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# Spacing and pressure to characterise arrival sequencing

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***Abstract*— This paper presents an analysis of the sequencing of arrival flights at four European airports representative of different types of operation with more than 14000 aircraft pairs. The motivation is to better understand and characterise how sequencing is performed in dense and complex environments during peak periods. The analysis, purely data driven, focuses on the evolution of flight additional time, spacing deviation and sequence pressure. The main results are: (1) at 15 minutes from final, the average flight additional time varies from 4 to 6 minutes (depending on the terrain), with a variability between ±2.5 and ±4 minutes; (2) at 15 minutes from final, the spacing deviation varies from ±3min to ±4min, and converges toward zero at 2min to final; (3) the sequence pressure (number of flights sharing the same arrival slot if no sequencing) is low at terminal area entry, and then peaks at some distance/time from final before decreasing toward a target pressure of one flight per slot, closer to final. The pressure levels and their peak distribution over the terminal area differ notably among destinations, highlighting the effect of the sequencing technique. Future work will involve analyzing high-pressure situations, in view of identifying the appropriate pressure characteristics, i.e. trade-off between the required minimum pressure and acceptable controller workload.**

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

## I. INTRODUCTION

This paper presents an analysis of the sequencing of arrival flights at four European airports representative of different types of operation (Dublin, Frankfurt Main, Madrid Barajas and Paris Charles-de-Gaulle). The motivation is to better understand and characterise how sequencing is performed in dense and complex environments.

The analysis relies on a data driven method introduced in [1][2] that focuses on the dynamic of spacing over time, investigating in particular convergence and stability aspects. This paper presents an extension towards the assessment of the sequence pressure, investigating the evolution of aircraft density in the sequence. The analysis considers peak periods during which significant sequencing takes place, using nearly three months of data with in total more than 14000 aircraft pairs.

The paper is organised as follows: after a review of related studies, it will present the method and the indicators of additional time, spacing deviation and sequence pressure. It will then go through the data collection and preparation. Finally, it will present the analysis of results, followed by a discussion.

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## 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 [3][4][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.[6].

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 [7].

When assessing the impact of new concepts in relation with sequencing, detailed analyses have been conducted [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, in particular late versus early sequencing actions, we introduced an analysis of instructions and eye fixations as a function of the distance from the final point [10].

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 behavior. Here, we are not aiming at building a mathematical model of the approach controller, however as stated in [11], "control theory is a good foundation for developing the intuition and judgment needed for smart cognitive systems engineering".

A high level approach has been proposed in [12], relying on three sets of indicators, in particular "flow based", to build a global picture of the whole traffic situation in the terminal area, however not informing on sequencing and spacing.

Numerous analysis of the spacing have been performed in the context of airborne spacing when studying the performances of different algorithms or of the flight crews [13][14][15][16][17]. Typical analyses involved in particular the relation between spacing accuracy (control error) and number of speed changes/variations (control effort) as well as the impact of the resulting speed profile on the rest on the chain of aircraft (reactionary effect). In all these cases, however, the situation was such that the spacing could be defined as both aircraft followed known paths.

The issue being that, in the general case, the spacing variable is not defined and formally 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 proposed, which extends the work presented in [1][2], is purely data driven and does not make any assumption in terms of sequencing techniques used or controller working methods. It proposes three indicators for three different perspectives: additional time for a single aircraft, spacing deviation for a pair of aircraft, and pressure for a sequence of aircraft. These indicators relies on a key element: the minimum time.

### A. *Minimum time*

The minimum time corresponds to the notion of *unimpeded time* introduced by the PRU [3][4][5] and defined as the transit time in non-congested conditions in an area around the airport (40NM or 100NM). This notion can be generalized to any point in the area.

Assuming a representative set of trajectories covering non-congested conditions, the minimum time from a given point to a fix common point (e.g. final approach fix) was initially defined as the flying time of the trajectory with the minimum flying time among all the trajectories of the same flow passing through this point [1][2] (see following figure, left).

In practice, we discretise the area in the form of a map of cells, each containing the minimum time from this cell to the final approach fix.

Although satisfactory, this method does not ensure a global minimum at every point, thus could induce occurrences of inaccurate values of additional time and spacing deviation. This is illustrated on the left figure below: the thick blue trajectory is considered the shortest one, except when crossing one of the orange trajectories which becomes for a short period the shortest one. The number of occurrences was nevertheless limited, decreasing when getting close to final, and was mitigated by smoothing.

To overcome this limitation, we have refined the method by considering segments/portions of trajectories. The minimum time from a given point to a fix common point is now defined as the minimum time along all possible paths (from this point to the fix common point), where a path is a succession of segments/portions of trajectories connected to each other (see figure right). Two portions of trajectories can be connected provided a constraint of maximum bearing change to guarantee a feasible turn. This constraint allows lifting the need to consider trajectories of a same flow. Note that other constraints may also be considered (e.g. altitude or speed).

In practice, we define a graph with nodes matching the cells and directed edges connecting the nodes together. We connect two nodes in the graph when a flight goes from one cell to the next in the traffic sample. The edge cost is the average duration to fly between the two nodes. We connect all the last nodes from each trajectory to special sink node, corresponding to the final point. To get the minimum time from a given point to the final point, we compute the minimum "distance" path (actually, minimum duration path) from the corresponding node to the final point node in the graph, using the classical Dijkstra algorithm. This ensures that the minimum time from any point is a global minimum. Note that the nodes have a directional information (i.e. we can get 2 nodes at the same 2D location, one used for North-bound traffic, and the other for West-bound traffic) and that edges can only be created between nodes provided the constraint of maximum bearing change.

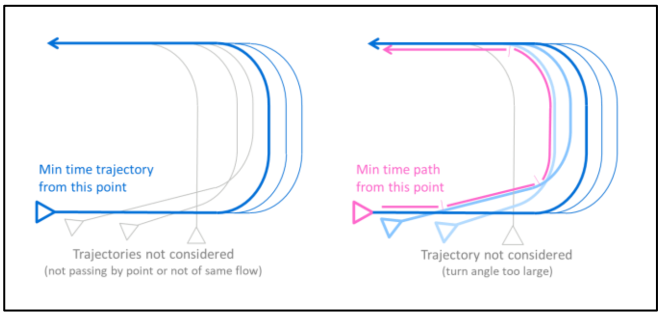


Figure 1: Minimun time, initial version (left) and new version (right)

This method better captures shortest paths and their associated minimum times. However, the minimum times may rely on same common segments/portions of trajectories (e.g. in final) and could be more sensitive to non-representative trajectories (too fast or too tight resulting from e.g. go-around or calibration flight). This means that the outliers filtering stage becomes even more important.

## B. *Additional time*

Similarly to the minimum time, the notion of *additional time* of the PRU can also be generalized to any time for a given trajectory. It can simply be defined as the difference between the remaining flying time and the minimum flying time.

The additional time represents the remaining delay to absorb: starting from the total amount of delay at the entry of the area and decreasing to zero at final point (a reversed definition could be considered, starting from zero and ending at the total delay).

In [2] we propose a decomposition of the additional time in two parts: the "individual" part related to the spacing deviation of the considered pair, and the "queue" part related to the "individual" part of all the preceding pairs in the sequence. The "queue" part will be propagated later to the considered pair and will reflect the reactionary effect. Note: there may be also a third part for deviations related to other factors than arrival sequencing (e.g. interaction with departures).

We showed that the queue additional time constitutes the largest part of the additional time. This suggests that, while the pairwise spacing is established (and kept), there is some sequencing effort even at a closer distance to the runway, due to the propagation of the individual additional time applied on the preceding pairs. Although not considered here, this decomposition remains of interest and will be reflected in a different way by the sequence pressure introduced later.

## C. *Spacing deviation*

The definition of spacing we propose relies on the combination of two existing notions: the minimum time introduced earlier and the *constant time delay* introduced by NASA for airborne spacing applications [13][14]. The constant time delay was introduced to define a spacing deviation with aircraft following same trajectories; it is based on the past positions of the leader aircraft with a given time delay corresponding to the required spacing. This notion can be generalised to any aircraft trajectories.

Let us consider a pair of consecutive landing aircraft denoted *leader* and *trailer*, with *s* their required time spacing[1]. Using the constant time delay principle, the spacing deviation (or spacing error) at time *t* considers the current position of *trailer* at time *t*, and the past position of *leader* at time $t - s$. Precisely, it is defined as the difference between the respective minimum times from these two positions (see figure below):

$$\textit{spacing deviation}\ (t) = \textit{min time}\ (\textit{trailer}\ (t)) - \textit{min time}\ (\textit{leader}\ (t - s))$$

This defines a spacing deviation at all times, with no assumption regarding aircraft path/navigation: aircraft may be following same or predefined trajectories, or may be on open vectors.

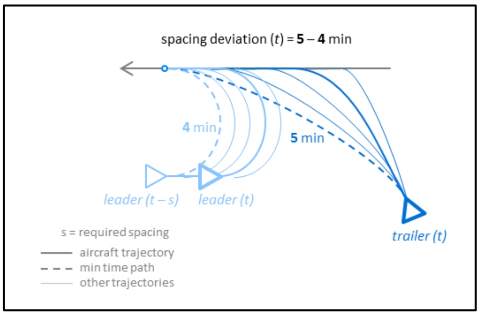


Figure 2: Spacing deviation

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 deviation to zero for all aircraft pairs in the sequence. Considering the aircraft are set by default on their shortest/fastest paths, the control action is to delay aircraft by acting on lateral (path stretching) and/or on longitudinal (speed reduction) dimensions. The additional time (delay) may thus reflect the control effort applied on each aircraft.

The intrinsic difficulty, beyond the handling of multiple pairs in parallel, is the interdependency among these pairs with potential reactionary effect. Indeed, during peak periods, every aircraft may be at the same time the trailer of a pair and the leader of the following pair. Hence, any action on an aircraft may impose to adjust the spacing on the rest of the sequence. This is typically the case when creating spacing to integrate two flows of aircraft. To limit this reactionary effect (and manage their workload), controllers tend to perform a progressive convergence by adjusting the spacing more accurately as aircraft get close to the runway, leaving a loose spacing when further away and even creating some buffer (extra spacing) to anticipate integration of aircraft.

## D. *Sequence pressure*

As an attempt to get insight on the sequence, we propose an indicator that measures the aircraft density in the sequence and will inform on the "pressure" at different time horizons. For this, we consider aircraft having a minimum time to go within the same time interval. Different lengths of time interval could have been considered, corresponding to different "granularity" of the measure. We have decided to consider a runway slot, set at 90 seconds (wake turbulence categories not considered).

We define the sequence pressure, for a flight, at a given time, as the number of flights sharing the same minimum time to final ±45 seconds.

Close to the final point, we expect a pressure of one aircraft (assuming a 90 seconds spacing on average), while it may vary at larger time horizons depending on the traffic demand and presentation (e.g. flights within a holding stack will generate a higher pressure).

[1] To simplify the interpretation of the spacing deviation curves, we decided to set the final spacing deviation to zero, considering that the required spacing was the final one. An analysis of the achieved spacing at major European airports may be found in [18].

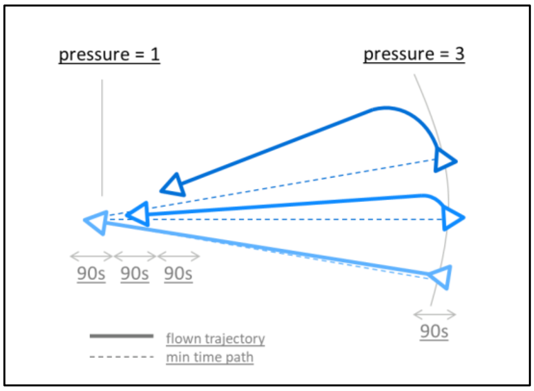

Figure 3: Sequence pressure

## IV. DATA COLLECTION AND PREPARATION

### A. Data collection

We selected four airports representative of different types of metering and sequencing: Dublin (EIDW) holding and point merge [19], Frankfurt Main (EDDF) tromboning, Madrid Barajas (LEMD) distant holding and vectoring, and Paris Charles-de-Gaulle (LFPG) upstream metering and vectoring. We consider a geographical focus area of 120NM radius around each airport to fully encompass the metering and sequencing area, with a minimum of 15 minutes flight time horizon.

The dataset is based on 80 days selected at random from 2018 and consists of position reports with an average update rate of 30 seconds (1 minute for LFPG) interpolated at a 10 seconds rate by splines. Two filters have been applied to ensure representativeness of data: (1) daytime operations (7h-21h local time) to exclude night procedures; (2) 'normal' flights entering and exiting the area, excluding go-arounds, flights with exceptionally short or long flying time, or not flying over the final approach fix. This makes the filtered sample sizes to be: 29713, 21505, 30141, and 27343 flights respectively for EDDF, EIDW, LEMD and LFPG.

The Figure 4shows a random sample of 1000 flights per airport within the focus area, with all runway configurations superimposed.

### 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 based on all the recorded data. The cells differentiate themselves with heading, but other factors may be considered to refine the estimation like 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 future traffic position might not fall within existing cells (surface coverage holes). For this case study, square cells of 2/3NM width and 30 degrees heading bins were found to provide an appropriate trade-off.

The Figure 5 shows cells of minimum times, for each airport, toward one landing runway configuration. The colors represent the minimum time to final, from red (30 minutes) to blue (lower than 1 minute).

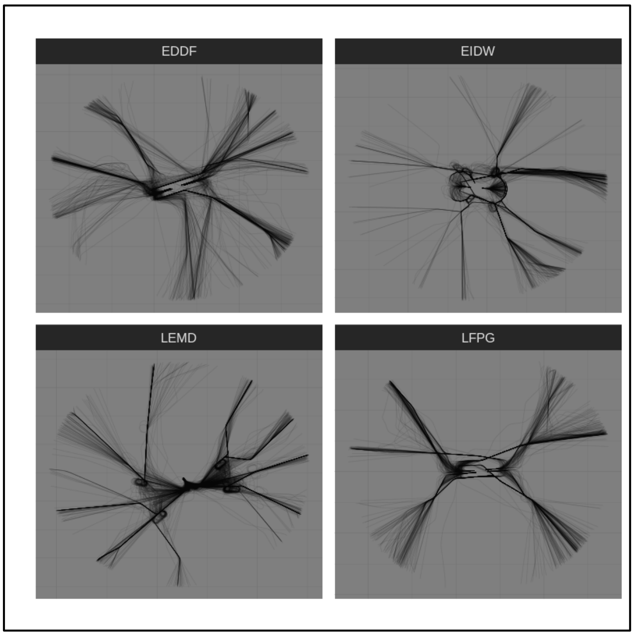

Figure 4 : Tracks samples

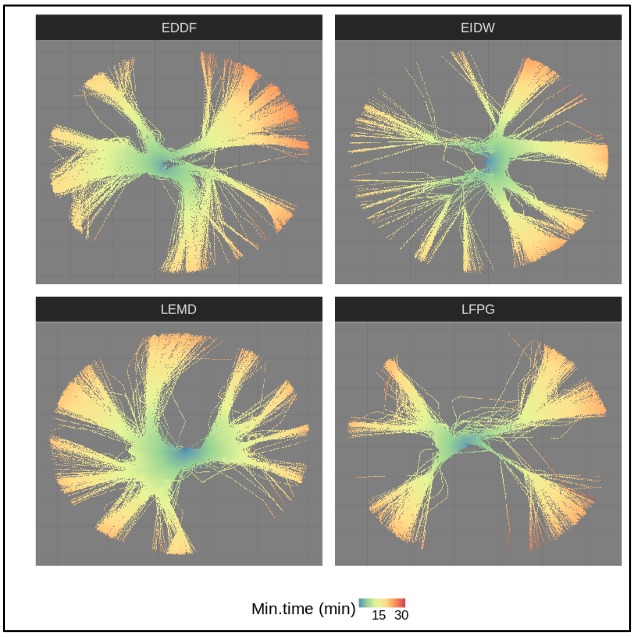

Figure 5: Minimum time map toward one runway configuration

### C. Data selection: peak hours

We focus the analysis on peak periods during which significant sequencing is expected to take place. The identification of the peak periods is based on the additional time in the focus area (see next figure). We consider one hour periods with an average additional time per hour greater than the 75th percentile value per airport (periods may be consecutive). This corresponds to values from 5 to 8 minutes (upper part of the boxes). Flights landing during these periods are considered for the analysis. At this stage of the data preparation, the dataset consists of 7744, 5067, 8226 and 6645 flights, 317, 315, 224 and 357 hours for EDDF, EIDW, LEMD and LFPG respectively.

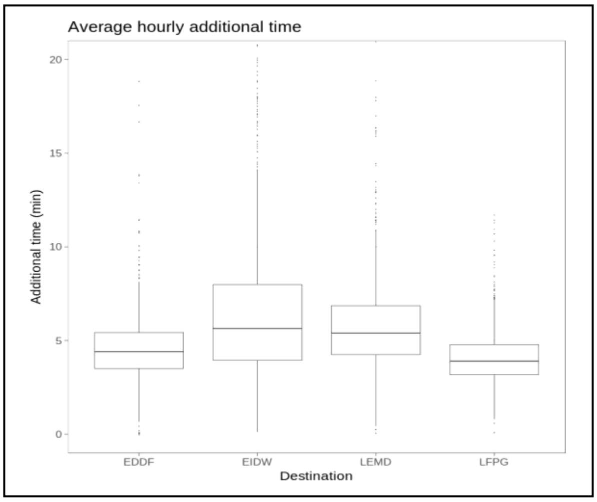


Figure 6: Average additional time per hour distribution

### D. *Data selection: aircraft pairs*

We further focus the analysis on aircraft pairs considered 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: 3307, 3104, 5295 and 2588 for EDDF, EIDW, LEMD and LFPG respectively, making more than 14000 pairs. These sample sizes are considered sufficiently large to be representative.

## V. DATA ANALYSIS

The analysis relies on the three indicators introduced in section III: additional time, spacing deviation and sequence pressure. More precisely, it will investigate the evolution or variations of these indicators at different time horizons, starting at 15 minutes to final.

The time horizon will be represented as "time to final", i.e. time to go along flown trajectory. It may have been represented alternatively as "minimum time to final", i.e. time to go as if flying fastest path. The "time to final" would correspond to an aircraft view (flown trajectory) while the "min time to final" to a controller view (static map of minimum times).

It is important to note that since the peak periods are based on different levels of congestion per airport, any comparison should be made with caution.

### A. *Additional time*

The following figure shows the additional time (y-axis) vs. time to final (x-axis), for all landing runways per destination, with gray samples (1000 random cases per airport), 90% containment (lower curve corresponds to the 5$^{th}$ percentile and upper curve to the 95$^{th}$ percentile) and a median blue curve.

Focusing on the median curves, at 15 minutes to final, the additional time is in the range 4-6 minutes (4 for LFPG, EDDF and LEMD, 6 for EIDW). The range between the 5$^{th}$ and 95$^{th}$ percentile at 15 minutes to final goes from 5 to 8 minutes (5 for LFPG, 6 for LEMD, 8 for EDDF and EIDW).

The level of additional time reflects the traffic demand and presentation in relation to the runway capacity. Typically, LFPG (lowest value) benefits from a metering performed upstream with the support of an arrival manager. In contrast, EIDW (highest value) receives traffic with limited look ahead and metering.

At 5 minutes time to final, the median additional time for all destinations is usually lower than one minute, with little variability; this probably means that the sequence is stable but adjustments (path stretching or speed reduction) are still needed to maintain inter aircraft spacing.

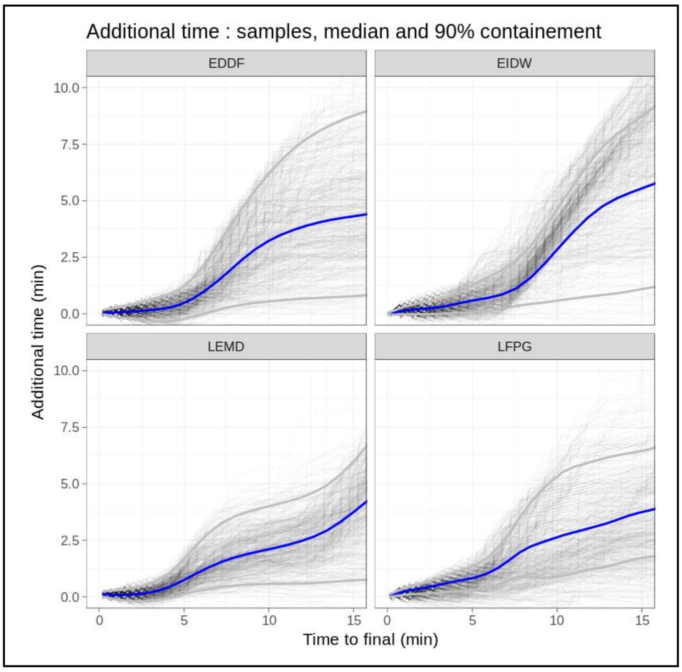


Figure 7: Additional time

### B. *Spacing deviation*

The following figure shows the spacing deviation (y-axis) vs. time to final (x-axis), for all landing runways per destination, with gray samples (1000 random cases per airport), 90% containment (lower curve corresponds to the 5$^{th}$ percentile and upper curve to the 95$^{th}$ percentile) and a median blue curve.

The median curves for all airports are aligned with the zero deviation, result of the symmetry between the positive and negative spacing deviation values observed on the containment curves. One possible reason for that symmetry is that when the spacing is increasing between two successive flights (i.e. the trailer aircraft gets more additional time than its leader), this decreases the spacing with the flight after the considered trailer aircraft (unless the third aircraft gets some additional time too to increase its spacing).

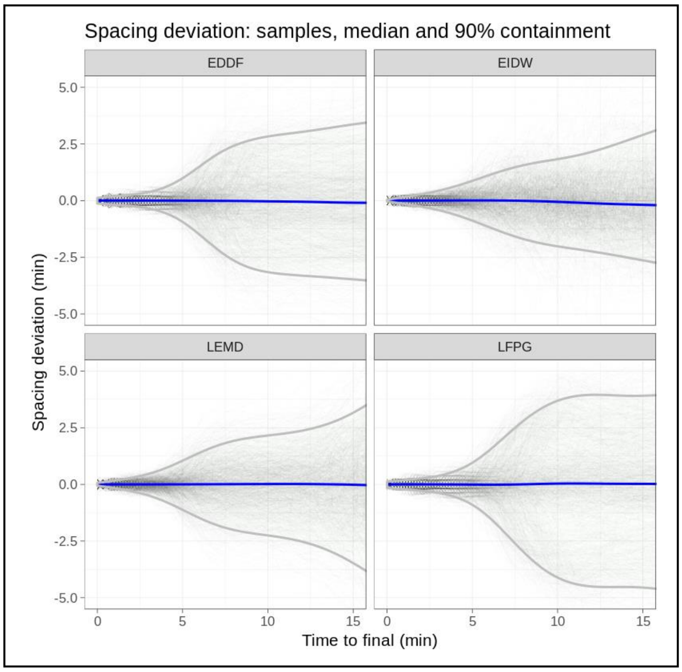


Figure 8: Spacing deviation

At 15 minutes from final, the 90% containment span ranges from 6 (EIDW, ±3 minutes) to 7 minutes (EDDF and LEMD, ±3.5 minutes), while it is about 8 minutes (±4 minutes) for LFPG. This deviation span at 10-15 minutes reflects the traffic presentation (level of smoothing/bunching) and the ordering of the aircraft (level of swap between flights).

For LFPG, with a metering upstream, the high deviation span may be due to an ordering different from the natural order. This may result from the need to optimize the runway utilization (fill any gaps between the two landing runways) and the landing sequence (grouping by wake turbulence categories in a context of significant traffic mix). In contrast, the deviation span is reduced for EIDW probably due to a single landing runway and less traffic mix.

The spacing is obtained at 2 minutes to final for all destinations (deviation span close to 0), however with different convergence speeds. It is progressive for EIDW and LEMD, while it is concentrated with a high speed in the 5-10min for EDDF and LFPG.

### *C. Sequence pressure*

The following figure shows the sequence pressure (y-axis) vs. time to final (x-axis), for all landing runways per destination, with gray samples (1000 random cases per airport), 90% containment (top curve 95$^{th}$ percentile, lower one, 5$^{th}$ percentile flat equals to one except EIDW), and a blue curve representing the average related to the 90% containment.

The average curves remain constant at a pressure of one flight, except for EIDW with values up to two flights between 10 and 5 minutes to final. This suggests some form of permanent pressure during the peak periods, and higher in the area than at entry. This may result from back propagation of the sequencing (additional time), starting earlier and lasting longer than the periods considered, before settling down. We may recall that EIDW has the highest additional time among the four airports.

The upper containment curves converge to the target of one flight per slot (i.e. a pressure of 1), however they differ significantly among the airports. LFPG shows a constant low pressure, LEMD a high pressure at 15 minutes decreasing gradually, EDDF an increase at 5-10 minutes before settling down, and similarly for EIDW but settling down earlier at 5 minutes.

These observations may reflect the various types of metering and sequencing: metering upstream prior entry (and also probably runways not saturated) and sequencing close to final (vectoring) for LFPG; far metering (holding) followed by close sequencing (vectoring) for LEMD; metering (tromboning, sort of linear holding) followed by close sequencing (turn to final); and metering (holding) followed by sequencing achieved early (point merge, short linear holding at a fix iso distance from final) for EIDW.

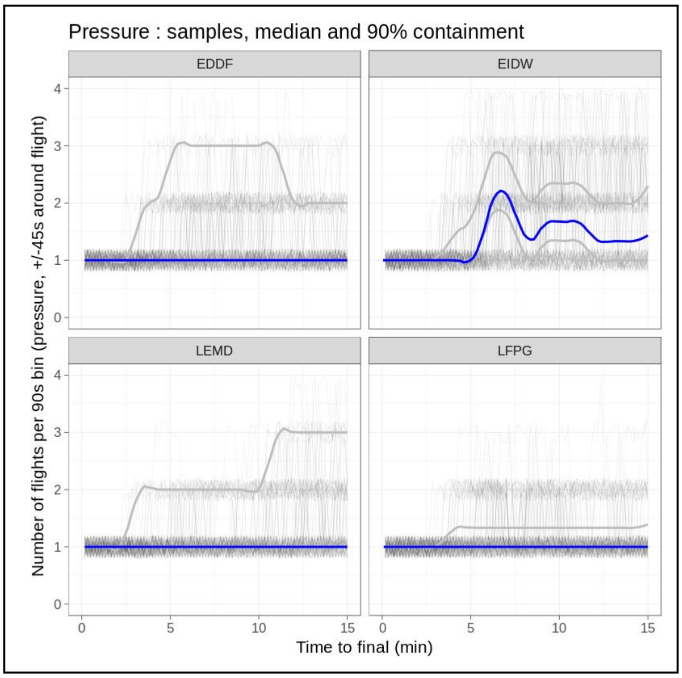


Figure 9: Sequence pressure

The figure below presents the same sequence pressure information for the two most represented runways in our dataset (graph top title made of ICAO destination and runway name), by landing runway. We can see similar patterns for the different runways, with the exception of a sustained period for EIDW10 (long downwind) and a high pressure at entry for LEMD32L.

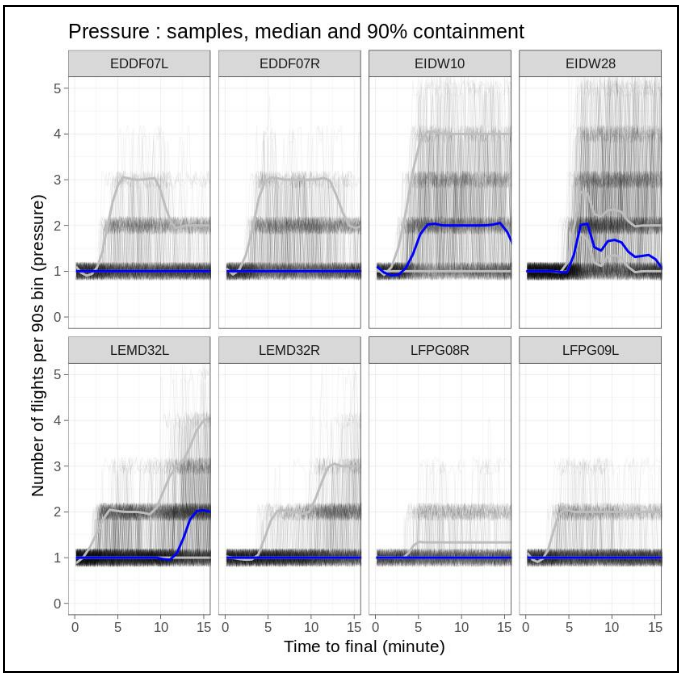


Figure 10: Sequence pressure (two most used runways per airport)

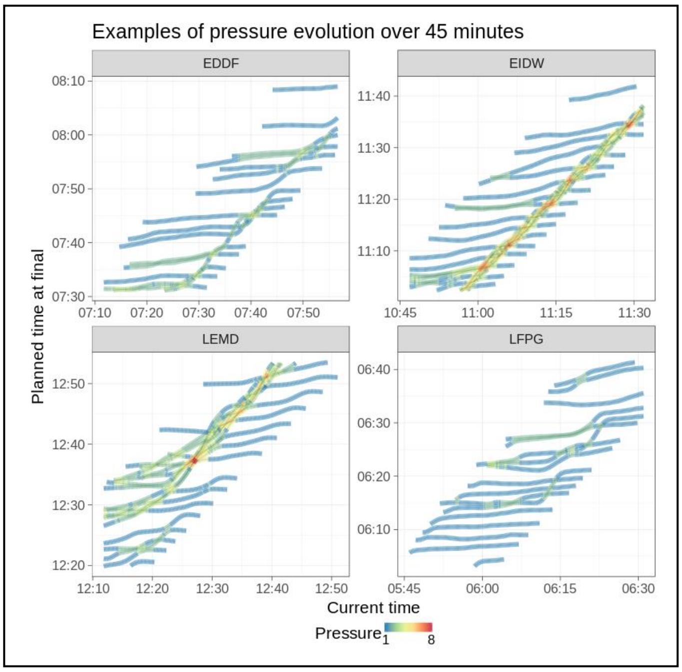


Figure 11: Example of seqeunece pressure over time

The next figure presents one example of the pressure evolution over time (per destination and toward a given runway) selected among the highest-pressure cases. The x-axis is the current time, the y-axis is the minimum time to final, and the pressure is represented with a colour coding from blue (1 flight, i.e. the flight itself) to red (8 flights sharing the same ±45 slot)).

For all destinations, near entry (left x-axis values), the different pressure values shows different levels of bunching (e.g. on these examples, some bunching patterns for EDDF and LEMD). When getting closer to the final point (right x-axis values), the time difference between consecutive flights in the sequence is the required spacing (or more) and the pressure is close to one (a must).

Having a low pressure at entry does not guarantee it will stay low, due to potential back propagation of additional time. For EIDW and LEMD (holding), there is a “hot” spot, where the flights are kept close to each other (in terms of arrival slot) before being released at the right place in the landing sequence. The pressure values do not evolve very much before entering this spot. Note that for LEMD, since the holding stacks (corresponding to the pressure red area) are at a relatively far distance from final, there is still some pressure evolution (green lines) occurring after it.

For EDDF (tromboning), such a “hot” spot appears too, but with smaller pressure values, while some pressure evolution is visible before it, suggesting controller actions before the tromboning area. For LFPG (upstream metering), the pressure values never gets high, and we see slight pressure evolution at different locations/time-to-go, suggesting a more scattered management of the sequence.

Finally, the next figure map shows the maps of average pressure (one landing runway). This map corresponds naturally to the previous curves and confirms the location of the pressure areas for each destination, reflecting the different types of metering and sequencing.

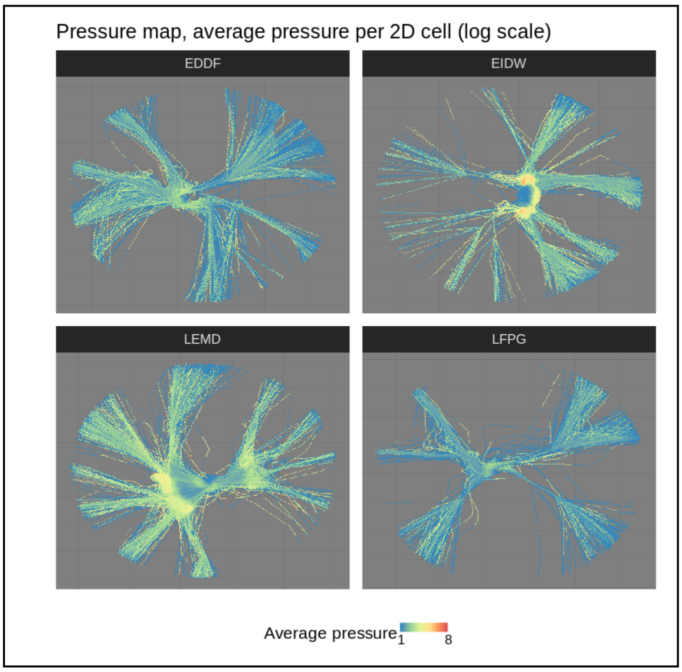


Figure 12: Pressure map toward one runway

## VI. DISCUSSION

This section is an initial attempt to interpret the results.

The arrival management relies on two objectives: (1) maximise runway throughput and (2) minimise aircraft delay and controller workload. (1) requires to put a minimum pressure on the runway ("reservoir" of aircraft) which may lead to aircraft delay and to a high workload close to final; (2) requires to manage the traffic presentation (smoothing/metering of traffic) which may lead to under utilisation of the runway(s) and overloads in upstream sectors. A key aspect of sequencing during peak periods is the risk of knock-on effect, with back propagation of delays within the sequence.These considerations raise the question of trade-off between pressure, delay and workload, which is specific to each environment.

To better understand the sequencing work we have introduced three indicators:

- Additional time, focusing on one aircraft at a time, representing the overall controller delay action. This is the visible action of sequencing.
- Spacing deviation, focusing on one aircraft pair at a time, generating a part on trailer aircraft additional time. This is the cause for sequencing of this pair, but does not capture the whole sequence, and in particular any back propagation.
- Sequence pressure, focusing on the whole sequence, representing the density and how additional time may back propagate.

The additional time represents the delay applied to an aircraft for sequencing and results from controller interventions (speed reduction or path stretching). In addition to degrading flight efficiency (more track miles and less opportunities for continuous descents), it may generate workload (controller and flight crew) depending on the technique used (open loop vs closed loop instructions) and proximity to final (critical phase of flight). An increase of additional time may result from back propagation of additional time downstream (see "queue additional time" in section III 0). The additional time may thus be considered as a form of necessary cost. It should be kept as low as possible in particular near final, however a certain amount is inevitable during peak periods to keep pressure and flexibility.

The spacing deviation represents the inter aircraft spacing error. Large deviations when entering the area may reflect bunches in the incoming traffic or a sequence order different from the natural order. Large negative deviations (i.e. not enough spacing) may result in significant delaying actions, but may enable an optimisation of the landing sequence (runway balancing and re-arrangement depending on wake turbulence categories). Large positive deviations (i.e. too much spacing) may result in gaps in the sequence. A variation of spacing deviation may results from back propagation of variations downstream. Spacing deviation on final is thus an operational objective. It should progressively converge to zero starting with a spread at entry depending on the need to optimise the landing sequence.

The pressure represents the aircraft density in the sequence. A high pressure at a given distance or time to final corresponds to multiple aircraft at this distance/time, hence to multiple negative spacing deviations, which may be very demanding to set to zero, in particular with vectoring close to final. A high pressure may result from and reinforce a back propagation of additional time. Conversely, a low or moderate pressure at far distance corresponds to positive spacing deviations hence potentially under utilisation of the runway(s). Pressure is a way to meet the operational objective of maximising runway utilisation. It should be maintained at an appropriate range, not too far from final, when operating close to maximum runway capacity. Moreover, when sequencing reshuffling is required, having many aircraft sharing the same distance/time to final can be convenient for the controller, since he/she has only one time reference to consider in building the sequence toward the final.

With this in mind and with caution, we may consider that the additional time of the four airports are quite high at 15 minutes to final (3 runway slots), but seems acceptable at 5 minutes (below 1 minute). The spacing deviation may also appear significant at 15 minutes (3 slots) but the gain due to possible optimisation of the landing sequence would have to be assessed. The pressure shows varied situations, in particular when considering runways individually. It may be considered too low for LFPG08R if the runway is close to saturation, too high at entry for LEMD32L, too high during a long period for EIDW10; finally EDDF07L, EIDW28 and LFPG09L may appear as good candidates with a moderate pressure. The variations of the curves (and the number of outliers) for EIDW28 should nevertheless be investigated as may reflect some form of sensitivity.

The various characteristics observed are directly related to operational objectives (runway throughput,..) and constraints (airspace, environment, ..), and also result from the way arrival management is operated, and in particular how working methods have been developed over years. The type of analysis presented may support adjustment or re-design of routes or operating methods, in order to better adhere the desired characteristics, specific to each environment.

## VII. CONCLUSION

This paper presented an analysis of the sequencing of arrival flights at four European airports representative of different types of operation with more than 14000 aircraft pairs. The motivation is to better understand and characterize how sequencing is performed in dense and complex environments during peak periods. The analysis, purely data driven, focuses on the evolution of flight additional time, spacing deviation and sequence pressure.

The main results are: (1) at 15 minutes from final, the average flight additional time varies from 4 to 6 minutes (depending on the terrain), with a variability between ±2.5 and ±4 minutes, lower variability reflecting cases with sequence order nearly frozen, higher variability, greater rescheduling; (2) at 15 minutes from final, the spacing deviation varies from ±3min to ±4min, and converges toward zero at 2min to final; (3) the sequence pressure (number of flights sharing the same arrival slot if no sequencing) is low at terminal area entry, and then peaks at some distance/time from final before decreasing toward a target pressure of one flight per slot, closer to final. The pressure levels and their peak distribution over the terminal area differ notably among destinations, highlighting the effect of the sequencing technique.

Future work will involve analyzing high-pressure situations, in view of identifying the appropriate pressure characteristics, i.e. trade-off between the required minimum pressure and acceptable controller workload.

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