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EUROPEAN AIRSPACE COMPLEXITY AND FRAGMENTATION CORRELATION RESEARCH

ABSTRACT

Within different European airspace areas, Air Traffic Control Officers (ATCOs) handling en-route traffic are usually facing different workload levels while performing mostly the same on-duty tasks. The reason for this arises due to the different airspace complexity levels in which ATCOs have to, by taking into consideration and respecting the same internationally acceptable safety requirements, manage air traffic and its traffic flows. This research paper tries to give an answer to question: “What is the current European airspace fragmentation status in dependence of commonly accepted and measured airspace complexity indicators?” The research is based on Performance Review Unit's (PRU) data and its computation gathered from 37 European Air Navigation Service Providers (ANSPs). Within conducted quantitative research the total European airspace area of 11,203,200 km^2 was analysed. Based on obtained results, the existence of differently associating areas within European airspace leads to the conclusion that European airspace is fragmented into different homogeneous and sized spatial patterns identified within research paper.

KEY WORDS: air traffic management; European airspace; complexity; fragmentation

1. INTRODUCTION

Nowadays European Air Traffic Management (ATM) represents a complex interdependent system with a high number of participating stakeholders which may in different areas have a greater or smaller significance impact on the European ATM (EATM) system's performances. Strategic air traffic planning and development in the European Civil Aviation Conference (ECAC) area depends on many elements among which airspace complexity covers an important role. After Single European Sky (SES) initiative establishment, within different air traffic planning and development studies the consideration of airspace complexity as one of ATM's safety related performance indicator become more important. The choice of research topic is based on the relevance of on-going changes occurring at European and regional levels which also reflect on the airspace complexity performances, e.g. Free Route Airspace (FRA) concept implementation. Due to fact that air traffic demand could be highly spatially variable, the main issues referring European airspace homogeneity and fragmentation are of high importance. Furthermore, carried research is supported by the Airstat software. It is based on a mathematical model designed for testing the European airspace homogeneity and fragmentation status. The main software's purpose is to provide technical support in carrying out quantitative studies referring European airspace complexity performances analysis. Besides, use of an appropriate mathematical model is aimed at examining airspace areas with spatially similar airspace complexity performances. It takes into consideration ANSPs' spatial position within researched area. Considering all mentioned, research paper try to answer the following questions: “Where are located spatial clusters and how intense is the clustering?, Do spatial performances differ and which features are most alike?, How big and homogenous are spatial patterns?...” Specified questions can be synthesized within the main research question and thus give it the research purpose by answering: “What is the current European airspace fragmentation status in dependence of commonly accepted and measured airspace complexity indicators?”

2. EUROPEAN AIRSPACE COMPLEXITY ASSESSMENT METHODOLOGY

Although years before it was used in different variations, term of airspace complexity was properly addressed in the middle of the last decade by establishment of "ATM Cost-effectiveness (ACE) Working Group on Complexity". It was set up in 2003 by members of European Air Navigation Service Providers (ANSPs), EUROCONTROL's unit - Performance Review Unite (PRU), Civil Air Navigation Services Organisation (CANSO) and representatives of airspace users and European Commission. The Working Group's main objective was to define airspace complexity and agree on a set of high level complexity indicators for en-route airspace that could be applied in ANSP benchmarking analyses. Years before, both in scientific and professional publications, there was no commonly agreed definition applicable to ATM. Thus complexity was widely used term to describe studied "level of difficulty." Frequently, the same term was mistakenly used for explanation of "air traffic complexity" which actually presents only a part of the broader meaning term "airspace complexity". In 2006 "ACE Working Group on Complexity" published "Complexity Metrics for ANSP Benchmarking Analysis" document which defined airspace complexity definition, metrics and indicators applicable for Europe-wide application.

Mentioned document defines airspace complexity as "the external factors that impact the controller workload and/or the level of difficulty of the ATC task, without (considering) the internal, ATC procedures-related factors" [1]. In same source additional four different complexity dimensions, i.e. indicators have been defined: traffic density dimension expressed by adjusted density indicator, traffic in evolution dimension expressed by potential vertical interactions indicator, flow structure dimension expressed by potential horizontal interactions indicator and traffic mix dimension expressed by potential speed interactions indicator. Although indicators are partly applicable to Terminal Manoeuvring Area (TMA), the selected indicators have been chosen to be used only for measuring air traffic under jurisdiction of Area Control Centres (ACCs). Also, it was recognised that the indicators do not fully take into account the impact of external constraints such as the need to interface with systems having different capabilities (e.g. transition from Reduced Vertical Separation Minima (RVSM) to non RVSM or from imperial to metric standards). Mentioned four indicators are measured by using a grid which observed airspace volume splits into corresponding number of 4D cells. The indicators are then measured separately per every cell. Later on they join each other and so cover a totally observed airspace volume. As the Figure 1 shows, 4D cells are defined by spatial parameters length (dx), width (dy), height (dz) and temporal parameter (dt).

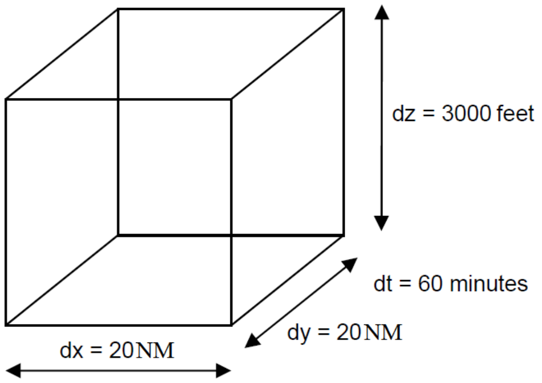

Figure 1 - 4D cell dimensions

It is also necessary to define two following terms which are important part of applied airspace complexity methodology. "Flight hours" represents a term which denotes a sum of the flight hours controlled in a given volume (e.g. in a cell *k*) over a time period and it is expressed as follows:

$$T_k = \sum_{i \in cell_k} t_i \quad . \tag{1}$$

Second important term for understanding airspace complexity assessment methodology is determined as an "interaction". It defines that e.g. aircraft (*a*) is in interaction with aircraft (*b*) if the two aircraft are simultaneously present in the same cell *k*. The most important data obtained by interaction counting is expected duration of interaction (in hours) expressed by the following equation:

$$D_k = \sum_{i \in cell_k} \left(\sum_{\substack{j \in cell_k \\ j \neq i}} t_i \cdot t_j \right) . \tag{2}$$

Adjusted density (AD) represents a complexity indicator in relation with traffic density. Traffic density is defined as a measure of the traffic amount that exists within a given volume unit over a given time unit. It is a non-dimensional parameter defined as the ratio of hours of interaction and flight hours. Hours of interaction are expressed by expected duration of interaction which is calculated by adding durations of all interactions in all cells associated with an ANSP/ACC. To get the adjusted density indicator obtained result is then divided by the total flight hours within the same ANSP/ACC:

$$AdjDens_{ANSP} = \frac{\sum_{Days}\sum_{Cells} D_k}{\sum_{Days}\sum_{Cells} T_k} \quad . \tag{3}$$

The Vertical Different Interacting Flows (VDIF) indicator is a complexity measure arising from the interactions between flights in different flight phases. Two aircraft are considered to interact vertically if they are simultaneously present in the same cell k and have different attitudes (climbing-cruising-descending). It is expressed as the hourly duration of potential vertical interactions (4) per flight hour (5):

$$V_k = \sum_{i \in cell_k} \left(\sum_{\substack{j \in cell_k \\ i \neq j \ attitudes}} t_i \cdot t_j \right) , \tag{4}$$

$$VDIF_{ANSP} = \frac{\sum_{Days}\sum_{Cells} V_k}{\sum_{Days}\sum_{Cells} T_k} \quad . \tag{5}$$

Similar to the VDIF, Horizontal Different Interacting Flows (HDIF) indicator represents a complexity measure arising from the different interactions between flights with different headings. Therefore, interaction is counted when the difference between headings of two aircraft is greater than 20° and it is expressed as the hourly duration of potential horizontal interactions (6) per flight hour (7):

$$H_k = \sum_{i \in cell_k} \left(\sum_{\substack{j \in cell_k \\ i \neq j \ headings}} t_i \cdot t_j \right) , \tag{6}$$

$$HDIF_{ANSP} = \frac{\sum_{Days}\sum_{Cells} H_k}{\sum_{Days}\sum_{Cells} T_k} \quad . \tag{7}$$

Airspace complexity is also articulated by the Speed Different Interacting Flows (SDIF) indicator which measures interactions between aircraft with different speeds. A speed interaction is counted when the difference between the speeds of a pair of aircraft is greater than 35 NM/h and it is expressed as the hourly duration of potential speed interactions (8) per flight hour (9):

$$S_k = \sum_{i \in cell_k} \left(\sum_{\substack{j \in cell_k \\ i \neq j \ speeds}} t_i \cdot t_j \right) , \tag{8}$$

$$SDIF_{ANSP} = \frac{\sum_{Days}\sum_{Cells} S_k}{\sum_{Days}\sum_{Cells} T_k} \quad . \tag{9}$$

To obtain a comprehensive airspace complexity status additional two complexity indicators were introduced: structural index (SI) and complexity score (CS). VDIF, HDIF and SDIF complexity indicators results are mostly influenced by the structure of the traffic flows while the adjusted density is conditioned with traffic volume. Structural index computation is based on the sum of the relative indicators' (r_DIF) components (10.1) which can be parsed (10.2) as follows:

$$SI_{ANSP} = r\_VDIF + r\_HDIF + r\_SDIF \quad , \tag{10.1}$$

$$SI_{ANSP} = \left(\frac{VDIF_{ANSP}}{AdjDens_{ANSP}} + \frac{HDIF_{ANSP}}{AdjDens_{ANSP}} + \frac{SDIF_{ANSP}}{AdjDens_{ANSP}} \right) . \tag{10.2}$$

Considering that the structure of the traffic flows and traffic volume aspects affect the overall complexity they are combined into complexity score (CS) indicator. It represents multiplication product of adjusted density and structural index:

$$Complexity\ score_{ANSP} = AdjDens_{ANSP} \cdot SI_{ANSP} \quad . \tag{11}$$

3. EUROPEAN AIRSPACE FRAGMENTATION ASSESSMENT METHODOLOGY

Various European air traffic stakeholders as well as different scientific sources recognize European airspace fragmentation as one of the main causes contributing to European ATM system's inefficiency and dysfunctionality. Therefore, different authors usually define various scenarios and guidelines for future EATM development. In this context, research of European airspace fragmentation status in correlation to airspace complexity with its well-defined research questions enriches the current knowledge and represents an effort with the aim of overcoming the current European airspace fragmentation level. Applied European airspace fragmentation assessment methodology is based on analytical studies by applying spatial autocorrelation methodology. The main goal of applied spatial autocorrelation methodology is that it answers the research question not only by mathematically analysing data, but it also includes data's spatial interaction analysis. In this case, applied methodology looked up a correlation between the ANSPs' airspace complexity and their Areas of Responsibility' (AoRs) spatial position within European ATM Network.

Spatial autocorrelation can be defined as the relationship among values of a single variable that comes from the geographic arrangement of the areas in which these values occur [2]. It corresponds to the Tobler's first law of geography ("Everything is related to everything else, but near things are more related than distant things") thus spatially identifying similarities and differences between adjacent areas. Within research, it was measured globally (across the whole observed area) and locally (in parts of observed area). Global spatial autocorrelation is expressed by Global Moran's I and measured as an average value of all local Moran's indexes (I_i):

$$I = \frac{1}{n}\sum_{i=1}^{n} I_i \quad . \tag{12}$$

It detects spatial patterns across the entire area of interest whereby it does not reveal where significant patterns appear. Also, it is analogous to Pearson's correlation coefficient ranging from -1 to +1 where:

- -1 indicates strong negative autocorrelation,
- 0 denotes completely random values allocation,
- +1 signifies strong spatial autocorrelation.

Decomposition of global statistics into local is possible by focusing on a close neighbourhood by determining local structures of spatially similar values. Studies using local spatial autocorrelation are considered more accurate than studies that only take into account global statistics. Local Moran's I analyses whether the observed value at AoR (i) is independent of neighbouring localities AoRs (j) by taking into account sample mean ($\bar{x}$), number of AoRs (n) and the spatial weight (w_{ij}) of the connection between area AoR (i) and AoRs (j). According to Fotheringham et al. [3] local Moran's I can be measured by using following equation:

$$I_i = \frac{(x_i - \bar{x})\sum_{j=1}^{n} w_{ij}\,(x_j - \bar{x})}{\sum_{j=1}^{n}(x_j - \bar{x})^2/n} \quad . \tag{13}$$

Considering that the data values are fixed and that only their spatial arrangement could vary, further research included statistical significance (z-score) and probability (p-value) test. Although both statistic tests are associated with standard normal distribution, z-score represent a measure of standard deviation (14) while p-value is referring probability:

$$Z_I = \frac{I - E(I)}{\sqrt{Var(I)}} \quad . \tag{14}$$

Within these tests degree of risk is often given in terms of critical values and/or confidence levels. If very high or a very low z-score associated with very small p-value is found in tails of the normal distribution they represent a critical value. The critical z-score value when using a 95% confidence level is -1.96 and +1.96 standard deviations while the p-value associated with a 95% confidence level is 0.05. Within research these values were used as degree of risk. A key contribution of this part of applied assessment methodology is that the z-score between -1.96 and +1.96 and with p-value larger than 0.05 defines pattern represents a pattern that could be very likely classified as a random pattern. On the other hand, if AoR's z-score is large enough and located in the tails of the normal distribution (-2.58 < z-score > 2.58) it represent statistically significant hot spot or a statistically significant cold spot. Figure 2 shows critical values distribution.

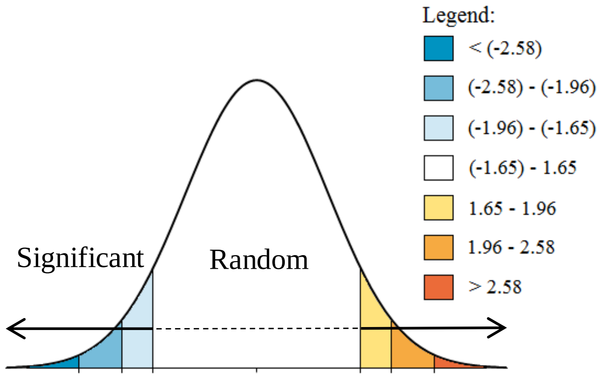

Figure 2 - Critical value (z-score) distribution

Applied Airstat software integrates all analytical methods and it is designed as a tool able to answer all defined research questions. It converts data and provides useful information which can support different stakeholders' future development plans.

4. RESULTS

To identify spatial patterns, applied mathematical model included a data obtained from Performance Review Unit's database which is shown by Table 1. To overcome potential research shortcomings, e.g. European air traffic performances' seasonality which also reflects on airspace complexity performances, as the reference data were used complexity scores capturing averaged annual values for 2018.

Table 1 - Averaged 2018 complexity score values and ANSPs' belonging AoRs' sizes [4]

ANSP	AoR [km^2]	CS
Albcontrol	36,000	3,28
ANS CR	76,300	8,87
ANS Finland	409,000	1,71
ARMATS	29,700	1,04
Austro Control	80,900	8,64
Avinor*	731,000	2,01
Skyeyes	39,500	10,65
BULATSA	145,000	4,76
Croatia Control	129,000	6,13
DCAC Cyprus	174,000	3,21
DFS	390,000	10,80
DHMI	982,000	5,94
DSNA	1,010,000	7,91
EANS	77,400	2,21
ENAIRE	506,000	4,83
ENAV	732,000	5,86
HCAA	537,000	3,24
HungaroControl	92,600	6,91
IAA	457,000	1,91
LFV	627,000	3,00
LGS	95,900	2,53
LPS	48,700	7,05
LVNL	53,100	7,79
MATS	231,000	0,93
M-NAV	24,700	3,91
MoldATSA	34,800	0,59
NATS*	880,000	10,84
NAV Portugal*	671,000	3,28
NAVIAIR	158,000	3,59
Oro Navigacija	74,800	2,14
PANSA	334,000	4,16
ROMATSA	254,000	4,53
Sakaeronavigatsia	88,700	2,51
Skyguide	69,700	13,14
Slovenia Control	20,400	8,18
SMATSA	127,000	6,59
UkSATSE	776,000	1,19

*Continental AoR [km^2]

Over the past two decades many activities and initiatives were lunched as well as various regulatory packages implemented. Their common purpose was to minimize the European airspace fragmentation level and enhance ATM system's efficiency. Despite these efforts it has been still recognized that ATM system's performances significantly vary by regions in Europe, both spatially and temporally. Therefore following research results on a macro-regional level try to depict EATM's fragmentation status in relation to airspace complexity. Research included data from 37 ANSPs and spatially covered an area of 11,203,200 km^2 shown by Figure 3.

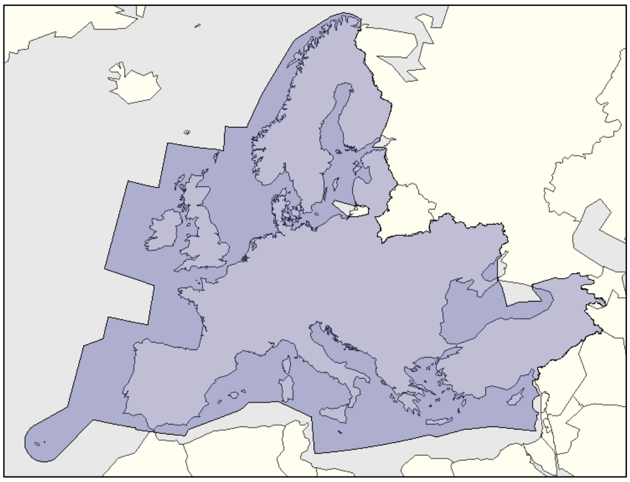

Figure 3 - Spatial overview of researched airspace

Obtained global Moran's I result (*I = 0.42868*) indicate existence of a positive spatial autocorrelation. That indicates that spatial patterns with similar values tend to group on the map. In this case AoRs with the above-average local Moran's indexes are bordering with below-average value areas. Those spatial patterns (shown by Figure 4) cover 21.40% of totally researched airspace.

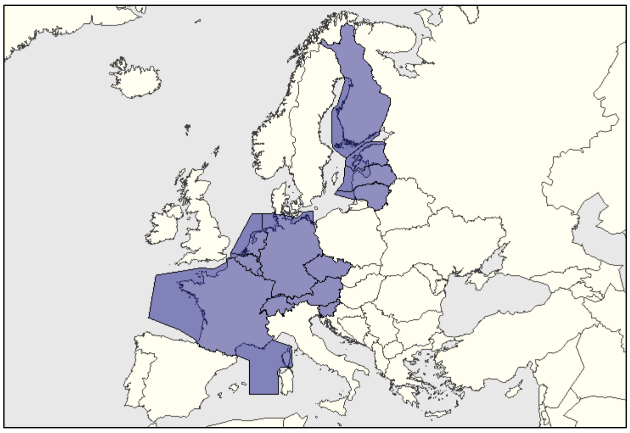

Figure 4 - Spatial patterns with similar values

Within Figure 4 it can be seen that European airspace is differently fragmented. The most of airspace volume (78.60% of overall researched area) doesn't differ in each other, i.e. they represent a random distribution pattern and spatial majority. Whether labelled spatially associated areas represent uniform spatial patterns or there are values that significantly deviate and possibly represent cold spot or hot spot, it can't be defined by application of global Moran's I methodology.

Further results discussion puts a focus on the local statistics and critical values analysis. Local statistics' results indicate that AoRs shown within Figure 4 give the largest contribution to the global Moran's I positive value. Although presented spatially similar AoRs differ from their adjacent AoRs, it can't be define how significantly spatial patterns differ from the rest of the observed area nor whether and to what extent they differ in each other. From following Figure 5 it can be seen that data input and local Moran's indexes distribution share vary if input data is placed in the context of similarity to adjacent values.

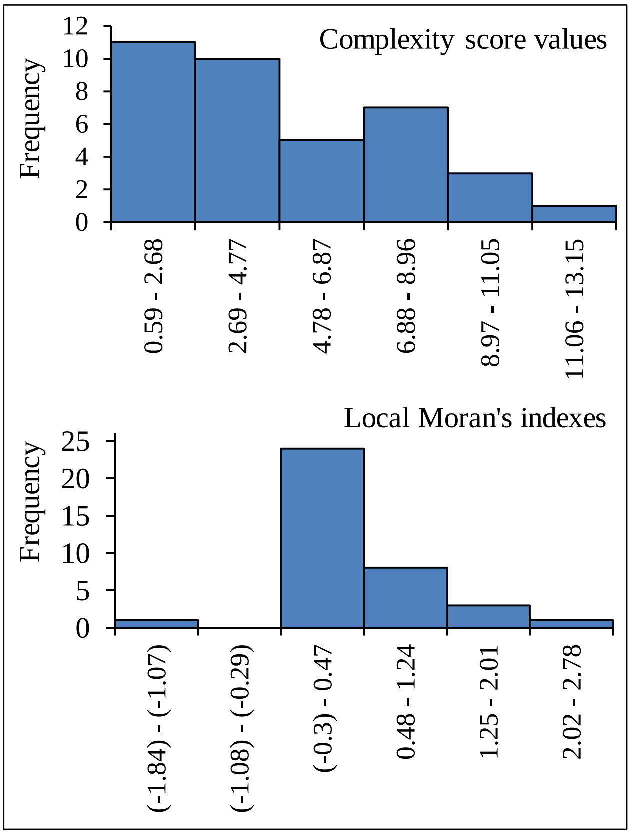

Figure 5 - Input data and local Moran's indexes distribution share

Although global Moran's I value is positive, two spatial patterns spatially associating adjacent AoRs can't be yet declared as clusters. Without looking at statistical significance there is no basis for knowing if the observed patterns represent clusters. To find out does clusters actually exist it was necessary to test the null hypothesis - which states that "there is no spatial clustering of the values associated with the geographic features in the study area".

Considering determined degree of risk and on the basis of obtained z-score and p-value results it was possible to evaluate whether the researched area represent clustered, dispersed or random pattern. Taking into account that the absolute value of the z-score is not large enough (0.581788) and that p-value is not statistically significant (0.2810) the null hypothesis cannot be rejected. Therefore, it is quite possible that the spatial distribution of feature values is the result of random spatial processes.

Critical value (z-score) test was carried out for every AoR's complexity score value. In such a way it was possible to find out which complexity scores' value distinct the most from rest of observed values and define potential cold spot or hot spot. According to obtained results it can be concluded that the complexity scores' values can be classified into three categories; random data category which represent the largest category, medium high critical value (MHCV) category whose z-score values are ranging from +1.65 till +1.95 and very high critical value (VHCV) category with z-score values higher than +2.58. Following Figure 6 shows two pie charts which depict critical values' shares in relation to its data and spatially distribution.

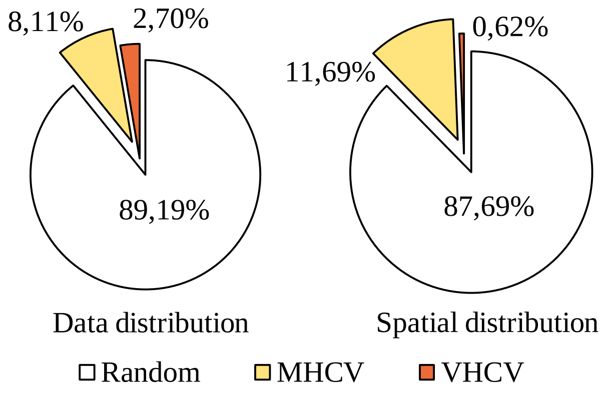

Figure 6 - Critical values results distribution share

5. DISCUSSION

Nowadays EATM system needs to cope up with steadily growing annual air traffic volume. Frequently it pushes its performances management to its limits. Such a situation implies the need for continuous monitoring of EATM system's performances with special emphasis on safety. Safety together with capacity, cost-effectiveness and environmental performances represent one of main future EATM development pillar. Steiner et al. consider that sufficient safety and environmental performances are a necessary condition for further airspace capacity increasment [5]. In accordance with mentioned, during the last two decades a significant progress was made by Single European Sky ATM Research (SESAR) programme which was enabled by Single European Sky legislation. SESAR through projects and concepts development, e.g. dynamic Demand Capacity Balancing (dCDB) concept, continuously tries to minimize airspace complexity level and design it in such a way that it will be able to respond to current predictions of future air traffic increase. In such way airspace complexity level minimization streamlines ATCOs' workload and allows a higher level of safety related performances. Therefore, airspace complexity needs to be patiently addressed within future EATM development plans.

Simultaneously with air traffic increase in Europe, within the ATM context the complexity term began to appear more frequent than before. Complexity is not a synonym for workload, although it has been proven multiple times that the increase in complexity results in the increase in workload which in turn limits the airspace sector capacity [6-8]. Airspace complexity is difficult to define unambiguously as it represents a condition which spatially and temporal varies differently across European airspace. It often varies from hour to hour, day to day, time of year and especially in AoRs with accentuated seasonality traffic while it frequently spatially varies in dependence of ANSPs' AoRs macro-regional position and air traffic flows.

By analysing the literature referring ATM complexity it is possible to note an absence of a generally accepted definition and taxonomy, as well as diversity of methodologies and indicators. Beside authors' discrepancies, differences between impacting factors effecting ATCOs' workload and airspace complexity can be also found between two regulatory bodies' definitions; EUROCONTROL and Federal Aviation Authority (FAA). Considering the fact that research analysed European airspace it was proper to apply EUROCONTROL's methodology, definitions and indicators. Therefore, used airspace complexity indicators were synthesised as complexity scores and used as the reference data.

European airspace fragmentation, same as airspace complexity, represents a term that began to be more seriously considered and more frequently used within the last two decades. Within different EATM related sources it is most often mentioned as a partial cause contributing to the current EATM system's inefficiency and as a barrier limiting its future development potentials. Besides the fact that they have started to apply more often than before, comparing the terms of airspace complexity and airspace fragmentation, it can be concluded that both can be identified as critical conditions in which potentially increasing of both could lead to performance deterioration of ATM system.

Unlike the above mentioned similarities, they opposite in a way that there are many different airspace complexity measurement methodologies and indicators while on the other hand there is a lack of airspace fragmentation measurement methods. Therefore this research presented a novel approach in airspace fragmentation analysis.

European airspace fragmentation assessment methodology was based on applying spatial autocorrelation methodology. It can be concluded that such a research approach gave a representative findings. They identified two areas with similar AoRs' values which represented a potential clusters. Later on, based on critical value and significance tests it was determined that the pattern of spatial distribution is random and that clusters do not exist. However, by comparing results of local Moran's Indexes and critical values it was found that Switzerland, i.e. Skyguide's AoR with the highest deviated value represent a hot spot within European airspace in terms of airspace complexity. Notable are also z-scores of Skyeyes, NATS and DFS which represent a medium high critical values based area and cover 11.69% of totally researched airspace.

6. CONCLUSONS

In this paper a research of European airspace fragmentation level in correlation with airspace complexity has been presented. Based on obtained findings it can be concluded that the pattern of spatial distribution is random and that clusters do not exist. Although the majority of features are randomly distributed (78.60%), two areas were identified as areas which spatially associate adjacent AoRs. The existence of differently associating areas within European airspace leads to the conclusion that European airspace is fragmented into different homogeneous and sized spatial patterns. Further research has been found that although complexity score values differ in the context of its spatial distribution it can be found out that they do not differ so much. Based on local statistics' results it can be seen that 70.27% of all values associate with adjacent values which are not significant. To identify potential cold or hot spots further research placed a focus on the critical values analysis. Based on obtained results it can be concluded that within researched European airspace Switzerland, i.e. Skyguide's AoR with the highest deviate value represent a hot spot and that complexity score values of Skyeyes, NATS and DFS with z-scores ranging from 1.65 till 1.96 represent a medium high critical values based area and cover 11.69% of totally researched airspace.

Based on the fact that in different sources Free Route Airspace (FRA) concept is frequently seen as one of fragmentation problem solving method, a new research analysing FRA implementation effects on airspace complexity could give more information how future European airspace complexity and fragmentation correlation would look like. Therefore, for future work it would be useful to research how the FRA implementation affected airspace performances in terms of airspace complexity.

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