Influence of FRA implementation on Traffic, Safety, Complexity and Workload in MUAC Airspace

Tamara Pejovic*
EUROCONTROL,
Aviation Intelligence & Performance Review
Brussels, Belgium
tamara.pejovic@eurocontrol.int

Dusan Crnogorac
University of Belgrade, Faculty of Transport and Traffic Engineering
Computer Center
Belgrade, Serbia
crni@sf.bg.ac.rs

Fedja Netjasov
University of Belgrade, Faculty of Transport and Traffic Engineering
Division of Airports and Air Traffic Safety
Belgrade, Serbia
f.netjasov@sf.bg.ac.rs

***Abstract*—Air traffic performance of the European air traffic system depends not only on traffic demand but also on airspace structure and its traffic distribution. These structural (airspace structure) and flow characteristics (factors such as traffic volume, climbing/descending traffic, mix of aircraft type, military area activity) influence airspace complexity, which can affect controller workload and influence the probability of safety occurrence. In other words, all these dynamic and static complexity components can potentially have an impact upon the safety of the air traffic management system. Previously defined benchmark analysis was used on MUAC airspace to test how performance indicators, could be used to asses operational and safety performance, and for assessment of potential benefits of operational environment changes in airspace due to implementation of Free Route Airspace (FRA). MUAC case study results have shown that positive correlations exist between: a) traffic, complexity and workload; b) potential losses of separation and conflict risk; and c) complexity and workload. More specifically, changes in traffic demand and traffic patterns do influence complexity, workload as well as safety performance. Analysis has also shown that there is a strong interdependency between these parameters on the example of FRA implementation.**

Keywords- air traffic complexity, controller workload, conflict risk assessment, air traffic management, safety performance

I. INTRODUCTION

Air traffic in the European airspace continued to grow for the sixth consecutive year in 2019, making last year a new record year in terms of traffic volume: the number of flights controlled reached an all-time record of more than 11.1 million [1]. The forecast growth (pre-COVID-19) indicated that by 2021, the European sky will handle over 12.3 million operations [2]. This is an incredible challenge for the safety, the en-route sector capacity and impact on the environment.

The implementation of two operational concepts, the Free Route Airspace (FRA) and Functional Airspace Block (FAB), are seen as crucial 'tools' for solving those issues. By definition, FRA is a specified airspace wherein users can freely plan a route between a defined entry point and a defined exit point, with the possibility of routing via intermediate (published or unpublished) waypoints, without reference to the air traffic service (ATS) route network, subject of course to availability. Within such airspace, flights remain subject to air traffic control (ATC) for the separation provision and flight level (FL) change authorizations. The overall benefits of free route operations are distance and flight timesaving, resulting in less fuel consumption and a notable reduction of engine emissions, which benefits the environment [3]. In addition, safety performance improvements are expected, due to fewer conflicts, as the same number of aircraft should be spread over more routes. Namely, Netjasov et al. [4] on FAB Europe Central (FABEC) example and Pejovic et al. [5] on Northern Europe Free Route Airspace (NEFRA) example, have shown, that the application of FRA concept could have a positive influence on safety performances relative to structured routing.

Operational performance of European air traffic system depends on traffic demand but also on airspace structure and its traffic distribution. These structural (e.g. airspace, procedure) and flow characteristics (e.g. traffic volume, climbing/descending traffic, mix of aircraft type, military area activity) influence airspace complexity, which can affect controller workload and influence the probability of safety occurrence. In other words, all these dynamic and static complexity components can potentially have an impact upon the safety of the air traffic management (ATM) system. In order to analyse interdependencies between traffic changes (both in terms of volume and patterns) and safety, complexity and workload, analysis of correlations between various parameters was done on the example changes with introduction of FRA. Potential impact of FRA implementation on safety, complexity and workload was estimated using spatial and correlations analysis of realised traffic before and after implementation of FRA in Maastricht Upper Area Control Centre (MUAC, as part of FABEC) airspace (June 2017 to 2019).

II. STUDY APPROACH

Objective of this research is to study potential impact of implementation of FRA and interdependencies between traffic, safety, complexity and workload within MUAC. To analyse how future changes in airspace structure and traffic flow could influence complexity and safety performance, a showcase methodology for analysing safety and complexity performance

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in FABEC airspace in 2017, before full FRA implementation was proposed in [6, 7, 8].

The current study is a follow up, zooming into a smaller airspace and adding air traffic controller (ATCo) workload in the scope of analysis. More precisely, as a use case for analysis of interdependencies between traffic demand, safety, complexity, and ATCo workload, MUAC airspace was selected and analysis focused specifically on relationships around implementation of FRA: 1) safety performance analysis zooming into changes in number of potential Losses of Separation (pLoS) and conflict risk, 2) analysis of pLoS characteristics, 3) analysis of complexity and Workload, 4) analysis of complexity and safety with flight level change, and 5) analyses of correlation between traffic, complexity, safety indicators and workload.

Overall, MUAC analysis served as a test case of how performance indicators (existing and the new ones) could be used to assess operational and safety performance, and hence identify advantages and benefits of such operational concept changes.

III. Assessment of complexity, safety performances and ATCo workload

Air traffic complexity is estimated using the EUROCONTROL complexity methodology developed for ANSP benchmarking analysis [9], while safety performance, measured by changes in number of pLoS and conflict risk, is assessed using the Conflict Risk Assessment Tool [4].

Complexity methodology approach is taking a macroscopic view, and it is considering four complexity components: adjusted density, potential vertical, horizontal, and speed interactions (which form the structural index). A single metric, ‘complexity score’, which incorporates these four separate parameters, was considered as the simplest for benchmarking purposes [9].

Conflict Risk Assessment Tool is intended for the analysis of realized air traffic, consisting of flight trajectories crossing a given airspace, with the aim of assessing safety performance. It contains separation violation detection module [4] which simulates flights (following discrete simulation logic with constant time steps) and compares the actual separation of aircraft following predefined flight trajectories (both in horizontal and vertical planes) with a given separation minima in order to detect pLoS. pLoS is defined as situation when two aircraft come closer to each other than a specified minimum distance both in the horizontal and the vertical plane.

ATCo workload was assessed using the Macroscopic formula embedded in Network Strategy Tool (NEST) and as its name indicates, the workload evaluation is performed at a macroscopic level, i.e. only a few controller tasks are considered. This formula is originally based on method which splits workload into three main groups; routine tasks, climb and descent monitoring, and conflict monitoring [10, 11].

Macroscopic formula in NEST, however, estimates workload using simplified macroscopic formula, combining number of controlled aircraft (hourly entry rate), the monitoring task (average time spent in the sector) and the de-conflicting task (number of potential conflicts) [11]. The overall showcase methodology is presented in Figure 1.

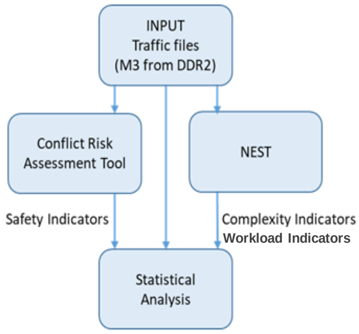

Figure 1. Structure of the methodology

The methodology main assumptions were as follows [7]: a) a time increment of 10 sec is chosen as a result of the balance between run time and quality of loss of separation detection; b) all events lasting only 10 sec were excluded from further analysis in order to deal with potential trajectory inaccuracies; c) the safety minima separations used were horizontal separation (5 NM) and vertical separation (1000 ft); however, those values are relaxed for 10% (4,5 NM and 900 ft) in order to deal with potential position and altitude inaccuracies; d) the tactical actions by the pilots and ATCos as well as their behavior in traffic separation are not analysed (input trajectories were actual / flown and therefore it was not easy to extract pilots and ATCos interventions from them).

IV. Traffic data and scenarios

EUROCONTROL Data Demand Repository (DDR2) traffic demand data was used as a source of trajectory information. The analysis of complexity, safety performance, and workload was done using the tactical flight model flight trajectories (M3 files in NEST terminology [11]) that represent the closest estimate available for the flight trajectories handled by controllers on the day of operations. The sample flights were filtered to exclude: military flights, as these are not scheduled flights and flights with origin or destination airports being “ZZZZ” or “AFIL”, as these indicate incomplete flight data.

Only airspace and traffic above FL245 was considered (covering both lower and upper part of MUAC airspace) in three traffic scenarios covering four weekends (Figure 2):

- June 2017 (before FRA implementation, total of 53515 handled flights),
- June 2018 (implementation of FRA during weekends – Friday 22:00 to Monday 04:00, total of 53096 handled flights), and
- June 2019 (a year after implementation, FRA still used during weekends, total of 51027 handled flights).

In each scenario, analysis was done on the level of MUAC airspace as a whole, and on three separate airspace sector-groups (Brussels - BUTA, DECO – DUTA and Hannover - HUTA). Figure 2 shows number of handled flights in a given scenario (up), and distribution between sector-groups (down). Handled flight is a flight that could appear and count in different airspaces, e.g. one flight passing through three airspaces is counted as three handled flights. The drop of this number observable in 2019 was caused by a range of measures to reroute traffic (vertically or laterally) from congested areas, primarily BUTA sectors and Karlsruhe UAC (change in average daily flights in MUAC (2018 vs. 2019) of -0.5% [12]). For each traffic scenario, calculation of complexity parameters and workload (using the NEST tool) and safety performance (using the Conflict Risk Assessment Tool) was done using the same input.

V. RESULTS

A. Safety performance analysis

Number of pLoS: This indicator is generally increasing (Figure 3, up) as distribution of crossing points is different in FRA airspace in relation to a structured airspace (the same was observed in [4]). During first phase of FRA implementation (2018) increase is observed in BUTA, while pLoS in HUTA and DUTA slightly decrease (Figure 3, down). The potential reason for such change could be the traffic redistribution.

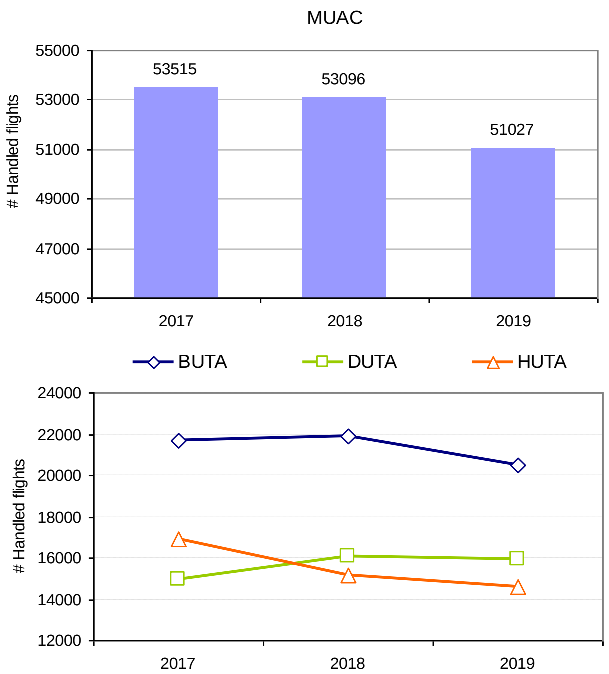

Figure 2. Traffic sample (number of handled flights) for MUAC and sector-groups

A small decrease with full FRA implementation (2019) is observed in BUTA, however, it is still higher than in 2017 (before FRA implementation). In HUTA and DUTA pLoS increase in 2019 however still below 2017 values. Generally, in BUTA number of observed pLoS is higher (Figure 3, down), which is probably in correlation with the highest traffic volume (Figure 2, up) and by the redistribution of traffic flows causing redistribution of pLoS (Figure 4).

pLoS clusters: Clustering of pLoS was performed using the Density-Based Spatial Clustering (DBSCAN) algorithm, which groups elements that are in close proximity, i.e., elements in a ε-neighborhood and surrounded by a minimum number of neighbors.

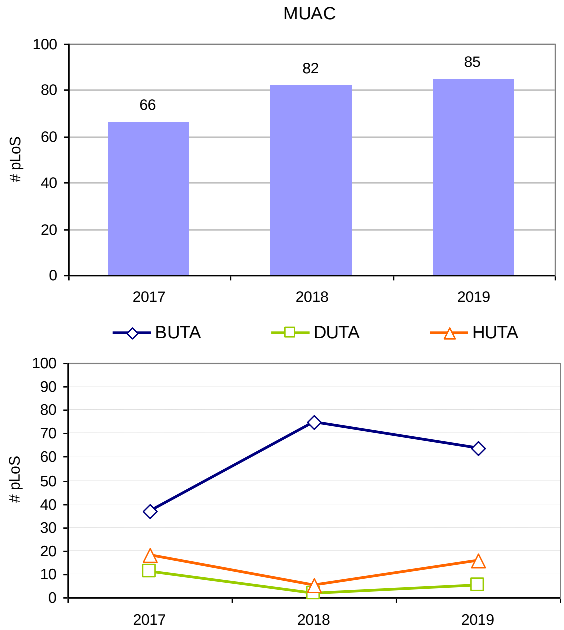

Figure 3. Number of pLoS's within MUAC and sector groups

The algorithm requires two parameters: the maximum radius of the neighborhood (ε) and the minimum number of elements (min Pts) required for a cluster.

The DBSCAN does not require to be initialized with the number of clusters to create, but it autonomously finds the number of clusters suitable for the problem. This property fits our scenario since we cannot estimate the correct number of typical "hotspots" a priori. The maximum radius of the neighborhood was identified using calculation of the k-nearest neighbor distances in a matrix of points.

A suitable value for the ε-neighborhood for DBSCAN was determined to be $\varepsilon = 0.35$, whilst the minimum number of elements to identify cluster was set at min Pts = 5.

Cluster analysis of pLoS shows that the number of "hotspots" after FRA implementation has reduced however, density of "hotspot" (number of pLoS within area) as well as size of the clusters area increased, which is contrary to the expectations of FRA implementation.

Average hourly number of pLoS: In case of the whole MUAC airspace average hourly values are slightly increasing (between 0.3 in 2017 and 0.4 in 2019). In 2019, reduction of average number of pLoS is only observed in BUTA sector group (0.29 in 2019 from 0.35 in 2018), however, it is still higher than in 2017 (0.17). Contrary, DUTA and HUTA sector groups show reduction of average number of pLoS in 2018, and besides slight increase in 2019, the values are still lower than in 2017 (values in all years are below 0.1).

Number of pLoS per handled flight: This indicator is increasing in case of the whole MUAC airspace (Figure 6, left) mainly because the magnitude of increase of number of pLoS is larger than decrease of handled flights from year to year. An increase in 2018 and 2019 is observed in BUTA sector group while in DUTA and HUTA values are lower in 2019 than in 2017.

Risk of conflict: This indicator combines severity and duration of each PLoS, and handles more information about pLoS then a simple number of pLoS. It increases with the increase of number of pLoS but also due to the change in type of pLoS (overtaking, crossings, and head-on encounters), their severity (magnitude of separation minima breach) and duration.

In MUAC airspace as a whole, risk of conflict is increasing from 2017 to 2019 (Figure 6, right), while in the case of separate airspace groups an increase is observed in 2018 and 2019 in BUTA, and in 2019 in HUTA. In DUTA sector group airspace risk of conflict is lower both in 2018 and 2019 than in 2017.

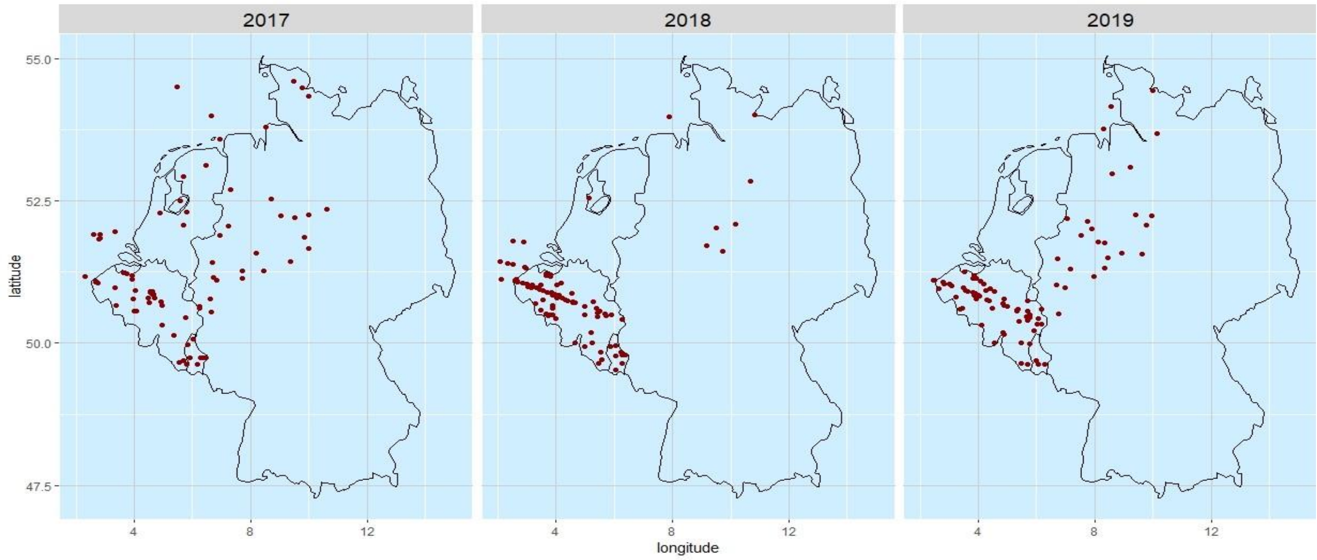

Figure 4. Distribution of pLoS within MUAC airspace

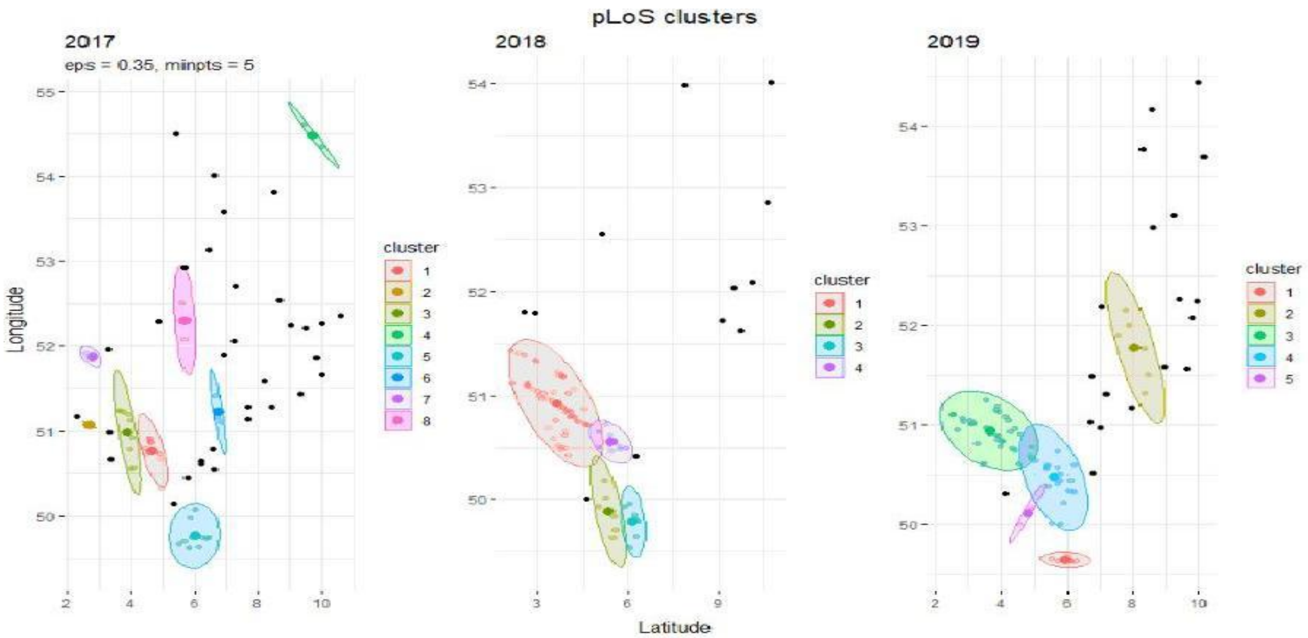

Figure 5. Density based spatial clustering of pLoS within MUAC

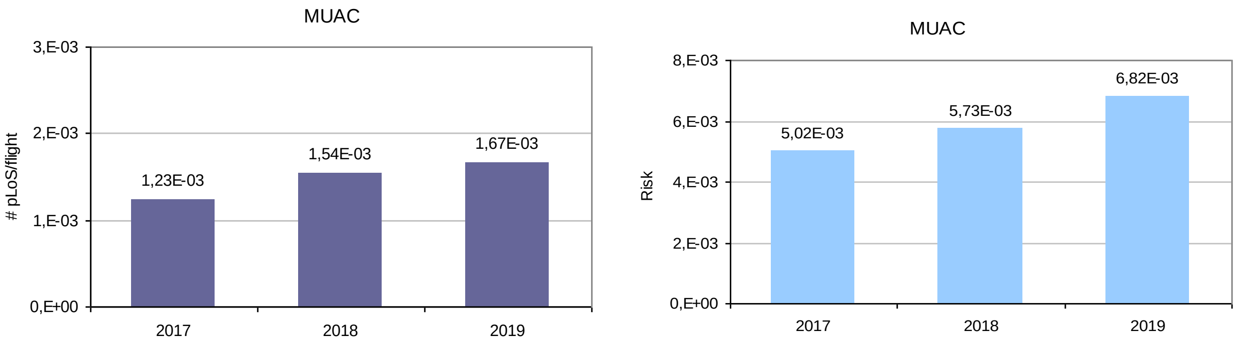

Figure 6. Number of pLoS per handled flight (left) and Risk of conflict (right)

B. *Analysis of potential losses of separation*

pLoS duration and severity: Each pLoS is characterised by the combination of severity (related to the breach of separation) and duration. The severity of the pLoS depends on the minimum distance (spacing) between the pair of aircraft and the applied separation minima [7, 8].

Results of pLoS duration analysis shows that majority of pLoSs are short, up to 30 sec (roughly three-fourths in all three scenarios), while almost 90% do not last more than 40 sec (Figure 7, top).

Results of vertical severity analysis (related to breach of vertical separation minima, 1000 ft) show that in roughly 50% of cases (in 2017 and 2018) and in 30% of cases (in 2019) severity value is 1 (Figure 7, middle), meaning that both aircraft are at the same point in the horizontal plane (although they could be properly separated vertically) or in the case when both aircraft are at the same altitude (however they could be properly separated horizontally).

Contrary, roughly in 80% of cases (Figure 7, bottom), horizontal severity (related to breach of horizontal separation minima, 5 NM) has maximum value of 0.6 meaning that horizontal breach of separation goes up to 3NM.

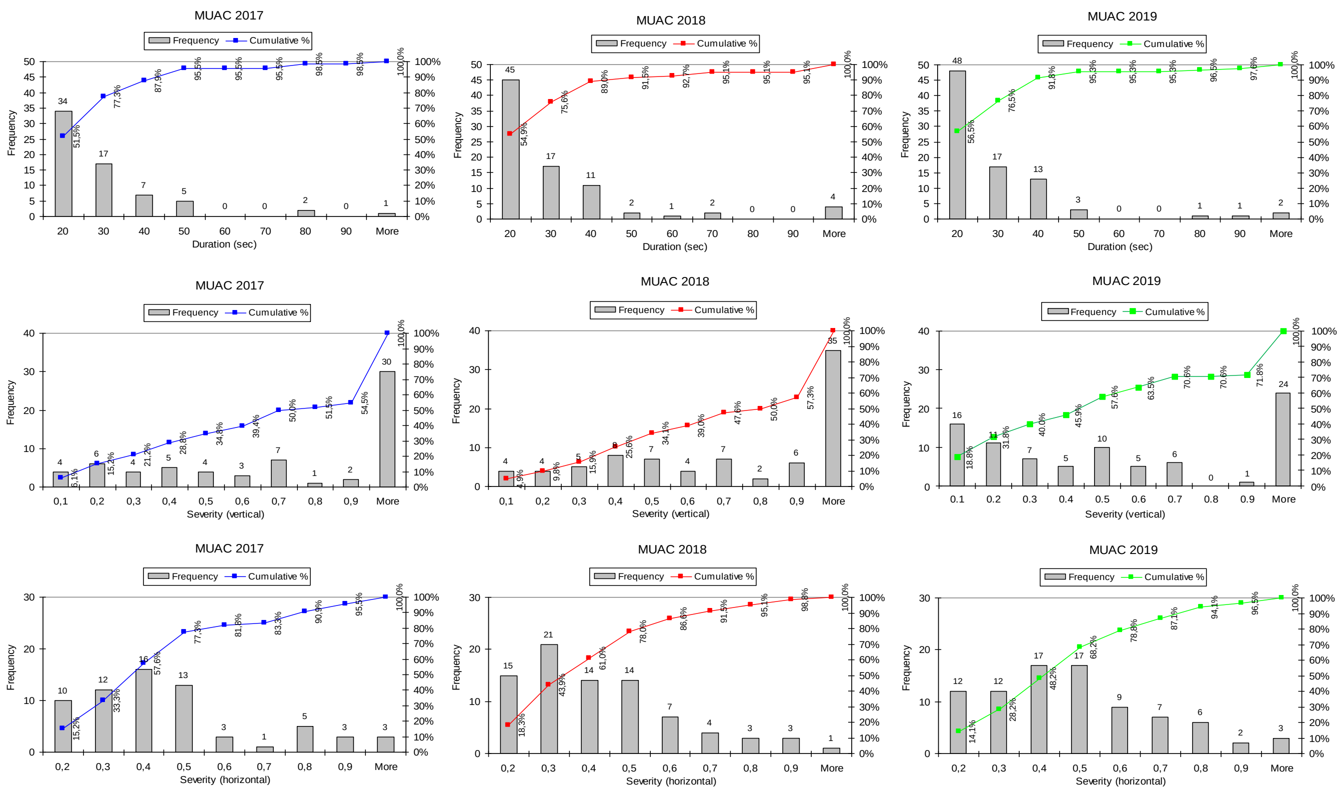

Figure 7. pLoS duration (top), severity in vertical plane (middle) and severity in horizontal plane (bottom)

C. *Complexity and Workload analysis*

Average hourly complexity score per airspace and per year is shown in Figure 8 (left). In MUAC airspace complexity has increased in 2018 and decreased in 2019. In case of sector group airspaces complexity is highest in BUTA, with values in 2018 and 2019 higher than in 2017. Complexity in HUTA and DUTA has decreased during FRA implementation (2018) with only small increase in 2019 (still lower than in 2017).

Deeper analysis of complexity parameters shows that the main reason for increase in complexity of MUAC airspace, during FRA implementation (2018), could be mainly due to changes in adjusted density. Duration of all accumulated interactions and the total flight hours has similar absolute values for all years, however their relative values (the adjusted density) are higher in 2018 and lower in 2019.

During FRA implementation adjusted density changed by 5.4% in 2018 and -8% in 2019 respectively, whilst traffic decreased by approximately -0.8% and -3.9%. This indicates that the traffic and the adjusted density are not directly linear functions, and can provide different assessments of a same traffic situation. Structural index parameters relative values (the percentage of potential interactions, i.e. specific interactions hours which are normalised by the total number of interaction hours) vary little between phases (Figure 9).

Thus, the progressive deployment of the FRA has not strongly changed the geometries of the flows intersections. Namely, interaction between two aircraft in complexity calculation, i.e. structural index, is based on type and hours of interactions in horizontal and vertical plane and changes in speed. As structural index do not change much one can assume that geometries of these interactions do not change. This does not mean that some flows have not possibly shifted. For that reason, it could be assumed that the complexity, very relevant concerning the workload of the air traffic controllers, seems to be not compromised (overall change -0.3%).

Average hourly ATCo workload per airspace and per year is shown in Figure 8 (right). Workload for the whole MUAC airspace, in 2017 and 2018 are almost the same whilst in 2019 is slightly reduced. Workload in BUTA is roughly 30% higher than in HUTA and DUTA airspaces. Workload values were based on traffic data only and considering the macroscopic nature of formula used, workload values provides initial estimate of workload changes, more than a real values of the workload itself on a given day/hour. Running separate workload analysis/validation with MUAC experts would however be beneficial and bring operational improvements.

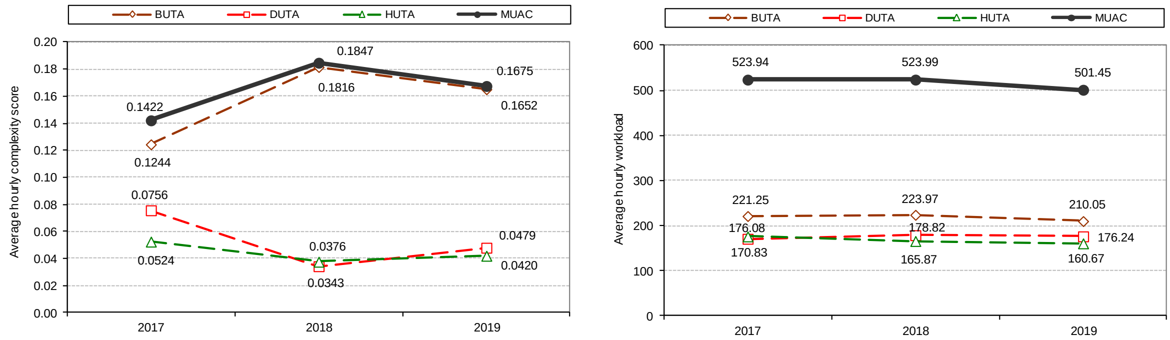

Figure 8. Average hourly complexity score (left) and Average hourly ATCo workload (right) per airspace and year

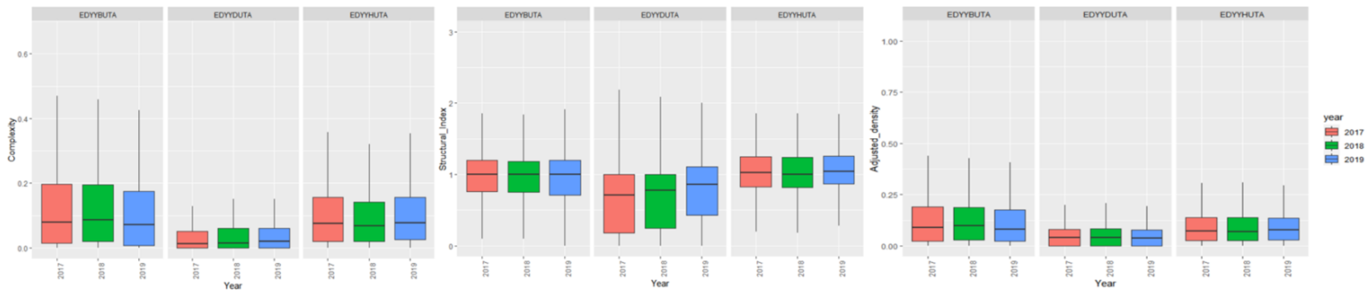

Figure 9. Distribution of complexity score, structural index and adjusted density over years and for different sector-group airspace

D. *Complexity and safety per flight level*

The distribution of an average hourly complexity score and the number of pLoS per FLs is shown in Figure 10. The highest average values of complexity score and number of pLoS are observed on higher altitudes (FL350 to FL380) which correspond to the levels used for en route cruising. Having in mind that FL355 (vertical grey line, Figure 10) was chosen as arbitrary division between Lower and Upper MUAC airspace, it can be seen that peak values are in Upper airspace.

Similar behaviour was observed in the case of sector groups as well, with the highest values in BUTA (complexity score over 0.22 in all three scenarios).

Distributions of average hourly complexity score and number of pLoS per FL are similar for all three scenarios in MUAC (Figure 10), with minor increase of maximum value throughout the years (from 0.15 in 2017, 0.17 in 2018 to 0.16 in 2019). It can be seen from figure that higher average complexity values and higher numbers of pLoS are on higher FLs where there is more traffic.

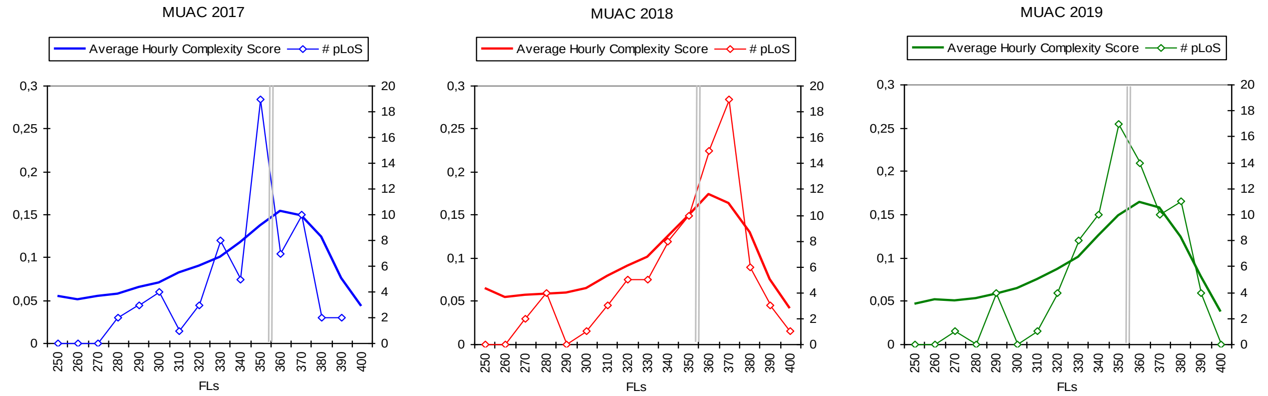

Figure 10. Distribution of average hourly complexity score and number of pLoS per FL

E. Correlation between traffic, complexity, safety indicators and workload

General principle for correlation study is shown in Figure 11 (lines represent correlations analysed). A sample consisted of 216 hours for each analysed year (four weekends in June, from Friday 22:00 until Monday 04:00). Following text contain results of correlation analyses for MUAC airspace as a whole and separately for airspace sector-groups.

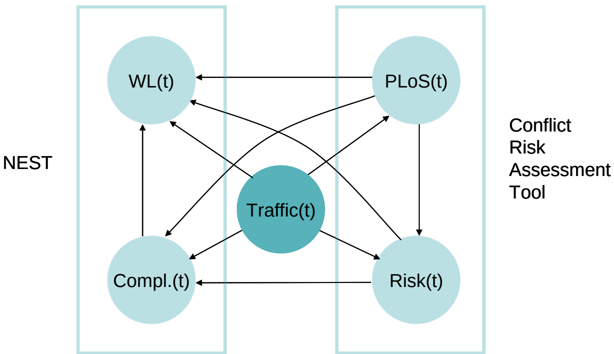

Figure 11. Correlations studied

MUAC airspace correlations: A strong positive linear correlation (bold R^2 values - Figure 12) was found between traffic and workload for all three years, as well as between number of pLoS and risk of conflict, traffic and complexity, and between complexity and workload.

BUTA/DUTA/HUTA sector group airspace correlations: A strong positive linear correlations (bold R^2 values - Figure 13) were found between traffic and workload for all three years for BUTA and DUTA sector-group. Likewise, positive linear correlations, for all airspaces, were found between pLoS and risk. Finally, a positive linear correlation was also found between complexity and workload for BUTA and HUTA sector-groups.

MUAC R2	Traffic	PLoS	Risk	Complexity	Workload
Traffic	2017	0,0612	0,0455	**0,7079**	**0,9143**
	2018	0,0098	0,0176	**0,7119**	**0,9238**
	2019	0,0810	0,0808	**0,6864**	**0,9151**
	PLoS	2017	**0,7977**	0,0822	0,0699
		2018	**0,7763**	0,0573	0,0238
		2019	**0,8672**	0,1078	0,0979
		Risk	2017	0,0620	0,0497
			2018	0,0521	0,0311
			2019	0,1030	0,0974
			Complexity	2017	**0,8836**
				2018	**0,8743**
				2019	**0,8660**

Figure 12. MUAC correlation results

Findings in both experiments are as expected, i.e. with traffic increase; one can expect the higher complexity, which is ultimately followed by higher ATCo workload. Contrary, increase in traffic leads to increase in number of pLoS and risk of conflict. In terms of strength of correlations, correlations in MUAC airspace as a whole are slightly stronger than the ones observed in sector-groups (BUTA/DUTA/HUTA).

VI. CONCLUSION

Air traffic performance of the European air traffic system depends on traffic demand but also on airspace structure and its traffic distribution. These structural and flow characteristics influence airspace complexity, which can affect ATCo workload and influence the probability of safety occurrence. Current analysis focused on MUAC airspace (as a whole vs. sector-groups), and has investigated whether dispersion of traffic after FRA implementation is sufficient to create complexity decrease and whether changes in complexity has not compromised safety performance and/or increased ATCo workload.

Findings seem to not be as expected. Namely, number of pLoS increased after FRA implementation, as well as average number of pLoS per flight, and hour, and risk of conflict; although traffic sample was smaller. However, these results should be taken with caution due to trajectory information used, more specifically M3 rough envelope and the fact that these flown trajectories already incorporate ATCo intentions.

BUTA - R2	Traffic	PLoS	Risk	Complexity	Workload
Traffic	2017	0,0337	0,0239	0,4502	**0,8901**
	2018	0,0102	0,0118	0,6480	**0,9370**
	2019	0,0450	0,0516	0,6218	**0,9461**
PLoS		2017	**0,8146**	0,1455	0,0678
		2018	**0,7938**	0,0881	0,0229
		2019	**0,9031**	0,1473	0,0737
Risk			2017	0,0909	0,0430
			2018	0,0737	0,0235
			2019	0,1433	0,0804
Complexity				2017	**0,7034**
				2018	**0,7868**
				2019	**0,7445**

DUTA - R2	Traffic	PLoS	Risk	Complexity	Workload
Traffic	2017	0,0195	0,0124	0,4369	**0,7301**
	2018	-0,0168	-0,0158	0,3527	**0,7126**
	2019	0,0142	0,0043	0,4133	**0,7138**
PLoS		2017	**0,9192**	0,0974	0,0135
		2018	**0,9431**	0,0044	-0,0109
		2019	**0,6754**	0,0555	0,0037
Risk			2017	0,0890	0,0087
			2018	-0,0033	-0,0100
			2019	0,0380	0,0008
Complexity				2017	0,3111
				2018	0,2263
				2019	0,1991

HUTA - R2	Traffic	PLoS	Risk	Complexity	Workload
Traffic	2017	0,0079	0,0091	0,3242	0,4111
	2018	0,0001	0,0010	0,1035	0,1464
	2019	0,0164	0,0173	0,1235	0,1772
PLoS		2017	**0,7446**	0,0512	0,0385
		2018	**0,7580**	0,0612	0,0314
		2019	**0,8309**	0,1491	0,1354
Risk			2017	0,0446	0,0373
			2018	0,0487	0,0332
			2019	0,1445	0,1333
Complexity				2017	**0,9291**
				2018	**0,9597**
				2019	**0,9582**

Figure 13. BUTA/DUTA/HUTA sector-group correlation results

Cluster analysis of pLoS pre and after FRA implementation, shows reduced number of "hotspots" after FRA implementation however, density of "hotspot" (number of pLoS within area) as well as size of the clusters area increased, which is contrary to the expectations of FRA implementation. Size of the cluster area is also determined by proximity of the points (i.e. pLoS). In other words, the numbers of high density hotspots have decreased, and in 2018 and 2019 we have larger areas where pLoS do occur. This also proves the fact that pLoS in FRA airspace cannot be easily anticipated as in the airspace with standard routes.

The progressive deployment of the FRA has not strongly changed the geometries of the flows intersections. For that reason, it could be assumed that the complexity seems not to be compromised (overall change -0.3 %). ATCo workload generally decreased which could be explained by smaller number of handled flights, however higher decrease was not possible due to increase in number of pLoS.

Overall, MUAC case study results have shown that positive correlations (R^2) exist between: a) traffic (in terms of number of handled flights), complexity and workload; b) pLoS and conflict risk; and c) complexity and workload. More specifically, changes in traffic demand and traffic patterns do influence complexity, workload as well as safety performance. Analysis has shown that there is a strong interdependency between these parameters on the example of FRA implementation.

Proposed showcase methodology for analysis of performance in MUAC airspace has potential to become generic analysis for other airspaces and the whole European airspace, and could be ultimately used for monitoring purposes by different entities. Further work to improve methodology and results, could evolve around using different trajectory data, such as automatic dependent surveillance broadcast (ADS–B) data, and validation of results with MUAC. This would allow calculation of a more accurate estimate of the changes by excluding the impact of the flight planed trajectory which is present in the M3 trajectory. A separate analysis using last filed flight plan data (M1 trajectory) could be used to estimate the FRA impact on a planned trajectory. The FRA impact and potential benefits, are expected to be more visible on flight plan trajectory, taking into consideration the ATC factor, giving direct clearances to many aircraft from entry to exit points of airspace that should have exist pre and post FRA implementation. Lastly, presented methodology, could be also enhanced by isolating all additional factors, such as, airspace constraints and airline route preferences.

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