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Reducing CO2 emissions of arrivals by acting on departure times

A perspective for 30 European airports

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***Abstract*—This paper investigates the reduction of airborne delays by acting on departure times as one option to act rapidly on CO2 emissions. Following our previous work exploring the theoretical feasibility, we performed a trade-off analysis at European level driven by a cost function integrating airborne, ground and extra delay, with different weightings. We relied on a model of the today arrival flow management process with a simplified mechanism to trigger ground delays and with realistic uncertainties. We added a control of airborne delays with a ground delay capping of 30 minutes. We considered 30 European airports and selected fair weather days in 2019 for a total of more than 2 million flights. The control parameters were optimized according to a cost function for each airport and per day. The medium cost scenario leads to an average reduction per flight during peak periods of 2.5 minutes of airborne delays and 194 kg of CO2 emissions, with airborne and ground delays of 5.2 and 4.4 minutes inducing an extra delay of 0.8 minutes. For all the selected days, the cumulated reductions of airborne delays and CO2 emissions reach 13k hours and 61k tons respectively, corresponding to a reduction of 11%, with 15% of traffic concerned. No loss of runway pressure was observed. 50% of the gain may be obtained with 7 airports and 80% with 14 airports. These trends confirm the interest of developing the idea further. Future work should involve in particular the analysis of the impact on airlines operations, at departure airports and on the network.**

Keywords-component; airborne delays, CO2 emissions, flow management.

I. Introduction

Arrival congestion in the terminal area leads to airborne delays resulting from holding or vectoring, which in turn increase fuel consumption and CO2 emissions. Our analysis shows that in 2019, more than 44,000 hours of arrival airborne delays above a 5-minute margin were recorded in the last 50NM at Europe's top 30 major airports. This corresponds to more than 200,000 tons of CO2. Reducing these airborne delays by acting on departure times is one, amongst the range of possible options, to act rapidly on CO2 emissions.

One challenge lies in the capability to control airborne delays by triggering ground delays few hours in advance, in the presence of uncertainties and exempted flights (e.g., long haul). Our previous work suggested a feasibility "in principle", focusing on the effectiveness of this control under realistic uncertainties, at four European airports [1]. Compared to today, the airborne delay could be effectively reduced with no apparent effect on the runway throughput, however with an extra delay and occurrences of large ground delays. These two side effects may have an impact on airline operations and at departure airports.

Based on these outcomes, the challenge addressed in this paper is to investigate trade-offs between performance and costs from a stakeholder standpoint by means of modeling. Precisely, we perform a trade-off analysis at European level, aiming at reducing CO2 emissions of arrivals while maintaining the runway pressure and containing the impact on ground and extra delays. This analysis is driven by a cost function integrating airborne, ground and extra delay, with different weightings. We considered 30 European airports and selected fair weather days in 2019 for a total of more than 2 million flights to provide insight into potential benefits compared to today's situation.

Following a state of the art, the paper introduces the methodology (input data, model, experiments) and then presents the results and discussion (sensitivity and trade-off analyses) before drawing the main conclusion and perspectives.

II. State of the Art

A. Lessons from the past

Historically, delaying flights on the ground prior to departure rather than in the air is not a new idea. It has, in fact, been at the root of the tactical phase of Air Traffic Flow Management (ATFM) for the last 50 years. However, the underlying motivations have significantly varied with time and circumstances, from avoiding traffic congestion to addressing fuel costs and reducing delays.

In 1970, the Federal Aviation Administration (FAA) established a Central Flow Control facility to cope with increasing delays due to congestion at the major U.S. airports, at the outset for safety reasons [2]. It is notable that shortly afterwards, in the wake of the 1973 oil shock, an explicit fuel conservation objective was added [3] and triggered, during that first energy crisis, a dedicated program aiming at minimizing excess fuel consumption in busy terminal areas by substituting ground delays for airborne delays [4].

In Europe, the need for a centralized ATFM organization became clear during the delay crisis at the end of the 1980s. From 1989, the Central Flow Management Unit (CFMU) established by EUROCONTROL progressively took over national flow management units, including in the tactical phase of ATFM [5]. The main objective was, and remains, demand/capacity balancing to reduce the risk of overloads, hence again, primarily for safety reasons.

B. Current situation

Nowadays, at busy airports where the focus is on throughput, ATFM measures do not in effect prevent occurrences of significant airborne arrival delays. This is in part because regulation thresholds based on available capacity may include a certain amount of airborne holding. As a matter of fact, high airborne arrival delays have been measured in conjunction with lower ATFM airport delays at some of the top European airports and resulted in excess fuel consumption and emissions [6] [7]. Therefore, there are clear opportunities to further act on ground delays and reduce airborne arrival delays (hence fuel burn and CO_2 emissions) in a systematic manner. In 2014, ICAO advocated for the absorption of known delays by holding aircraft on the ground, rather than in the air, thanks to collaborative decision making [8]. In the same timeframe, noting the persistently high values of airborne delays for arrivals at certain airports, the EUROCONTROL Performance Review Commission suggested to investigate “possibilities to reduce holding times at airports through a better support of the network while ensuring a continuous arrival flow into the airport” [6].

From an economical perspective, Past studies have shown that not only delaying aircraft on the ground is more fuel- and environmentally efficient [9], but airborne delays are also typically more costly for airspace users at least from a single flight perspective [10]. Noting that the cost assessment of applying ground delays however encompasses other aspects, such as the effects on departure airports and those of delay propagation on airspace users’ operations [11] [12], models were also proposed, aiming at minimizing/optimizing the total cost of airborne and ground delays [13] in some cases including a trade-off with environmental considerations [14] [15].

Arrival management, in place at busiest airports, supports metering to start absorbing airborne delays, typically 120-150NM from the runway, and up to 350NM at some places [16] [17]. The role of in-flight delay absorption was also investigated, including improvements to flow management performance through in-flight speed reductions or speed control [18] [19] [20] [21] or by adopting minimum fuel consumption speed in cruise [22]. Several recent studies looked at further enhancing arrival management mechanisms and bridging the gap with ATFM. As part of SESAR, live trials and demonstrations of the use of target times of arrival to regulate arrival flows were conducted [23] [24]. In particular at London Heathrow a reduction of peak airborne delays was observed, with savings on ATFM delays compared to conventional regulation, and no negative effect on runway throughput, using a local demand and capacity balancing tool. Such mechanisms remain, however, subject to network impact assessments.

C. Related studies

In close relation to our intended work, reference [25] analyzed the impact of applying ground holding to keep airborne delays in the terminal area below a defined threshold, based on a posteriori analysis of real 2008-2009 traffic data from Tokyo Haneda. The study also identified the factors affecting these airborne delays (e.g., runway configurations/operations, traffic demand) and the risk of over control. This work was further complemented by a modelling study using one day of traffic data archive, still at Tokyo Haneda [26], where the authors looked at the effect of varying airborne delay target thresholds on ground and airborne delays, also including in-flight delay absorption for international flights. Results were consistent with those from the previous study, with airborne delays remaining within the defined margins and only rare occurrences of lost throughput.

Finally, for a fair representation of arrival and flow management processes, realistic uncertainties need to be included in any modelling. A number of studies looked at factors affecting airborne delays and more specifically their relationship with airport capacity and actual throughput [27] [28] [29], and provide useful inputs for modelling the impact of uncertainties be it in terms of delays or capacity prediction [30] [31] [32] [33] [34] [35] or more globally on the application of ATFM under uncertainties [36] [37] [38]. Stochastic delay cost functions were investigated [39] [40] and found to be outperforming a deterministic approach in the frame of downstream delay propagations under uncertainties [41]. The prediction problem may also consider a different granularity than individual flights, based on e.g., average delays per time intervals [42] and statistical distributions of uncertainties. In the Tokyo Haneda study [26], uncertainties on departure times and flight durations were reflected through multiple runs/Monte Carlo simulations.

III. METHODOLOGY

A. Airports and traffic data

We selected 30 of the busiest European airports (without the Turkish airports for which track data was not available) in 2019. We will call them TOP30. We collected all 2019 EUROCONTROL flight plan data for flights going toward the TOP30. This data includes planned, regulated (i.e., with flow management ground delay applied) and actual times for departures and landings. It also indicates which flights are exempted from regulations (i.e., flights that cannot be imposed ground delay: most often long-haul flights originating outside of the Network Manager area).

We considered “normal” days defined as fair weather days without exceptional airborne arrival delays. On these days, it is more likely to have a better arrival capacity estimate and the potential delays associated, required for better decision making. We identify fair weather days by the absence of regulation at destination due to weather and keep days with median arrival delays within ±20% median for each destination for the year.

After this filtering, we had 180 days per destination on average (minimum 85 for EGLL, maximum 254 for EKCH). This represents a total of 2 million arrival flights, with a daily average about 400 arrivals (minimum 200 for EDDH, maximum 700 for EDDF). We assume this data set is large enough to be representative.

B. Arrival capacity

Arrival capacity figures per destination are required to simulate the arrival management process, in particular to predict airborne arrival delays and how they evolve when the traffic demand is modified by applying ground delays. Since these figures were not available, we estimated them via calibration, assuming a constant arrival capacity per destination. To do so, we sequence arrival traffic based on their actual entry times in the terminal area (50NM) with a given inter-aircraft time separation (first-come first-served policy, no wake-vortex consideration or multiple runways assignments) and record resulting delays. We select as calibrated capacity the time separation value best matching the delay distribution estimated from track data[7], using the Earth-movers distance to measure the proximity between delay distributions. Note: in real operations, we may assume that a Flow Manager at destination would set appropriate arrival capacity few hours in advance for delay prediction, possibly with system support.

C. Baseline situation: "Today"

We present here the main characteristics of the current situation ("Today"): simulated airborne delays (en-route plus terminal area delays), flight durations, exemption rates and flow management current practices (observed ground delays and percentage of regulated traffic). Using the calibrated capacity figures (III.B), and the modelling method (III.E), we get the following airborne delay distributions (Figure 1). The boxplots are complemented by the mean airborne delay values (black dot), usually larger than the median (delay distributions often skewed, with many smaller values and few much larger values).

Cumulated over the selected days per destination, the total (simulated) airborne delay is about 80000 hours, of which 25000 hours above a 5-minute margin. Overall, the TOP30 median flight duration is slightly less than 2 hours and the 3rd quartile about 2.5 hours. Highest flight durations range from 5 to 18 hours. The rate of flights exempted from regulations varies according to destination: 12% on average, greater than 20% for EDDF and LFPG and close to 40% for EGLL. Such significant exemption rates may impact the effectiveness of the concept (higher ground delays or target not met). Finally, Figure 2 shows the average ground delay versus the percentage of regulated traffic (regulation set at destination). Only 7 destinations over the 30 regulate more than 10% of their traffic, with an average ground delay between 7 to 17 minutes.

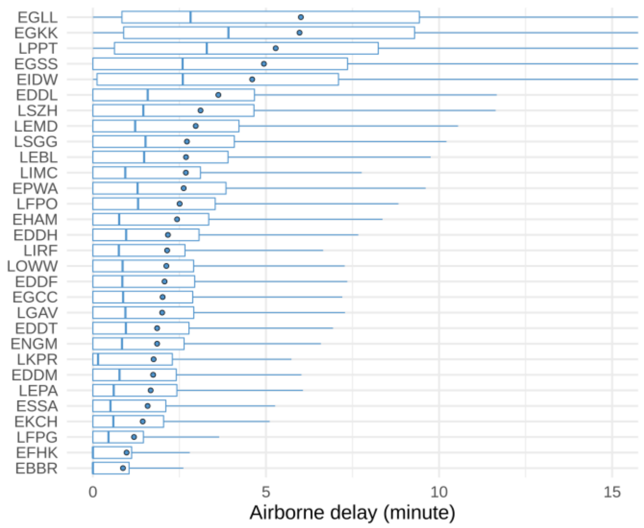

Figure 1: Airborne delay distribution in "Today" scenario

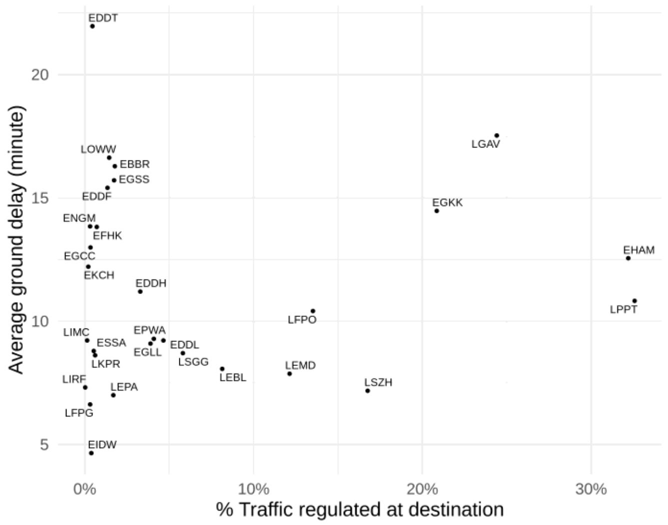

Figure 2: Ground delay vs. percentage of regulated traffic

D. Uncertainty model

Departure times and flight durations are affected by significant uncertainties. We collected actual departure time differences between estimated and actual off-block times (EOBT - AOBT) from network management data, along with each flight regulation status (regulated yes/no): this forms a large dataset of off-block time deviations from which we sample departure time errors (we do not consider taxi-time uncertainty here, due to lack of data) according to the flight regulation status. Flight durations' uncertainties are modeled as proportional to their duration. The flight duration error rate follows a normal law with mean 0 and standard deviation 2% [37]. Moreover, since a major source of flight duration uncertainty is related to wind prediction errors, it makes flights coming from similar areas (direction/distance) to have correlated flight duration errors. We simulate that effect by sampling shared values between flights from a similar bearing and distance (short/medium/long haul categories).

Figure 3 shows the combined uncertainty of departure times and flight durations before off-block time, based on 2019 data. For non-regulated flights (blue curves, one curve per destination), the median deviation is 3.5 minutes, 50% of the deviations are between -3 minutes (leaving block early) and 11 minutes (late), 80% of the values (between 10th and 90th percentiles) are between -9 and 20 minutes. For regulated flights (green curves), the median deviation is about 3 minutes: 50% of the deviations are between -2 and 10 minutes, 80% between -5 and 17 minutes (range about 25% lower than for non-regulated flights). We observe that even if flight durations distributions differ with destination, they do not have a visible impact on the uncertainty before off-block time.

We apply these uncertainties to the model, which are updated during the simulated flight progress as detailed in III.E.

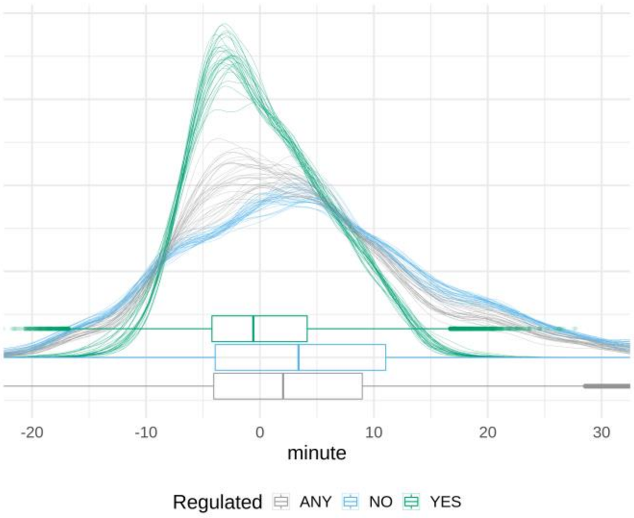

Figure 3: Total off-block time and flight duration uncertainty before off-block (one curve per destination)

E. Simulation model

We simulate arrival traffic toward destination on a given day prior to flights departure until their landing[1]. At a high level, we perform the following steps every simulated 15 minutes:

1. estimate / update time of arrival (ETA)
2. schedule / sequence time of arrival (STA)
3. distribute delay between air and ground (STA-ETA)

1) Step 1: Estimate / update time of arrivals

We estimate / update arrival times by considering the simulated flight uncertainties evolution (off-block time and flight duration, cf. III.D). Before departure, estimated arrival times (ETA) are only based on flight plan times and have both the uncertainties linked to off-block time and flight duration. At flight departure, the off-block time uncertainty goes to zero, while the estimated flight duration is the flight plan's one. During the flight, the estimated flight duration converges toward the actual flight duration in a linear fashion. After flight landing, the ETA is the actual time of arrival (ATA).

2) Step 2: Schedule time of arrivals

We schedule / sequence the traffic at destination (i.e., we compute STAs) based on the latest updated ETAs (cf. step 1) with a first-come first-served (FCFS) policy, and flights separated at least by the constant calibrated time separation of the destination airport (cf. III.B). At that stage, we derive an estimated flight delay (STA-ETA) that we allocate by default to airborne delay. Note: we give a queueing priority to exempted flights (FCFS- policy applied between exempted flights), like in the current European slot allocation mechanism.

3) Step 3: Distribute delay between air and ground

We can transfer some of the estimated flight delay from air to ground (only for non-exempted flights, still on ground until a frozen horizon before planned off-block time). The actual proportion of transferred delay depends on three parameters:

1. an airborne delay control function
2. an airborne delay control target
3. a ground delay capping value

In this study, we consider two control functions: the mean over a 30 minute period and the maximum. For the mean function, we want the average airborne delay over 30 minutes periods (fixed time periods, like 10:00 to 10:30) to be lower or equal than the control target. For the maximum function, we want the airborne delay per flight to be lower or equal than the control target. For example, with the maximum function and a delay target of 6 minutes, if a flight has a predicted delay of 8 minutes, 6 minutes will be allocated to the airborne delay and 2 minutes to the ground. For both functions, we limit the requested ground delay to the ground delay capping.

Figure 4 illustrates the behavior for two scenarios. On the left, we have a "Do nothing" scenario without any airborne delay transfer, on the right a "6 minutes max no uncertainty" scenario. For one flight, each blue dot represents the airborne delay (actual one, measured at landing) and each orange the ground delay. The smoothed curves show an "average" estimate of these delays for all flights. As expected in the delay-controlled scenarios, the airborne delays do not get higher than 6 minutes (excepted for few exempted flights).

[1] The model runs on the R statistical platform and uses the discrete event simulation library *rsimmer*

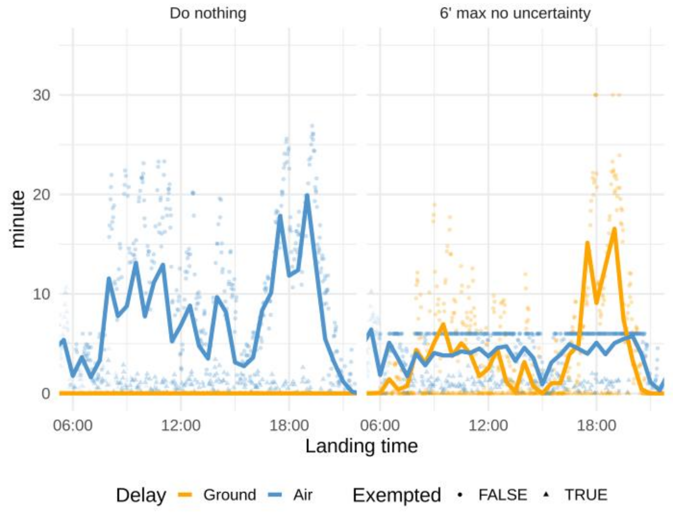

Figure 4: "Do nothing" and control scenario with 6 minutes target without uncertainty

The previous figure shows an ideal situation without any uncertainty applying and a baseline where no actions were considered, leading to high airborne delay peaks (especially around 6PM). Figure 5 shows a "Today" scenario, with actual regulations toward destination (e.g., around 6PM with the orange curve peak on the left panel) on the left and the same 6 minutes delay target maximum, but with uncertainty applied on the right. In that case, we see that there are some blue dots (airborne delays) higher than the prescribed 6 minutes limit, but, overall, the smooth delay curves show that, compared to the "Today" scenario, a level of delay control was obtained, even if not perfect due to uncertainties.

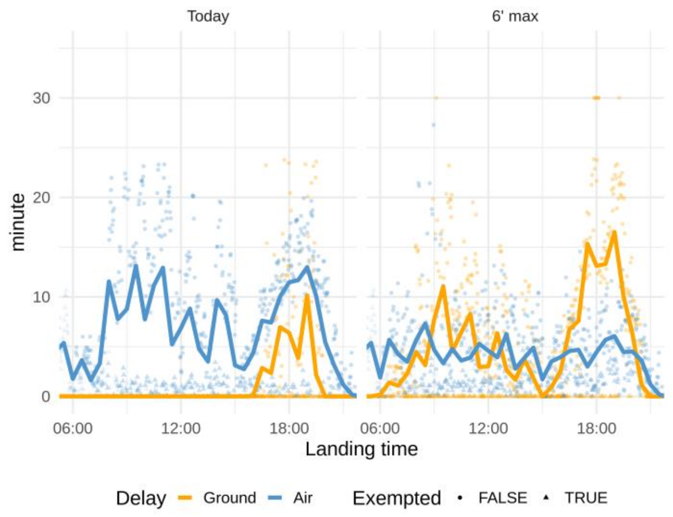

Figure 5: "Today" and control scenario with 6 minutes target and uncertainty

F. *Experimental scenarios*

For each destination and day, we simulate two baseline scenarios "Today" and "Do nothing" and multiple "delay target" scenarios.

In the "Do nothing" scenario, we cancel all the regulations at destination (i.e., flights regulated by the destination airport use their initial planned times not regulated ones). No delay is transferred toward the ground.

In the "Today" scenario, all regulations are applied and no (additional) delay is transferred toward the ground. The measured ground delays are the results of the current practices, not of the simulated airborne delay transfer to the ground. It might happen in these real operations that the constant arrival capacity assumption does not hold (e.g., capacity drop), and that some real regulations lead to high ground delay in those cases that will not be reflected in the other scenarios.

We consider two parts in the study with different "delay target" scenarios. The first one is a sensitivity analysis (cf. IV.A) to assess the effect of the control parameters (III.F) during peak periods (average airborne delay over 30' greater than 10' (selected empirically) in the baseline "Do nothing" scenario). It considers all the combinations (40) of the following parameters:

- two control functions: maximum per flight or mean over 30 minutes)
- five delay control targets (2, 4, 6, 8 or 10 minutes)[2].
- four ground delay capping (10, 20, 30 minutes or none)

The second part provides a benefit assessment over the TOP30 (airborne delay and CO2 reduction, cf. IV.B) for selected delay control parameters. Relying on the sensitivity analysis (cf. IV.A), the control function and ground delay capping are fixed for all destinations (mean function, 30 minutes ground delay capping), while one "optimum" control target (among 2, 4, 6, 8 and 10 minutes) is selected for each destination and day. Indeed, the optimum setting (in terms of a cost, defined hereafter) might vary from one day to another depending on traffic patterns.

We define one airport daily scenario cost as the weighted sum of three components: ground delay, airborne delay, and extra delay.

We define extra delay as the difference between the total delay (airborne plus ground for a selected scenario) vs. the airborne delay in the "Do nothing" scenario (i.e., only airborne delay used to sequence the traffic, hence, relying on traffic with little uncertainty). It can be related to loss of runway throughput and punctuality.

We use a cost/weight of 1 unit for ground delay and 3 for airborne delays [38]. We found that setting an extra delay unit cost was not straightforward, hence we choose to show results for three values: 1 (as ground delay), 3 (as airborne delay cost) and 6 (double airborne delay cost). The cost function may be expressed as follows:

$$Cost = ground\ delay + 3\times\ airborne\ delay + n\times\ extra\ delay$$
$$(n = 1, 3 \text{ or } 6)$$

[2] No zero target as some airborne delays are required to keep runway pressure.

Once the extra delay unit cost is defined, we can compute the daily airport scenario cost for each target and identify the one minimising it, as illustrated with big dots on the Figure 6 (colour matches the extra delay unit cost, x-axis the delay target and y-axis the scenario total cost). Note: we observe that for higher extra delay unit cost, the selected delay target is higher: this is expected since higher delay target means higher buffering in the terminal area and lower extra delays.

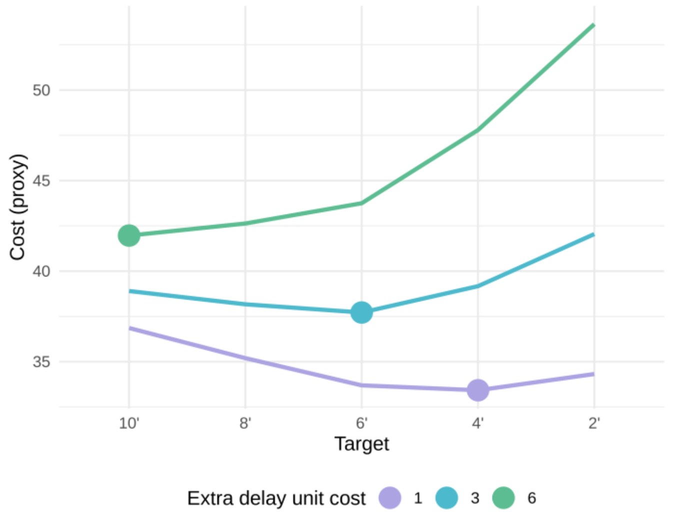

Figure 6: Cost variability with delay target and extra delay unit cost (for one destination and one given day)

Note: we consider delay control periods as 30 minutes peak periods with an average airborne delay greater than the selected delay target. This means that for a lower delay target, the control action will apply to more time periods, over more flights, as shown on Figure 7.

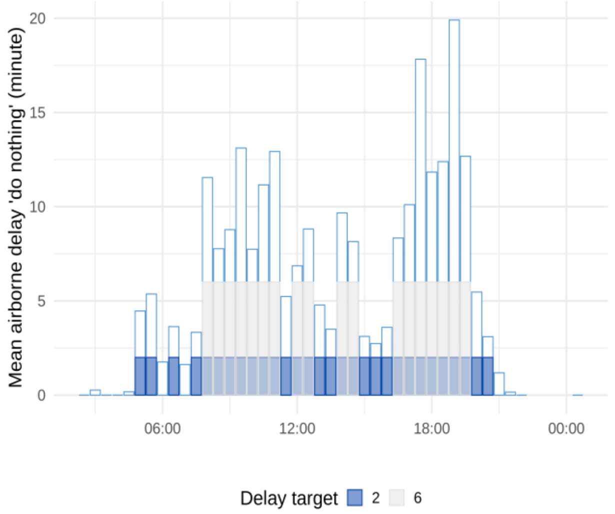

Figure 7: Selected peak periods vs. delay target selected

For each scenario, we get for each flight airborne and ground delays. We derive from these values:

- ○ CO_2 emissions = airborne delay × 25kg/min
- ○ Total delay = airborne delay + ground delay

We detail how the individual metrics are aggregated together per scenario and how we compare scenarios together in the results section.

IV. Results and Discussion

This section is split in two parts: a sensitivity analysis for the control parameters and for the two control options, followed by a trade-off analysis on one control option, varying cost weightings. The scope is on the TOP30.

A. *Senstivity analysis*

The objective here is to assess the effect of the control parameters (III.F) during peak periods. We consider: two control options (mean over 30 minutes and maximum), five airborne delay targets (from 10' to 2') and four ground capping (no, 30, 20, 10 minutes); two baselines ("Today", the current situation reference and "Do nothing", reference without airborne delay control). In the "Today" scenario, ground delays come from observed regulations.

Figure 8 shows the effect on the delays' mean values (y-axis, airborne in blue, ground in orange and total in black). We identify the control option by the line types (dotted for maximum, solid lines for the mean over 30 minutes).

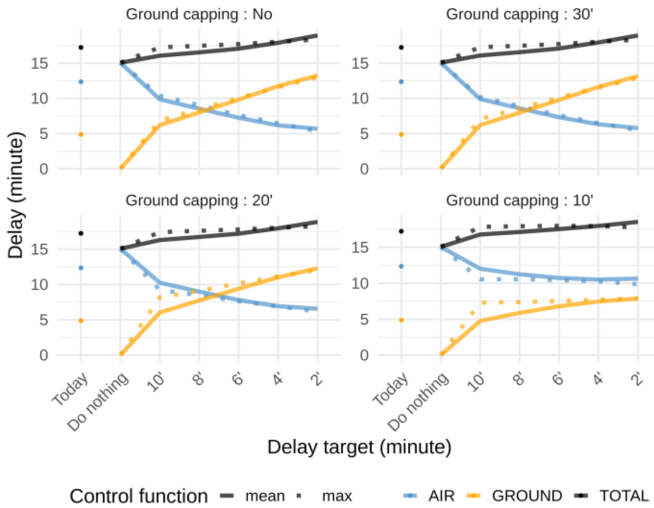

Figure 8: Effect of control parameters on mean delays

As anticipated, when decreasing the target, airborne delay decreases and ground delay increases. The total delay is also increasing, although moderately, highlighting the imperfect delay transfer due to uncertainties. The difference between the total delay value vs. "Do nothing" is denoted "extra delay". We observe little difference between the two control options. The ground delay capping setting has no visible effect until reaching the lower value of 10 minutes. In that case, the decrease of airborne delays stops around the 6 minutes target.

The next two figures report the 95th percentile and maximum values respectively, to show any excessive ground delays that may impact the departure airports. With no ground capping, the 95th percentile of the ground delay is at most 30 minutes for all targets, hence higher than 30 minutes in 5% of the cases.

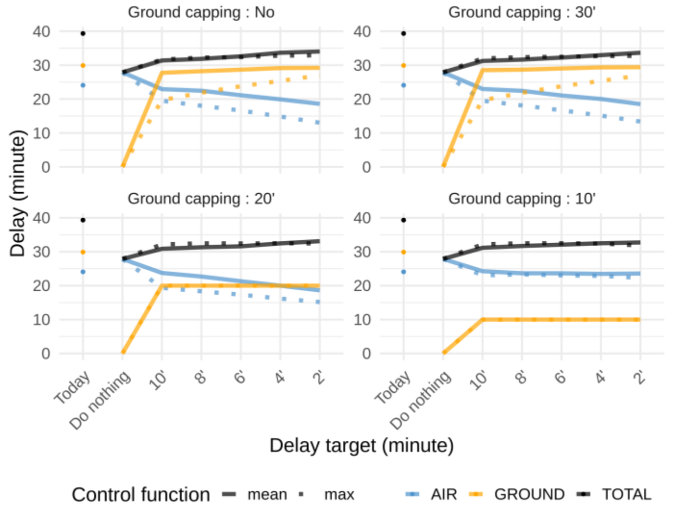

Figure 9: Effect of control parameters on 95th delays

Figure 10 shows that ground delay capping is effective, (maximum ground delay lower than the capping). The maximum ground delay observed without capping is about 50 minutes for all targets (except “Today” scenario, where it gets higher than 100 minutes).

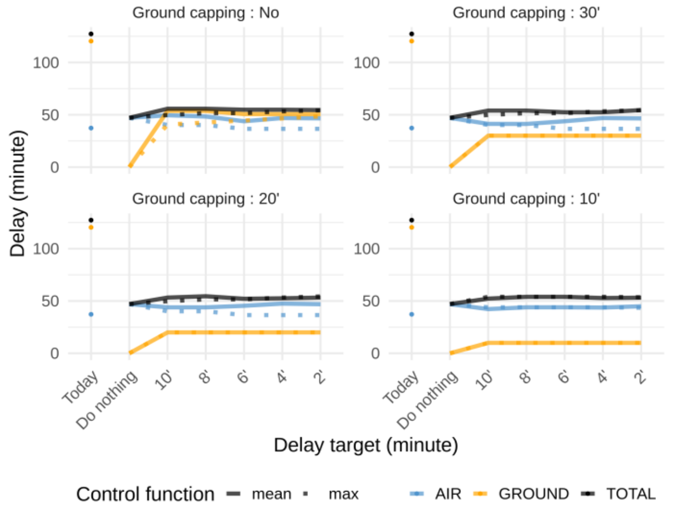

Figure 10: Effect of control parameters on max delays

Overall, the control functions are similar and their selection does not seems to be critical; limiting the ground delay capability down to 30 minutes, or even 20, does not have significant adverse effect on the average delay transfer, while containing occurrences of excessive ground delays.

B. Trade-off analysis

We consider the cost function introduced previously and report the optimum control target, the effect on airborne, ground and extra delays for the concerned flights, the runway utilization and finally the CO_2 reduction compared to “Today”. Given the sensitivity analysis (IV.A), we locked two of the three control parameters: mean control function and 30 minutes ground delay capping. Then, we select an optimum target per destination, per day, for each extra delay unit cost level (1, 3, 6, cf. III.F).

a) Optimum target

Figure 11 shows the average optimum target per destination vs. the extra delay unit cost (dots). For the lower unit cost, the median target is 4 minutes (i.e., targeting an average airborne delay of 4 minutes maximum over 30 minutes periods). We can observe that the median increases with the unit cost, from 4 to around 5.5 minutes.

The optimum target varies with destination (box plots); for example, for the highest extra delay unit cost, EKCH has a 3 minute target while others (e.g., EGKK, LPPT) have a target around 8 minutes. One of the drivers for these differences is the average airborne delay at these destinations: for EKCH, average delays greater than 8 minutes are rare, and controlling for such target will bring no benefit; while for destinations where it is more common, managing these higher delay periods will be more beneficial.

The proportion of the traffic landing during the controlled periods (dot colors) shows a significant variability among destinations from less than 10% up to 50%. This is linked both to the target (higher traffic proportion for lower targets) and the delay patterns (duration of high delays periods). As expected, this proportion reduces with the extra delay cost increase. On average, there is 20% of the traffic landing during controlled periods (low extra delay unit cost), 15% and 13% for the medium and high costs.

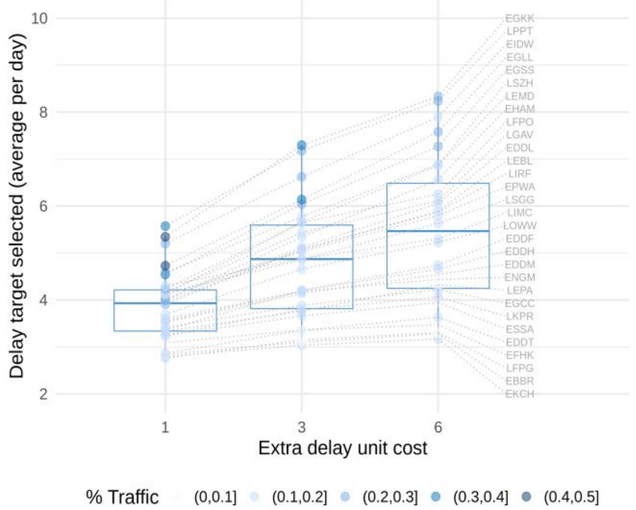

Figure 11: Selected "optimum" target and associated percentage of traffic concerned

b) Statistics per flight during controlled periods

The 30 minutes traffic periods with a predicted average airborne delay greater than the target will be under “control”. Figure 12 shows the average airborne delay and associated CO2 reduction per flight during these periods vs. the extra delay unit cost. The reduction is greater than 2 minutes for airborne delays and from -177kg to -199kt CO2 emissions per flight for all extra delay cost scenarios. Since more flights will be concerned for the lower extra delay unit cost scenarios, higher cumulated airborne delay and CO2 reduction may be anticipated.

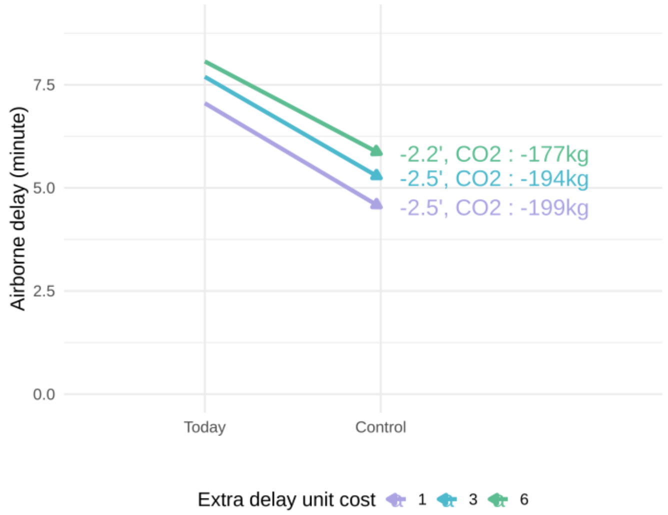

Figure 12: Average airborne delay per flight during controlled periods: today vs. control

Figure 13 shows the average delays per flight and their distribution between ground (orange bar) and airborne delays (blue bar) during controlled periods for the “Do nothing” and selected “Control” scenarios. The red label shows the percentage of extra delay (vs. “Do nothing”). As illustrated in the sensitivity analysis, with more stringent targets (linked to lower extra delay unit cost) there is more extra delay (cf. Figure 8). Indeed, with the lower extra delay unit cost, we observe an extra delay about +14%, compared to 7% for the highest cost scenario.

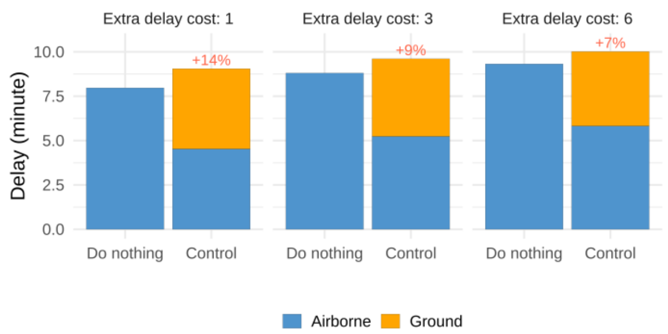

Figure 13: Average ground, airborne and extra delays per flight during controlled periods

c) Runway throughput

When transferring airborne delays toward the ground, we shall ensure there is enough traffic buffering at destination to maintain the runway throughput. Figure 14 shows the ratio of the number of landings in control scenarios vs. “Today”. The extreme values are contained between 99% and 101%, with a median slightly lower than 100% for the 1 unit cost and increasing toward 100% for the 6 unit cost. This suggests that the average targets selected maintain the runway pressure.

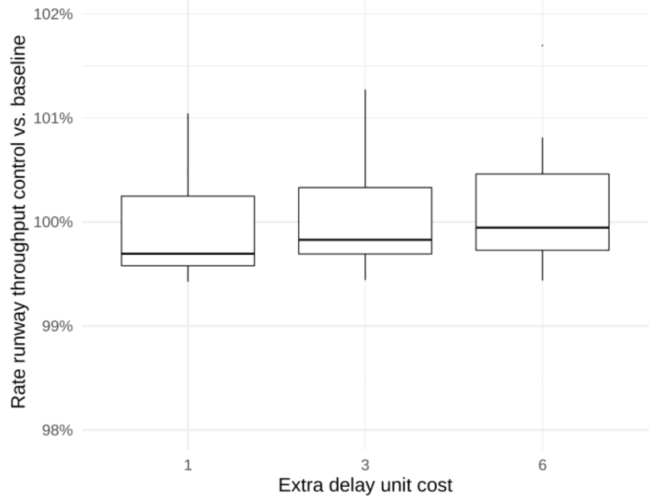

Figure 14: Runway throughput ratio

d) Airborne delay and CO2 reduction

Figure 15 shows the daily average percentage of reduction of airborne delay and CO2 emissions compared to “Today”, per destination. The median reduction goes from 10% (higher unit cost) to 15% (lower unit cost). The reduction interquartile reduces with the extra delay cost from 10% to 25% for the lower cost, down to 7% to 12% for the higher.

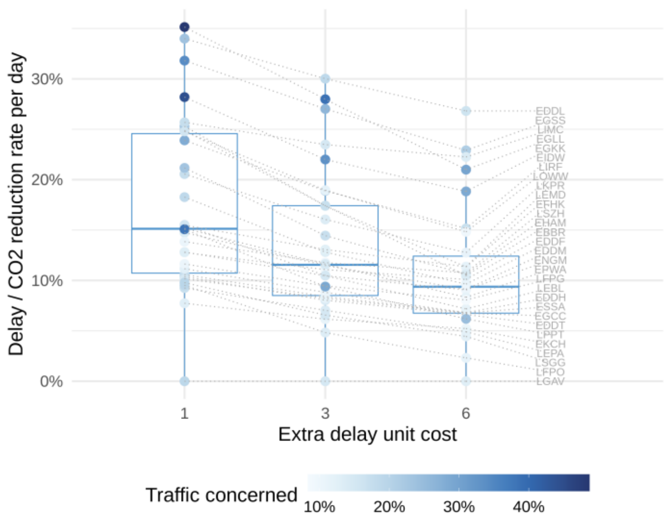

Figure 15: Airborne delay and CO2 reduction percentage per day

Figure 16 complements the previous figure with the absolute values over the day (with a 25kg fuel burn / 75kg CO2 per minute of airborne delay) per destination. The medians range from 2 to 2.5 hours airborne delay reduction per day depending on the extra cost. EGLL is an outlier with an average reduction greater than 15 hours for all cost scenarios (operating close to saturation during the day), but with a higher extra delay duration, especially for the lower cost (about 5 hours).

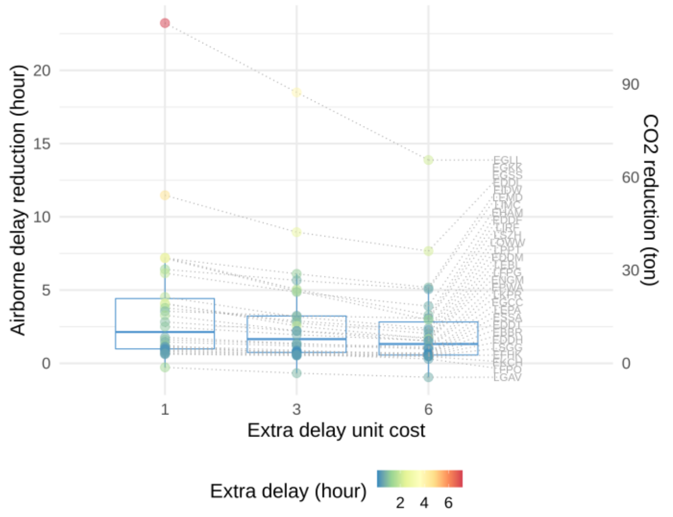

Figure 16 : Average airborne delay and CO2 reduction per day

Figure 17 shows the cumulated reduction of airborne delays and CO2 emissions, over all the selected days (fair weather days), with stacked bars sorted by contribution. The reduction of airborne delays and CO2 emissions ranges from 10k to 15k hours, and from 47k tons and 70k tons with the TOP30 depending on the cost. The relative contribution of each destination varies greatly, with more than 80% of the reduction related to 14 destinations, and 50% to 7 destinations.

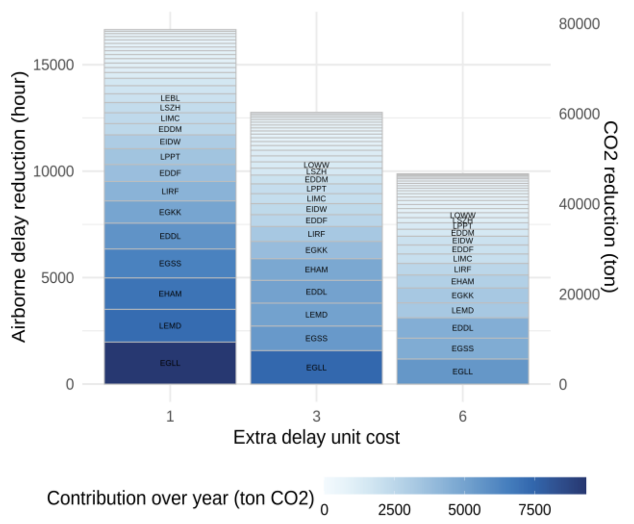

Figure 17: Cumulated reduction of airborne delays / CO2 emissions over all selected days

V. Conclusion and Perspectives

We performed a trade-off analysis of the control of the airborne delays, with the objective to reduce CO2 emissions of arrivals while maintaining the runway pressure and containing the impact on ground and extra delays. This analysis was driven by a cost function integrating airborne, ground and extra delay, with different weightings. We relied on a model of the today arrival flow management process with a simplified mechanism to trigger ground delays and with realistic uncertainties (off-block, take-off, in-flight). We added a control of airborne delays with a ground delay capping of 30 minutes. We considered 30 European airports and selected fair weather days in 2019 for a total of more than 2 million flights. The control parameters were optimized according to a cost function for each airport and per day.

The medium cost scenario leads to an average reduction per flight during peak periods of 2.5 minutes of airborne delays and 194 kg of CO2 emissions, with airborne and ground delays of 5.2 and 4.4 minutes inducing an extra delay of 0.8 minutes. For all the selected days, the cumulated reductions of airborne delays and CO2 emissions reach 13k hours and 61k tons respectively, corresponding to a reduction of 11%, with 15% of traffic concerned. No loss of runway pressure was observed. 50% of the gain may be obtained with 7 airports and 80% with 14 airports.

These trends confirm the interest of developing the idea further. Future work should involve several aspects: in the shorter term, improving the proposed model (cost function, network effects) to better analyze the impact on airlines operations departure airports and on the network; identifying how this fits with other means of airborne delays/CO2 reduction (e.g. tactical use of target-time of arrival, strategic demand/capacity balancing) and then progressing toward operations (e.g.; how to perform the proposed ideas with the current network management toolset, getting more accurate arrival delay estimates).

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