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Enroute Traffic Overflows versus Arrival Management Delays

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Abstract*—This paper presents a sensitivity analysis on the potential interactions between arrival management and network management when extending the arrival horizon. The analysis focuses on regulated enroute traffic overflows and on arrival management delays. It relies on a macroscopic modelling of arrival management delay, capturing the effect of arrival management horizon and the interaction with the network management by setting delay constraints. The model was applied on 50 days of peak periods traffic demand toward the four busiest European airports in 2017 (more than 25 000 flights). The percentage of arrival flights crossing regulated areas goes up to 60% at 400NM. The results reveal two effects of the potential interaction. Firstly, when network management regulations are not integrated by the arrival management, traffic overflows may occur for extended horizons. For a 400NM horizon, overflows up to +21% were detected (95% percentile). Secondly, when regulations are integrated, overflows disappear but flight efficiency is slightly reduced with a shift from enroute and ground delays towards terminal delay. For a 400NM horizon, this shift is respectively of 35s and 11s, leading to an increase of terminal delay of 46s (+42%). These results raise the question of trade-off and level of performances expected in terms of capacity limits (tolerance), considering that short term flow management measures may apply.

Keywords: arrival management, network management, traffic overflow, delay.

I. INTRODUCTION

This paper presents a sensitivity analysis on the potential interactions between arrival management and network management when extending the arrival horizon. These interactions are of two natures. Arrival management propagates delays upstream which may lead to overflows in enroute areas regulated by the network management. Conversely, network management creates constraints which may lead to shift arrival management delays downstream towards the terminal area. Extending the arrival horizon creates more overlap between both processes, increasing the potential for interaction.

The analysis assesses the effect of arrival horizon extension and network management constraints integration on arrival management delays and planned regulated traffic overflows. It relies on a macroscopic modelling of arrival management delay, capturing the effect of arrival management horizon and the interaction with the network management by setting delay constraints. The model was applied on 50 days of peak periods traffic demand toward the four busiest European airports in 2017 (more than 25 000 flights).

The paper is organized as follows: after a review of related studies, it presents the modeling, the setup and a characterization of the traffic and regulations, finally the results in terms of arrival management delays and network management traffic overflows.

II. STATE OF THE ART

Significant work has been done previously on the question of interactions and trade-offs between different traffic management processes. In [1], the interaction between ground delay programs and traffic management advisory is managed by exempting flights closer to destination from the latter, to avoid a double delay penalty. These delays were measured for the Atlanta airport and revealed a large imbalance between included and exempted flights: proposals to find best flow rates based on a fast-time simulation approach were made to manage it. A sensitivity analysis of the exemption radius distance effect is made in [2], proposing to manage ground delay program uncertainty (e.g. cancellation) by using en-route speed control, as illustrated on a Chicago test case. The transfer of delay from terminal to en-route is also considered in [3] to improve flight efficiency, by solving a multi-objective optimization problem.

A similar interest in delay distribution estimation associated with the traffic management initiatives (TMI) is seen in [4]. In particular, the interaction between successive TMIs is quantified by the probability (estimated analytically) that one TMI over/under control the traffic flow seen by the downstream TMI, as illustrated on a test case for San Francisco airport. Taking an operational flow management point of view, [5] illustrates the challenge of finding trade-offs between multiple, possibly contradictory objectives for flow control strategy and propose metrics and associated visualizations to help in human decision making.

Trade-off in delay distribution between en-route and descent delay absorption is considered in [6] and estimated by means of analytical and simulation studies for different strategies (first come first served or priority sequencing). Focusing on the enroute part of the delay absorption, [7] suggests that a one-time speed reduction of aircraft during en-route, the simplest form of speed control, could be appropriate while metering point at the gate to the terminal area serves as a buffer for uncertainties in trajectory prediction. This simplicity

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is likely practical for a ‘traffic management coordinator’ who monitors the flows over several sectors or centers, and who can coordinate actions, such as speed control decisions, with the corresponding controllers.

The proposed modeling here complement the above approaches by considering the interaction of traffic management processes (strategic network management and tactical arrival management), created by the geographical arrival management horizon extension. In particular, the effect of the tactical arrival management on the planned decisions made at the strategic/network level is considered, illustrated by delay distribution, for different horizon scenarios and network management (regulations) consideration.

III. MODEL

We detail in this section the model of arrival management delay and network management integration.

The integration of network management, in particular in a context of extended arrival management horizon, is a future scenario that do not represent today’s operations. The model relies on a certain number of assumptions explained hereafter. In addition, to allow for a sensitivity analysis on large datasets, we decided to rely on a macroscopic model which makes simplifications described hereafter.

The key elements of the model are: arrival flights, horizon, delay absorption capacity and strategy, runway capacity and regulations. The airspace is modelled as concentric circles around destination, from 0 to 400NM by 50NM step (the terminal area is within the first 50NM circle). The airspace is further split into 20 degrees portions defining elementary pieces of airspaces. Regulated areas are approximated by the pieces of airspaces they intersect.

The following map (Figure 1) shows the terminal area (first 50NM circle) and the en-route circles from 50NM to 400NM around one of the airport considered (here Paris Charles-de-Gaulle). Note: We have set the slice length to 50NM and 20 degrees as a trade-off between too small areas that would not capture traffic flows and too large areas that would lack accurate matching with network management regulated areas.

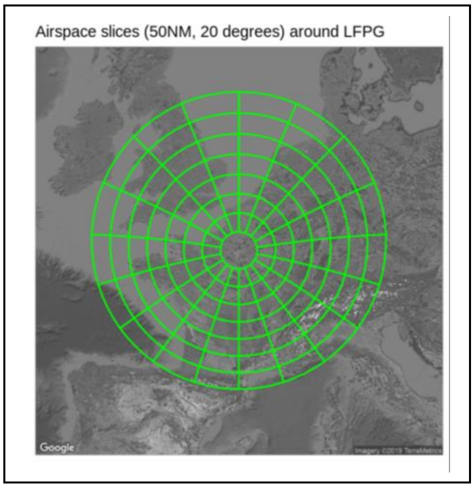

Figure 1 : En-route airspace slices, extending up to 400NM from destination

The model allocates all the arrival flights on their respective shortest ways, delaying the flights exceeding runway capacity limits while respecting delay capability limits in regulated areas. The delaying mechanism is formulated as a standard mathematical linear decision problem (using PuLP, a python linear programming API) and is performed at minimum “cost” by considering a delay strategy preference under arrival and network management constraints.

The delay strategy preference is based on three potentially conflicting considerations: maintain a minimum pressure on the runways, absorb delays on the ground or in enroute. The model considers delay at closer distance to destination first and progressively upstream until on the ground when necessary, allowing for a minimization of uncertainties. Indeed, for the given current system level of uncertainty, pre-planning pop-up flights was found to be counterproductive [10], this is the reason why our model setup ground delay for arrival management as one of the last delay method.

To reflect this preference, the delay strategy relies on the following priority order: (1) terminal area, up to terminal minimum pressure; (2) en-route, first at closer distance to destination and then progressively upstream, up to maximum delay absorption capacity (reduced if regulations); (3) ground, for traffic within horizon; and (4) terminal area, for the delay in excess. The delay strategy is enforced by setting cost corresponding to the priority order. Note: for model simplicity and sequence robustness, the planned arrival flight order is maintained (no dynamic resequencing).

The arrival management constraints are: (1) aircraft separation at landing based on minimum time separation constraint (linked to runway arrival capacity); (2) zero en-route or ground delay at greater distances than the arrival management horizon; (3) maximum en-route delay limit per slice to feasible delays within the area; and (4) maximum ground delay limit to reasonable values.

The network management integration constraints are: (1) zero en-route and ground delay for the flights planned to cross a regulated slice, before their slice exit. This to ensure adherence to the network management planned traffic within regulated areas. (2) Limited en-route and ground delay for the flights crossing a slice that will be regulated after their entry: their entry time shall be the regulation start time at the latest. This to ensure that only planned traffic cross regulated areas during the network management regulations.

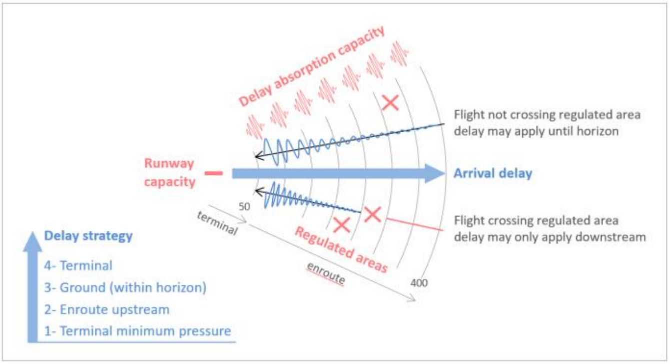

Figure 2 : Elements of the model

IV. SETUP

This section presents the main inputs of the model: environment, arrival capacity, traffic, regulations, delay parameters and experiment variables.

A. Environment

The analysis considers the four busiest European airports (Frankfurt-Main (EDDF), London-Heathrow (EGLL), Amsterdam-Schiphol (EHAM), and Paris-Charles-de-Gaulle (LFPG)) and the surrounding 400NM radius areas, representative of high density and complexity environments (see Figure 3 below). It focuses on arrival peak periods when arrival management is most required.

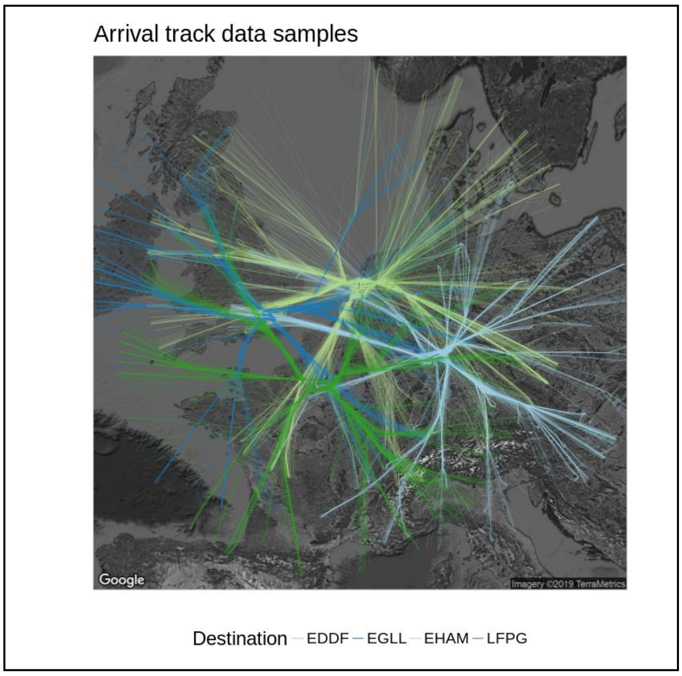

Figure 3 : Trajectories to the four airports within 400NM from destination

B. Arrival capacity

The declared overall arrival airport capacity for 2017 (in movements/hour) were the following: EDDF 60, EGLL 45, EHAM 68 and LFPG 64.

The number of runways typically used simultaneously for arrivals and their typical traffic share (estimated from actual track data) were: EDDF 2 runways (57% and 43%), EGLL 1 runway (100%; second 2% runway ignored), EHAM 2 runways (70% and 30%), LFPG 2 runways (59% and 41%).

Each runway arrival capacity is set to the declared overall arrival airport capacity[1] multiplied by the typical runway traffic share. We translate this capacity figure into a constant minimum time separation constraint. Note that we assume that all the arrival runways are independent from each other.

The capacity set for each runway is the declared overall airport capacity times its typical traffic share. This capacity figure translates into a time separation: e.g. for LFPG, on the 59% runway: $3600 / 64 * 0.59 \approx 95$s. We acknowledge that these figures are not actual required time separation (e.g. no wake vortex categories, no specific procedures modeled) and assume they are giving appropriate scheduling arrival delays.

C. Traffic

We selected randomly, for each destination, 50 days of 2017 traffic, to cover different traffic situations and get a large enough dataset. For each day, we obtained the regulated flight plan data[2] and identified the highest (in number of flights) three consecutive hour time periods. These flights constitutes the traffic demand sample (cf. Figure 4), between the two green vertical bars) for that day and destination.

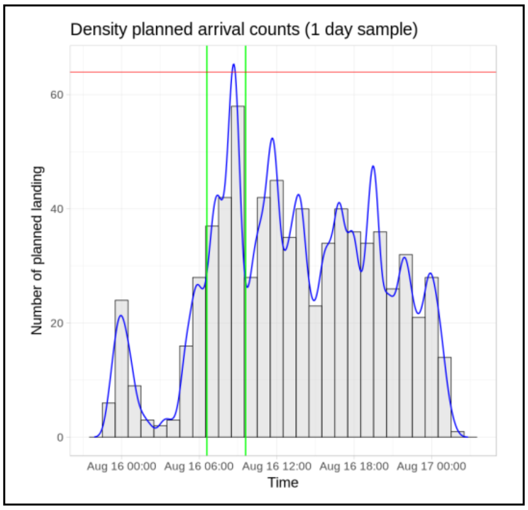

Figure 4 : 3 hours traffic demand extraction

The 50 days, three hours peak data sample comprises more than 6000 flights for each destination (26 560 total), with daily sample sizes in the range from 110 to 170 arrival flights. We assume that these sample sizes are large enough for reliable statistical measurements.

D. Regulations

We consider regulation data extracted from the same source as the flight plan data (EUROCONTROL DDR2). The regulation data files we are using describe the regulated airspaces (combinations of airspace blocks) with the start and end times of the regulations. The flights that are crossing these regulated airspaces might be subject to ground delay (depends on the other delays they might be subject to, exemption rules, other flights delays etc.) to ensure that the traffic demand does not exceed the available capacity. This corresponds to the regulated flight plans we are using as input traffic.

In the present work, when a flight is crossing a regulated airspace, even if that flight was not subject to regulation delay, we consider it to be constrained by the network management regulation (for the case with network management integration). The reason is that if many flights are departing from the

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[1] https://ext.eurocontrol.int/airport_corner_public

[2] https://ext.eurocontrol.int/ddr/historicaltraffic

network management plans (e.g. due to large en-route arrival management delays), the regulations actions might be jeopardized. Note that we are not considering short term regulations measures, applicable to cherry-picked flights. We assume that these concern a small enough proportion of the traffic.

E. Delay parameters

The delay related parameters are:

- Terminal area pressure delay set to 2 minutes. Note that this does not correspond to actual, observed terminal area pressure, in particular for London. This setting is based on [11].
- En-route delay absorption capacity per 50NM set to 30 seconds. This corresponds to a maximum delay obtained by speed control over 50NM distance (typically around a speed reduction of 7%).
- Ground delay capacity set to 30 minutes. We assume that larger values would not be acceptable for tactical arrival management purposes.

F. Experiment variables

The independent variables are the arrival horizon (0, 100, 200, 300 and 400NM) and the network integration status (without, with), leading to 10 combinations. This makes 10 experiments to be performed for each traffic sample: 50 days × 4 destinations × 10 experiments = 2000 runs.

V. TRAFFIC AND REGULATION CHARACTERISTICS

The section presents initial indications in terms of flights departing within horizon, flights crossing regulated areas, durations and locations of regulations, and flights constrained by regulations.

Figure 5 presents the ratio of the arrival traffic demand that could get ground delay, since they are taking off within the horizon (pop-up flights). These ratios are similar to those found in [10]. At 350NM, the ratio of pop-up flights over total traffic is between 20% (EGLL) and 30% for the 3 other destinations.

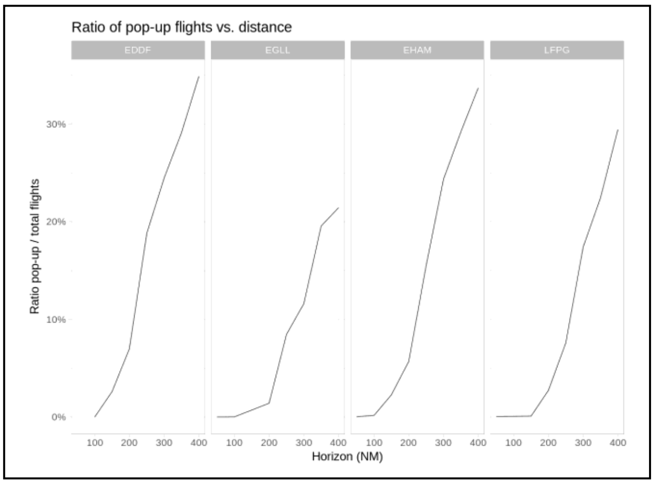

Figure 5 : Pop-up flights ratio

The next figure (Figure 6) shows the ratio of flights crossing regulated slices (y-axis) at a distance lower or equal to the horizon (x-axis) : its range starts from 30-40% at a 50NM horizon (regulated slice just before the terminal area entry), and then increase up to about 60% at 400NM (EGLL and EHAM). The high rate (>30%) at close distance to terminal area means that this amount of flights will get little en-route or ground delay when integrating the network management constraints.

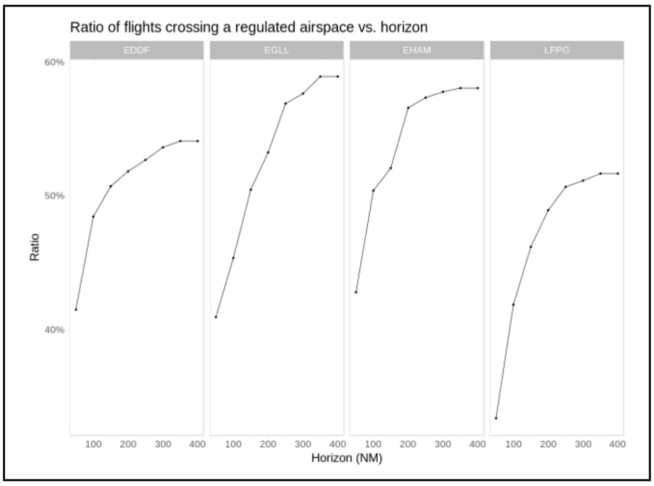

Figure 6 : Crossing regulated slice flights ratio

The following set of maps (Figure 7) details the previous information by showing where the regulations apply and how much time the traffic is spending within these regulated areas. The last 50NM (the modeled terminal area) is void (ignored) and some flows cross heavily regulated areas (e.g. red/orange/yellow areas on a Westbound flow for EGLL, Eastbound for EDDF, Northbound for EHAM and Southbound for LFPG). The black circles give a distance reference, with 50NM between them.

These regulations create delay constraints on flights crossing them. These delay constraints propagate upstream, since, for respecting the constrained entry/exit times in regulated slices, the delay upstream is limited (it can even be zero). The following map (**Figure 8**) shows this propagation, with constrained flights per slice colored in orange (green if no constraint).

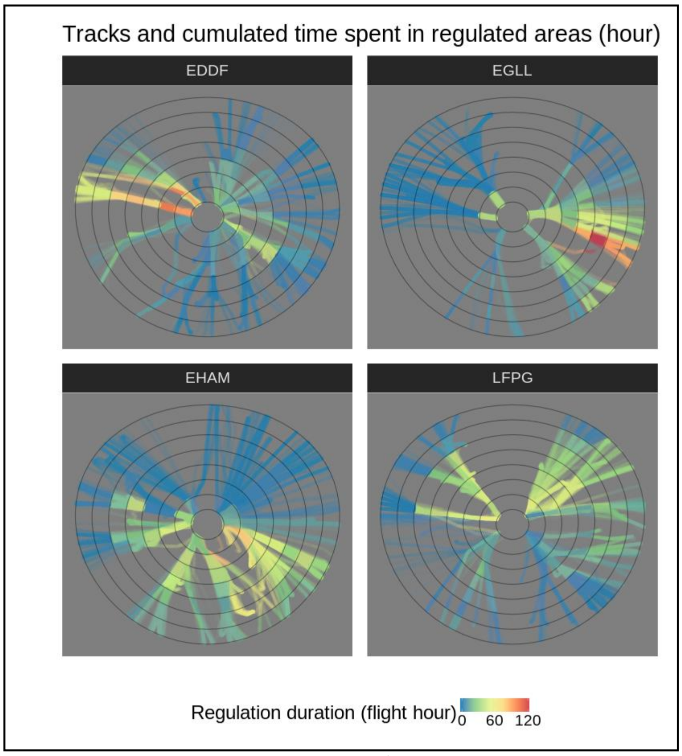

Figure 7 : Regulation flight hours

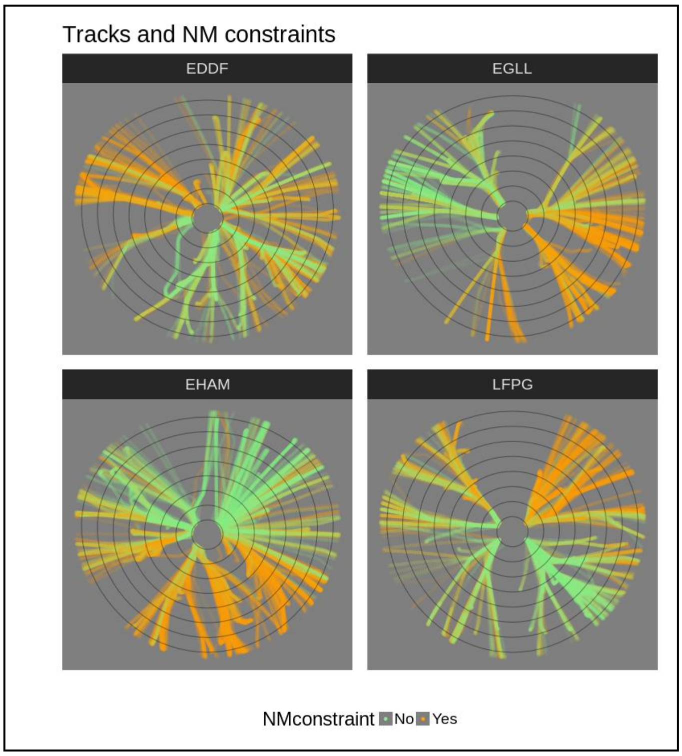

Figure 8 : Regulations and flight constraints

VI. ARRIVAL MANAGEMENT DELAYS

We present here the impact of network management integration on arrival management delays.

Figure 9 shows delay evolution (y-axis, in minute) vs. arrival management horizon (x-axis, called “Horizon” for short, 0-400NM). We distinguish the delays per type (terminal area in orange, en-route in blue and ground in green), destination and NM integration level (without/with). Each thick middle line represents the average delay value among all flights. These lines are continuous, but measures are discrete at 0, 100, 200, 300 and 400NM. The colored envelope corresponds to the average +/- the standard deviation values (negative values zeroed).

The measures made at 0NM are exactly the same for both NM integration level, since there is no en-route or ground delay applied. They show the total terminal area delay (only) to be absorbed to sequence the arrival traffic.

Note: the average delay at 0NM for London Heathrow (EGLL) is close to 4 minutes. This is lower than the EUROCONTROL Performance Review Unit additional time (8 minutes for 2017) [8]. We performed a test with lower capacity figures (e.g. 5% lower) and obtained an average delay closer to these 8 minutes: when the demand gets very close to the available capacity, delay increases very sharply. We decided to keep the input capacity values and not to alter them.

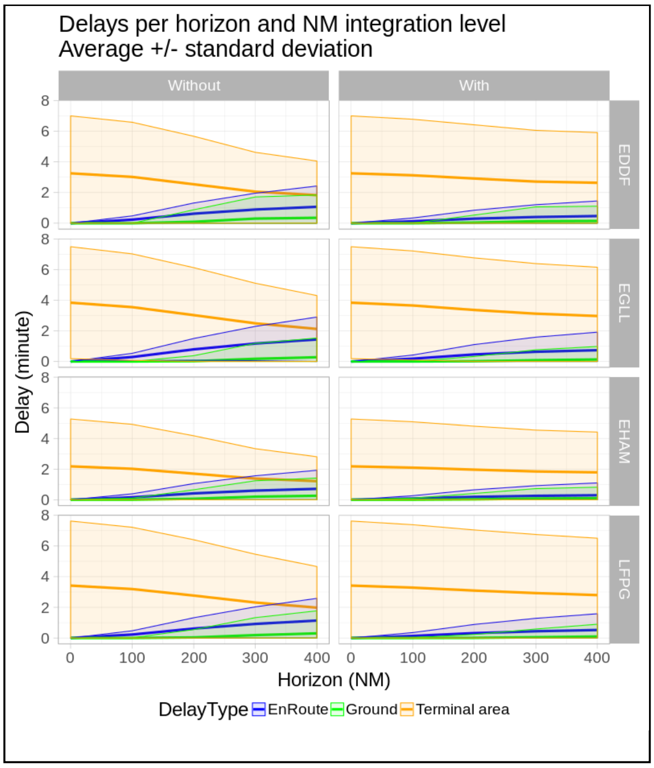

Figure 9 : Delay distribution with and without NM integration

Average terminal area delays decrease with the horizon extension, shifting more delay toward en-route and ground, for all destinations and NM integration level.

For the cases without NM integration (left column), this delay decreases linearly (from 0 to 400NM) of -100s for EGLL, -85s for EDDF and LFPG, and -50s for EHAM.

That decrease does not plateau: the delay capability transfer toward En-route and ground was too modest to absorb all the delay remaining after applying terminal area pressure. Using a different delay strategy, for example, with ground delay priority, greater delay En-route capability using path stretching etc. will distribute the delays differently.

The terminal area delay standard deviation is also decreasing (difference between upper and average orange curves). This decrease is about -90s for all destinations (e.g. from 4.2 to 2.7 minutes for LFPG): the greater delays are reducing more than the average delays.

For the cases with NM integration (right column), the average terminal area delay decreases (from 0 to 400NM) of -50s for EGLL, -42s for EDDF and LFPG, and -20s for EHAM. These delay decreases are 2 times smaller than the “without NM integration” case. Overall, at 400NM, the NM integration results in an average transfer over the four destination of about 35s and 11s of en-route and ground delays toward terminal delay (+46s, about +42% compared to the non integrated case).

The standard deviation is also decreasing, similarly for all destinations of -30s (e.g. from 4.2 to 3.7 minutes for LFPG): this is 3 times smaller than the “without” case.

Note: We tested (pairwise Wilcoxon test) the hypothesis that there was no difference between each flight terminal area delay with and without NM integration and a 400NM horizon. The test was statistically significant at a 0.05 level (p-value < 2.2e-16): terminal area delay differs with and without NM integration.

The Figure 10 zooms on the average en-route and ground delay presented on the previous figure. En-route delays represents between 75% and 100% of the overall en-route and ground delays combined. The average ground delay remains very close to zero due to two factors: first, many flights are entering the horizon airborne and cannot get ground delay; second, the delay strategy puts ground delay last but one, making it useful mainly for flights with higher delays.

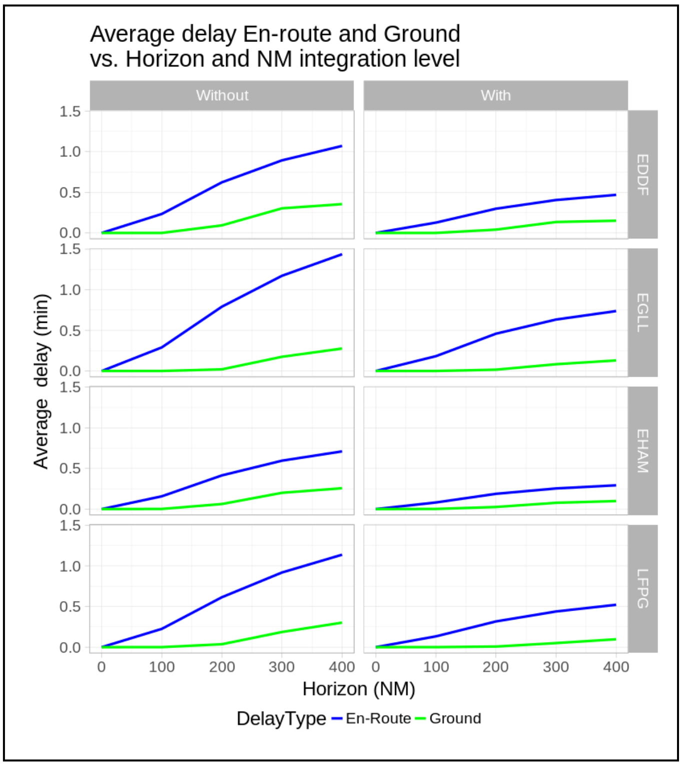

Figure 10 : Average en-rounte and ground delays with and without NM integration

The previous figures show delay figures for the overall arrival management horizon, the following maps shows average delays for the en-route slices and terminal area. This a more detailed view, and help in seeing higher delays areas. These delays are for the scenarios with 400NM horizon, with and without NM integration. We present the delays with a square-root color scale to better distinguish nuances within lower delay values (0-minute in blue, 5 minutes in red).

The first difference between the two set of maps (Figure 11 and Figure 12) is the terminal area delay increase (middle inside circle), matching the previous delay curves. On the second set of maps (with NM integration), traffic flows had reduced delay capability: we see large 0-delay areas (in blue) matching regulations locations (cf. previous Figure 7 and Figure 8). Unconstrained areas show similar average delays as on the first set of maps: we did not delay more the unconstrained flights to compensate for the constrained ones (equity).

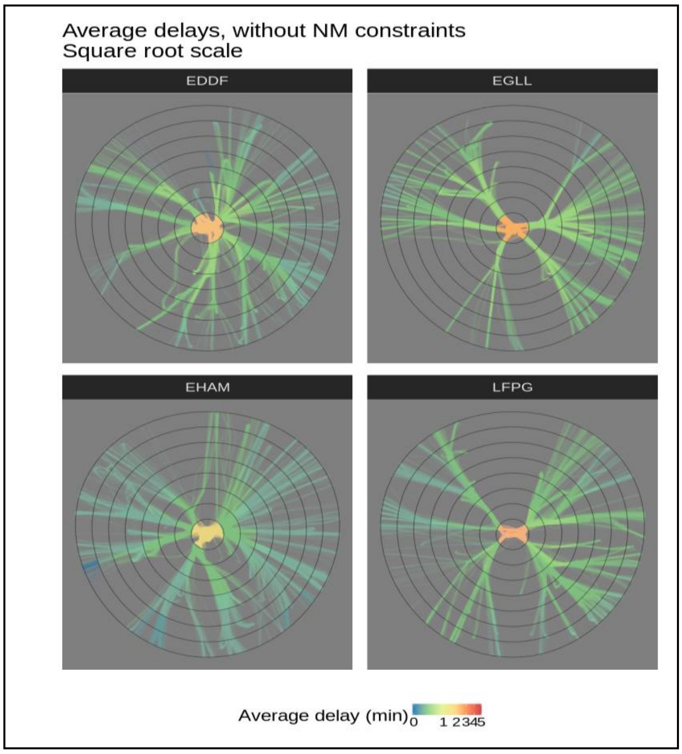

Figure 11 : Delay distribution without NM integration, 400NM horizon

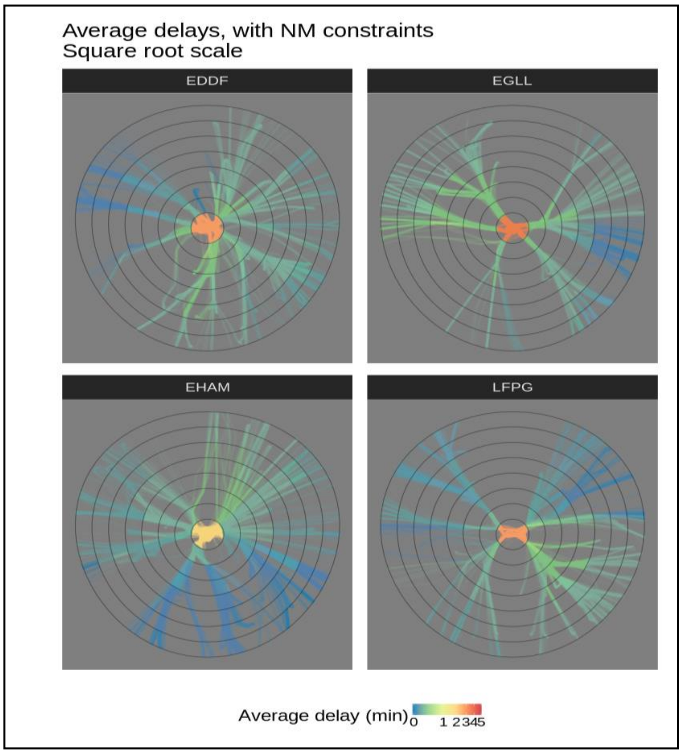

Figure 12 : Delay distribution with NM integration, 400NM horizon

VII. TRAFFIC OVERFLOWS

We present in this section the effect of unconstrained arrival management delay on network management traffic counts.

Actual and planned traffic counts in regulated slices are the same with NM integration: all the next results apply for the case without NM integration. It shows the impact of arrival management horizon and associated en-route and ground delays increase on network management planned traffic counts *within regulated areas*.

Figure 13 shows planned traffic counts within regulated slices (x-axis) vs. actual traffic counts difference (y-axis) per destination and horizon, without NM integration. We report traffic counts every 5 minutes. The blue vertical line is corresponds to the 75th percentile (21 flights): we will focus on planned traffic demand (within regulated areas) greater than this line on the next figure.

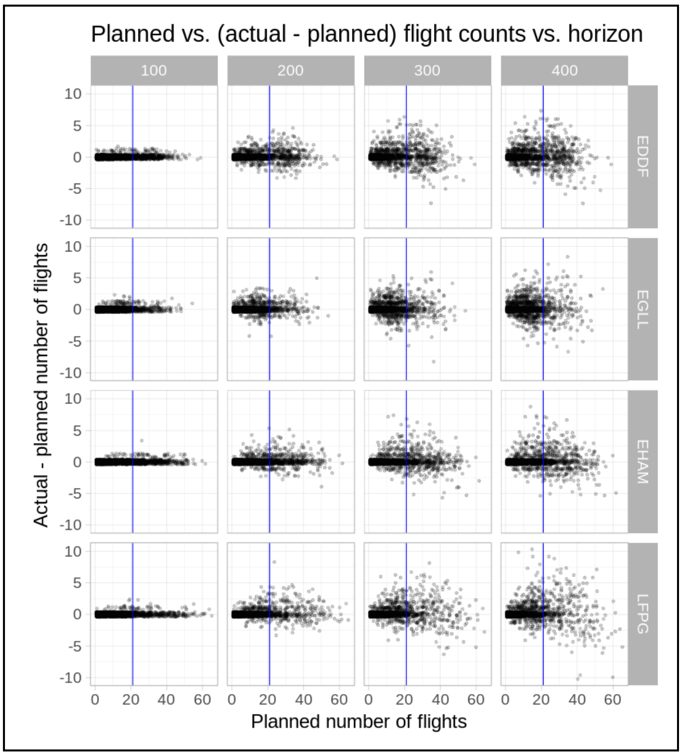

Figure 13 : Planned traffic vs. actual difference counts

As expected, the spread between actual and planned traffic counts is increasing with the horizon. That spread does not correlate with the planned demand level: e.g. at 400NM, we see a similar spread for 20 or 40 planned flights.

Figure 14 aggregates the previous dataset information (for the higher traffic counts cases): it shows the proportion of measurements (y-axis) with actual counts equal to planned (blue), lower (green) or greater (orange, overflow) vs. horizon (x-axis) and destination.

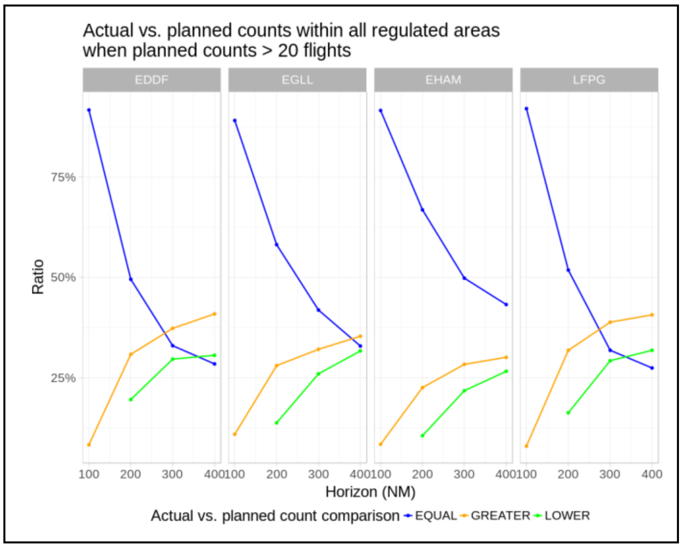

Figure 14 : Traffic difference per destination and horizon

The curves evolution for the different destinations are similar: overflow red curves increases up to a maximum of 30% (EHAM), 35% (EGLL) and 40% (EDDF & LFPG) of the traffic counts. Underflow curves reach lower rates than overflows: a likely reason is that delayed traffic is more likely to stay for longer periods within regulated areas, leading to more overflows than underflows.

Note that the greatest increase occurs between 100 and 200NM, above 200NM, the increase rate is smaller. One of the reasons is simply that most regulations of concern for the traffic sample are located closer to the destination.

The previous figure (Figure 14) has a binary view: actual counts are greater than planned ones or not. Figure 15 details the distribution of the ratio "actual counts *over planned traffic counts"* within regulated areas. We present the distributions with boxplots, colored according to the horizon, and grouped by destination.

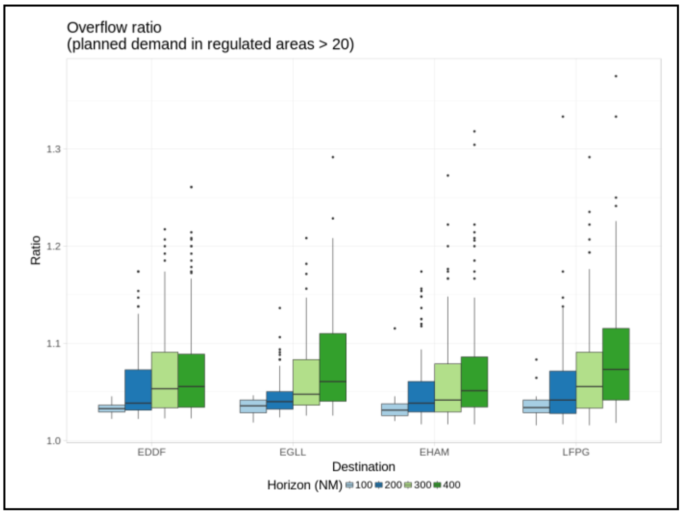

Figure 15 : Traffic difference per destination and horizon

We see that the median overflow ratio increases with the horizon for all destinations (as expected), with different amplitudes, capturing differences in potential interactions.

At 400NM, the median overflow ratio is in the range from 5% to 7%, typically, an average overflow of one or two flights. The 75th percentile overflow ratio is in the range 9% to 11% (typically an overflow close to three flights). Extending to the 95th percentile, the range goes up to 18% (EDDF, EGLL and EHAM) and 21% for LFPG.

Finally, the higher traffic overflow rates might have a different effect on the Network management regulations if they are concentrated over a small area or evenly distributed. The next figure (Figure 16) shows the overflow counts per slice (for the 400NM horizon scenarios).

We see overflow slice "hotspots" on North-West flows to EDDF, close to destination, and on Westbound flows to EGLL, within the 200-250NM slices. Overflows are distributed over a greater area for LFPG and EHAM.

These views might help in managing the identified overflow hotspots and higher overflows ratios, and find trade-offs between a strict adherence to Network management plan counts and the potential benefits of applying arrival management delay upstream.

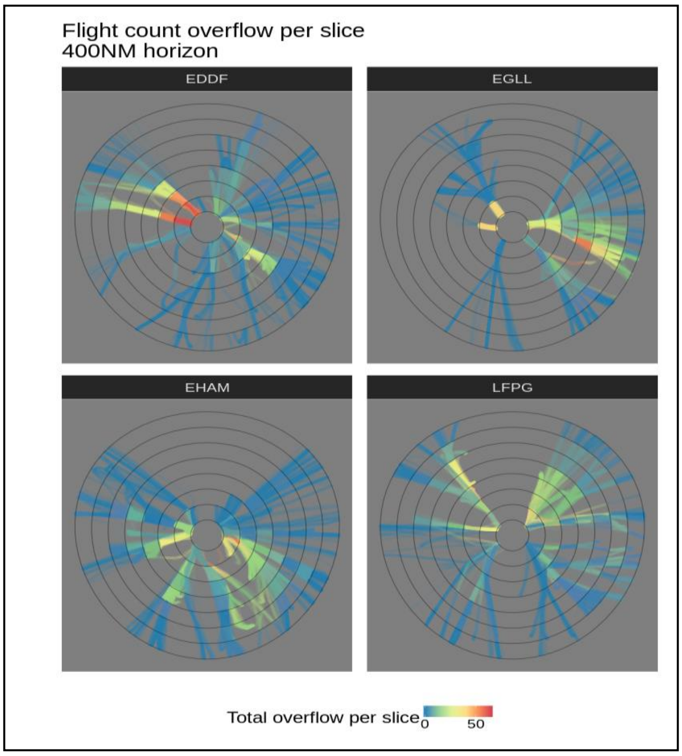

Figure 16 : Traffic overflows per slice (400NM horizon case)

VIII. CONCLUSIONS

This paper presented a sensitivity analysis on the potential interactions between arrival management and network management when extending the arrival horizon. The analysis focuses on regulated enroute traffic overflows and on arrival management delays.

It relies on a macroscopic modelling of arrival management delay, capturing the effect of arrival management horizon and the interaction with the Network management by setting delay constraints. The model was applied on 50 days of peak periods traffic demand toward the four busiest European airports in 2017 (more than 25 000 flights). The percentage of arrival flights crossing regulated areas goes up to 60% at 400NM.

The results reveal two effects of the potential interaction. Firstly, when network management regulations are not integrated by the arrival management, traffic overflows may occur for extended horizons. For a 400NM horizon, overflows up to +21% were detected (95% percentile). Secondly, when regulations are integrated, overflows disappear but flight efficiency is slightly reduced with a shift from enroute and ground delays towards terminal delay. For a 400NM horizon, this shift is respectively of 35s and 11s, leading to an increase of terminal delay of 46s (+42%).

These results raise the question of trade-off and level of performances expected in terms of capacity limits (tolerance), considering that short term flow management measures may apply.

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