An analysis of sequencing arrivals at three European airports

Raphaël Christien, Eric Hoffman, Aymeric Trzmiel, Karim Zeghal
EUROCONTROL Experimental Centre
Brétigny-sur-Orge, France

Abstract—This paper presents an analysis of the sequencing of arrival flights at three European airports (Frankfurt Main, London Heathrow and Madrid Barajas) during peak periods with more than 24000 aircraft pairs. The underlying motivation was to better understand and characterise how sequencing is performed in dense and complex environments. The analysis, purely data driven, focuses on the dynamic of spacing over time between consecutive aircraft, investigating in particular convergence and monotonicity.

The two main results are: (1) progressive convergence of the spacing, with a spacing deviation up to ±2.5min at 10min to final, and ±45s at 5min to final; and (2) non-monotonous convergence (periods of divergence) with an extra variation of spacing up to 2.5min at 10min to final, and 45s at 5min to final. These values may reflect the level of bunching that has to be resorbed by the sequencing, and the level of sensitivity while acquiring and maintaining spacing during peak periods in such dense and complex environments.

Future work will involve investigating how this approach may help identifying best practices and assessing the impact of a change (e.g. procedures, operating methods).

Keywords: arrival sequencing, aircraft spacing, approach control, data analysis.

I. INTRODUCTION

This paper presents an analysis of the sequencing of arrival flights at three European airports (Frankfurt Main, London Heathrow and Madrid Barajas). The analysis relies on a method purely data driven recently introduced and tested on simulation data [1]. It focuses on the dynamic of spacing over time between consecutive aircraft, investigating in particular convergence and monotonicity.

The underlying motivation is to better understand and characterise how sequencing is performed in dense and complex environments. The analysis considers peak periods, during which significant sequencing takes place, using three months of data with in total more than 24000 aircraft pairs.

The paper is organised as follows: after a review of related studies and an overview of the method, it will go through the data processing required to compute the spacing indicators related to convergence and monotonicity. The analysis of the sequencing will then be presented.

II. STATE OF THE ART

A comprehensive framework has been developed by the Performance Review Unit (PRU) of EUROCONTROL to characterise the performances of the arrival management process [2][3][5]. Two key elements introduced are the notions of unimpeded time and additional time in the Arrival Sequencing and Metering Area, an area of 40NM (extended to 100NM in some analyses) from the airport. The unimpeded time is the transit time in the area in non-congested conditions. The additional time is the difference between the actual transit time and the unimpeded time. It represents the extra time generated by the arrival management and “is a proxy for the level of inefficiency (holding, sequencing) of the inbound traffic flow during times when the airport is congested.” This indicator is used (together with other indicators such as the flow management delay) in particular to compare the performance of the main airports in Europe and in the U.S.A. [4].

The work presented here builds on these notions of unimpeded time and additional time in an area around the airport, and aims at characterising further how the sequencing is performed. Similar types of indicators were also used at the level of individual flights, such as terminal area transition time deviation, to detect any potential perturbations and assess the resilience of scheduled Performance-Based Navigation arrival operations [6]. Analyses focusing on the spacing on final have been also conducted [7].

When assessing the impact of new concepts in relation with sequencing, detailed analyses have been developed [8][9][10]. They consider different dimensions such as human factor (e.g. workload, radio communications, instructions), flight efficiency (e.g. distance and time flown) and effectiveness (e.g. achieved spacing on final) using simulation data (human in the loop or model based). To highlight the geographically based nature of the sequencing activity, we introduced a geographically based analysis of instructions and eye fixations consisting of displaying these data as a function of the distance from the final point [10]. This enabled to highlight in particular effect such as late or early sequencing actions.
All these studies aimed at assessing the impact of a new concept, and considered the observable actions for sequencing. Although they informed on the sequencing activity of the controller, the dynamic of the spacing is not considered as an element of the analysis. Furthermore, the need for operators related data, in particular instructions, makes uneasy the analysis of current (live) operations. From a control theory perspective, the spacing variable is the key element that should enable the understanding of the human behaviour. Here, we are not aiming at building a mathematical model of the controller, but as stated in [11], “control theory is a good foundation for developing the intuition and judgment needed for smart cognitive systems engineering”.

Numerous analysis of the spacing have been performed in the context of the “airborne spacing” concept when studying the performances of different algorithms or of the flight crews [12][13][14][15][16]. Typical analyses involved in particular the relation between spacing accuracy (control error) and number of speed changes/variations (control effort) as well as the effect of the resulting speed profile on the rest on the chain of aircraft. In all these cases, however, the situation was such that the spacing could be defined: both aircraft followed known paths.

The issue being that, in the general case, the spacing variable is hard to formally define and measure, or even does not exist. In vectoring for instance, while it is straightforward to measure the spacing at a final common point, it is unclear how to define the spacing between two aircraft being vectored on different paths but whose resume paths to the common point are unknown in advance. In this case, the spacing is part of the cognitive process of the approach controller and is not accessible.

III. METHOD

The method used here is data driven and does not make any assumption in terms of sequencing techniques used (e.g. vectoring, tromboning) or controller working methods [1]. Furthermore, no assumption is made regarding aircraft path/navigation: aircraft may be following same or predefined trajectories, or may be on open vectors.

It proposes a definition of spacing between two aircraft at all times in the area considered. The method relies on the combination of two existing notions.

Firstly the constant time delay introduced by NASA to define a spacing deviation for aircraft following same trajectories [12][13]. It considers the past positions of the leader aircraft with a given delay corresponding to the required spacing. This notion will be generalised to any aircraft trajectories.

Secondly the unimpeded time introduced by the PRU to define the additional transit time in the area considered [2][3][5]. It considers the minimum flying time at the entry point of the area, obtained from recorded data during non-congested periods. This notion will be generalised to any point in the area.

Let us consider a pair of consecutive landing aircraft denoted leader and trailer, with s their required spacing in time. Using the constant time delay principle, the spacing deviation (or spacing error) at time t is defined by considering the current position of trailer at time t, and the past position of leader at time t – s.

Since aircraft do not necessarily follow the same trajectory, we have to consider a reference point common to both trajectories such as the final approach fix. The spacing can be defined by considering the flying time to this reference point as if both aircraft were flying the shortest possible trajectories.

Precisely, we define the spacing deviation at time t as the difference between the minimum times from the position of trailer at time t, and from the position of leader at time t – s as follows:

\[
\text{spacing deviation (t)} = \min \text{time (trailer (t))} - \min \text{time (leader (t – s))}
\]

Assuming a representative set of trajectories including non-congested periods, the minimum time from a given point to a fix common point is the minimum time along all trajectories passing through this point to the fix common point. Practically, this implies to compute first all the minimum times for the area considered, typically under the form of grid (per runway and per flow of traffic / entry point).

With a spacing defined at all times, the sequencing can be formulated as a problem of manual control: the objective is to set the spacing error to zero by acting on lateral (e.g. vectoring) and/or on longitudinal (e.g. speed) dimensions. The intrinsic difficulty is to control multiple aircraft pairs at the same time that are chained during peak periods with potential cascading effects.

To capture the sensitivity of the sequencing, we will consider the variations of spacing in excess to set the deviation to zero. Precisely, this is obtained by measuring the variations diverging from zero, i.e. spacing increases while the current spacing deviation is above zero and conversely (cf. Figure 2). This will be denoted “extra variations”.

Figure 1. Defining spacing deviation
IV. DATA PREPARATION

A. Data collection and filtering

The case study is based on a dataset for Madrid Barajas (LEMD), Frankfurt Main (EDDF) and London Heathrow (EGLL), from the 1st of January to the 18th of March 2017 (78 days). The dataset consists in position reports, updated at an average rate of 30 seconds. It contains about 130000 arrival flights (37485, 43927 and 47491 for LEMD, EDDF and EGLL respectively).

We consider a geographical focus area of about 80NM radius around each airport to encompass the sequencing area.

To ensure enough representative data, only major flows (defined as a pair of entry point and landing runway) will be considered, making up of more than 80% of the dataset.

We retain typical arrival flights that enter and exit the focus area. In particular, this excludes go-arounds, flights with exceptionally short or long flying time within the area, and aircraft not flying over the final approach fix (or without data close enough to the runway).

This makes the filtered sample sizes to be: 26196, 30748 and 35981 flights respectively for LEMD, EDDF and EGLL.

The following figure shows a random sample of about 1000 flights for each destination within the focus area.

B. Data construction: minimum time

As presented in section III, minimum times are computed in all the cells of a 2D mesh covering the focus area on the basis of all the recorded data. These minimum times to final are computed per flow (defined as a pair of entry point and landing runway), for each destination.

Note that other factors may be considered to refine the estimation like heading, speed, altitude, aircraft type, wind.

The selected cells size shall not be too large to allow for accurate trajectory deviations assessment. It shall not be too small, as the number of flights per cell will be insufficient to ensure reliable estimates (as a rule of thumb, 10 flights per cell can be considered as a minimum). For this case study, square cells of 1NM width were found to provide an appropriate trade-off.
The minimum times are used to fit thin plate splines [20] for each associated flow: this allows smoother, continuous minimum times estimation from area entry to final approach fix to be performed, reducing the cells boundary aliasing effect.

The result of this computation is shown on the figure below, for each destination, with one map per configuration. The colors depict the minimum time to final, from red (20 minutes) to blue (lower than 1 minute), with overlaid maps and iso-contours per flow. The iso-contours on the map are sampled with a one minute time step.

We consider periods with an average additional time per hour greater than the 3rd quartile value per destination (see boxplots figure below). This corresponds to average values of 5, 4 and 12 minutes for LEMD, EDDF and EGLL respectively (upper part of the boxes on the figure below). Since, the peak periods are based on different levels of congestion per destination, this will not allow for direct comparison.

Flights landing during these periods are considered for the analysis. At this stage of the data preparation process, the dataset consists of 13509, 12016 and 13771 flights for LEMD, EDDF and EGLL respectively.

### Data selection: aircraft pairs

We focus the analysis of aircraft pairs considered to be close enough to require sequencing: we selected pairs with a final spacing lower than 200 seconds at the final approach fix.

This makes the aircraft pairs sample sizes to be: 7664, 5656 and 11593 respectively for LEMD, EDDF and EGLL. These sample sizes are considered sufficiently large to be representative.
V. ANALYSIS OF SEQUENCING

A. An example

This section focuses on a single pair of successive aircraft landing on the same runway (cf. Figure 7) to illustrate the notions of spacing deviation and extra variation of spacing.

Spacing deviation for the aircraft pair example is reported on the figure below, measured every 10s from 15min to 0min before final. The dot colors show convergence and divergence toward zero spacing deviation (respectively blue and red). The colors are matching the 2D view above.

A zero value corresponds to the final spacing, whereas negative (resp. positive) values correspond to an actual spacing lower (resp. higher) than final spacing requiring, for example, path stretching (resp. shortening).

It can be observed at 15 minutes to final (for the leader aircraft) that the spacing deviation is around -1 minute: additional spacing is required. Between 12 and 9 minutes to final, the spacing is steadily decreasing toward a spacing deviation of -2.5 minutes: this corresponds on the 2D view above, as the heading to the right given to the leader aircraft; then, the spacing deviation decreases (diverges) to about -4 minutes during the leader turn to final prior converging back toward the spacing deviation target (zero). A slight positive divergence (extra spacing, last series of red dots) is measured during the trailer turn to final.

This example illustrates that spacing deviation convergence toward zero is not always monotonous.

To capture this aspect of non-monotonicity and reflect the level of sensitivity, we introduced the metric of extra variation of spacing (cf. description in III) as the cumulated sum of the divergences amplitudes. This is computed from 0 to X, with X varying from 1min to 15min with a 1 minute time step, as illustrated on the figure below.

Note: the following analysis relies on peak periods based on different levels of congestion per destination (cf. additional times IV.C) that do not allow for direct comparison.

The following graph shows the spacing deviation curves for 1000 pairs of aircraft selected randomly (lightgray curves). It also shows a median curve\(^1\) and a 90% containment (from 5% to 95%) of the spacing deviation values.

In the following graphs, for readability purposes, the spacing is presented in the range [0,15] minutes for the three airports even if for EGLL many flights may still be in holding stacks at 15 minutes to final.

\(^1\) The median curve is obtained by connecting the median values of the spacing deviation measured every 6s to final. It does not correspond to an actual spacing deviation curve for a given aircraft pair.
The median curves for all destinations are all aligned with the zero deviation, suggesting that there is usually symmetry between the positive and negative spacing deviation values. This symmetry is seen also on the containment curves.

For LEMD and EGLL, the containment curves follow a pretty linear rate. For EDDF, such a linear part exists in the 10-5 minutes to final, while in the 15-10 minutes range, the curves are relatively flat (no spacing evolution).

It can be observed that, at 10min to final, the spacing deviation is about ±2.5min for EDDF, ±2min for EGLL and ±1min for LEMD. At 5min to final, these values decrease to ±42s, ±48s and ±30s for EDDF, EGLL and LEMD respectively, showing the convergence toward zero.

We decided to select three distinct clusters per destination. On the figure below, the typical pattern associated to each cluster is represented by a thick colored line.

Three typical patterns are observed for all destinations: the “spacing obtained” patterns, starting and staying close to zero (middle curves for all destinations, light green); the “less spacing needed” upper patterns, starting above zero (dark blue); the “more spacing needed” lower patterns (or flights sequence swap cases, light blue).

C. Spacing deviation typical patterns

It is possible to have another look at the spacing deviation by identifying typical patterns through statistical clustering. We selected a robust clustering technique (Partitioning Around Medoids, PAM [17], calculations performed using GNU R [18] and the cluster package [19]) that partitions all the spacing curves into k clusters in which each curve belongs to the cluster with the nearest mean, serving as a typical representative.

All patterns seem close to zero deviation from 5 to 0 minutes to final for all destinations: usually, the spacing is already obtained at that stage.

The “spacing obtained” patterns for the different destinations are pretty similar: the spacing is kept pretty close to the final spacing value.

On the “less spacing needed” patterns, LEMD has a spacing reduction needed around 1minute, and shows a relatively linear convergence curve from 15 to 5 minutes to final. EDDF has a spacing reduction required around 2 minutes, and is reducing it in the 7-5 minute to final range. EGLL has a spacing reduction...
required around 2.5 minutes and is reducing it linearly from 15 minutes to about 5 minutes to final.

The “more spacing needed” patterns show a pretty symmetrical shape to their “less spacing needed” counterparts for all destinations.

D. Extra variation of spacing

Note: the following analysis relies on peak periods, linked to different levels of congestion per destination (cf. additional times IV.C) that does not allow for direct comparison.

The following graph illustrates these extra variations with light gray curves samples (1000 random cases per destination), 90% containment (lower curve corresponds to the 5% percentile and the upper curve to the 95% percentile) and a median curve (see footnote 1).

Looking at the upper curves, at 10 minutes (more likely after holding stacks for EGLL), the extra variation values are about 2 minutes for EGLL (2.5min) and EDDF (2min), and around 45s for LEMD.

Looking at the 5 minutes to final point, the upper values are 25s, 40s and 15s for EDDF, EGLL and LEMD respectively.

The decrease of the median value is pretty linear for LEMD and EGLL suggesting that extra variation occurs all over the 0-15 minutes range in a similar fashion.

For EDDF there is a flat part from 15 to 10 minutes: extra variations of the spacing occur mainly within the last 10 minutes (e.g. little sequencing action before). This seems consistent with the flat parts on the spacing deviation curves already observed in the previous section.

E. Spacing deviation vs. extra variation

We investigated whether there is a relation between extra variations amplitude and spacing deviation. The graph below plots the values of spacing deviation vs. their associated extra variation (colored dots) at 5 and 10 minutes before final. These dots are bounded by an area delimiting the “middle” 90% of the data points (bagplot, [21]) for the 5 and 10 minutes datasets.

There is no obvious relation between both variables. High values of extra variation may be induced by large or small initial spacing deviation. However, for EGLL, it seems that highest values are induced by small initial deviation: upper boundary of around 4 minutes of extra variation for a zero initial spacing at 10 minutes (blue containment), while it is usually lower for larger values of spacing deviation (positive and negative). Further investigations are needed to capture the cascading effect and identify the possible causes.

VI. CONCLUSION

This paper presented an analysis of the sequencing at three European airports (Frankfurt Main, London Heathrow and Madrid Barajas). The analysis focuses on the dynamic of spacing over time between consecutive aircraft. The computation of the spacing relies on a model purely data driven calibrated on and applied to more than 24000 aircraft pairs. Two aspects were investigated.

The first aspect aimed at capturing the magnitude of the sequencing task and the amount of effort involved. It was assessed using the spacing deviation (difference between current and final spacing). The values (90% containment) are in the order of ±2.5min at 10min to final, and ±45s at 5min to final. These values may reflect the level of bunching that has to be resorbed by the sequencing during peak periods.

The second aspect aimed at capturing the monotonicity of the sequencing and the difficulty of the task involved. It was assessed using the extra variations of spacing deviations (variations of spacing in excess to set deviation to zero). It goes up to (95% percentile) 2.5min at 10min to final, and 40s at 5min to final. These values may reflect the level of sensitivity while acquiring and maintaining spacing in dense and complex environments (multiple arrival flows, cascading effect).
Future work will involve refining the model, identifying possible causes of large spacing variations, and understanding the relation between spacing deviations and spacing variations. It will also involve extending the analysis to other airports, and beyond, investigating how this approach may help identifying best practices and assessing the impact of a change (e.g. procedures, operating methods) in a given environment.

REFERENCES