B04 Research Opportunities in the Synchronization of Arrival Traffic

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Abstract

The main task in synchronizing arrival traffic is to create smooth trajectories for an efficient use of the runways. Current decision support tools for such a task typically consist of sequencing and metering, that is to establish a reasonable sequence of aircraft arriving from different routes and to calculate for each aircraft the required en-route delay that is necessary to respect the safety separations. The major limitations of such tools are trajectory prediction uncertainties, limitations of en-route capacity and the generation of precise navigation maneuvers. These limitations decrease the confidence of decision makers in the tools. In the future, traffic management coordinators want more options to solve their problems and not yet another tool that they do not trust. In this context, we propose three ideas that increase the insight in the task of managing arrival flows. These are the impact of prediction uncertainties on the stability of traffic sequences, strategies to distribute en-route delays under uncertainty and characteristics of efficient arrival flows. The intuition of our approach is to generate understandable strategies to create efficient arrival flows. This includes information on the fuel performance of different merging strategies and on the risk that a decision support tool will generate imprecise advisories. Work on these ideas is currently underway at the Electronic Navigation Research Institute.

1 Introduction

The main requirement in air navigation is to guarantee that aircraft never collide during their flight. For this, flights are typically guided by Air Traffic Controllers from their departure to their destination. Based on radar screens and their experience, the controllers give navigation instructions to the pilots in order to keep aircraft a safe distance from another at all moments during the flight.

During the last years it has been recognized that the *conditions* to guarantee safe flights involve a planning process that is by far longer than the flight duration of individual flights. Figure 1 shows the flight planning horizon, including an 'execution phase' (minutes to hours), a 'mid/short term phase' (hours to months) and a 'long term phase' (several months before take-off). The reason for this long planning horizon is that the growth of traffic demand is typically higher than the growth of airspace capacity.

In this context, Air Traffic Management (ATM) is defined as the 'dynamic, integrated management of air traffic and airspace — safely, economically and efficiently — through the provision of facilities and seamless services in collaboration with all parties' [1]. In order to realize this definition, ICAO (International Civil Aviation Organization) developed a 'Global ATM concept' [1]. It consists of seven components such as conflict management to avoid collisions between aircraft, airspace organization to define efficient sector and route structures or demand/capacity balancing to identify traffic flows that respect the airspace capacity. One of the remaining four components is 'Traffic Synchronization', the topic of this article.

The article is organized as follows: in the next section we introduce the concept of traffic synchronization with a focus on arrival flows. Then, we discuss the technical requirements of a system that is capable to support Traffic Management Coordinators in their task of synchronizing arrival traffic. Based on this, we propose three research opportunities that advance the current state-of-the-art in decision support for traffic management coordinators. Finally we discuss the overall approach and conclude with the main facts.

2 Synchronization of Arrival Traffic

The main idea behind traffic synchronization is that the conditions for safe and efficient traffic flows are met across all sectors, and during all phases of flight (departure/en-route/arrival) [1].

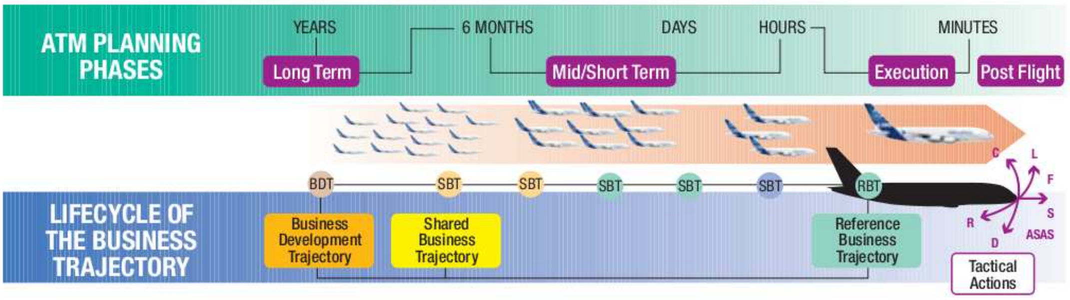
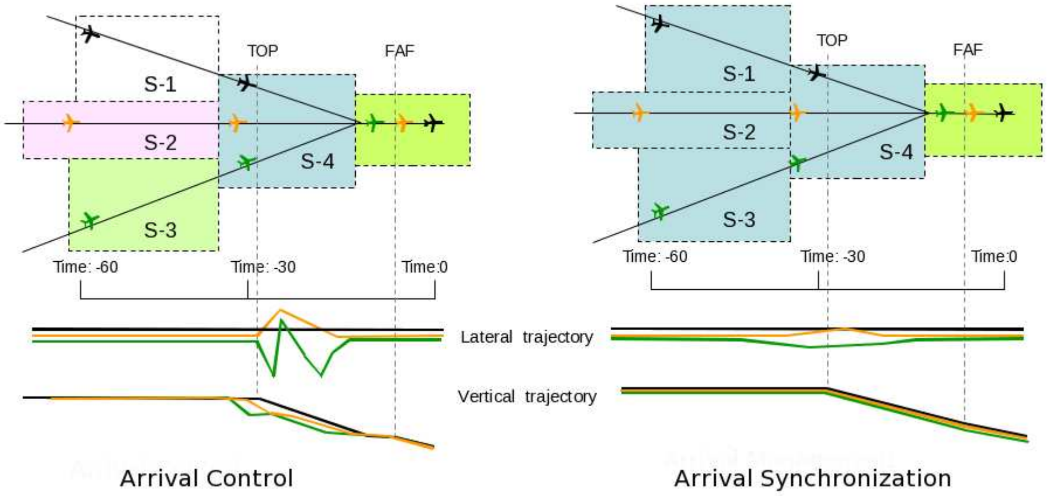


Figure 1: Planning horizon in ATM. (Sesar [2]).



Arrival Control

Arrival Synchronization

Figure 2: Arrival Control and Arrival Synchronization.

It takes place during the 'execution' phase of ATM planning. There is an overlap with strategic conflict management on the one side and demand/capacity balancing on the other side [1]. This means that flight trajectories have to be identified that are conflict-free on the one side and as efficient as possible on the other side. But research in Europe and the U.S. suggests that synchronizing traffic in complex airspace (e.g. en-route with traffic crossings) is currently too difficult to achieve [3, 4]. Moreover, the major source of congestion in Japanese airspace are the metropolitan airports and their surrounding airspace [5]. For these reasons we focus in this article on the synchronization of arrival traffic.

A typical arrival pattern is that two or more traffic flows merge at the boundary between an en-route and the terminal control center. The task of traffic management coordinators (TMC) in this context is to create the conditions for an efficient use of the runways. For this, they need to estimate roughly (in the order of minutes) how much and when to delay flights in the upstream sectors to the arrival. The higher the altitude of a delay, the more fuel efficient it is. On the other hand, predictions over long time horizons introduce uncertainties (e.g. certain aircraft will still be on the ground), with the risk of under-usage of runway capacity. Synchronization of arrival traffic has thus to identify strategies to

1. distribute en-route delays among sectors
2. balance ground-delays with en-route delays

Figure 2 compares the current situation with the concept of arrival traffic synchronization. Today's operations are dominated by 'arrival control' (left part). This means that aircraft are mainly handled by the controllers of the sector prior to the merging point. During periods of high demand or bad weather (where separations between aircraft have to be enlarged), arrival control often results in inefficient lateral and vertical trajectories (bottom left). In 'arrival synchronization' (right part), navigation instructions will already be given in upstream sectors to the arrival (up to 40 minutes in advance). It is expected that this concept leads to smoother trajectories, with the consequences to optimize runway capacity, increase the fuel efficiency of flights and reduce controller workload [1]. It is also expected that the concept creates greater flexibility in the planning process, for example to better accommodate airlines priorities of specific flights (user-preferred trajectories).

3 Decision Support for Traffic Management Coordinators

In the previous section we described the concept of arrival traffic synchronization. In this section we describe the technical requirements of a system that is capable to support Traffic Management Coordinators in their task of synchronizing arrival traffic.

3.1 System Requirements

As mentioned above, arrival traffic management coordinators need to create favorable conditions for an efficient usage of the runway. This means that a maximum number of aircraft has to be delivered to the terminal area, without exceeding the capacity constraints. Difficulties in this task arise during traffic peak hours and during bad weather, in which the capacities may change dynamically (because the separations between aircraft need to be increased). Decision support tools for this task exist, and they typically consist of (1) *sequencing*, i.e. establishing a reasonable sequence of aircraft arriving from different routes and (2) *metering*, that is to calculate for each individual aircraft the required en-route delay that is necessary such that safety separations between all aircraft in the sequence are respected and the runway is optimally used.

An example of such a tool is the Traffic Management Advisor (TMA) [6]. It is mainly designed for traffic management coordinators of an en-route center that is next to the terminal area. Its principles are displayed in Figure 3, where two flows merge into one arrival flow. It estimates the arrival times e_i of all aircraft at the gate to the terminal area, sequences them according to a *first-come-first-served* rule ($e_1 < e_2 < \ldots < e_n$), and solves the separation constraints (metering step). The result is a delay d_i (minutes) for every aircraft i, such that the separation constraints are satisfied and the runway is optimally used. With this information, the traffic management coordinators can see how much to delay flights in the upstream sectors. After possibly manipulating the results by hand (e.g. change of sequence), maneuver recommendations can then be communicated to the controllers of the different sectors.

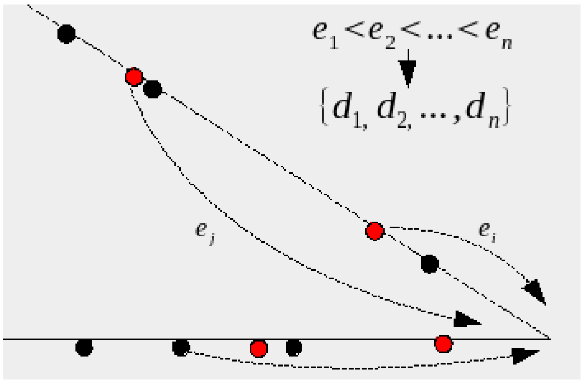


Figure 3: Sequencing and metering two arrival flows.

3.2 System Limitations

While the TMA is already operational in several U.S. control centers, there are three main limitations in the use of an arrival synchronization system: (i) trajectory prediction uncertainties, (ii) limitations of en-route capacity and (iii) the generation of precise navigation maneuvers.

- Firstly, predictions of the *estimated time of arrival* (ETA) over long time horizons introduce uncertainties. This is because of unknown weather conditions, conflict maneuvers or because certain aircraft will still be on the ground when their ETA is needed. If certain aircraft arrive earlier or later than their ETA at the merging point, the computed sequence may be unrealistic. When this happens occasionally, such situations can be corrected manually (the coordinator adjusts the computed sequence by hand). But if this situation occurs too often, no reliable traffic sequencing can be done [4].
- Secondly, airborne delays are materialized either by speed control or by path stretching. Aircraft dynamics impose a limitation on delay that can be absorbed by speed control, especially during descent [7]. This means that, depending on the length of a sector s, an aircraft may only absorb a fraction $d_{i,s} < d_i$ of its calculated delay. Similarly, limitations of path stretching depend on the sector geome-

try, which are more complicated to determine analytically. Thus, a strategy to distribute the delay of an aircraft between several sectors is necessary.

- And finally, current systems only compute the delays that are necessary to meet the sequence constraints but does not propose solution trajectories to materialize them. In the future, a shift from such 'time based' systems to '4D trajectory-based' systems is announced by the major airspace programs [1, 2, 8].

4 Research Opportunities

In the previous section we discussed the three major limitations of current decision support systems for arrival traffic. In this section we describe three research opportunities that advance the current state-of-the-art in decision support for traffic management coordinators. The common line of these ideas is to generate strategies to create efficient arrival flows. This includes information on the fuel performance of different merging strategies (e.g. only speed control on the main route vs. speed control and path stretching on major and feeder routes) and on the risk that a decision support tool will generate imprecise advisories (e.g. depending on the traffic complexity).

4.1 Uncertainties in Sequencing Operations

The determination of a sequence that optimizes runway capacity is a difficult optimization problem [9]. In practice, the principle of *first-come-first-served* is often proposed as a reasonable heuristic. In both cases, the estimated time of arrival of aircraft at the metering point has to be known in order to establish a sequence. But ETA predictions suffer from uncertainties that grow in distance and in time. For example, to predict the estimated time of arrival of an aircraft that is still on the ground at the time of prediction introduces considerable uncertainty because the pre-departure uncertainties are known to be larger than en-route uncertainties (e.g. [10]). This is confirmed by experiments in complex airspace where current tools computed unrealistic sequences that are of no help for the controllers [4].

A research question is thus an analysis of the impact of prediction uncertainties on the stability of traffic sequences. It is clear that the problem depends on the distance between successive aircraft in both flows and on the prediction errors. We propose a probabilistic approach, in which both of these quantities are considered to be random variables. More formally, given a sequence

$$s = (e_1 < e_2 < \ldots < e_n) \tag{1}$$

where $e_i \in \mathbb{R}$ is the estimated time of arrival of aircraft i, we are interested in the probability that random disturbances ϵ_i of these arrival times will switch the sequence. For two aircraft i, j we have:

$$\begin{aligned} P(S_{ij}) &= P(e_i + \epsilon_i \geq e_{i+j} + \epsilon_{i+j}) && (2)\\ &= P(\epsilon_i - \epsilon_{i+j} \geq e_{i+j} - e_i) && (3)\\ &= \int_{k=0}^{\infty} f(k) G(e \leq k) dk && (4) \end{aligned}$$

where f is the density of the random variable $\epsilon = \epsilon_i - \epsilon_{i+j}$ and G the distribution function of the random variable $e = e_{i+j} - e_i$.

Coming back to Figure 3, one can for example think of the two flows R_m, R_f as Poisson processes with the rates λ_m and λ_f (aircraft per hour). Borrowing results from the theory of Point processes [11], the distribution of the random variable e is then known. Similarly, knowing the distribution of the variable ϵ, the above integral can be calculated. Our initial results indicate that the switching probability stabilizes early and at a low level [12]. Such results give confidence to a decision maker who wants to understand the behavior of his/her sequencing tool before using it.

4.2 Distribution of en-route delays

We have seen that a traffic management coordinator asks for strategies to *distribute* delays between several sectors. The higher the flight level of a delay, the more fuel efficient it is. But decisions taken far from the metering point introduce the risk of using the runway capacity inefficiently. Research on a trade-off between the benefits and risks of en-route delays has to be done.

A method to identify a conservative strategy to distribute a delay d between N sectors is to see this problem as a game between a traffic management coordinator who tries to create the most fuel and runway efficient sequence, and 'nature' who tries to do the opposite. This idea is put forward by [13] and can be formalized that for every aircraft

$$\Delta^* = min_{\Delta} max_{\omega} \sum_{i=n}^{N} C(\Delta_i, \omega_i) \tag{5}$$

s.t.

$$\sum_{i=n}^{N} \Delta_i + \omega_i = d \tag{6}$$

where Δ_i is the delay of the aircraft in sector i (the decision variable), ω_i is a random variable that describes the uncertainty in the transit time of sector

i and C is a cost function (giving for example more cost to delays in low altitude sectors). A similar approach would be to study the average behavior of the system, in which the above optimization would be replaced by the minimization of the expected value of the cost function.

In a long-term vision, this research thread will also integrate traffic synchronization with demand/capacity balancing, as required by ICAO [1].

4.3 Fundamental Properties of Arrival Traffic Flow

While much is known about the dynamics of single aircraft (e.g. [7]), the trajectory prediction and control of multiple aircraft remains a difficult problem. Technically, the reasons lie in the nonlinearity and the combinatorial nature of the problem. But also conceptually, current approaches often lead to uninterpretable results [14, 15].

In order to keep societies' confidence in ATM, transparent strategies to identify efficient flows are needed. Fundamental research can help to build a basis for such strategies. Research questions include for example,

- what are the conditions for low average delays ?
- what are the characteristics of efficient flow patterns ?

A simple approach, inspired by the analysis of vehicular traffic, would describe the acceleration of an aircraft to be dependent on the distance to its neighbors [16]. A merging flow can then be described as a coupled system of motion equations

$$d^2x_i/dt^2 = f(x_i, x_{i+1}) \tag{7}$$

where $x_i(t)$ is the position of aircraft i at time t, x_{i+1} is the closest neighboring aircraft and f describes the resulting speed adaptations. A solution to such a system describes the 4D trajectories of all aircraft. In general, this risks to be a complicated result but the stationary solutions (nominal speed) of system (7) represent the ideal case, in which merging aircraft would fly without any controller intervention. The conditions for a stationary solution are certainly met during the night. But a traffic management coordinator needs to know under which other conditions traffic patterns are fuel and workload efficient.

Such conditions can be derived from a theoretical analysis. The output of this research is a better understanding of the qualitative behavior of arrival flows. This is a complementary approach to the goal of further automating current controller operations.

5 Discussion

In Section 3 we cited that users often have no confidence in tools for arrival traffic synchronization. The reasons for this include unrealistic traffic sequences or metering advices that are difficult (or impossible) to materialize. To improve the situation, there are two possibilities: one can improve the tools or one can create the traffic conditions that the tools can handle.

For the first, it is necessary to improve the data accuracy (for example more frequent radar track updates) and the solution algorithms (for example the generation of 4D trajectories to materialize enroute delays). The context of such work is to solve arrival problems 'case by case', by creating solution trajectories for any input of problem trajectories. This is already investigated by other researchers [17] and in previous ATM programs (e.g. [18]).

The second possibility is less developed. It consists of analyzing traffic patterns in order to generate general strategies on how to create efficient arrival flows. Examples have been discussed in section 4, but the main intuition is to create advice in the form of: 'whenever a cluster of 10 aircraft arrives on the major route and a cluster of 4 aircraft arrives from the feeder route', then

- 'using *only* speed control *only* on the major route has a fuel performance of $\sim$ 85% and a risk of sequence swap of 14 %'
- 'using speed control *and* path stretching on *both* routes has a fuel performance of $\sim$ 95% but a risk of sequence swap of 32 %'

Such results give more options to a traffic management coordinator who wants to create the conditions in which controllers and decision support tools can work appropriately.

6 Conclusions

The purpose of the synchronization of arrival traffic is to create the conditions for an efficient use of the runways, across all sectors and all arrival routes. This corresponds to the determination of trajectory maneuvers that take already place in the upstream sectors to the arrival terminal. It is expected that this concept leads to smoother arrival trajectories, with the consequences to optimize runway capacity, increase the fuel efficiency and reduce controller workload. It is also expected that the concept creates greater flexibility in the planning process, for example to better accommodate airlines priorities of specific flights (user-preferred trajectories).

We discussed the technical requirements and limitations of decision support system for arrival traffic. Based on this we proposed three ideas that advance the current state-of-the-art in decision support for traffic management coordinators. The intuition of our approach is to generate understandable strategies to create efficient arrival flows. This includes information on the fuel performance of different merging strategies (e.g. only speed control on the main route vs. speed control and path stretching on major and feeder routes) and on the risk that a decision support tool will generate imprecise advisories (e.g. depending on the traffic complexity).

We believe that this approach gives more options to a traffic management coordinator who wants to create the conditions in which controllers and decision support tools can work appropriately.

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