Delay assignment optimization strategies at pre-tactical and tactical levels

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***Abstract*—This paper compares different optimization strategies for the minimization of flight and passenger delays at two levels: pre-tactical, with on-ground delay at origin, and tactical, with airborne delay close to the destination airport. The optimization model is based on the ground holding problem and uses various cost functions. The scenario considered takes place in a busy European airport and includes realistic values of traffic. Uncertainty is introduced in the model for the passenger allocation, minimum time required for turnaround and tactical uncertainty. Performance of the various optimization processes is presented and compared to ratio by schedule results.**

I. INTRODUCTION

Airports are limited in capacity by operational constraints [1]–[3]. In some cases, a significant imbalance might exist between capacity and demand; Air Traffic Flow and Capacity Management (ATFCM) initiatives are then implemented to smooth traffic arrivals, transferring costly airborne delay, carried out with holdings and/or path stretching, to pre-departure on-ground delay [4]. As defined in [5], during the tactical phase of ATFM (the day of operations) on-ground delay at the airport of origin is issued by assigning slots to flights affected by regulations.

Even if there is no particular operational constraint, the tactical capacity of the airport is limited by different factors such as traffic mix, runways in use, local weather or wake separation [1]. This means that, tactically, controllers need to synchronize arriving flows and individual flights to meet the runway system capacity [6].

In this paper, in order to differentiate the process of on-ground delay assignment, carried out hours/minutes before takeoff, from the airborne delay required to manage incoming flights at an airport, the authors refer to *pre-tactical delay* to the former and to *tactical delay* to the latter.

The degree of uncertainty on the actual arrival time decreases as flights approach their destination [7]. Hence, optimization carried out prior departure might suffer from inefficiencies due to this traffic variability and a tactical optimization close to the arrival could be performed. This paper aims to analyze different objectives that can be optimized at these two time frames (on-ground, prior departure, and airborne, close to the destination) and their impact on flight and passenger centric metrics.

Section II presents the background information regarding the management of inbound traffic. In Section III, the formulation of the optimization model and of the different objectives functions considered are presented. Section IV describes the scenario parameters. The main results, and conclusions and further work are detailed in Sections V and VI respectively.

II. BACKGROUND: MANAGEMENT OF INBOUND FLIGHTS

A. Ground delay: pre-tactical optimization

When dealing with a slot assignment problem, a Ratio by Schedule (RBS) prioritization of flights is the current practice [5]. The required delay will be transformed into ground delay carried out prior departure. This RBS policy is considered to be the fairest delay assignment even if economical optimum cannot be guaranteed.

Other approaches rather than RBS, if yet not implemented, could be considered and extensive research has been conducted to assign, the required delay, in a most cost effective manner [2], [8]–[10].

In this paper the model developed in [9] is implemented considering different cost functions, as explained in Section IV. RBS, as being the current practice, will be used as the baseline for this research.

B. Airborne delay: tactical optimization

When the aircraft arrive to the proximity of the airport, sequencing and merging are required to optimize the airport utilization [6], [11], [12]. Europe is in the process of implementing Extended Arrival Management systems (E-AMAN). The objective of such systems is to extend the management of arrivals up to a 500 NM horizon from the airport in order to move part of the sequencing and Terminal Maneuver Area (TMA) delay to the en-route phase. Note that the decision of the horizon extension depends on the context in which E-AMAN is applied. Controlled times of arrivals (CTAs) are issued to flights in order to manage delay, usually with speed adjustments [13]. This strategy leads to reductions on fuel and emissions along with improved en-route capacity. Airports such as Heathrow, Rome or Stockholm are already implementing this technology with an horizon that varies from around 190 NM for Stockholm to 250 NM for Rome and 350 NM for Heathrow and that could be extended up to 550 NM [14].

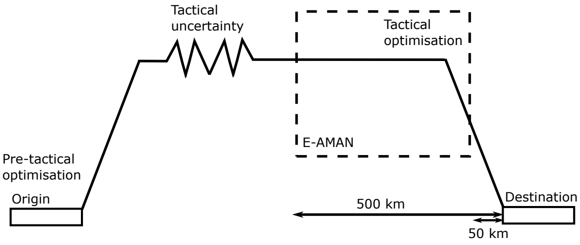


Fig. 1. System overview, optimization phases

At this tactical phase, benefits in terms of fuel, emission and noise can be obtained with procedures such as continuous descent operations (CDA) [15].

III. PROBLEM FORMULATION

As shown in Figure 1, in this paper, the tactical optimization is carried out within the E-AMAN domain. Two radii from the airport of destination are considered: an outer radius indicating the entry of the flight in the E-AMAN domain and an inner radius where the flights are transferred to the final approach controller. The aircraft will be delivered to the final approach controller at a pace that meets the capacity of the runway and the final sequencing will be performed by the final approach controllers. Note that, the objective of this optimization is to analyze if a different strategy rather than RBS could lead to benefits in terms of delay. Other costs, such as fuel consumption and the particularities regarding how the delay is performed, are not considered.

If the capacity at the arrival airport is abnormally reduced, an ATFM regulation is expected to be issued. The optimization will then be realized at a pre-tactical level to assign delay on-ground and deliver the demand at the arrival airport, and hence at the E-AMAN, within the airport capacity limits.

Different capacity slots are considered when optimizing the flows at a pre-tactical and at a tactical level having wider temporal window at a pre-tactical level as higher uncertainty exist. Hence, a smooth traffic at the arrival to the E-AMAN and a throughput that does not exceed the airport capacities at the end of the tactical phase are obtained. The optimization process ensures that the capacity per slot window is not exceeded but the spacing between aircraft within each slot is not ensured.

The maximum delay that can be assigned to a flight is also different at pre-tactical and tactical level: it is possible to hold on-ground flights as long as needed, while once the flights are within the E-AMAN domain they are airborne and, therefore, cannot be hold infinitively.

Besides these differences the pre-tactical and the tactical model follow the same formulation as the same problem is solved: the assignment of flights to slots. Note also that the pre-tactical optimization will be carried out once for all the flights affected by the regulation while the tactical optimization is a dynamic process in the sense that aircraft can be assigned different arrival times each time the optimization is performed; the final arriving time is the last one assigned before the aircraft reaches the inner radius.

A. General ground holding problem formulation

The model considered is the simple deterministic ground holding problem (GHP), where constraints only apply on the destination. This model will be applied to assign delay to aircraft. For a given set of time intervals $(t = 1, 2, \ldots, T)$ corresponding to the actual times of arrival, and a set of aircraft $(f = 1, 2, \ldots, F)$ corresponding to flights that will arrive and then depart from the studied airport, the following inputs are defined: b_t is the constrained airport arrival capacity at time interval t and $STA(f)$ (scheduled time of arrival) is the earliest time interval at which aircraft f is scheduled to arrive at the constrained destination airport. To prevent a flight from getting assigned a slot earlier than the earliest time it could arrive, the time intervals start at $STA(f)$ for each f in the pre-tactical phase and at the earliest possible arrival time at the tactical phase. The decision variables are defined as:

$$x_{ft} = \quad \begin{array}{l} 1 \text{ if aircraft } f \text{ is assigned to arrive at time interval } t \\ 0 \text{ otherwise} \end{array}$$

the deterministic ground holding problem can then be formulated as

$$\min \sum_f \sum_t c_{ft} x_{ft} \tag{1}$$

$$\text{subject to} \qquad \sum_f x_{ft} \leq b_t, \text{ for all } t \tag{2}$$

$$\sum_t x_{ft} = 1, \text{ for all } f \tag{3}$$

where c_{ft} is the cost of assigning aircraft f to arrive at time interval t and will be detailed in the next subsection. Note that Equation (2) corresponds to the capacity constraint applied at each time interval t, whereas Equation (3) imposes the fact that a flight must arrive exactly once. More details on this general GHP model can be found for example in [9].

B. Cost functions

In this research the delay incurred by flights and passengers is analyzed. As it was shown in [16], the delay and cost experience by passengers differs from the one obtained with flight centered metrics. These differences are partially due to passenger missed connections. In this paper, however, individual passenger flows are not modeled and only passengers carried per fight are assumed.

Four cost models c_{ft} are studied and compared in both pre-tactical and tactical phases of the optimization process presented here:

- *GHP Flight*: the delay per flight is minimized, that is
$$c_{ft} = t - STA(f), \tag{4}$$
- *GHP PAX*: the delay per passenger is minimized, that is
$$c_{ft} = PAX_{arr}(f)(t - STA(f)) \tag{5}$$
where $PAX_{arr}(f)$ is the number of arrival passengers assigned to aircraft f, see Section IV-B2 for the details of the assignment of passengers per flight,

- *GHP Reac*: the total delay per flight, including the reactionary delay, is minimized. Reactionary delay is calculated as the difference between the arrival time t and the latest time of arrival (LTA) that would not generate delay in the subsequent departure flight of the same aircraft. LTA is calculated as follows: $LTA(f) = STD(f) - MTT(f)$, where $STD(f)$ is the subsequent scheduled departure time of aircraft f from the airport of study, and $MTT(f)$ is the minimum turnaround time needed for aircraft f, details of how to obtain this data is found in Section IV-B3. Finally this cost function is defined as the sum of the arrival delay plus the reactionary delay multiplied by a factor 1.8, corresponding to the extra delay that reactionary delay generates with respect to arrival delay. As reported by [17], in 2014, the ratio reactionary to primary delay was 0.80, which means that, on average, every minute of primary delay resulted in some additional 0.80 minutes of reactionary delay. In the model:

  $$c_{ft} = (t - STA(f)) + 1.8(t - LTA(f)), \qquad (6)$$

  Note that in this case we are assuming that the delay is propagated due to the late arrival and we are not considering the possibility of the outbound flight being delayed independently on the arrival delay. This 1.8 factor could also be improved by considering operational parameters such as aircraft type or time of the day.
- *GHP Reac PAX*: the reactionary delay per passenger is considered, leading to a total delay per passenger to minimize expressed as follows:

  $$c_{ft} = PAX_{arr}(f)(t - STA(f)) + PAX_{dep}(f)(t - LTA(f)), \qquad (7)$$

  where $PAX_{dep}(f)$ is the number of departure passengers assigned to the aircraft f.

IV. SCENARIO AND STOCHASTIC MODEL

A. System overview

Figure 1 presents the overview of the systems modeled in this paper. The tactical optimization can be carried out with or without a pre-tactical optimization. The pre-tactical phase will be required when the airport capacity is abnormally reduced. In that case controlled time of departures (CTD) will be issued to the flights, which should take off within a 15-minutes window, i.e., between 10 minutes before and 5 minutes around this CTD. As shown in [7], the actual time when the aircraft will arrive at the airport once departed is subject to variability as the flight is affected by factors, such as weather, tactical flow management by air traffic control and direct routes.

Three different flights datasets will be considered, the originally demand, the controlled demand, where on-ground delay has been issued at a pre-tactical phase, and the tactical demand, where flights will be considered when arriving at the domain of the E-AMAN.

1) Pre-tactical phase model: The first phase of the optimization process consists in solving the problem in the pre-tactical phase, in a static process. Slots t are typically considered of 10 to 15 minutes-length. These slots are wide enough as to ensure a smooth traffic at the arrival to the E-AMAN The optimization process is applied considering as input the STA and obtaining a regulated demand.

2) Tactical phase model: Tactical uncertainty is added to the regulated demand in order to obtain the actual arrival demand to the airport, see Section IV-C for more details on this uncertainty addition.

In the tactical phase, the optimization that would be performed by the controllers at the E-AMAN, within the inner and outer radii, is modeled. The airspace considered is located around the airport within two radius, outer and inner. In our case of study, radii of 500 km and 50 km are considered (270 NM to 27 NM), the center of these radii being the arrival airport. In this airspace, traffic will arrive according to the actual demand and a *dynamic* optimization is carried out so that traffic reaches the inner radius within slot windows t of 1 to 3 minutes width, and is thus metered within these slots to the final approach controller.

Every time an aircraft enters this airspace (outer radius), the delay assignment optimization is solved for a distinct problem. The earliest arrival times at the inner radius of all flights within the considered airspace are computed and an optimization is realized. The earliest arrival time is computed assuming that the aircraft could fly a straight trajectory toward the destination airport, which is in line with ATCO practices of giving direct instructions and pilots requesting these trajectories [18]. In some cases, this earliest arrival time may be earlier than the original intended scheduled arrival time, leading to negative tactical delay. This is a dynamic process in the sense that aircraft can be assigned different arrival times each time the optimization is performed; the final arriving time is the last one assigned before the aircraft reaches the inner radius. When a RBS policy is applied, once the aircraft enters the E-AMAN horizon, a slot is given and this assignment is no reviewed.

In this case, the delay will not be performed on-ground but as holding, path stretching and/or speed adjustments within the E-AMAN domain airspace. For this reason a maximum of 35 minutes of delay can be assigned for an individual flight.

B. Scenario

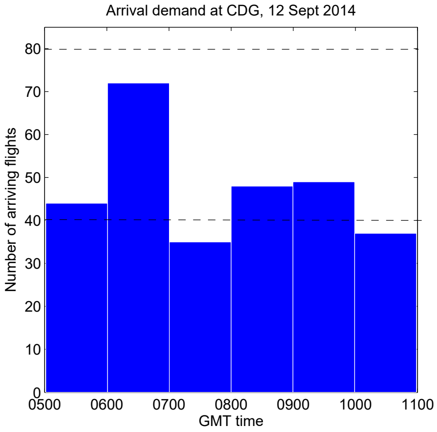
As summarized in Table I, an scenario is formed of a set of parameters defining the:

- traffic demand, scheduled departure, arrival and following departure times;
- scheduled and minimum time required for turnaround;
- passengers demand to individual flights;
- airport capacity;
- tactical inner and outer radii distances; and
- pre-tactical and tactical optimization window width.

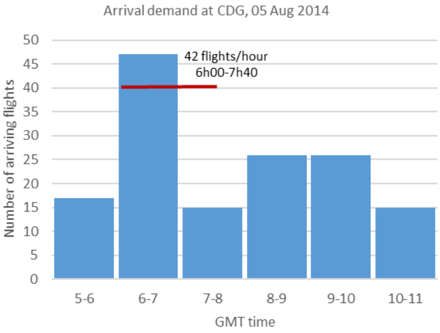
All the previous parameters will be estimated once to generate the scenario to which apply the optimization models. To this scenario, tactical uncertainty will be applied 50 times, in a

TABLE I
SCENARIO AND STOCHASTIC PARAMETERS

Model part	Model sub-part	Description	Times generated
Scenario	Traffic demand	• Based on 12SEP14 CDG arrivals • Between 5:00 and 11:00 GMT • Canceled flights considered pre-tactically but not tactically • Flight within inner radius excluded	Once
	Turnaround	• AC type for turn around • AC types top 10 used • AC category otherwise • Burr and Weibull distribution fitting • $MTT(f) = max(rand(0.1, 0.4), STT(f))$	
	Passenger demand	• Triangular distribution between 60%-95% centered at 85%	
	Capacity	• 80 acc/h nominal • 40 acc/h regulated	
	Radii	• Outer 500 km (270 NM) • Inner 50 km (27 NM)	
	Optimization window	• 15' pre-tactical (20acc/15' nominal, 10acc/15' regulated) • 3' tactical (4acc/3' nominal, 2acc/3' regulated)	
Tactical noise	• Difference between controlled and actual arrival times • Burr distribution		Monte Carlo 50 times



(a) Arrival demand at CDG (12 Sep 2014)



(b) Example of regulation at CDG [19]

Fig. 2. Arrival demand at CDG with capacity

Monte Carlo simulation, generating results that do not depend on a particular tactical uncertainty.

Both in pre-tactical and tactical optimizations, the GHP cost functions presented in Section III-B are compared to a RBS formulation.

1) Traffic demand and capacity: The demand at Paris CDG airport on September 12th, 2014 has been considered for the simulations; it was a busy Friday without any major disruption. The morning traffic, between 5.00 GMT and 11.00 GMT, is analyzed. For the traffic scheduled, data from EUROCONTROL Demand Data Repository 2 (DDR2) [19] has been used. Note that this data is the filled flight plan and might differ from the actual schedules but is the final flight plan and hence the final demand.

During these 6 hours of study the total number of aircraft arriving and departing from CDG is 273. The hypothesis that every arriving aircraft will eventually depart is made. Canceled flights were considered in the demand at the pre-tactical phase, but not in the tactical phase. Also, flights taking off within the inner radius or realizing a circular flight were disregarded.

Considering the demand data and historic regulations at CDG, an ATFM regulation between 6.00 GMT and 8.00 GMT is modeled. A nominal capacity of 80 arrivals per hour is considered when no regulation is applied, ensuring that the pre-tactical optimization does not affect the demand, and the regulated capacity is set to 40. These values have been obtained studying the traffic demand and examples of regulation as seen in Figure 2.

For the optimization, slot windows of 15 minutes are considered in the pre-tactical phase, i.e. 20 (nominal) or 10 (regulated) aircraft every 15 minutes, and of 3 minutes in the tactical one, i.e., 4 or 2 aircraft every 3 minutes.

2) Passenger model: For each flight, the type of aircraft has been considered and the number of passengers in each flight determined as a function of the maximum capacity of the aircraft. A triangular distribution has been used to allocate passengers between 60 and 95% of the maximum occupation, with a peak of the distribution at 85%, which is considered the target value. Air France reported an overall load factor of 84.7% for 2014 [20] and the Association of European Airlines reported an average load factor of 83.6% for September 2014 [21].

This allocation process led to a total of $38,010$ arrival

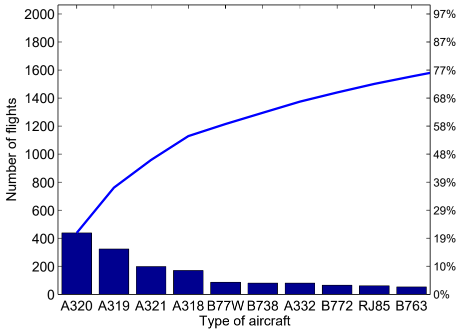


Fig. 3. Classification of flights depending on aircraft type

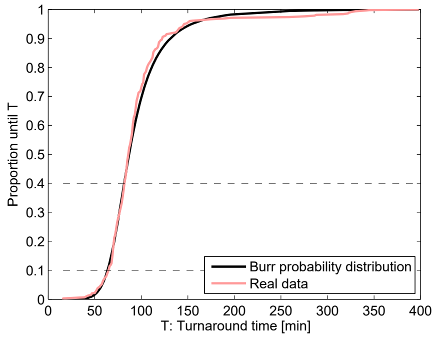


Fig. 4. Probability distribution of A320 turnaround time

passengers and $37,603$ departure passengers during the 6-hour study. There are no itineraries modeled and hence arriving and departing passengers are considered independent.

3) Turnaround model: Some arriving flights delayed at the airport might propagate this delay to their subsequent departure (reactionary delay). To be able to model this propagation effect, the scheduled turnaround times (STT) and the minimum time required to do the turnaround process (MTT) have been computed for each flight.

First, the tail number has been used to model turnaround times at CDG linking arriving and departing aircraft. 24h turnaround has been considered when no subsequent flight has been found on the dataset.

The minimum turnaround time has been estimated based on the aircraft type of the flights. The most common types of aircraft operating at CDG have been identified and a simple statistic study carried out to evaluate the distribution of turnaround times based on aircraft type. Taking into account the 10 most common aircraft types, 75% of all types are covered (see Figure 3).

For each of these 10 types of aircraft, a probability distribution has been calculated for their turnaround time, as shown for example for the A320 in Figure 4. For the remaining 25% of flights with a different aircraft type, a distribution has been used based on their aircraft category: a Burr distribution for medium aircraft and a Weibull one for heavy aircraft.

Based on the distribution times of the turnaround at the airport, the MTT has been computed for each individual flight as a random value between the 10 to 40% interval of the probability distribution for the aircraft type of the flight, see Figure 4. Note that if this MTT is lower than the STT then the MTT has been considered to be the STT.

In future work, a more complete study could be realized to better estimate these minimum turnaround times considering other operational parameters [22].

C. *Tactical uncertainty*

Tactical uncertainty has been modeled in the simulations allowing us to obtain more realistic results, as one could not expect the traffic to arrive synchronized at the arrivals as planned at a pre-tactical phase.

A statistic study has been realized to measure the difference between scheduled times of arrival (once the traffic has been regulated) and the real times of arrivals in several European airports. The traffic used have been obtained from DDR2 dataset [19]. This uncertainty has been found to follow a Burr distribution, and has been computed 50 times for the day studied in order to obtain 50 different simulations depending on this delay.

V. RESULTS

The following metrics have been computed and analyzed per flight and per passenger for each one of the simulations:

- mean arrival delay,
- mean tactical delay, i.e, delay generated at the E-AMAN,
- mean reactionary delay,
- mean total delay (arrival and reactionary)
- number of flights with reactionary delay,
- maximum reactionary delay.

The tactical delay is defined as the actual arrival time obtained in the tactical phase with respect to the scheduled arrival time resulting from the pre-tactical phase, once the tactical uncertainties have been added.

Note that in the following subsections only the metrics presenting the most interesting results have been selected. Results are presented using 95% trust intervals for the 50 simulations, with different tactical uncertainty.

All the different strategies defined in Section III-B will be benchmarked against the reference strategy of serve flights as they are scheduled to arrive (RBS). In the RBS baseline, the assignment of slots is permanent, once the flights are issued a slot there is no further revision of this allocation.

The computation time required for the optimization is small, for the 6 hours under study (285 arrival flights) the pre-tactical optimization takes 1 second and the tactical dynamic optimization, i.e., 273 optimizations, once every time a flight enters in the outer radius 13 seconds (between 0.04 and 0.05 seconds per individual optimization).[1]

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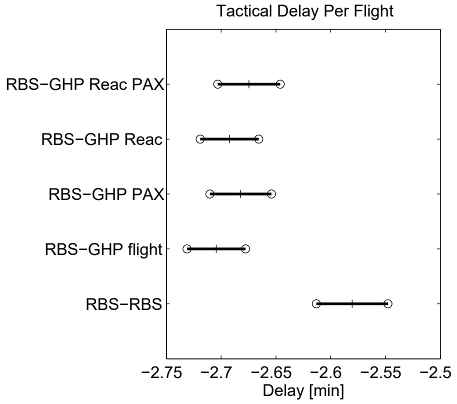
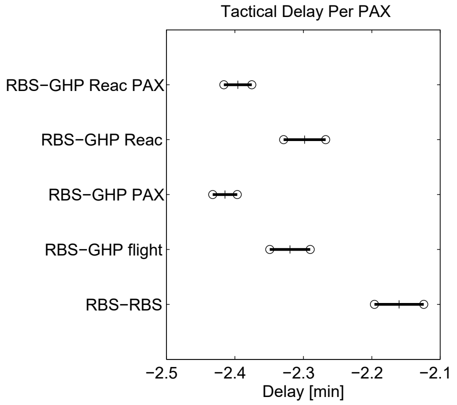
[1] Computer specifications: Dell Intel i7, @1.80GHz 2.40GHz; 64 bits; 8 GB RAM; SSD 256 GB.



(a) Delay per flight



(b) Delay per PAX

Fig. 5. Trust intervals for tactical optimization results

A. *Tactical results*

In order to compare an arrival manager than only focuses on providing a RBS at tactical level with a more sophisticated system that applies the 4 different cost functions described in Section III-B, a RBS strategy is fixed at a pre-tactical level.

Among all the metrics previously listed, there are only two where the trust intervals do not overlap for the different strategies: mean tactical delay per flight and mean tactical delay per passenger. This means that for all the other strategies the results obtained are equivalent and therefore there is no significant difference between using a particular optimization among the others.

Figure 5a shows the results of the mean tactical delay per flight. As the flight can choose a direct trajectory, in some cases, time can be recovered from the original regulated arrival time. For the mean tactical delay per flight, all the optimizations except RBS overlap, meaning that there is not a significant different between the strategies. They all perform better than a simple RBS, though the maximum difference is only of 0.1 minute per flight. Thus, it can be concluded that there is no significant difference with respect to the flight mean tactical delay for the different strategies.

If focus is given to the mean passenger delay (Figure 5b), the different optimization strategies present results that are significantly different. If the optimization focuses on minimizing the delay for flights, the results for the passengers are better than a simple RBS and there is no difference between only optimizing the arrival delays or considering the reactionary effects. As expected, if the optimization considers passengers delay, the best results are obtained. Note how, again, there is no difference between focusing on the arrival delay or considering also the reactionary delay. The reduced effect when focusing on the reactionary delay can be attributed to the fact that the delay that can be managed at the tactical phase is relatively small.

As there is no significant difference between the different optimization strategies when focusing on the flights delay, we could consider that for an E-AMAN that considers optimization of delay, the best strategy would be to focus on the tactical passenger delay as better performances than RBS are obtained for the passengers without having a negative impact for the flight delay. However, the benefits are small in comparison to a simpler RBS, at most 0.25 minute per passenger. Thus, the benefit obtained can be considered marginal against the costs and complexity required to implement such optimization strategies. It has been checked that as traffic arrives to the E-AMAN at the ratio of the capacity of the airport, there is no observable difference in the results if the capacity is assumed to be the nominal one for the whole simulation period.

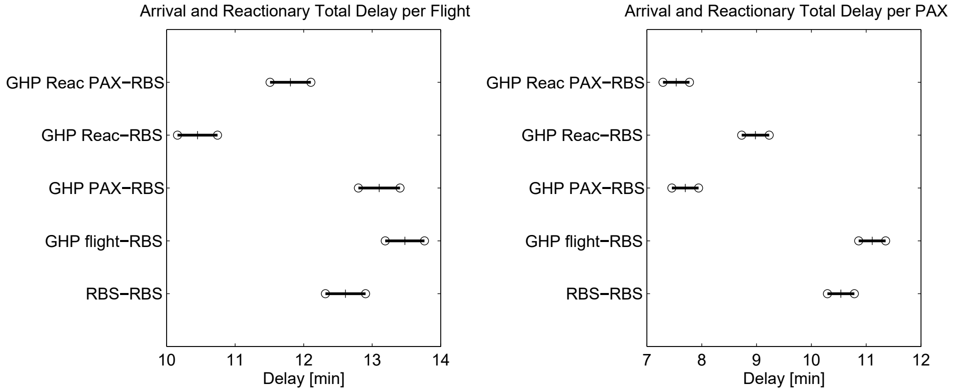
B. *Pre-tactical results*

In this section, and given the results of the previous one, a simple RBS is applied in the tactical phase, while the 4 models of GHP described in Section III-B and RBS are applied and compared at the pre-tactical phase, applying the same 2-hour traffic regulation.

Figure 6a shows that, when looking at the total delay per flight (arrival delay + 1.8 reactionary delay), the optimal result is obtained, as expected, when minimizing this total delay, see Equation (6). This choice of cost function (*GHP Reac*) allows to save around 3 minutes of total delay per flight with respect to minimizing only the arrival delay (*GHP Flight*). Interestingly if the optimization considers only arrival delay (*GHP Flight*), the results are worse than if a simple RBS is applied. This means that reactionary delay is being generated. This could be expected as RBS keeps aircraft as close as possible to their original schedule, while this is not necessarily the case when a minimization of arrival delay is conducted.

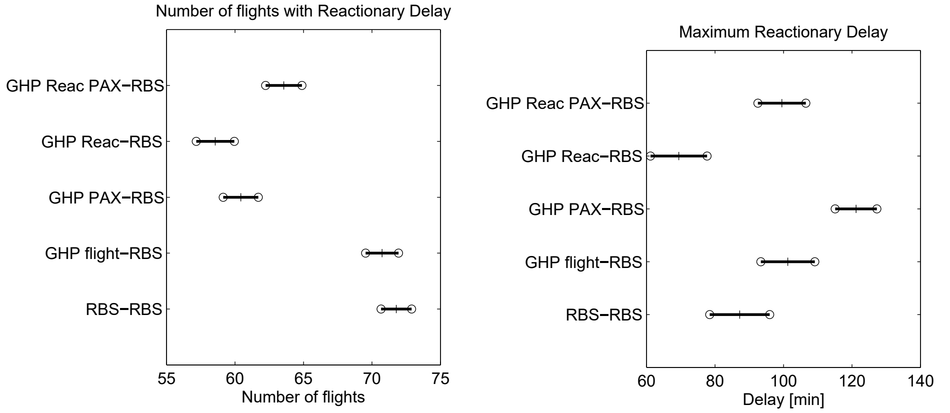
In Figure 6b, the total delay per passenger is presented. In this case, the best results are obtained with the cost functions minimizing either the arrival delay per passenger (*GHP PAX*), see Equation (5), or the total delay per passenger (*GHP Reac PAX*), see Equation (7). Both results are equivalent and represent a saving of around 4 minutes per passenger with respect to minimizing the arrival delay per flight.

Though these parameters have not been included in the cost functions, it is interesting to analyze how many flights are affected by some reactionary delay, and what would be the maximum reactionary delay affecting a flight. Figure 6c shows that minimizing the total delay per flight (*GHP Reac*) reduces



(a) Total delay per flight

(b) Total delay per PAX



(c) Number of flights with reactionary delay

(d) Maximum reactionary delay

Fig. 6. Trust intervals for pre-tactical optimization results

by 15 flights (20%) the maximum number of affected flights, with respect to using RBS or minimizing only the arrival delay per flight. The same tendency is observed in Figure 6d, where the maximum reactionary delay observed at least in one flight is 52 minutes shorter when minimizing the total delay per flight (*GHP Reac*), than when minimizing the arrival delay per passenger (*GHP PAX*). The number of flights affected by reactionary delay are similar in the *GHP Flight* and in the *RBS*; however, *GHP Flight* delivers a worse total delay, hence the optimization of arrivals without considering the propagation of delay leads to higher turnaround delays per affected flight. It could be interesting to include these two parameters, number of flights affected by reactionary delay and maximum reactionary delay, in the cost functions of future studies.

The previous results indicate that two cost functions globally stand out, leading to the best results: minimizing the total delay (arrival plus reactionary) per flight (*GHP Reac*) and per passenger (*GHP Reac PAX*). Figure 7 shows the difference between the delay assigned per flight with these two strategies with respect to RBS. The delay assigned per flight is computed as the average delay assigned to that flight for the 50 simulations. This comparison allows us to analyze the fairness of the optimized solution, as higher variabilities with respect to RBS might lead to higher inequalities. A negative value means that there is less arrival delay with the optimized function than with the RBS. For both GHP cost functions the median is located at 0, meaning that half of the flights do better with RBS and the other half do worse. *GHP Reac PAX* presents a higher variability with respect to the distribution of the differences. This is particularly clear with the maximum values: with *GHP Reac* cost function a flight can benefit up to 32 minutes with

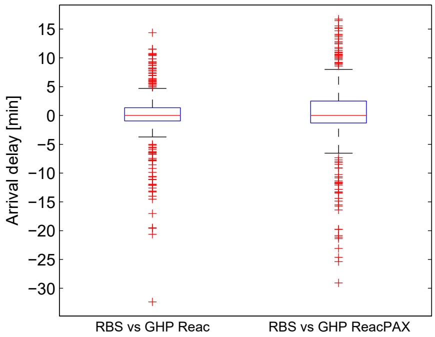


Fig. 7. Box diagram of difference of mean arrival delay: difference between RBS and GHP Reac (left), and between RBS and GHP Reac PAX (right)

respect to RBS, while in the worst case scenario it would have 14 minutes of delay; for *GHP Reac PAX*, the best improvement is 29 minutes and in the worst case 17 minutes are added to the RBS results.

VI. CONCLUSIONS AND FURTHER WORK

In this paper, the performance of an extended arrival manager, with respect to flight and passenger delays, applied in an area comprised between 500 and 50 km around one of the major airports in Europe, has been analyzed.

Different optimization strategies have been considered: flight and passenger centric metrics and focusing on just arrival delay or including reactionary delays. Results show that in the scope of an E-AMAN, the distances and possible delays that can be assigned do not justify the application of a more sophisticated strategy than RBS. Hence, this system should focus on the minimization of the delay at arrival applying a simple RBS rule.

If the scope of optimization is enlarged to include the pre-tactical phase, benefits can be obtained by optimizing the assignment of delay instead of only considering the schedules of the flights. When these optimizations are performed, focusing only on arrival delay without considering the reactionary effects might be counter-productive; variability is added to the flight arrival times, leading to higher reactionary delays. Minimizing the total delay for passengers (including the reactionary delay) is the best strategy from the passengers perspective. However, it leads to higher reactionary delay for flights with respect to a flight centric optimization. If focus is given to flight total delay, the benefit per passenger is reduced in a small portion and the variability with respect to the RBS delay assignment is reduced improving the fairness of the solution.

Results show how different stakeholder interest should be considered since, in some cases, with different optimization strategies, the same performances can be obtained at flight level while improvements can be observed for passenger centric metrics.

The results for passenger delays are preliminary in the sense that passengers have been assigned to flights but passenger connections have not been explicitly modeled. This leads to a prioritization of higher seat aircraft but not to a minimization of total delay and missed connections. If passenger connections are considered, the difference between passenger and flight centric optimizations are expected to increase.

In future work, not only the delay but also the cost of this delay should be modeled. As reported in [23], the cost of delay is not linear with respect to the delay, and hence higher delays produce significantly higher costs. Individual passenger itineraries should also be modeled to explicitly consider passengers connections and the propagation of delay at passenger level, as in this paper, only aircraft propagation of delay is considered. Moreover, this flight reactionary delay should consider the variabilities on this propagation linked to operational parameters such as the aircraft type or the time of the day.

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