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Causal Analysis of Airline Trajectory Preferences to Improve Airspace Capacity

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Abstract

The problem of fitting the maximum number of aircraft into ATC sectors, keeping in mind aircraft separation and safety standards, area navigation direct routings and other factors, is known as the airspace capacity problem. Above the European airspace, a high density network of air traffic can be found which is determined by the workload of controllers. Constraint Programming (CP) is a powerful powerful paradigm for representing and solving a wide range of combinatorial problems. The PARTAKE project fosters adherence of air space user's trajectory preferences enhancing Trajectory Based Operations (TBO) concepts by identifying tight interdependencies between trajectories and introducing a new mechanism to improve aircraft separation at the hot spots by the mean of CP. The underlying philosophy is to capitalize present freedom degrees between layered ATM planning tools, when sequencing departures at airports by considering the benefits of small time stamp changes in the assigned slot departures.

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Keywords: Air traffic management; Trajectory Based Operations; Decision Support Tool; Airspace capacity

1. Introduction

As widely known, air transport industry plays a major role in world economic activity and remains one of the fastest growing sectors of the world economy. Because of the continued growth in civil aviation, in many places,

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demand often exceeds the available capacity of the air transport system to accommodate air traffic, resulting in significant downstream effects[1].

The processes used in the International Civil Aviation Organization (ICAO), such as the Flight Plan, have proved their efficiency, however it is well accepted that there are several shortcomings regarding their performance.

According to the ICAO (Doc. 9854), it was already recognized in the 1980s that the existing approach to the provision of Air Traffic Services (ATS) and the air navigation system was limiting continued aviation growth and constraining improvements in safety, efficiency and regularity. However, it became clear that the changes needed to improve the operational concept cannot be achieved by revolution but have to undergo an evolutionary process.

The ICAO ATM operational concepts are applied in several integrated service areas. To better understand the complex interrelationships a short description is summarized. In this research, the ATM System is understood as a holistic entity consisting of seven ATM conceptual components[1]:

- Airspace organization and management
- Demand/capacity balancing
- Aerodrome operations
- Traffic synchronization
- Conflict management
- Airspace user operations
- ATM service delivery management

In order to have a well-functioning ATM system, all these components have to be present and properly integrated. In addition to the seven concept components, the exchange and management of information used by the different processes and services is of great importance.

Furthermore, the airspace organization and management provides the strategies, rules and procedures by which the airspace will be structured to accommodate the different types of air activity, volume of traffic, and different levels of service and rules of conduct. These management activities are underlined by the demand and capacity balancing that can be divided into strategic-, pre-tactical-, and tactical stages[1].

In Europe, an Air Traffic Flow Management (ATFM) service has been established to use the given capacity to the maximum extent possible keeping in mind the guiding principles safety, continuity and expeditious for the flow of air traffic. On strategic level, demand and capacity balancing will respond to the fluctuations in schedules and demands using the Integrated Initial Flight Plan Service (IFPS) where Airspace Operators (AO) and Air Traffic Service Units (ATSU) can specify their most economic and efficient flight plan or repetitive flight plan. All activities are based on principles of the Air Traffic Flow and Capacity Management (ATFCM) and regional European supplementary procedures described in the ICAO document 7030. Information can be retrieved from the System Wide Information Management (SWIM) platform, an advanced technology program designed to facilitate greater sharing of ATM system information, such as airport operational status, weather information, flight data, status of special use airspace, and National Airspace System (NAS) restrictions. At this stage, planning activities are fulfilled with a timeframe of seven or more days before the operation day.

At pre-tactical and tactical stage demand and capacity balancing evaluates the current allocation of the ATM service provider, airspace user and aerodrome operator assets and resources against the projected demands applied approximately 6 days to 1 day before the operation day. Approaching the operation day, demand and capacity balancing focuses more detailed on demand management to adjust imbalances where activities take place between 5 days and 3 hours prior to departure. The system involved at this stage is the Enhanced Tactical Flow Management System (ETFMS) that receives metadata from the IFPS by Air Traffic Service (ATS) Data Exchange Presentation format and based on this input tracks the aircraft with accurate near-to-real-time data, recalculating 4D profiles of flights allowing traffic demand to be understood more precisely. Integrated in the ETFMS is the Computer Assisted Slot Allocation (CASA) system that operates under the “First-Planned, First-Serve” policy. The CASA system calculates the Estimated Time Over for each point of entry in each sector and allocates the Estimated Off-Block Time (EOBT) plus the taxi-time at the departure aerodrome and finally provides the Calculated-Take-Off-Time (CTOT) that must be followed within a -5 to +10 minutes’ slot window[2].

At operational level, the strategic ATFCM concept is taken over by the Air Navigation Service Provider (ANSP) using Air Traffic Control (ATC) systems as for instance the Flight Data Processing System (FDPS) that is based on a trajectory-based model and which is interconnected with external sources (e.g. Network Manager) to exchange data.

Attempting to improve the slot situation, new information processes and systems are under development to meet the current European capacity demands. The goal hereby is to improve the flight planning process and the supporting systems to create shorter routes, reduce emissions, reduce delays and improve the connectivity of trajectories. As a result, the ATFCM adherence measured at its effect and safety level can be revealed and the overload of ATC workload in dense sectors could be decreased.

The paper is organized as follows: Section 2 explains the PARTAKE Project, section 3 describes the tight trajectory detection, and section 4 outlines the tight trajectory resolution. Solutions obtained and an outlook for future research will be given in section 5 and 6.

2. The PARTAKE project

The approach presented in this paper follows the research project PARTAKE[3]. It is a Research Exploratory H2020 project that aims to help mature new concepts for ATM emerging technologies and methods proposing new approaches to improve airspace capacity. The seeks to improve the present demand/capacity balance in ATM by introducing small ground delays in the programmed departure that will not affect the planned traffic since the slot time window assigned to each aircraft will be preserved. The mayor challenge PARTAKE is facing is to reach a robust combination of Reference Business Trajectory (RBT) time stamps.

The vision of the PARTAKE project is to enable a flexible synchronization mechanism that will support an efficient and competitive use of the ATM services based on an intelligent cooperative combination of the time stamp component of the RBT agreed by the Airspace Users (AU's). The core research activities in PARTAKE are geared toward the next 4 concepts:

2.1. Tight trajectory interdependencies: Mitigating adherence problems

In PARTAKE[4], 4-dimensional trajectories (4DT) are considered as a precise description of an aircraft path in space and time which include the ”centerline” of the path, using Waypoints (WPs) to represent specific steps along the path, together with appropriate buffers to describe the associated position uncertainty. The path contains altitude descriptions for each WPs and suitable indications about the time(s) at which the trajectory will be executed. Some of the WPs in a 4DT path may be associated with Controlled Time of Arrivals (CTAs). Each CTA is defined by a Target Time of Arrivals (TTAs) requirement that must be met by the aircraft within a specified time tolerance. Therefore, CTAs actually represent time “windows” for the aircraft to cross specific waypoints and will be used to improve the clearance between aircraft at identified concurrence events.

2.2. Gap Analysis of time stamp combinations to improve time clearances

A causal model is used to analyse the RBT's interdependencies quantified by the temporal looseness. Tight interdependencies (i.e. loose of separation minima) can be relaxed by a small adjustment of the CTOTs of the involved aircraft preserving the TTA and the slot assigned at strategic level. In this way, the "first planned, first served" policy used by most airports could be improved since this policy is justified only due to a lack of tools and relevant information that could analyse the downstream impact of different sequencing departures on saturated sectors.

2.3. Improving adherence robustness through relaxing some non-relevant time stamp contracts

Tight interdependencies enhances the propagation of perturbations, thus, the effects of a poor time waypoint adherence in a high density sector can generate a huge amount of changes in the rest of the trajectories, whereas poor time waypoint adherence in those sectors without tight interdependencies do not create side effects. There are few sectors in Europe with tight interdependencies, which allow adjusting waypoint time-stamps in those areas with a low occupancy factor and negligible soft interdependencies. Thus to preserve time stamp agreements at tight waypoints, it is possible to relax time stamps in some areas to compensate the effect of potential uncertainties (departure time uncertainty and cruise speed uncertainty) or to extend the functionality provided by calculating the CTOT.

2.4. Dynamic, multi-objective optimization model to support AU's business targets

ATM metrics such as Traffic Density, Peak Load, Occupancy and Number of Conflicts will be evaluated in each sector based on the AU's trajectories and the PARTAKE trajectories to synthesize performance comparative indicators at micro level, so the different stakeholders will be able to check the benefits of the developed tools.

In PARTAKE, pre-flight RBT's (at departure) and en-route RBT's (network scope) are mapped into micro-regions pre-flight (trajectory scope) to identify interdependencies and compute feasible clearances to relax tight interdependencies while preserving ATFM TTA and departure slot time constraints. The model to identify the tight trajectory interdependencies will be specified in Coloured Petri Net formalism for an efficient causal analysis while the time stamp control will be evaluated in Constrain Programming (CP). A Service-Based Architecture (SOA) will be used to implement the interface with SWIM while agent-based technologies will be deployed to evaluate in a simulation environment the acceptability of the solutions by the AU's.

3. Tight trajectory interdependencies detection

PARTAKE methodology considers three steps to detect tight concurrence events before the take-off times are slightly adjusted by CP. The first process is the Macro-mapping process, followed by the second process the Micro-mapping process. The third process is based on a Filtering process. Once the tight concurrence events have been detected, slight adjustments on the takeoff time based on CP solutions are applied.

The macro and micro detection process are based on the traffic mapping onto a grid of square macro-cells (12 NM). The grid spans over European Civil Aviation Conference (ECAC) airspace in its totality. The input trajectories (RBT) must be discretized in time-equidistant samples. Each sample contains the horizontal position, indicated by geographical coordinates, and altitude. The position in the sequence of discrete points represent the relative time instant with respect to the known CTOT. The time stamp of each trajectory point can therefore be calculated from the sequence according to the sampling period.

All trajectories are loaded and mapped onto the grids of square macro-cells. Entry and exit times are registered in order to get the cell occupancy time window. Detection at macro-cell level is implemented by determining those macro-cells where more than one aircraft has been detected, indicating the presence of regions that may contain concurrence events. Next step is micro mapping: each macro-cell with potential concurrence events is divided into four microcells, with quadrants named I, II, III and IV. The partition procedure is shown in Fig. 1a, where C_{i1} refers to quadrant I of cell C_i etc.

To determine whether a trajectory occupies one of the four microcells (squares of 6 NM), the trajectory points within the macro-cell are analysed and the occupancy time window $[t^a_{entry}, t^a_{exit}]$ is registered. Detection at micro-cell level is implemented by determining those micro-cells where more than one aircraft has been detected. The detection process cannot be limited to one (macro or micro) cell occupancy analysis. The potential concurrence events with trajectories at the surrounding cell must be also investigated. Fig. 1b illustrates this shifting analysis. All the potential conflicts are registered providing position information about the quadrant and the cell of the overlapping of two or more aircraft and the aircraft involved in the overlap. This set of potential concurrence events is the input for the next filtering module.

The filtering process to be implemented in this module shall filter those trajectories either losing the required clearance (separation minima) or in a risk of losing it after mitigation measures are applied. The filtering process is based on the collective micro-regions detected in the mapping tool. For these collective micro-regions, entry and exit times are used to determine the temporal looseness, referring to the size of the overlap or clearance between aircraft pairs.

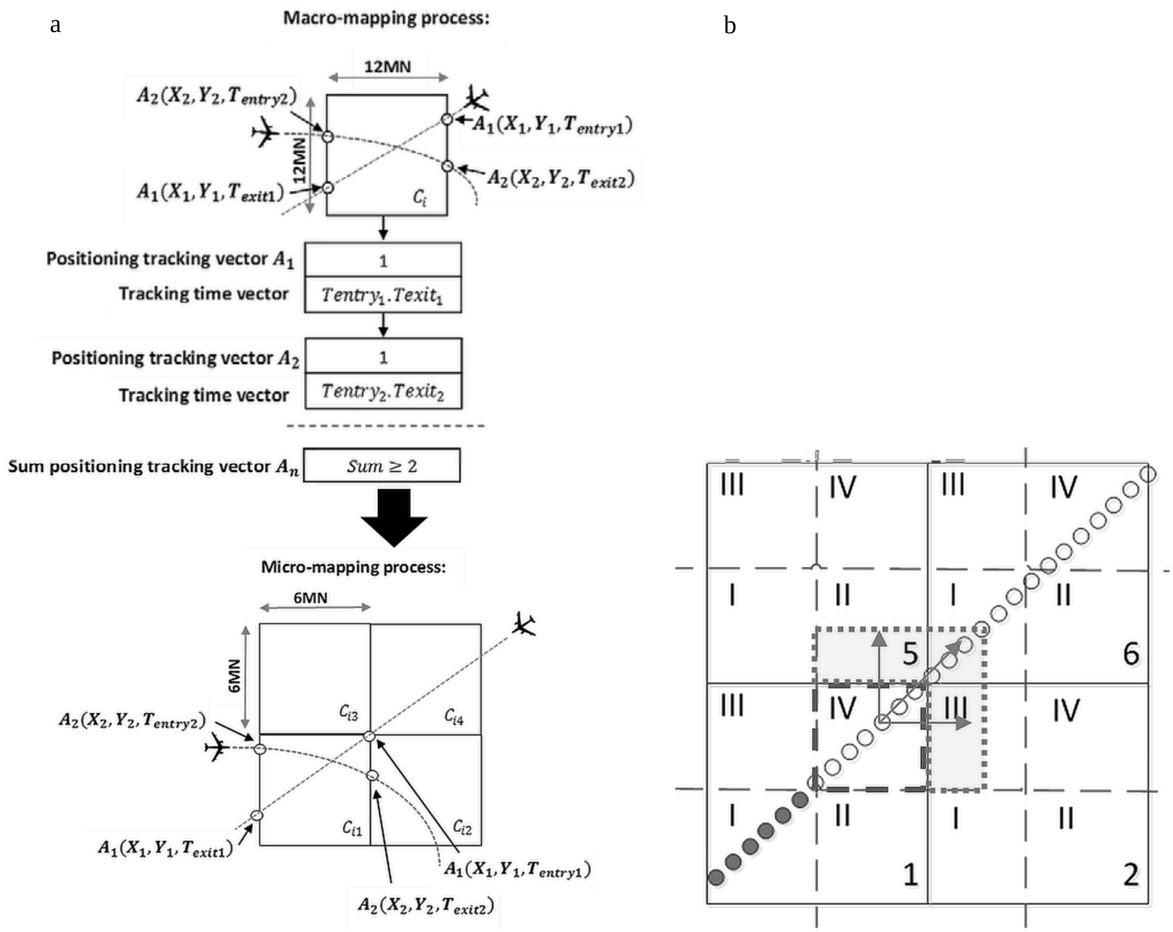

Fig. 1. (a) Micro and macro mapping processes; (b) Neighbourhood detection.

The calculation of the temporal looseness H between time windows of aircrafts $a_1$and a_2 in a collective micro-region is expressed as follows:

$$H = \min\left(t_{exit}^{a_1}, t_{exit}^{a_2}\right) - \max(t_{entry}^{a_1}, t_{entry}^{a_2})$$

Concurrence events exist when H is positive, indicating an overlap, whereas events with a negative H value have a clearance time, indicating a potential concurrence event. Based on the calculation of H (the size of an overlap or clearance), it is possible to identify the ‘‘tightest’’ concurrence events, or potentially concurrence events, for each pair of aircraft. Hence, to shorten the overall list, all redundant or highly slack events between pairs of aircraft are eliminated, whereas the most critical or closed interactions are retained. Because departure slot allocation times must be respected, the maximum value for a time adjustment on CTOTs will be considered to be between -300 s and $+600$ s. Therefore, potential concurrence events with a clearance time longer than 600 s have sufficient time separation to be neglected, even when the maximum adjustment time is applied. A safety buffer S can be added to the 600 s in order to ensure a clearance time S between any pair of aircrafts going into a collective micro-region.

4. Tight trajectory interdependencies resolution

The mitigation tool aims at finding the proper mitigation actions for elimination the detected tight interdependencies. In PARTAKE, trajectories that show a tight interdependency should be resolved by applying a CTOT shifting of +5 and -10 minutes and slight speed adjustments since the TTA need to be preserved as much as possible (see Fig. 2). Because of the strong complexity associated with solving time adjustment allocation problems and to find solutions within a reasonable computational time, the fine-tuning process is implemented as a Constraint Programming (CP) model, expressed in terms of three main entities: decision variables, their corresponding domains, and constraints relating them.

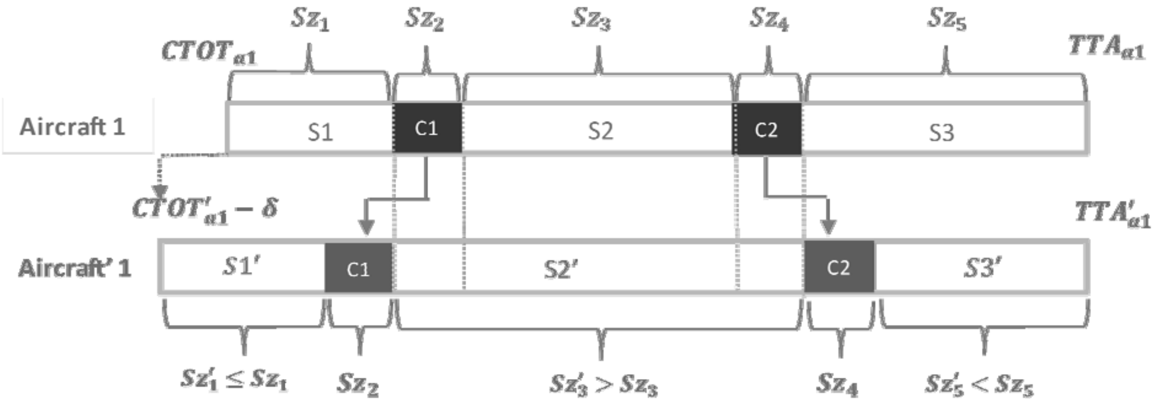

Fig. 2. Modifications on the A/C RBT by CTOT Shifting and Speed adjustments actions.

In PARTAKE, TTA adherence is a main objective to enhance capacity at arrival airports. Clearly, the TTA cannot be preserved by shifting the CTOT and therefore, the full trajectory. Therefore, speed adjustment should be introduced in the A/C trajectory. To meet TTA conditions, the trajectory is divided into segments. The Fig. 2 illustrates this concept. For instance, aircraft 1 in the figure is divided into five segments: C_1 and C_2 represent the concurrence events while S_1, S_2 and S_3 are the segments between the concurrence events. In the modified trajectory, the segment S_1' is shifted according to the applied delay on the CTOT to avoid the first concurrence event while S_3' is shortened in time by speed change in order to preserve the TTA within the margin. The intermediate segment S_2' is extended in time by flying with reduced speed to avoid concurrence event C_2.

The mitigation algorithm shall be formulated as an optimization problem where the constraints are formulated to remove the tight interdependencies. The mitigation tool is based on the following modelling structures (see Table 1).

Table 1. Mitigation algorithm modelling structures.

Data structure	Explanations
A set of aircrafts	
C set of cells at a collective microregion	
$C_A = \{< c, a > \mid \forall c \in C, \forall a \in A\}$	$c_a =< c, a >$ the pairing between the aircraft a using a given cell c at the microregions.
$RBT_a = \{\hat{g}_i^a \mid \forall a \in A,\ i = 1..p(a)\}$	$\hat{g}_i^a$ is a segment of the aircraft a trajectory and p is the number of segments required for describing the trajectory
Decision variables:	
d.v. $\delta_a \in [-\delta_{min}, \delta_{max}], \forall a \in A$	To ensure that the departure adjustment of the aircraft remain in the defined timeframe of [-5,10] minutes
d.v. $P_{c_a} \in [c_a^{te} - \delta_{min}, c_a^{ts} + \delta_{max}], \forall c_a \in C_a$	Interval for the occupancy of the cell c by an aircraft a with its'

size and start and end time

d.v. $F_c = \{P_{c_a} | c_a \in C_A\}, \ \forall c \in C$

Each of the cells can be occupied by one aircraft at a time, so the aircrafts going through the cell must be sequenced accordingly.

d.v. $G_a, \ \forall a \in A$

Representation of the entire flight trajectory where s_a will be the take-off time and e_a the arrival time in the solution.

d.v. $g_i^a, \ \forall a \in A, \ \forall i \in 1..p(a)$:

$$sz(g_i^a) \in [sz(\hat{g}_i^a) - l(\hat{g}_i^a), sz(\hat{g}_i^a) + l(\hat{g}_i^a)]$$

Interval variables representing the segments of the G_a and their size.

d.v. $T_a = \{g_i^a\}, \forall a \in A$

Sequence variable T_a is introduced to set the relationship between the trajectory segments g_i^a and the entire trajectory G_a:

Objective function and constraints:

minimize

$$w_1 \sum_{a=1}^{n} |\delta_a| + w_2 \sum_{a=1}^{n} L(G_a)$$

It might happen that no solution is found because time adjustment is bounded so it is possible that the required delays δ_a cannot be compensated by the speed adjustments. For this reason, the TTA constraint is relaxed. The number of TTA violations can be counted for introducing its minimization as an objective together with the objective function to minimize the total delay of the aircraft takeoffs.

subject to {

$$s(g_i^a) = CTOT_a \pm \delta_a \ \forall a \in A$$

The duration of the flight is determined by the constraint of the take-off time and the time to arrival

$$\forall P_{c_i}, P_{c_j} \in F_c$$

No overlap is guaranteed for the concurrence event P_{c_i} at a position prior to any P_{c_j} by constraining its exit time to be lower or equal to the entry time of the subsequent proximate events

$$NO(F_c) \Leftrightarrow \pi(P_{c_i}) < \pi(P_{c_j}) \Rightarrow e(P_{c_i}) \le s(P_{c_j})$$

The *no overlap* constraint that imposes a set of interval variables to not overlap each other in time

$$span(G_a, \{g_i^a\}), \forall a \in A, \forall g_i^a \in T_a$$

The constraint *span* states that the interval flight spans over all present intervals from the set segments.

$$\forall a \in A, \ \forall i, j \in 1..p(a)$$

$$NO(G_a) \Leftrightarrow \pi(g_i^a) < \pi(g_j^a) \Rightarrow e(g_i^a) \le s(g_j^a)$$

Interval variables do not overlap each other

$$e(g_i^a) \le s(g_j^a) : \ i \le j$$

One segment has to start before the next

$$e(g_i^a) = s(g_j^a) : j = i + 1$$

start of segment j results after the end of segment i

$$\begin{cases} s(g_i^a) = s(P_{c_a}) \\ e(g_i^a) = e(P_{c_a}) \end{cases} \Leftrightarrow \begin{smallmatrix} s(\hat{g}_i^a) = c_a^{te} \\ e(\hat{g}_i^a) = c_a^{ts} \end{smallmatrix}, \forall c_a \in c_A$$

The P_{c_a} interval variable, that is used in combination with the sequence variable F_c to remove the concurrence events at cell c, must be linked with the concurrence segments of the trajectory T_a

5. Results obtained for trajectory adjustments

The data that was used for this experiment was obtained from an over-stressed scenario with the duration of 2 hours that is composed of 4010 4D trajectories flying above the European airspace. The trajectories were discretized every second giving information about longitude, latitude, altitude and speed and TBO were assumed to be without uncertainty. Originally, this scenario was designed and analyzed in the STREAM project and EUROCONTROL SESAR WP-E project.

Before introducing slight departure time adjustments, conflicts can be clearly seen in the Gantt. After executing the presented algorithm for mitigating trajectories with potential concurrence events, all conflicts could be removed by applying delays on the CTOT and/or adding speed adjustments with less than 10% modification of the RBT proposed originally by the airline. The ILOG CP solver was limited to 180 seconds to get the best suboptimal solution. All the experiments were performed on a Window 10 computer with an Intel Core I7 CPU 2,30 GHz and 16GB RAM.

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