

AIR TRAFFIC COMPLEXITY METRIC FOR EN-ROUTE AND TERMINAL AREAS

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One of the core elements of an ATM system, critical in assurance of ATC and ATFM functions as well as for future concepts such as dynamic airspace configuration and advanced traffic flow management is the ability to measure and predict traffic complexity.

The approach of this paper is to adopt a measure of complexity which should balance the qualitative and quantitative variables for a certain portion of airspace (FIR Bucureşti) taking into account a normal traffic situation. Is the first paper which defines a weighted linear air traffic complexity function using the Analytic Hierarchy Process. AHP is perhaps the most widely used decision making approach in the world today. Its validity is based on many thousands of actual applications in which the AHP results were accepted and used by decision makers.

Keywords: Air Traffic Complexity Metric, Analytic Hierarchy Process, Complexity Function, ATM, ATFM.

1. Introduction

Worldwide air traffic is increasing at a rapid rate without being concentrated in peak traffic hours but rather having a quasi-constant distribution in time due to traffic flow measures applied. En-route capacity of the European airspace specific to the “core area” is dependent on a series of factors among which one of the most important is the controller workload. Controller workload is affected by many factors with impact on the air traffic sequence and ATC sector and capacity is usually estimated using the number of aircraft within the sector for a certain period of time and sometimes using different models and software programs.

In order to ensure a safer and more efficient utilization of the airspace within the European Union, the European Commission has implemented a concept named “Single European Sky” aiming to reform the European air traffic management system. This project, in the same time with the establishment of the Functional Airspace Blocks, will lead to a more consolidate and efficient air traffic management environment within the European Union, and eventually, after

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a period of time, to a reduced number of ATS providers and less control centers controlling flights across Europe.

In accordance with (EC) Regulation No 549/2004 which lays down the framework for the creation of the single European sky, an Air Traffic Management (ATM) system provides services to enable safe, orderly and efficient aircraft operations within a certain airspace. The ATM system consists of three components: Air Traffic Control (ATC), Airspace Management (ASM) and Air Traffic Flow Management (ATFM). The ATC function ensures that the aircraft within the airspace are separated at all times, ASM is a planning function with the primary objective of maximizing the utilization of available airspace by dynamic time-sharing and, at times, the segregation of airspace among various categories of airspace users on the basis of short-term needs, while the ATFM function organizes the aircraft into flow patterns to ensure their smooth and efficient movement.

One of the core elements of an ATM system, critical in assurance of ATC and ATFM functions as well as for future concepts such as dynamic airspace configuration and advanced traffic flow management is the ability to measure and predict traffic complexity.

The controller workload is a subjective attribute and is an effect of air traffic complexity. In an operational environment, changes in traffic flows and airspace will be better managed, both strategically and tactically, if an accurate measurement and prediction of traffic complexity for a particular airspace is available. Additionally, higher levels of automation can be proposed for future operations. Should automation degrade and if the design calls for a human operator to manage the situations, the measures of complexity are crucial so that human workload limitations are not exceeded.

Complexity measures could be used to determine the areas where airspace design changes may be necessary. Airspace can be redesigned and examined to ensure that the complexity of the redesigned airspace is same or lower than its previous level. There are also other areas where the measure of the air traffic complexity can be used like in measuring the probability of ATCO's human error within a certain ACC. This probability can be very useful as an input into the safety analysis of an ANSP in order to highlight incident "hot-spots". A high value of this probability should determine the training managers within an ANSP to focus the recurrent training on the specific areas which can lead to the occurrence of such high probability. The development of a metric that predicts controller workload as a function of air traffic characteristics in a volume of airspace is essential to the development of both air traffic management automation and air traffic procedures.

A review of the literature in the field of air traffic complexity in last years shows that a large number of studies deal with relationship between complexity

and air traffic controller workload. The concept of complexity is introduced, and it is represented as the "weight" of the traffic situation, i.e. possible impact of the exact traffic situation on the air traffic controller workload.

Both the US and Europe aviation communities have been very interested in developing quantifiable metrics for air traffic complexity, although there are still a lot of European air navigation service providers which establish sectors capacity and split or collapse the ACC sectors taking into account only the number of flights predicted to enter into a certain volume of airspace. Indeed this is a very important factor but it's not the only one which should be taken into account when determine the air traffic complexity for a sector. The term complexity, or so called "dynamic density" in certain papers like [2],[3], is defined as the collective effect of all factors, or variables, that contribute to sector level air traffic control complexity or difficulty at any given time, or in other views as a "measure of control-related workload that is a function of the number of aircraft and the complexity of traffic patterns in a volume of airspace" [2].

2. Previous related work

One of the first major projects related to the subject was the Complexity and Capacity (COCA) project [16] which was launched at the EUROCONTROL Experimental Centre (EEC) at the end of year 2000. Its main objective was to describe the relationship between capacity and complexity using an accurate performance metrics.

In order to define this metric, within this project it was used a quantitative approach to evaluate operational complexity of the air traffic flows which were crossing MUAC airspace and airspace environment characteristics. That approach consisted in developing a metric which should describe in a most accurate way the factors that were contributing to the complexity of MUAC sectors.

Those factors were defined considering both static (sector configuration and specific fixed aspects related to the airspace environment) and dynamic (e.g. operational behavior, traffic variability) data. After that, these factors were evaluated for all MUAC sectors in many sector configurations specific for that airspace. The results provided quantitative measurements of the selected factors which were used in the developing of the sector I/D cards.

The study proved that the method used to calculate workload had, in many situations considered within the project, a good correlation with the perception rate of the controller for that specific situation. EUROCONTROL concluded that the project should be followed by an additional study in order to determine those areas where the workload was highly increased by a combination of the factors already considered, or with other factors which were not yet taken into consideration.

Laudeman [2] has developed a metric called “Dynamic Density” which is more quantitative than others and is based on the flow characteristics of the airspace. The “Dynamic Density” is a weighted sum of the traffic density (number of aircraft), the number of heading changes ($\pm 15^\circ$), the number of speed changes (± 0.02 Mach), the number of altitude changes (± 750 ft), the number of aircraft with 3-D Euclidian distance between 0-25 nautical miles, the number of conflicts predicted in 25-40 nautical miles. The parameters of the sums have been adjusted by showing different situations of traffic to several controllers.

B. Sridhar from NASA [3], has developed a model to predict the evolution of a metric in the near future. Efforts to define “Dynamic Density” have identified the importance of a wide range of potential complexity factors, including structural considerations. The approach of his paper is to adopt a measure of complexity of the sector and center airspace that can be related to controller workload, and to examine how well it can be used with the predicted traffic estimates to forecast future workload levels. This assessment can then be used for traffic flow management decisions. The paper assumed it to be a good measure of controller workload, and studied how well dynamic density can be predicted up to a specified period in advance. A measure of airspace complexity was developed at the NASA Ames Research Center using the results of that paper. However we consider that a part of the factors chosen by the authors are not relevant for the complexity metric or their weights are too high for their real contribution to the overall workload environment.

Other approaches considered that traffic itself is not enough to describe the complexity associated with a certain airspace. The importance of including structural consideration has been explicitly identified in some work undertaken by EUROCONTROL in the past. In a study to identify complexity factors using judgment analysis, airspace design was identified as the second most important factor behind traffic volume [4].

G. Aigoin has extended and refined the geometrical class by using a cluster based analysis [6]. Two aircraft are said to be in the same cluster if the product of their relative speed and their proximity (a function of the inverse of the relative distance) is above a threshold. For each cluster, a metric of relative dependence between aircraft is computed and the whole complexity of the cluster is then given by a weighted sum of the matrix norm. Those norms give an aggregated measure of the level of proximity of aircraft in clusters and the associated convergence. From the cluster matrix, it is also possible to compute the difficulty of a cluster (it measures how hard it is to solve a cluster). Multiple clusters can exist within a sector, and their interactions must also be taken into account. A measure of this interaction has been proposed by G. Aigoin [6]. This technique allows multiple metrics of complexity to be developed such as average complexity, maximum and minimum cluster complexities, and complexity speeds.

Another approach based on fractal dimension has been proposed by S. Mondoloni in [13]. Fractal dimension is a metric comparing traffic configurations resulting from various operational concepts. It allows in particular to separate the complexity due to sectorization from the complexity due to traffic flow features. The dimension of geometrical figures is well-known: a line is of dimension 1, a rectangle of dimension 2, etc. Fractal dimension is simply the extension of this concept to more complicated figures, whose dimension may not be an integer. The block count approach is a practical way of computing fractal dimensions: it consists in describing a given geometrical entity in a volume divided into blocks of linear dimension d and counting the number of blocks contained in the entity N . The application of this concept to air route analysis consists in computing the fractal dimension of the geometrical figure composed of existing air routes. An analogy of air traffic with gas dynamics then shows a relation between fractal dimension and conflict rate (number of conflicts per hour for a given aircraft). Fractal dimension also provides information on the number of degrees of freedom used in the airspace: a higher fractal dimension indicates more degrees of freedom. This information is independent of sectorization and does not scale with traffic volume. Therefore, fractal dimension is a measure of the geometrical complexity of a traffic pattern.

The approach of this paper is to adopt a measure of complexity which should balance the qualitative and quantitative variables for a certain portion of airspace (FIR Bucureşti) taking into account a normal traffic situation (without weighting eventually emergency situations, malfunction of the ATC systems, communication failures, etc.). It is not the purpose of this paper to envisage the influence of the airspace design on the complexity metric. This will be the subject of a future work which will complete the results of the present paper.

In Section 3 there are presented in detail the variables which form the air traffic complexity function and their weight for the final value which defines the complexity for a certain sector.

3. Airspace Complexity Function using AHP

Within this Section it is presented the development of a weighted linear complexity function which includes both traffic density terms and traffic complexity terms. Further on in this paper it is presented the validation of this function.

The proposed complexity metric is likely to be the most useful if it can be implemented in an operational environment where it can be used to provide information in advance about the complexity of air traffic for the next 8-10 hours. The requirement that the complexity value should be computed with few hours in advance gave rise to the most important constraint in the development of the

complexity function. A computation in advance of the traffic complexity requires the use of flight plan data as input to the function.

The first step in developing the air traffic complexity function is to establish a comprehensive list of factors that contribute to air traffic complexity. The traffic factors included in the air traffic complexity function were selected after an informal interview with a panel of ATM experts from Romanian CAA and ROMATSA (the Romanian Air Navigation Service Provider) as well as a series of ACC and APP air traffic controllers with different levels of experience behind radar screens. The participants were presented with questionnaires which contained preferences for factors affecting the performance of the air traffic control process.

Seven traffic factors were identified as candidates for the air traffic complexity function, as follows:

1. N_{crz} = Number of cruising aircraft within a sector for a certain period of time
2. N_{clb} = Number of climbing aircraft within a sector for a certain period of time
3. N_{des} = Number of descending aircraft within a sector for a certain period of time
4. T_{rtf} = percentage of the total time considered during which the RTF frequency is in use
5. V_{met} = percentage of the total volume of the sector in use affected by adverse meteorological conditions (severe icing, severe turbulence, CB or TCU clouds, etc.)
6. T_{spd} = speed ratio (ratio between the speed of the fastest aircraft in the sector and the speed of the slowest aircraft in the sector)
7. T_{eng} = a factor representing the mixture of aircraft types within the sector in use (number and type of the engines equipping the aircraft within the sector in use)

The general form of the air traffic complexity function is as follows:

$$Fc = W_{crz} * N_{crz} + W_{clb} * N_{clb} + W_{des} * N_{des} + W_{rtf} * T_{rtf} + W_{met} * V_{met} + W_{spd} * T_{spd} + W_{eng} * T_{eng} \quad (1)$$

where W_{crz} , W_{clb} , W_{des} , W_{rtf} , W_{met} , W_{spd} , W_{eng} represent the weights associated to each candidate traffic factor consisting the complexity function.

In order to establish the weights values associated to each candidate traffic factor there was adopted the following approach. There was conducted an Analytic hierarchy process in which were involved a series of air traffic controllers, en-route and approach, with different levels of experience. The use of subjective weights derived from AHP addresses the possibility that air traffic controllers might be able to provide more accurate weights for traffic complexity terms when providing individual weights for each candidate traffic factor than can be obtained by the overall complexity rating for each 5 minute interval.

The foundation of the Analytic Hierarchy Process (AHP) is a set of axioms that carefully delimits the scope of the problem environment (Saaty 1986). It is based on the well-defined mathematical structure of consistent matrices and their associated right Eigen vector's ability to generate true or approximate weights (Merkin 1979, Saaty 1980, 1994).

The AHP methodology compares criteria, or alternatives with respect to a criterion, in a natural, pairwise mode. To do so, the AHP uses a fundamental scale of absolute numbers that has been proven in practice and validated by physical and decision problem experiments. The fundamental scale has been shown to be a scale that captures individual preferences with respect to quantitative and qualitative attributes just as well or better than other scales (Saaty 1980, 1994). It converts individual preferences into ratio scale weights that can be combined into a linear additive weight for each alternative.

The resultant can be used to compare and rank the alternatives and, hence, assist the decision maker in making a choice. Given that the three basic steps are reasonable descriptors of how an individual comes naturally to resolving a multicriteria decision problem, then the AHP can be considered to be both a descriptive and prescriptive model of decision making.

The AHP is perhaps, the most widely used decision making approach in the world today. Its validity is based on the many hundreds (now thousands) of actual applications in which the AHP results were accepted and used by the cognizant decision makers.

We first provide an initial matrix for the pairwise comparisons of the candidate traffic factors in which the principal diagonal contains entries of 1, as each factor is as important as itself.

Table 1

	N _{crz}	N _{clb}	N _{des}	T _{rtf}	V _{met}	T _{spd}	T _{eng}
N _{crz}	1	1/4	1/3	1/7	1/9	1/6	1/6
N _{clb}	4	1	3	1/6	1/8	1/5	1/5
N _{des}	3	1/3	1	1/7	1/9	1/6	1/6
T _{rtf}	7	6	7	1	1/2	3	3
V _{met}	9	8	9	2	1	6	6
T _{spd}	6	5	6	1/3	1/6	1	3
T _{eng}	6	5	6	1/3	1/6	1/3	1

In providing values in order to create the matrix it is considered the scale of relative importance developed by Saaty which is presented below.

Then we divide each element of the matrix with the sum of its column, we have normalized relative weight. The sum of each column is 1.

The normalized principal Eigen vector can be obtained by averaging across the rows: $w = [0.02288 \ 0.05215 \ 0.03287 \ 0.2287 \ 0.3973 \ 0.1430 \ 0.1129]$.

Table 2

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Demonstrated importance	An activity is strongly favored and its dominance demonstrated in practice
9	Absolute importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed
Reciprocals of above nonzero	If activity i has one of the above nonzero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i.	

Scale of Relative Importance (According to Saaty (1980))

Aside from the relative weight, we can also check the consistency of the answers. To do that, we need what is called Principal Eigen value. Principal Eigen value is obtained from the summation of products between each element of Eigen vector and the sum of columns of the reciprocal matrix.

$$\begin{aligned} \lambda_{\max} = & 36 * 0.02288 + 25.58 * 0.05215 + 32.33 * 0.03287 + 4.1 * 0.2287 + 2.16 * 0.3973 + \\ & 10.85 * 0.1430 + 13.52 * 0.1129 = 0.82368 + 1.334 + 1.0627 + 0.9377 + 0.8581 + \\ & 1.55155 + 1.5264 = 7.73488 \end{aligned}$$

Prof. Saaty proved that for consistent reciprocal matrix, the largest Eigen

value is equal to the number of comparisons, or $\lambda_{\max} = n$. Then he gave a measure of consistency, called Consistency Index as deviation or degree of consistency using the following formula:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (2)$$

Thus in our previous example, we have $\lambda_{\max} = 7.73488$ and seven comparisons, or $n=7$, thus the consistency index is:

$$CI = \frac{\lambda_{\max} - n}{n - 1} = \frac{7.73488 - 7}{6} = 0.12248 \quad (3)$$

Prof. Saaty proposed that we use this index by comparing it with the appropriate one. The appropriate Consistency index is called Random Consistency Index (RI).

Table 3

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Then, he proposed what is called Consistency Ratio, which is a comparison between Consistency Index and Random Consistency Index, or in formula

$$CR = \frac{CI}{RI} = \frac{0.12248}{1.32} = 9.27\% < 10\%, \text{ which means that our answers were consistent.}$$

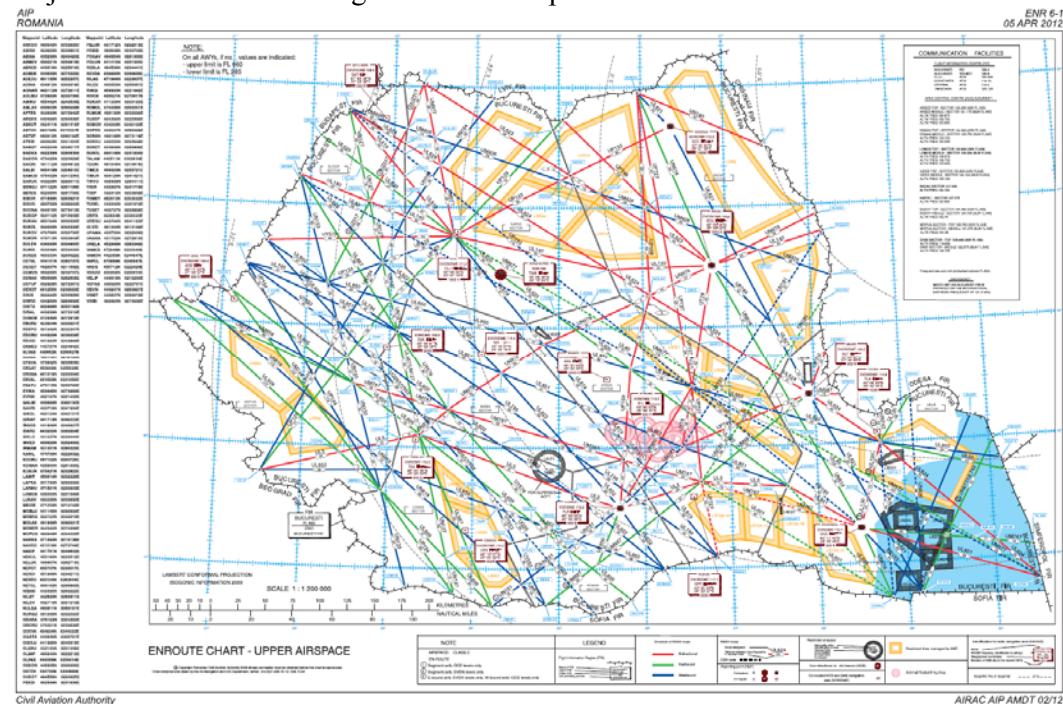
In conclusion, we have the following weighted function:

$$Fc = 0.02288 * Ncrz + 0.05215 * Nclb + 0.03287 * Ndes + 0.2287 * Trtf + 0.3973 * Vmet + 0.1430 * Tspd + 0.1129 * Teng \quad (4)$$

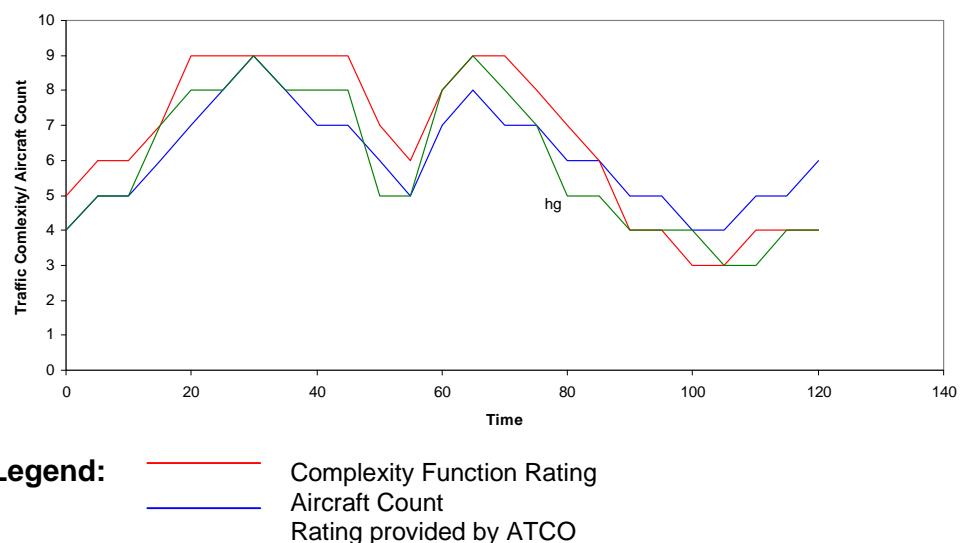
Further on, using this metric we will compute the air traffic complexity for NERDI sector within Bucharest ACC and then the result will be compared with the overall complexity rating for each 5 minute interval provided by ATCO's involved in the project.

NERDI sector it was chosen because it contains an airspace which copes greatly with climbs, descents as well as with overflights, so it can capture all sorts of phases of flight and all types of aircraft operating to/from Bucharest "Henri Coanda" International Airport.

Below we have the En-route Chart – Upper Airspace taken from AIP Romania which is specific for Bucureşti FIR containing NERDI sector with the major flow of traffic crossing Romanian airspace either westbound or eastbound.



Evolution of the Air Traffic Complexity within a period of 2 hours



The graphic above represents the evolution of the air traffic complexity function for a period of two hours for a certain sequence of traffic specific to NERDI sector. The sequence considered here was simulated in an ACC simulator and it was captured a comprehensive set of situations (different types and number of aircraft, various RTF frequency occupation, severe meteorological conditions affecting the sector) in order to involve all the function's factors. On the same graphic there were represented the rating provided by an ATCO at each five minutes interval and the aircraft count (also stated as a rating) for the same interval which is actually the method used in Bucharest ACC in order to establish the moment when a sector must be divided or collapsed with another.

4. Conclusions

The evolution of the results provided by the air traffic complexity function demonstrate that function's factors can capture elements which can balance a lot in the overall workload specific to a sector, elements which definitely are not taken into account when using the "aircraft count" method, and which can easily be subjectively evaluated by an ATCO when providing an overall rating for a sector complexity.

Containing factors like weather phenomena or aircraft type, the air traffic complexity function developed by the authors provides a better picture for the traffic situation than other similar approaches.

The real test for the function developed within this paper is represented by a method or algorithm which will be further elaborated, and which will use the results of the function in order to manage a dynamic sectorization for ACC sectors within Bucureşti FIR.

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