occurrences, this is, violations of aircraft separation, collision avoidance alerts and incidents. All of them are a posteriori indicators which can rarely be anticipated, and usually involve abnormal situations such as human errors, aircraft contingencies, strong weather conditions or ATM system failures (Vogel et al., 2013). As a priori safety measure the capacity is used in Europe as part of the safety net applied. Despite the upgrades in the onboard systems, humans still constitute the core of the ATM system. Thus, the capacity is mainly determined by the controllers' workload (Majumdar, 2005). But ATC's workload is a subjective value and can be measured only during the ATC activity. Simulations are a very frequent tool to assess the limits of the workload. And finally experience is used to fix a capacity to each sector. Admitting a number of aircraft in a sector higher than its capacity is considered as not safe, and delays or re-routings are applied to avoid it. In a posteriori assessment, indicators on capacity compare the aircraft entry counts with the capacity. It is considered as convenient an entry count at the 80% of the capacity. Higher values can compromise safety if prolonged too long, while lower values are considered as inefficiency of the ATM resources.

A large number of research works in the area of conflict detection exist (De Prins, 2008). They model the aircraft trajectory using 4D vector geometry, and determine the closest point of approach between two linear segments and the time remaining until the protection separation standard is violated. If the closest point of approach is less the minimum distance and the time remaining for the separation loss is within a look ahead window, then a conflict is declared. Conflict detection methods are embedded in current short-term collision avoidance tools. This tools can help the ATC in anticipating conflicting situations, but they are rarely used to evaluate a priori situations, because of the lack of predictability at the tactical level.

Many studies focus in the structured airspace, where conflicts are normally found in known merge navigation fixes or in airways crossing points. Air traffic controllers solve potential loss of separations with vectorizations, altitude or speed changes or re-routing to alternate network fixes. In FRA the separation losses between aircraft can emerge in any point of the airspace. The ELSA project (Gurtner et al., 2017) built an agent based air traffic simulator to evaluate new air traffic operational concepts. Using simple software agents ELSA simulated mechanistic controllers. The project conducted several runs with close to 2 thousand synthetic trajectories derived from historical planned flights of the area of central Italy. Strategical and tactical levels of de-conflicting were examined. The results were given by counting the actions required by the ATC agent. This number was defined as a new complexity indicator, and was compared with another 20 metrics from literature. They found that, in free routing, the air traffic controllers perform less operations, but these actions are more disperse over a large portion of the airspace. This disperse factor can potentially increase the complexity of the air traffic controllers' work, and thus their workload. Results also showed the existence of a quadratic relation between this complexity indicator and the density. Using regression and principal component analysis techniques authors also show that the four metrics from (Chatterji and Sridhar, 2001) were directly related with the number of ATC agent actions, validating in this way the ELSA proposal.

Given that the number of conflicts do not completely figure the workload of the air traffic controller, aviation communities have been very interested in developing new quantifiable metrics using the term complexity (Kopardekar et al., 2009)(Vogel et al., 2013). The air traffic complexity aims at being '*a measure of the difficulty that a particular traffic situation will present to an air traffic controller*' (Schäfer and Modin, 2003), but is implemented with a large number of metrics: in (Gurtner et al., 2017) is "the number of controller's actions" used for separating the traffic by a simulated ATC agent, while in (Flenera et al., 2007) it is determined by the numbers of flights within a managed sector, near its border, and on non-level segments.

(Toy, 2015) 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. 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) metrics is a modified aircraft counter. The main advantage of the TBX is that it can be computed easily and thus communicated in real-time. This fact makes TBX very appropriate to predict sector complexity under the business trajectory SESAR concept.

The Eurocontrol's working group on complexity defined a new indicator, the complexity score (ACE, 2006). Two main metrics define the complexity score: the adjusted density and the structural index. The adjusted density evaluates the potential interactions resulting from density, including uncertainty in the trajectories and time, while the structural index balances the density metrics according to the interaction geometry and aircraft performance differences. The metrics used reflect the difficulty to manage the presence of several aircraft in the same area at the same time, particularly if those aircraft are in different flight phases, have different performances, and/or have different headings.

NORTHEN EUROPE FREE ROUTE AIRSPACE DEPLOYMENT

The NEFRA programme was established on 11th March 2013. Six states of two Functional Airspace Blocks, the Denmark-Sweden (DK/SE FAB), and the Norway, Finland, Estonia and Latvia (NEFAB), signed a declaration of commitment in airspace development. They committed themselves to undertake necessary actions to ensure implementation of the FRA concept above FL 285 in the joined airspace, named as NEFRA. In the Norway airspace, BODO oceanic will be considered apart, within the ICAO NAT region. In (Holstila and Andersso, 2015) we can see details of the work done for the design and implementation of NEFRA, after a consultation process involving 18 stakeholders.

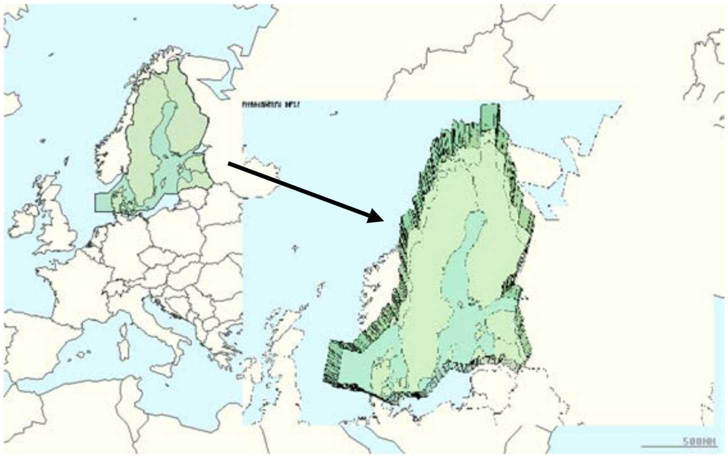
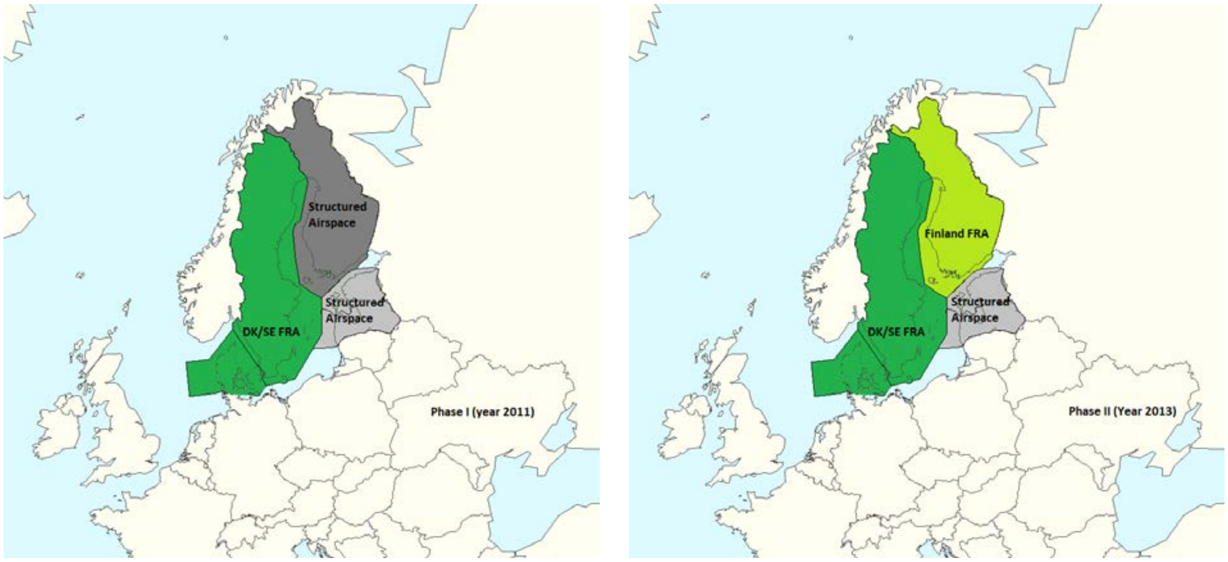


Fig. 1. The NEFRA area used for this study

Over 2500 flights are crossing NEFRA every day. Due to geographical location (see Fig. 1) NEFRA is used as a bridge to the East for flights between Europe and Asia, and to the West to connect North European flights with North America. The full plan completes in year 2020 when NEFRA will evolve to the Borealis FRA and offer joint free route airspace from FL285 to FL660 of all six countries. But before the programme started, each of the ANSP participating in NEFRA had already plans to implement the free route airspace concept following different approaches. The diversity of the lower limits established for each FRA range from the FL95 of former joint FRA between Finland, Estonia and Latvia, to the FL285 of the FRA in DK/SE FAB. In between Norway defined two FRA, one on the continental airspace with lower limit in FL135, and a second one in the oceanic airspace over FL195.

In consequence, the NEFRA project is planned to developing by stages: spans from the pre-NEFRA stage starting in 2011, until the ultimate full integrated NEFAB, and passing through the actual inter-FAB free route block currently active as NEFRA. NEFRA includes the following area control centers: EFIN (Finland), ESAA (Sweden), EKDK (Denmark), EETT (Estonia) and EVRR (Latvia). The Norwegian FRA is still managed separately and thus, its traffic is not included in this assessment. In Fig. 2 the four different stages are exposed, in green color the areas with free route and in grey the areas with structured airspace. They constitute the different scenarios which will be evaluated in this paper:



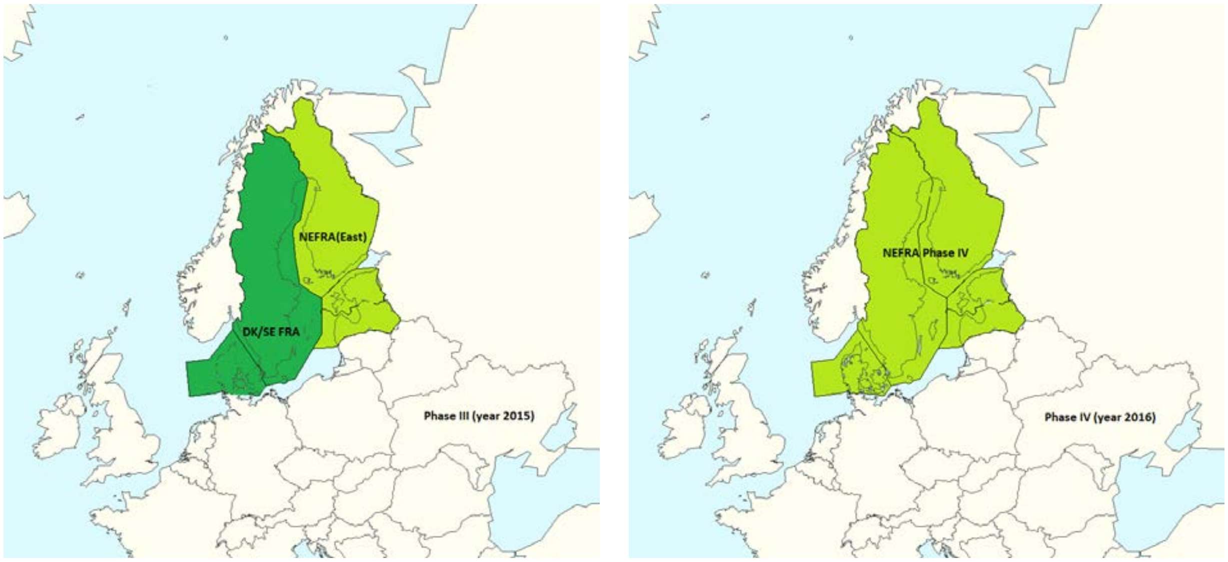


Fig. 2. Deployment Phases of NEFRA

Phase I is the pre-NEFRA stage in which only the Denmark and Sweden FAB has FRA implemented. This is a 52% of the airspace. Phase II corresponds with the first stage of NEFRA programme, when Finland deploys FRA in its airspace (36%). In phase III Latvia and Estonia join the Finland FRA as unique ATM block, the NEFAB (East). At this point the two FRA covert the 100% of the airspace, but they are still managed separately by the two FABs. Finally phase IV shows the current situation in which the FRA is managed in union of the 2 FABs.

MATERIALS AND METHODS

With the objective of assessing the evolution of the NEFRA across its 4 phases of deployment, we extract the actual traffic (or M3 traffic files) from the Demand Data Repository (DDR2) from Eurocontrol. These files contain the 4D trajectories crossing the selected airspace, and the aircraft type. Three different days for each of the four phases are selected. In total, twelve traffic days are extracted. The selected days are arbitrary normal operational days, avoiding holydays and days with contingencies, such as ATC strikes, weather incidents, military restrictions, volcanic ashes, etc. Only en-route NEFRA crossing traffic in considered. For Phase I we selected the oldest month available in DDR2, this is, December 2011. We choose two Fridays (16th and 23rd) and the Thursday in between (22nd). Then, for the other phases, three similar days (day 22nd and the two close Fridays) of same month of December on the following years (2013, 2015 and 2016) were also selected. The number of flights of each set of trajectories goes from 1,903 aircraft to 2,466 aircraft, increasing this number with the years. These numbers and the flight dates are shown in TABLE I

TABLE I CHARACTERISTICS OF REAL TRAFFIC USED FOR THE ASSESSMENT

Phase / year	Sample	Date	Weekday	# Flights	# Flight hours
Phase I / 2011	1	DEC 16th	Friday	2076	14055.45
	2	DEC 23rd	Friday	1918	13040.88
	3	DEC 22nd	Thursday	1903	13040.88
Phase II / 2013	1	DEC 13th	Friday	2352	15966.42
	2	DEC 20th	Friday	2319	16410.66
	3	DEC 22nd	Sunday	2169	15117.07
Phase III / 2015	1	DEC 11th	Friday	2381	15400.51
	2	DEC 18th	Friday	2340	14961.54
	3	DEC 22nd	Tuesday	2081	13804.59
Phase IV / 2016	1	DEC 09th	Friday	2390	15803.7
	2	DEC 16th	Friday	2451	15838.76
	3	DEC 22nd	Thursday	2466	15970.68

For each of these dates, indicators on safety and complexity are obtained using the Network Strategy Tool (NEST) (Eurocontrol, 2017). We assume that the benefits provided by the FRA concept, in terms of cost-efficiency and environment, are already proven (Nava-Gaxiola and Barrado, 2016), thus we want to assess that FRA does not compromise safety. Two suitable indicators are already available on NEST: First, the number of flight conflicts defined as aircraft separation lost, and second, the set of complexity metrics needed for calculating the complexity score.

AIRSPACE SAFETY: NUMBER OF SEPARATION LOSSES

The chosen safety indicator evaluates the potential conflicts of the air traffic as the number of the separation losses of the aircraft trajectories. The parameters of a separation loss are set to 5 NM in horizontal and 1000 ft in vertical. Since the actual historical traffic traces are actually de-conflicted by the air traffic controllers, no conflicts are found. For this reason, we run 10 fast-time simulations with the addition of some uncertainties. 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. Each run first simulates the trajectory in steps of 10 seconds and then looks for possible separation losses between pairs of aircraft. Moreover, NEST is able to calculate the conflict duration, the aircraft involved and the closest distance of the conflict.

The final safety indicator is computed as the number of separation losses averaged for all runs. It reflects the number of potential traffic separation infringements that the air traffic controlled in due must managed. The duration of the separation loss is used to classify a specific traffic sample as more or less complex in terms of air traffic controller workload.

AIRSPACE COMPLEXITY

This assessment uses the Eurocontrol complexity score (ACE, 2006) as airspace complexity indicator. Two main metrics define the complexity score: the adjusted density and the structural index. The structural index is derived from 3 other metrics of the potential number conflicts in specific situations classified as vertical, horizontal and mix of aircraft performances. The term potential refers to the probability that the coincidence of two aircraft in an area may happen during one hour period. The potential interactions can have additional complexity if they involve aircraft in evolution (vertical interaction or VDIF), in horizontal flights for headings of more than 30 degrees of difference (HDIF) and/or combining aircraft with different performances (SDIF). TABLE II summarizes them.

TABLE II COMPLEXITY SCORE INDICATOR COMPONENTS (ACE, 2006).

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

We have calculated them for the en-route traffic in NEFRA, excluding the traffic in the terminal areas. The calculations are done in airspace volume in 3D cells of dimension of 20 NM x 20 NM x 3000 ft. Twelve shifts of 10 NM horizontal and/or 1,000 feet vertical are applied to the 3D cells grid and mean of the results obtained to avoid frontier concerns. The complexity is computed separately for each cell and for discretized 60 minute periods, and finally averaged.

AJUSTED DENSITY

The adjusted density is defined as the quotient of two time periods: the duration of all potential interactions and flight hours, as shown in equation (1). The potential interactions are measured for each pair of aircraft 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. 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. Finally, the total flight hours in cell is the sum of the flight segments duration for all the aircraft crossing the cell during the hour period.

STRUCTURAL INDEX

Structural index depends on three type of complex interactions: horizontal, vertical and speed interactions. The horizontal interactions (HDIF) assesses pair of aircraft depending on their relative headings. Only pairs of aircrafts with a difference greater than 30° heading are considered. The vertical interactions (VDIF) measure only the interactions when aircraft in a climbing/descending phase have vertical speeds with more than 500 fpm of difference, including situations in which one of the aircraft is in cruise. Finally, the speed interactions (SDIF) provides a value of the mix of aircraft types. It considers pairs of interacting aircraft only if their different speed performances are greater than 35 kt in nominal cruise. The HDIF, VDIF and SDIF expressions are given in (2), (3) and (4).

$$HDIF = \text{duration of potential horizontal interactions} / \text{total flight hours in cell} \qquad (2)$$

$$VDIF = \text{duration of potential vertical interactions} / \text{total flight hours in cell} \qquad (3)$$

$$SDIF = \text{duration of potential speed interactions} / \text{total flight hours in cell} \qquad (4)$$

The previous indicators are transformed to relative indicators by the next equations (5), (6) and (7). These relative indicators can be interpreted as the percentage of potential interactions which are vertical, horizontal or due to the speed differences. An interaction can be classified in more than one type, thus the sum of the indicators can be greater than 1. Actually this sum (8) is

$$R_{VDIF} = VDIF / \text{Adjusted density} \qquad (5)$$

$$R_{HDIF} = HDIF / \text{Adjusted density} \qquad (6)$$

$$R_{SDIF} = SDIF / \text{Adjusted density} \qquad (7)$$

$$\text{Structural index} = R_{VDIF} + R_{HDIF} + R_{SDIF} \qquad (8)$$

the definition of the Structural index and it provides a macroscopic view of the complexity of the set of traffic flows in the area. The maximum would be 3 if every interaction met all the criteria.

COMPLEXITY SCORE

Finally, the Structural index and the Adjusted density are combined as in (9) to obtain the generic aggregation called Complexity score. The Complexity score brings a general overview of complexity in a particular airspace and traffic conditions by

$$\text{Complexity score} = \text{Adjusted density} \times \text{Structural index} \qquad (9)$$

considering the main two issues affecting complexity: the number of aircraft and their diversity.

RESULTS

The traffic evolution in NEFRA during the 5 years of the progressive introduction of the free route has been increasing in number of aircraft a 24% from 2011, with some temporary reduction during Phase III. The number of flight hours has also increased, but with a lower ratio (18.6%). Thus, the mean number of flight hours per aircraft, has a decrease of 4%. Details are given in the first three rows of TABLE III . This agrees with the expected effect of free route, where flights can have more direct routes, and therefore, faster flights. In the following sections we assess if this improvement in efficiency does not compromise the safety or the airspace using the two indicators presented in the previous section.

SEPARATION LOSSES

In the last two rows of TABLE III the number of separation losses are given for each of the four phases, first the absolute value and then relative to the number of aircraft. Both are mean values for the 3 days of each Phase.

TABLE III NEFRA PHASES TRAFFIC AND NUMER OF SEPARATION LOSSES

	Phase I	Phase II	Phase III	Phase IV
Mean #AC per day	1966	2280	2267	2436
Flight Hours	13379	15831	14772	15871
Mean FH/AC	2.27	2.31	2.17	2.17
# Separation Losses	91	112	97	96

Separation Losses per 100 AC	1.54	1.64	1.43	1.31

The overall results shows that the number of potential encounters between aircraft maintain similar values through the sequential phases, except for the increment of Phase II. Comparing this phase with Phase I we observe a significant increase on traffic while maintaining the borders for the three areas involved. In contrast, for Phase IV with even more number of aircraft, the situation becomes with an increase of this safety indicator (the best of all 4 phases) due to the full integration of 5 countries in NEFRA without any borders and with full FRA.

Moreover, analyzing the details of the separation losses found by the simulation, we observe that the duration of the separation losses has a high variance. Fig. 3 represents with a box-plot diagram the distribution of these durations for each simulated day. For readability, each phase have been linked with a color. The duration of a separation loss gives the measure of the level of the safety compromised by it. Notice that these durations are less than 15 seconds for all encounters in the majority of the days. Only some days of Phase II and Phase III show values above the 20 seconds. In contrast, all days of Phase IV, with the final free route deployment, have very short encounters duration (from 2 to 12 seconds) and outliers was been drastically reduced.

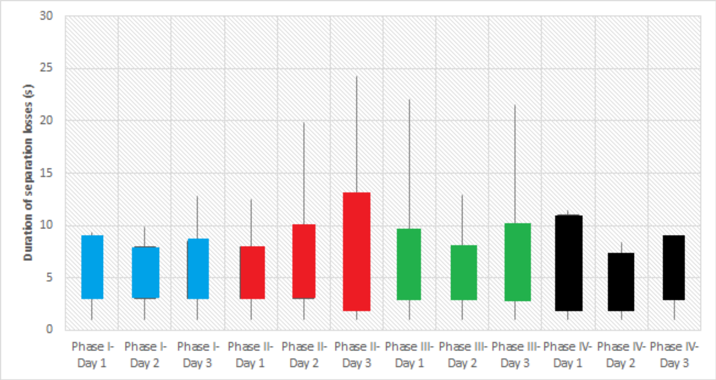


Fig. 3. Distribution of the duration of separtion losses

The results show the benefits of the deployment of the inter-FAB free route in terms of potential flight encounters given the more spread nature of the flight routes in FRA.

ADJUSTED DENSITY

The adjusted density results are shown in Fig. 4. Values of the adjusted density metrics are given together with the two time components of its equation. The right vertical axis is the scale for the adjusted density, while the left axis shows the accumulated durations in hours.

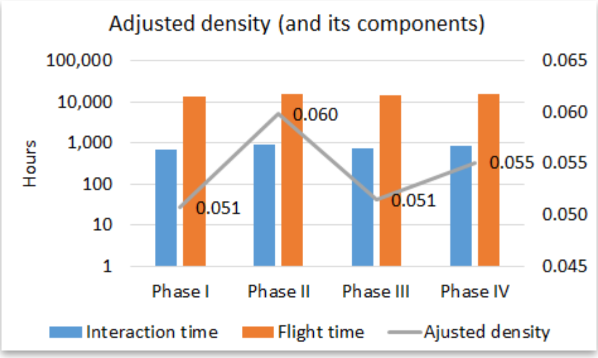


Fig. 4. Adjusted density values

We can observe that, in the logarithmic scale, the duration of the interactions and of the flights have similar absolute values for all NEFRA phases, but their relative values (the adjusted density) are higher for phases II and IV. Both phases had high traffic density, with phase IV having 7% more aircraft than phase II, but this is not the same for the adjusted density values, being an 11% higher in phase II than in phase IV. This shows that the aircraft density and the adjusted density are not directly linear functions, and can provide different assessments of a same traffic situation.

Nevertheless, there is a general correlation trend between the duration of the potential interactions and flight hours used to calculate the adjusted density metrics and approximately for every 10 hours of flight, there are potential interactions that span for one hour duration (regression with R^2=0.88, t=0.27).

Adjusted density results show that interactions are not only related with the traffic volume, but also with how this traffic is dispersed in the airspace, and with the more advanced deployment of the FRA we observe that the time duration of the interactions decreases in relation to the traffic.

STRUCTURAL INDEX

The complexity of the air traffic is based in the geometries of the traffic flows. To make it independent from the traffic density we used the relative values of the different types of potential interactions. Fig. 5 presents the results of the three relative complexity metrics calculated in accordance with equations (5), (6) and (7) of section IV. Each type of interaction can fall into the vertical, horizontal and/or speed categories depending on the attitudes, altitudes and speeds of the interacting aircraft.

Results indicate that these values, the R_{HDIF}, R_{VDIF} and R_{SDIF}, do not present significant changes between phases. Thus, the progressive deployment of the free route (from Phase I to Phase IV) has not strongly changed the geometries of the flows intersections. Therefore the complexity, very relevant in relation with the workload of the air traffic controllers, seems not compromised. In particular, vertical interactions are the less frequent interactions in all the phases. This fact is expected in cruise flight levels as found in the FRA.

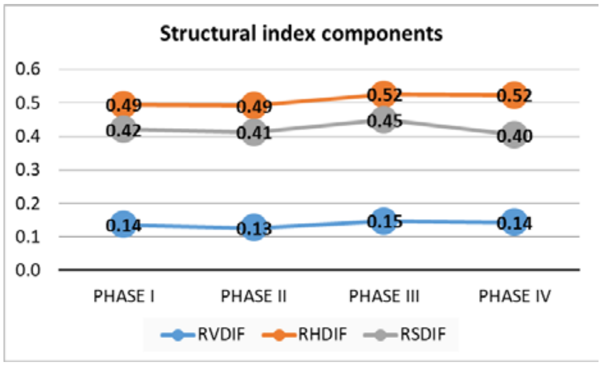


Fig. 5. Type of interactions results

The final values of the Structural Index are the given in TABLE IV . The lowest value is for phase II and the highest is for phase III, without a clear trend over time. When looking at the individual values per day it can be observed that they are very similar, with values between 1.0 and 1.2 except for two days (one of phase II and another of phase IV) which had a value bellow 1. No clear trends can be seen over the NEFRA deployment.

TABLE IV STRUCTURAL INDEX

	Phase I	**Phase II**	**Phase III**	**Phase IV**
Structural index	1.051	1.030	1.121	1.069

COMPLEXITY SCORE

Complexity score is directly related to the 2 previous metrics presented: the adjusted density and the structural index. It tries to provide a global indicator of the traffic encounters geometries and the actual traffic density. Results are shown in Fig. 6 per phase and per day.

They show that there is not notable increment of values of the complexity score, which stays in similar values, from 0.053 to 0.061, during all 4 phases. The lowest complexity score is for phase I, when the traffic volume is the lowest. Although the highest value of the complexity score is for last day of phase IV with a value of 0.066, the worst mean is given in phase II with a complexity of 0.061. This is an increase of 15% more than in phase I, and is very similar to the traffic increase. Comparing the last 2 phases, in which the only airspace difference is due to the elimination of the FAB border impact, we observe a significant traffic increase with no affections on the safety indicators. It seems that complexity does not have a negative trend during the deployment of the FRA on the North European airspace, since there are not notable increments of the complexity values although the number of flights have been increase in a 20% approximately from Phase I to Phase IV.

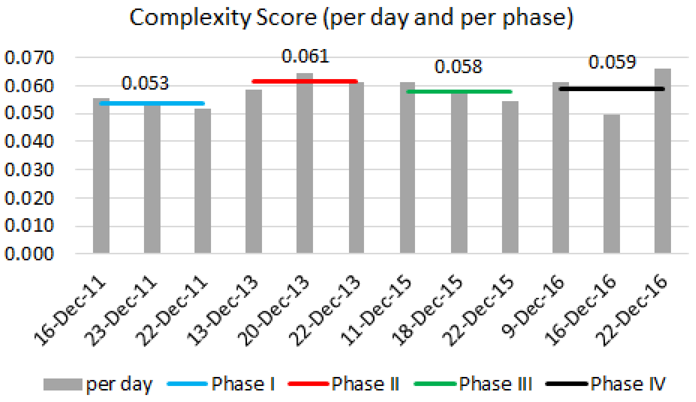


Fig. 6. Complexity Score

Fig. 7 shows the details of the values of the individual component used to calculate the complexity score. In the vertical axis we have the structural index and the horizontal axis the Adjusted Density. It can be observed that the values of the complexity index and of the adjusted density do not have any direct relation. This independency was already formulated in section III. In general, results also indicate that the structural index and adjusted density do not present peaks or notable increments during NEFRA development, even with the constant traffic increment.

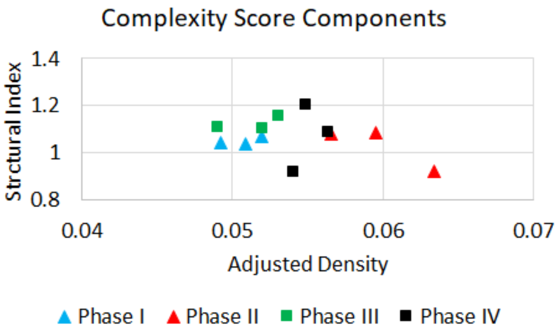


Fig. 7. Relation between complexity index compoments

TABLE V summarizes the main indicators of this study. Phase II has the worst safety indicators values, both on number of separation losses and complexity score. Although not following a linear rule, the two indicators seem to behave similarly trend. This starts with lower values in phase I, then a relevant increase in phases II which can be due to the traffic increase. But then, for phases III and IV, with similar o higher levels of traffic, the tendency is to improve the safety indicators although not reaching the levels of phase I. Comparing the last 2 phases, in which the only airspace difference is due to the elimination of the FAB border impact, we observe a significant traffic increase with no affections on the safety indicators.

TABLE V SUMMARY OF THE VOLUMEN AND SAFETY INDICATORS

Indicator	Phase I	Phase II	Phase III	Phase IV
Mean number of aircraft	1966	2280	2267	2436
Number of separation losses	91	112	97	96
Complexity Score	0.053	0.061	0.058	0.059

CONCLUSIONS

In airspace design the safety is a must. Several indicators are proposed to measure safety, but in general they are a-posteriori measures. Extensive simulations, with and without human-in-the-loop, have to be done to anticipate the safety of a new concept. Another way to approach the safety is with complexity indicators which can give an approximation to the workload involved in resolving situations that can compromise the safety. In this paper we measure the safety of the join deployment of the free route airspace concept at two FABs in the North of Europe, named as NEFRA. We use actual traffic trajectories belonging to the different deployment phases of NEFRA, at which we add some uncertainty and evaluate potential encounters using a fast-time simulation tool. Results on safety are given with two indicators: the number of separation losses and the complexity score. They indicate that safety levels have not changed in a significant way during the several phases of NEFRA deployment, on the contrary, the traffic characteristics of the area resulted in improved indicators as the FRA extended across FABs.

The results of this study on complexity metrics show a direct relation between traffic flight hours and potential interactions. Also, although the complexity score shall not be dependent on the density of the traffic, further studies must be performed using statistical tools to justify some values in which the both values seem related. Still, the actual co-relation between the inherent complexity indicators and the air traffic controllers’ workload shall be completed with the inclusion of apparent complexity metrics. Otherwise, the complexity indicators used to assess a new concept of operations will not be confident enough to measure the actual level of safety.

The extension of the FRA and the FAB concepts are in the current roadmap of the SESAR Master Plan for the European single sky. Both concepts have shown to provide good advantages to the airspace users in terms of cost reduction and both have shown to be mutually compatible and beneficial.

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