How the geometry of arrival routes can influence sequencing

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This paper reports on a study aiming at developing an intuitive route design for the sequencing of arrival flights in the terminal area. When introducing route structures to address the drawbacks of traditional vectoring techniques, the main challenge in high density environments is to guarantee an effective use of these routes during traffic peaks, where some form of path stretching is needed. The study relied on two series of iterative small scale human in the loop simulations conducted at the Experimental Centre with Paris CDG controllers. It enabled the identification of key design characteristics in terms of minimum distance to merge point, and angle between downwind and base routes. Controller feedback and initial analysis showed that the resulting route designs can facilitate sequencing even under high traffic peaks, drastically reduce vectoring and keep trajectories away from the axis area. The study also provides an initial analysis based on the evolution of the distance that may be re-used to assess new designs. Next steps will be to assess the applicability in the real Paris CDG environment which would require adaptations of the characteristics identified.

Keywords: arrival sequencing, approach control, route design.

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I. Introduction

This paper presents a stepwise approach followed to develop an intuitive route design for the sequencing of arrival flights in the terminal area. The objective is to identify key design characteristics to reduce the need for tactical interventions, in particular open-loop vectoring, while maintaining throughput. By introducing such route structures in the TMA, the motivation is to facilitate the sequencing tasks for controllers, and maximize adherence to these routes even under high traffic conditions. In turn, this is expected to maximize benefits in terms of safety, capacity, flight efficiency and environmental impact. The study relies on two series of iterative small scale human in the loop simulations conducted at the Experimental Centre with Paris CDG controllers.

The paper is organized in five parts: after a review of the state of the art, issues raised by an initial design in the first series of simulations are presented and discussed; the next sections present how those issues were addressed, in two steps, in a second series of simulation. The last section proposes initial considerations to explain and identify good design properties.

II. State of the art

The studies investigating possible ways to facilitate sequencing and maximize adherence to routes can be broadly split in two categories. The first one relies on the development of new support tools which may be integrated as
advanced functionalities of an arrival manager. Extensive work has been achieved in particular in the US [1][2][3]. Assistance to the controller may take the form of the projection of the preceding aircraft position along the trajectory of the concerned aircraft, the display of the spacing deviation error and/or speed or turn advisories.

The second category relies on the deployment of dedicated route structures. This is typically the case of the trombone-shaped routes deployed in Munich and Frankfurt in the 1990s with the introduction of P-RNAV. The route structure is made of parallel upwind and downwind segments that include a set of regularly spaced waypoints to support path stretching/shortening through route changes. This design has proved an effective way of systemizing the traffic flows to the runways. However, it reduces the flexibility (offered by radar vectoring) and during the peak periods controllers tend to revert to radar vectoring for the turn to final [4][5].

Another route based technique, known as ‘Point Merge’ has been deployed more recently in Oslo, Dublin and other places [6]. The route structure consists of a merge point and pre-defined legs for path stretching in the form of arcs equidistant from this point. The sequencing is achieved with a “direct-to” instruction to the merge point at the appropriate time. This technique has proven to be intuitive and effective; however, it has raised acceptability issues at some locations during validation phases [7][8][9]. Indeed, it induces in fact two significant changes in terms of working method: merging on a point (not onto an axis) and path stretching via closed legs (not through vectoring). The closed legs in particular may result for some controllers in a feeling of constraining the sequencing, restraining the degrees of freedom and putting the controller in a passive position, with in the end a concern that they would lose their vectoring skills. Therefore, in certain high density/complexity environments, a more progressive approach to deployment may need to be considered.

The motivation of the study was thus to develop an intuitive design retaining the principle of merging on a point (that provides most of the safety and environment benefits) but without the closed legs1, so as to reinforce acceptability. It was acknowledged that, although this design may appear as an intermediate solution, it would still constitute an improvement compared to today’s vectoring. This approach was considered for both Paris Orly and Paris CDG [7][8][9]. In the next sections, we will detail the investigations conducted for Paris CDG that led to the identification of the key design characteristics [10].

III. Initial design

The objective of the first series of simulations was to assess feasibility and applicability of the new technique (merge on a point without closed legs) at Paris CDG under high traffic peaks [9]. The underlying motivation was to enhance safety and to a lesser extent environment. Although different runway configurations were tested, each with its own airspace constraints, in the following, we focus on the less constrained one (27R) which offers the possibility to explore various design geometries and from which a generic environment was derived for the purpose of the study.

Instead of closed legs, arrival routes segments were defined from the entry points for base and downwind procedures, ending on a defined track. The two main design considerations were to provide sufficient space for vectoring (stretching) prior to merging with an appropriate passing distance to the merge point (not too close, i.e. in the range of 10NM). Two options were developed (Figure 1): the first one provides a “winding” effect (routes at approximately 90°, close to today), and the second one a “mixing” effect (opposite parallel routes). For both options, distances are 15NM for the base and 10NM for the downwind, by analogy with current design of initial approach segments at Paris CDG. The transition to final was made of two segments, the merge point being the entry point of the first segment.

The operating method remains similar to Point Merge: aircraft are left flying along a standard trajectory, and when the appropriate spacing with the previous aircraft in the sequence is reached, a direct to the merge point is instructed. Use of heading remains possible if necessary for further path extension prior to the ‘direct’ instruction.

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1 Merging on a point with vectoring is in fact common practice in upstream sectors to perform pre-sequencing. Similar design considerations may apply for sectors with high traffic loads (e.g. a point merge with legs had been developed and is in operation at Paris ACC).
Figure 1. Design of option 1 (left) and option 2 (right)

Flown tracks are shown in Figure 2. Both options were considered feasible with a perceived workload reduction compared to vectoring. Controllers reported that merging on a point still implies a significant change in term of operating method compared to today’s operations (vectoring onto an axis). Option 1 was found more intuitive and closer to current practices than option 2 which may raise acceptability issues\(^2\) in particular due to the quasi “head-on” situations (despite the 5NM offset and the vertical separation). Option 2 was therefore not retained. However, option 1 still induced significant vectoring: 74% of aircraft on downwind and 55% on base have been vectored. In terms of adherence to the procedure, it is also noticeable that the intermediate point after the nominal merge point was also used to merge arrival traffic. In option 1 it was even the one mostly used, leading to a higher proximity with ILS – which in the case of simultaneous parallel operations such as in Paris CDG, is not desirable.

Figure 2. Flown tracks of option 1 (4 runs) and of option 2 (2 runs)

IV. Re-design step 1

When re-assessing the outcomes of the previous step, two key characteristics appeared to be essential for the design of the route structure: minimum distance and angle between base and downwind flows [10].

The minimum distance to the merge point (when letting the aircraft fly the routes) has a direct effect on the sequencing. This distance influences the usable part of the standard trajectory for path stretching/shortening, i.e. the delay absorption capacity of the procedure. A too short distance means stretching effort, while a too large means

\(^2\) The “mixing” is commonly used in the point merge with closed legs (with a vertical separation prior leg entry). In that case aircraft are flying a closed procedure (e.g. RNAV1) which is not the case here.
shortening effort. A nominal distance of 10NM, with values down to 5NM, is considered of interest for validation. In addition, it is assumed that a similar minimum distance between downwind and base routes would facilitate the visual assessment of the sequence.

The angle formed by downwind and base routes is assumed to also have an effect on the sequencing. A too large angle would induce highly converging situations and complicate the visual assessment of the sequence as well as the maneuvering. A small angle is not considered realistic as it would imply long detour for one flow. A range of 60° to 120° is considered of interest for validation.

An additional factor, in relation with the angle, is the capacity for trajectory extension after the minimum distance and in particular the proximity with the runway axis for base flow (especially in the case of simultaneous operation of parallel runways), and the proximity, or possible crossings, between downwind and base flows (which may have to be managed through vertical instructions).

Various combinations of these two characteristics (minimum distance and angle) were selected and tested. The values considered for the minimum distance to the merge point were 5NM, 7.5NM and 10NM (Figure 3 left); and for angle between downwind and base routes: 60°, 90° and 120° (Figure 3 right). To limit the number of options, we decided to give preference to the most promising combinations: 10NM and 7.5NM, 90° and 120°. This led to four ‘preferred’ scenarios (distance in NM): 10NM/120°, 10NM/90°, 7.5NM/120°, 7.5NM/90°. For completeness, and confirm these were less relevant options, the cases of 5NM and 60° were also assessed through two scenarios: 10NM/60°, and 5NM/90°.

The final part was still composed of two segments before joining the ILS, the merge point being the entry point of the first segment.

The analysis of flown tracks shows that in all scenarios, the large majority of aircraft merge on the defined merge point, preventing going too close to the ILS axis (Figure 4).

When varying the distance (figure below, left), 10NM and 7.5NM were assessed as being adapted (with a preference for 10NM). On the other hand, 5NM was deemed difficult. The need for path stretching was particularly visible in that case as it provided a reduced maneuvering area resulting in a limited delay absorption capacity. Several aircraft from the base flow were path stretched out of the defined trajectory, while aircraft from downwind were path stretched further “abeam” of the merge point.

When varying angle (figure below, right), the preferred angle was 90° as it was considered more intuitive. 120° came as second choice as it is close to current geometry of vectoring patterns in Paris CDG, even though in that case controllers held on, and vectored aircraft from, the base flow prior merging on the point. This indicates a need for additional path stretching due to limited delay absorption capacity along base. With 60° the need for path stretching out of the standard base trajectory is reduced, while it even disappears with 90°. Nevertheless an angle of 60° may not be realistic in terms of entry point location for an environment with two entry points and one runway, unless a dedicated route segment is considered to join the base leg.
V. Re-design step 2: focused adjustments

The outcomes of the previous session led to two changes: a modification of the transition to final and a focus on a reduced set of values for the routes (minimum distance and angle).

The transition connecting to the final approaches was revised to comprise only one 4.5NM long segment (Figure 5), the merge point being its first point. Indeed two segments required more space, and induced the use of two reference points for sequencing. A single segment is expected to gain space and provide a common visual reference for sequencing base and downwind flows. The use of two points for sequencing was also linked to the position from which the ‘direct to’ is instructed, impacting the track angle change at the merge point. In order to address this issue, an optional/additional support point was implemented for early direct from downwind.

![Figure 5. Detail of the final part joining ILS](image)

Regarding the design parameters for the routes, in accordance with the results of the previous session, a minimum distance to the merge point of 10NM and 7.5NM were retained; and for the angle between downwind and base routes: 90° and 120° - leading to four scenarios: 10NM/90°, 10NM/120°, 7.5NM/90° and 7.5NM/120°.

The flown tracks are shown in Figure 6.

When varying distance, no significant effect was observed, although the 10NM was reported, as expected, as providing larger maneuvering area and more delay absorption.

When varying angle, with 90°, a small number of aircraft were vectored out of the defined trajectories compared to 120° - where a significant number of aircraft of the base flow were turned left. In line with the previous session, this indicates a further need for path stretching (so less delay absorption capacity) with an angle of 120°. As a result, more trajectories went close to the ILS with an angle of 120°, compared to 90° (again, this would have to be accounted for in view of an environment involving parallel approaches).

The different designs were considered comfortable, intuitive and efficient (few vectoring, lower workload, good task repartition).
A preference was reported for:

- 90° (over 120°) as it was more intuitive and provided more margins to ILS (120° resulted in slightly more trajectory extension, and slightly more need for vectoring).
- 10NM (over 7.5NM) as it resulted in a larger maneuvering area and increased delay absorption capacity (slightly more vectoring occurrences with 7.5NM). It was acknowledged however that it required more airspace and may not be applicable in all configurations.

![Figure 6. Flown tracks when varying distance (7.5NM and 10NM) and angle (left 90° and right 120°)](image)

VI. Rationale and design recommendations

As an attempt to understand and objectively explain the differences among the various designs tested, we analyzed in more details two designs: option 1 from the initial design as per Figure 1 (denoted ‘option 1’ below) and the 10NM/90° from the last session as per Figure 6 (denoted ‘option 2’ below).

The flown tracks that were shown previously are re-displayed side by side below with the indication (in red) of vectoring out of the standard procedure (Figure 7).

![Figure 7. Flown tracks of both designs](image)

In addition to the more orderly flown tracks, we can observe significant differences when considering the percentage of aircraft being vectored and the rate of adherence to the procedure (Figure 8). The first design induces more vectoring and a reduced adherence compared to the second for which vectoring is drastically reduced. It is important to note that this reduced vectoring is not detrimental to the accuracy as both have similar spacing on final (Figure 9).

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3 The two exercises were not initially intended to be compared. Nevertheless, we verified a posteriori that the traffic load and presentation (level of bunching at TMA entry) were similar, allowing this initial comparison with a sufficient level of confidence in the results.
To go further and try to understand the mechanisms that led to this improvement, we analyzed the evolution of the distance to the merge point as a function of the flown distance. We first plotted the evolution of the distance (Figure 10) as if aircraft were flying the full length of their standard route (the distance flown along that route being measured from an arbitrary starting point located at 20NM direct distance from the merge point). The main conclusion is that in the first design the distance curves for downwind and base routes start from slightly different initial distance values and decrease until reaching a common minimum at 13NM from the merge point. There is a relatively flat part around that minimum for the downwind, but no such part for the base. In contrast, with the second design, the two curves are overlapping quite early with a common flat part providing an area of iso distance at 10NM from the merge point.

We then plotted the evolution of the distance based on actual flown tracks and of its derivative (Figure 11), again with the indication (in red) of vectoring out of the standard procedure. With the first design, while the base flow

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4 The merge point was not defined the same way for the two exercises. To homogenize the results, we considered the merge point as being in both cases the entry point to the last segment before final - which induces a ~3NM distance shift for the initial design.
shows a homogeneous decrease, the downwind contains cases of significant variations of distance. In contrast, with the second design, both flows have more monotonous decreases (with a couple of exceptions) with a flat part corresponding to the usable portion of the route for path stretching.

Finally, we investigated the evolution of spacing deviations (Figure 12). This is measured per leader/trailer pairs of aircraft in the landing sequence, as proposed in [12]: the distance spacing deviation at time t is defined as the difference between the minimum distance to final fix from the position of trailer at time t, and the minimum distance from the position of leader at time $t - s$, where $s$ is the observed time spacing on final.

In line with the evolution of minimum distance, this measure shows a significantly quicker convergence towards the observed spacing on final for option 2.
This analysis may explain why the second design better facilitates the sequencing of arrivals. It also suggests that, beyond the size of the maneuvering area and the corresponding path stretching capabilities, the key element from a human factor point of view is the evolution of the distance (to a reference point on which the sequence is built) that the design intrinsically provides.

As a matter of fact, according to [11], sequencing can be formulated as a problem of manual control. The main control variable is the spacing with the preceding aircraft in the sequence. Its required value is attained through speed control, and if needed path stretching/shortening, for the trailing aircraft: the objective is to set the spacing deviation to zero for all aircraft pairs in the sequence.

In the route geometries studied here, when aircraft to be sequenced are still flying along their base and/or downwind segments, the projection of that control variable can be expressed as the difference between their direct distances to the merge point – corresponding to the curves from Figure 10 above. In that context, to maintain an easy and intuitive visual reference to build and maintain the sequence, it is essential that the design provides a regular evolution of these distances with a flat part to support stretching, and similar for the arrival flows to facilitate the merging.

VII. Conclusion and next steps

The study enabled the identification of key design characteristics in terms of minimum distance to merge point, and angle between downwind and base routes. Controller feedback and initial analysis showed that resulting route designs can facilitate sequencing even under high traffic peaks, drastically reduce vectoring and keep trajectories away from the axis area (of particular interest in the case of simultaneous parallel approaches). The study also provides an initial analysis based on the evolution of the distance that may be re-used to assess new designs. Next steps will be to assess the applicability in the real Paris CDG environment which would require adaptations of the characteristics identified.

VIII. References