TRAFFIC COMPLEXITY ANALYSIS TO EVALUATE THE POTENTIAL FOR LIMITED DELEGATION OF SEPARATION ASSURANCE TO THE COCKPIT

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Abstract

Following the EUROCONTROL ATM2000+ strategy the Evolutionary Air-ground Cooperative ATM Concepts (EACAC) study is investigating the delegation by controllers of separation assurance tasks to the cockpit, as a near term application in managed airspace. EACAC relies on two key points: limited delegation and flexible use of delegation. However, conditions of applicability depending on traffic complexity are required. A preliminary study using fast-time simulations has been carried out to analyze traffic complexity and thus to evaluate the potential for delegation. New metrics integrating constraining and interfering environmental aircraft have been defined, extending the notion of “cluster”. The proposed traffic complexity metrics are applied to different traffic samples from year 2000 to 2015, with different scenarios (standard or direct routes, and standard vertical separations or RVSM) for the Maastricht Upper Airspace. These new metrics provide encouraging results concerning the opportunities for limited delegation of separation assurance. The proposed metrics of traffic complexity are thought to be generic enough to be applicable in different contexts.

Introduction

The major challenge facing Air Traffic Control (ATC) is to enhance air traffic capacity while providing safety improvement. Following the EUROCONTROL ATM2000+ strategy [6] the Evolutionary Air-ground Cooperative ATM Concepts (EACAC) study, as part of the FREER-FLIGHT project, is investigating the delegation by controllers of separation assurance tasks to the cockpit, as a near term application in managed airspace [7].

EACAC relies on two key points: limited delegation and flexible use of delegation. Indeed, the task delegated to the cockpit by the controller can range from “basic” levels, e.g. monitoring and reporting, to “advanced” levels, e.g. implementation of solution. However, the conditions of applicability for each level mainly depend on the complexity of the problem. Typically, the delegation of the implementation (advanced level) is only envisaged for “simple” problems. In order to assess the potential for delegation, a preliminary study using fast-time simulations has been carried out to analyze traffic complexity.

Previous analysis of different aspects of airspace and traffic complexity have lead to various metrics. To evaluate sector capacity, the MBB method [11] defines a sector complexity based on the notion of unit of work.
integrating characteristics of traffic flow and forecast density. The NASA study [13] modeled the ATC complexity, i.e., the complexity of an air traffic situation as perceived by a controller. It identified various complexity metrics mainly based on traffic characteristics (e.g., traffic density, conflicts number, airspace structure) that impact the “cognitive abilities” of the controller, and combined them in a complexity function. The Dynamic density study [9] proposed a metric to estimate controller workload through a weighted dynamic density function. This function integrates similar indicators to those used in [13] such as traffic density and conflicts. The Tactical Load Smoother [10], a new multi-sector controller planning tool, provides a complexity map integrating similar traffic and airspace complexity indicators, with a prediction uncertainty. Traffic complexity analysis using these standard metrics have also been carried out for investigating the benefits of free-routing [3] or for assessing the potential of the “ASAS crossing procedure” [2]. A new metric of traffic complexity has been introduced by [1]: the notion of clusters which models complexity of conflict in term of aircraft involved. However, these metrics do not provide enough indications to assess the potential for delegation as defined in EACAC, in term of conditions of applicability. For that purpose, a new notion of environmental aircraft for a conflict is introduced: an aircraft not in conflict but in some vicinity, thus that may constrain or interfere in the resolution of the conflict. This extends the notion of cluster. The identification of such environmental aircraft is critical since they impact on the conflict resolution process. The proposed traffic complexity metrics are applied to different traffic scenarios from year 2000 to 2015.

The paper is organized as follows: the following section defines the metrics which were used, the next one describes the fast time simulation scenarios and parameters. The last two sections present the main results and provide comments in the context of EACAC.

Definitions of Traffic Complexity Metrics

In this section selected existing metrics pertaining to conflict and clusters are presented. In addition, the new different types of environmental aircraft are introduced along with a simple method of identifying them.

Conflicts

For conflicts, two principal indicators are considered. Conflict attitude describes the flight phase of each aircraft at the loss of separation: in cruise (Cr), climbing (Cl) or descending (De). Conflict geometry is based on the track angle between the 2 conflicting aircraft. Conflicts are classified in 3 categories: head-on (aircraft in opposite direction, angle of convergence less than 15°), overtaking (aircraft in same direction, angle of convergence less than 15°) and crossing (aircraft either in opposite or same direction, angle of convergence between 15° and 165°).

Clusters

When aircraft are involved in multiple conflicts close in time, the resolution processes overlap in time, resulting in possible interference between processes. Such situations have an impact on the complexity from a human [13] or a system point of view. This group of interfering conflicts is modeled by the notion of clusters [1]. The number of aircraft involved in a cluster is a significant traffic complexity parameter.

A cluster is defined as a group of aircraft which are in conflict “directly” or “indirectly”, using transitivity of time closure. For example, if A and B are in conflict, and A and C are also in conflict, A, B and C are in the same cluster if both resolution processes (A vs. B) and (A vs. C) overlap.

Constraining and Interfering Aircraft

An environmental aircraft is defined with respect to a given aircraft in conflict referred to as subject aircraft.
environmental aircraft is not part of the conflict with the subject aircraft but it is in some vicinity of the subject aircraft, and may therefore constrain or interfere in the resolution of the conflict. Three kinds of environmental aircraft are introduced depending on the impact on resolution:

- **Surrounding aircraft**: an aircraft which has no impact on the subject aircraft resolution process.
- **Constraining aircraft**: an aircraft which constrains the subject aircraft resolution process, but not involved in any conflict during that process: it has to be considered in the elaboration of the new subject aircraft trajectory.
- **Interfering aircraft**: an aircraft which is itself in conflict and whose own resolution process may interfere with the subject aircraft resolution process, *i.e.* there is an overlap of both resolution processes.

The interfering and the subject aircraft may be in the same cluster through the transitivity of time closure. However, they may rather belong to two distinct clusters which are “close” in distance. Here, we extend the standard definition of cluster, as a transitive closure of time and distance.

Figures 1, 2 and 3 summarize each case. For each figure, aircraft A and B are in conflict. E is the environmental aircraft. The dotted lines correspond to possible resolution trajectories for A.

**Figure 1.** Surrounding aircraft. E is far enough from A and does not constrain A in the elaboration of its new trajectory.

**Figure 2.** Constraining aircraft. E constrains A in the elaboration of its new trajectory.

**Figure 3.** Interfering aircraft. E is in conflict with X and the elaboration of both new trajectories for A and X are interfering.

**Identification of Different Environmental Aircraft**

For the purpose of environmental aircraft identification, the following time intervals are defined (Figure 4):

- \( \Delta R \): time span of the resolution process.
- \( \Delta S \): time interval between the last opportunity to maneuver to solve the conflict and the loss of separation.
- \( \Delta L \): look-ahead time, *i.e.* the time interval during which constraining aircraft have to be considered. \( \Delta L \) always starts at the beginning of the resolution process but may extend beyond the end of the loss of separation.

**Figure 4.** Graphical representation of the time periods associated to a conflict.
A possible way to detect the constraining aircraft is to use a conflict solver exploring systematically all possible solution trajectories and identifying as a side effect the constraining aircraft, e.g. the MAICA study [4] detects constraining environmental aircraft using the GEARS algorithm [8].

In the context of the study, we identify a constraining aircraft for the subject aircraft as an aircraft intersecting a specified volume around the subject aircraft during the look-ahead time ($\Delta L$). It should be noted that a constraining aircraft obtained by this method may not be constraining from a solver point of view. In addition, surrounding and constraining aircraft are not differentiated. An interfering aircraft for the subject aircraft is identified as a constraining aircraft in conflict with an other aircraft and whose resolution process overlaps that of the subject aircraft.

**Simple Clusters**

The number of “simple” problems occurring in traffic is an indicator of its complexity. We introduce the definition of simple cluster to model this notion.

A simple cluster is a cluster involving only 2 conflicting aircraft with a maximum of 3 constraining environmental aircraft (an aircraft is constraining for a cluster if it is constraining for at least one aircraft of the cluster). An upper bound of 3 constraining aircraft is a rough estimate of the characteristics of “simple” problems as inferred from discussions with a few ATC controllers. Additional studies are required to validate this upper bound.

**Simulated Scenarios**

**Traffic Data**

The airspace considered is the Maastricht Upper Airspace (MUA) which is one of the busiest en-route airspaces in Europe. The traffic sample was obtained from the EUROCONTROL Central Flow Management Unit (CFMU). The flight plans are from a representative day in September 1996. The flight plans follow the route network and the ATC procedures defined for the day they were issued. This sample was validated by controllers from the MUA Center as representative of real traffic. A traffic sample conforming to Reduced Vertical Standard Minima (RVSM) (single alternate distribution) was adapted from the original sample. Both samples conformed to standard routes.

In addition, two new traffic samples, based on direct routes, were derived from the two previous ones. For these two traffic samples (standard and RVSM) the semi-circular rule was applied for the allocation of the Requested Flight Level (RFL).

Thus, four different scenarios, based on the four traffic samples, were simulated:

- standard routes with standard vertical separations
- direct routes with standard vertical separations
- standard routes with RVSM separations
- direct routes with RVSM separations

Traffic growth forecasts [12] were used to derive traffic samples for the year 2000 to 2015 from the original 1996 sample. Traffic growth ratios are given in Table 1.

<table>
<thead>
<tr>
<th>Year</th>
<th>2000</th>
<th>2005</th>
<th>2010</th>
<th>2015</th>
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<tr>
<td></td>
<td>23%</td>
<td>46%</td>
<td>74%</td>
<td>101%</td>
</tr>
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The additional flights are generated by randomly duplicating and shifting in time existing ones. The conflict free condition at sector entry is also enforced.

**Simulation Parameters**

The RAMS tool [5] developed by EUROCONTROL was used to simulate the different traffic samples. A post-processing tool was developed to compute the complexity metrics (cluster and environmental aircraft). The following rules were applied:
• Only conflict detection is performed. Aircraft always stay on their original flight plan.
• A conflict is an actual loss of separation. The separation minima are 5Nm for lateral and longitudinal separations and ICAO standards for vertical ones: 1000ft below FL290 and 2000ft above for standard separations, and 1000ft up to FL410 for RVSM.
• The volume defined for detection of environmental aircraft is a cylinder centered on the subject aircraft with a radius of twice the lateral separation (10Nm) and a height of four times the vertical separation.

The following numerical values for the three time intervals were used:
• ∆S is null. The resolution can occur up to the beginning of the loss of separation.
• ∆R is 5 minutes. This is considered to be the typical time before the loss of separation for a controller to start a maneuver to solve a crossing conflict.
• ∆L is 7 minutes. In the traffic samples used the mean conflict duration is about 1min 30s. Therefore, for the majority of the conflicts, all constraining aircraft up to the end of the loss of separation are identified with a look-ahead of 7 minutes (see Figure 4).

Simulation Results

The results of the simulations are presented below, in the order used to define the metrics. Unless otherwise mentioned, results are for the year 2005 with standard routes and standard vertical separations scenario.

Conflict Evolution

To begin with conflict analysis, the evolution of number of flights and conflicts through years is presented in Figure 5.

Figure 5. Evolution of the number of flights and conflicts through years
The ratio, number of conflicts / number of flights, is increasing with years. It means that the number of conflicts increases more rapidly than the traffic growth. This result is consistent with other studies, e.g. [1].

The same trend is observed with direct routes and standard vertical separations but with a reduction of about 30% in the number of conflicts. This reduction is both due to a better distribution of traffic in the airspace and the application of the semi-circular rule. Again, these results are consistent with those in [1,3].

Conflict Geometry and Attitude

The distributions of conflict geometry and attitude are presented in Figures 6 and 7.

Figure 6. Conflict attitude distribution.
Figure 6 shows that a very high proportion of conflicts, close to 90%, involves at least one aircraft in cruise (Cr). In 28% of conflicts both aircraft are in cruise (Cr/Cr) and 60% involve a climbing or descending aircraft (Cl or De) against an aircraft in cruise.
Figure 7. Conflict geometry for all conflicts and for the main conflict attitudes.

Figure 7 shows that whatever the conflict attitude, the proportion of crossing conflicts is high, especially for conflicts with both aircraft in cruise (Cr/Cr). For the three others scenarios, results are similar.

Cluster Characteristics

The results concerning cluster characteristics are presented in Figure 8, which focuses on the composition of clusters in terms of number of aircraft.

Figure 8. Cluster composition in number of aircraft.

A high proportion (~70%) of 2 aircraft clusters can be observed. This proportion slightly decreases by 9% between 1996 and 2015, but even in 2015, 67% of clusters are 2 aircraft clusters. In particular, in 2005, 70% of the clusters are composed by only 2 aircraft (i.e. simple conflict), and 16% are clusters of 3 aircraft.

The results obtained with direct routes and standard vertical separations show a higher proportion of clusters with up to 3 aircraft than with standard routes, the difference being around 5%. In the case of RVSM, (for both standard and direct routes) the proportion of clusters with up to 3 aircraft is nearly identical to that obtained with standard vertical separations.

Environmental Aircraft around Clusters

The distribution of the number of environmental aircraft for 2 aircraft clusters are presented in Figure 9. In this figure, three groups of environmental aircraft are distinguished:

- constraining aircraft group
- interfering aircraft group
- mixed aircraft group. Such group contains at least one interfering aircraft and one constraining aircraft.

Figure 9. Number of environmental aircraft around cluster of 2 aircraft.

It was found that 62% of the 2 aircraft clusters are surrounded by no more than 3 constraining aircraft.

Simple Clusters

Figure 10 shows the percentage of simple clusters for different upper bounds of constraining aircraft number.
Figure 10. Percentage of simple clusters for different numbers of constraining aircraft.

Figure 10 shows a decrease of the percentage of simple clusters (with an upper bound of three) from 50% in 1996 to 35% in 2015 with a value of 44% in 2005. These curves also highlight the effect of the value of the upper bound of the number of constraining aircraft. It can be seen that there would be a decrease of about 60% in the percentage of simple clusters if the upper bound were reduced from 3 to 0.

Compared to normal routes, the results obtained with direct routes and standard vertical separations show an increase in the number of simple clusters (upper bound of 3) which varies between 16% and 25% according to years. In the same way, RVSM with standard routes leads to an increase of about 25% in simple clusters compared to vertical standard separation results and RVSM with direct routes leads to an increase of about 18% compared to vertical standard separation results.

Influence of Resolution and Look-ahead Periods

As mentioned before, the resolution and look-ahead times were chosen in an en-route airspace context with a majority of crossing conflicts. An initial investigation of the influence of such parameters is performed here. The Figure 11 presents the results obtained by increasing both the resolution and look-ahead time intervals (ΔR and ΔL).

Figure 11. Influence of resolution and look-ahead periods on the percentage of simple clusters.

For a given value ΔR, there is a decrease of about 10% in the percentage of simple clusters when ΔL is increased from ΔR to ΔR plus 2 minutes. Then for ΔL set at ΔR plus 2 minutes, there is a decrease of 55% of simple clusters when ΔR increases from 1 to 10 minutes. For a given set of (ΔR, ΔL) values, switching from normal to direct routes causes an increase of about 10% in the percentage of simple clusters. These results indicate that the longer the resolution and the look-ahead periods, the greater the number of environmental aircraft and the smaller the number of simple clusters. Nevertheless, it should be noted that the resolution and look-ahead times will need to be carefully adapted to each context.

Application to the Concept

Although EACAC aims at covering two major classes of application, crossing and overtaking applications, typically for en-route airspace, and sequencing operations, typically in TMA, only en-route delegation potential was evaluated. As mentioned in the introduction, the conditions of applicability for each level of delegation depend on traffic complexity. The basic level requires no condition whereas, the advanced level is only envisaged for “simple” problems. The figure of 44% of simple clusters
in 2005 provides a first encouraging evaluation of the potential for delegation. In addition, results show that, both RVSM and direct route, two short-term evolutions of ATC, maintain or increase the potential for delegation.

However, three points should be considered. Firstly, all these simple clusters may not be delegated typically due to airspace constraints (e.g. sectors boundary, reserved areas). Secondly, the number of constraining aircraft has been over estimated (no distinction between surrounding and constraining aircraft). Thirdly, results are only based on actual losses of separation: the potential losses of separation are not measured. However, such occurrences could also be delegated in a similar way with similar benefits.

Finally, it may be also interesting to mention the fact that 60% of conflicts involve one aircraft in cruise and one climbing or descending aircraft. Indeed, from an operational point of view, conflicts with an aircraft in cruise and a climbing or descending aircraft are typically well adapted to the proposed delegation concept [7].

**Conclusion**

In the scope of analyzing traffic complexity, new metrics integrating constraining and interfering environmental aircraft have been defined. These new metrics provide encouraging results concerning the opportunities for limited delegation of separation assurance. Further studies are required to correlate these results with “live” data and to integrate airspace complexity aspects to the proposed metrics. The proposed metrics of traffic complexity are thought to be generic enough to be applicable in different contexts. The simple cluster metric could be applied for strategic and tactical complexity management in a free-flight context or in more conventional airspace. In addition, the metric could be integrated into a new controller tool to identify conflicts likely candidates for delegation.

**References**