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Considering TMA holding uncertainty into in-flight trajectory optimisation

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Aircraft crew are aware of the delay they have experienced at departure. However, uncertainties ahead, and in particular holdings at arrival, can have an impact on the final performance of their operations. When optimising a trajectory the expected cost at the arrival gate should be considered. Consequently, taking into account potential congestion and extra delay at the arrival airspace is paramount to avoid taking sub-optimal decisions at the early stages of the flight. This paper presents a framework to optimise trajectories in the execution phase of the flight considering expected delays at arrival. A flight from Athens (LGAV) to London Heathrow (EGLL) is used as illustrative example, systematically exploring a range of departure delays and expected holdings at arrival.

Key Words : Trajectory Optimization, Flight execution phase, Uncertainty, Airline Costs

1. Introduction

A continuous growth of traffic demand leads to the situation in which terminal maneuvering areas (TMA) could become the bottleneck of the entire air transportation system. In some concepts of operations, aircraft arriving at a busy TMAs, might be required to hold until sequenced to the approach – an event that will increase its flying time, fuel usage and will impact in arrival punctuality. Other TMAs try to avoid holding patterns, but at the expense of more intensive (and unpredictable for the aircraft crew) radar vectoring; by implementing sequencing and merging concepts such as tromboning or point merge;[1, 2)] and/or by tactically limiting the speeds of the aircraft upon their entrance into the TMA (*i.e.*, linear holding) as performed with an Extended Arrival Manager (E-AMAN).[3)]

The actual holding time at the TMA could substantially vary from the expected (average) value due to uncertainties inherited in this process. For instance, an aircraft flying under good weather conditions and average traffic in the TMA will most likely have an average holding time. On the other hand, a flight approaching an airport with reduced capacity, *e.g.* due to bad weather, is more likely to present higher uncertainty.

Cutting-edge pilot decision support tools, such as Pacelab Flight Profile Optimiser (FPO) developed by PACE[4)] or ClearPath developed by AVTECH,[5)] are gradually being deployed in commercial aviation. These tools aim at computing tactical trajectory updates in order to improve the execution of the flight when uncertainty has already been materialised, *e.g.* a new weather forecast has been up-linked, a significant route shortcut has been granted by the air traffic control, an en-route flight level is available. Yet, these tools mainly optimise for direct operating costs (*i.e.*, trip fuel and trip time) and do not consider downstream uncertainty. Crew can usually introduce an estimation on expected delay at arrival, but this bases the optimisation on crew experience on a given route and focuses on delay rather than expected cost, which will materialise as a function of the arrival time at the gate. This might lead to sub-optimal decisions such as to recover some delay, at a high fuel expense, with no significant benefit; or conversely, passenger missed connections which could have been averted by speeding up trading some fuel due to high delay is expected at the destination TMA even if the initial departing delay is low.

Note that if an E-AMAN system is in place, the delay required per flight will be coordinated by this centralised system. However, flights will not have an arrival slot (and delay) assigned to them until they are closer to the airport. Therefore, airlines still have the possibility to try to recover delay if congestion is expected prior having an arrival slot assigned. The prototype presented in this paper could also be used to assess the trade-off between delay and costs in a future concept of operations when arrival slots can be *negotiated*, as envisioned in SESAR for instance.

Pilot3, an Innovative Action funded under the Clean

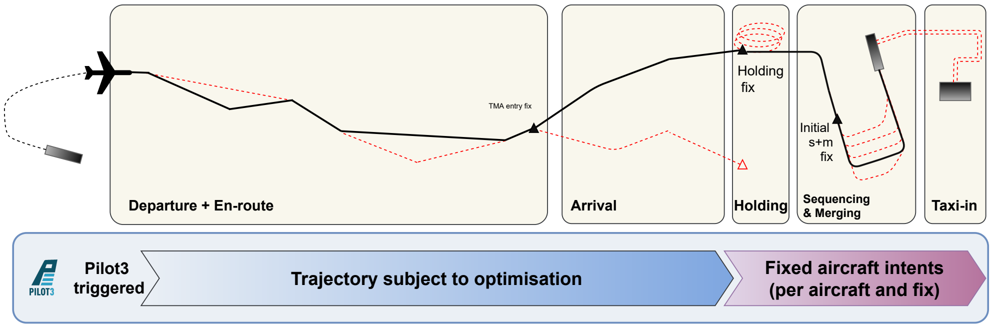


Fig. 1 Trajectory optimisation concept for Pilot3

Sky 2 programme, aims at developing a software prototype for supporting crew decisions for civil aircraft in the execution phase of flight. By triggering the tool, the software provides at least two trajectory options, along with information on different indicators to aid the crew to select the most suitable one. This selection considers the multi-criteria business objectives of the airline, including the impact those decisions have on the airline's network. In particular Pilot3 provides an optimisation framework for trajectories considering the expected total cost and operational uncertainties.

In this paper, delays in the TMA (holdings in particular) are integrated in the cost function to optimise the trajectory. Our objective is to analyse how these holdings can affect the optimal trajectory and hence, the decision performed by the crew. It is out of the scope of this paper to explain how this holding is estimated.

A systematic range of departure delays and holding times are analysed for a flight with destination to London Heathrow (EGLL), one of the most congested airports in Europe and one of the most challenging TMAs, since it serves several airports in the London area. London TMA typically operates with four holding stacks, entailing that aircraft are progressively being taken out of the bottom of the stack and vectored to the final approach, allowing aircraft holding at higher levels to descend to lower ones.[6] An analysis of traffic data from Sep. 2018 shows that around half of flights arriving to EGLL have some holding, which in extreme cases can reach up to 35 minutes.[7] The average holding times, however, are much shorter: about 8.5 minutes at the beginning of 2014, falling to 7.5 minutes in 2016.[8]

2. Methodology

In the general case, Pilot3 could be triggered at any point of the flight (from the departure procedure to the initial descent). Pilot3 optimises the aircraft trajectory from the current aircraft state (*i.e.*, the moment Pilot3 is triggered) down to FL100 at the proximity of the destination airport (see Figure 1). Below this altitude, the actions of the aircraft are significantly limited and highly standardised; and moreover, the aircraft trajectory is likely to be modified several times by tactical ATC intervention, thus forcing the pilot to no longer follow an optimised trajectory plan. In this regard, Pilot3 will compute the remaining trajectory plan assuming standard operations (*i.e.*, a fixed sequence of aircraft intents) in a similar way it is currently done by on-board flight management systems.[9]

Operational uncertainties considered in the optimisation framework include: holding time; distance to be flown during the final approach, sequencing and merging phase (understood as the distance from FL100 to the runway); and taxi-in time. It is assumed that all these uncertainties are experienced after FL100 (even if the holding could be before, it is just a temporal displacement). Pilot3 will consider, not only the average expected value of these sources of uncertainty, but their distribution when computing the expected cost of delay, as presented in section 2.1..

As all uncertainties are limited to the FL100 to gate phase, and the optimisation of the trajectory finishes when reaching FL100 in the descent, the optimiser developed can be considered deterministic. This optimiser will minimise the expected total cost computed as expected cost of fuel and expected cost of delay as a function of arrival time at FL100 as presented below.

2.1. Cost function modelling

The total cost that a flight will experience is composed of two components: cost of fuel and cost of delay.

Cost of fuel considers the amount of fuel used by the optimised trajectory from triggering point to FL100, and the expected fuel used for the processes from FL100 to gate: holding, sequencing and merging and taxi-in.

The cost of delay depends on the arrival time at the gate, as this will be translated into reactionary delay, passenger satisfaction, compensations and missed con-

Table 1 Main characteristics to compute the operational flight plan (OFP).

Flight schedule	Flight dispatch	Other operational information
Airline: British Airways	Cost Index: 10 kg/min	Estimated taxi-out: 10'
Aircraft type: A320-231	Cost of fuel: 0.5 Eur/kg	OFP trip time: 216'
Stage: LGAV - EGLL	Payload: 144 passengers† + 1,000 kg Cargo	Buffer at arrival (taxi-in and padding): 9'
SOBT: 05h15 UTC	LOGAN 2H arrival + ILS approach to runway 09R	Planned holding point: LAM
SIBT: 09h10 UTC	Weather forecast issue/applicability: 2016-07-28 5h UTC	124 connecting passengers

†According to the EU-OPS 1.620[10] flights "within the European area" shall account per adult passenger 97kg (luggage included).
SOBT/SIBT: Scheduled off/in-block time – UTC: Coordinated universal time – ILS: instrumental landing system

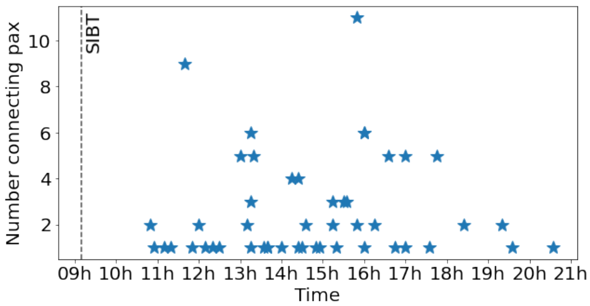


Fig. 2. Passenger groups connecting at EGLL into follow up flights on the LGAV — EGLL flight

nections, crew and maintenance costs, etc. This cost function is highly non-linear and discontinuous. It can be seen as a step-wise function, as increments are produced linked to events, *e.g.* reaching the threshold for having to compensate passengers due to Regulation 261[11], if they are entitled, or breaching a curfew at the end of the day due to reactionary delay.[12]

Most of the events which generate the cost of delay have some degree of uncertainty associated: the uncertainty of when the cost will actually materialise (*e.g.* how many passengers will actually miss their connection for a given arrival time at the gate); and the uncertainty of the cost value itself (*e.g.* how many passengers will claim compensation even if entitled). With these considerations, the optimisation framework estimates the expected cost of delay as a function of arrival time at the gate.

Then, given an arrival time at FL100, the actual time of arrival at the gate, and hence the associated cost of delay, is determined by the convolution of the stochastic processes of potential holding, final approach/sequencing and merging from FL100 to runway and tax-in times.[13] The distribution of times for these processes are considered instead of just their average time. This is required to computed the expected cost of delay function as the estimated cost of delay at the gate is non-linear as previously indicated. As shown in section 4., the consideration of this uncertainty will have a significant impact on the shape of the expected cost function and hence on the outcome of the optimisation and the crew and flight behaviour.

By combining the expected cost of fuel and delay, Pilot3 computes the expected total costs (**ETC**) function which will be used for the optimisation. This approach substantially differs from the most widely used in flight planning, in which the direct operating costs (DOC) are computed as a weighted sum of cost of fuel, (nominal) cost of trip time and route charges (*i.e.*, air navigation fees). The so called Cost Index (**CI**) is the weighting parameter that relates the cost of time versus the cost of fuel in this kind of approach.[14]

2.2. Trajectory optimisation: CI as a proxy

The trajectory optimiser software Dynamo,[15] which uses a point-mass representation of the aircraft and high-fidelity aircraft performance and meteorological data, is able to optimise the vertical profile of a flight for a given CI. This is done by selecting the set of flight altitudes (via grid search) and speeds (via pre-optimised tables as function of CI) that minimise a DOC-type cost function.

Therefore, for a given CI a trajectory can be generated with Dynamo. The expected cost of delay function when reaching FL100 (as explained in section 2.1.) is then used to compute the expected total cost of this trajectory: cost of fuel obtained by Dynamo from triggering point to FL100, average cost of fuel for final phases of the flight (holding, sequencing and merging and taxi-in), and expected cost of delay.[9]

With this framework, the optimisation performed consists on obtaining the best CI such that the ETC is minimised. This is done by the use of a binary-search algorithm.[16] Note that even if CI is used to generate the trajectories, the final optimisation minimises the total cost function (*i.e.*, the ETC) and not DOC.

3. Scenario and case studies

This section specifies the flight and case studies used to illustrate the methodology proposed in this paper and to show the impact of having estimations of hold-

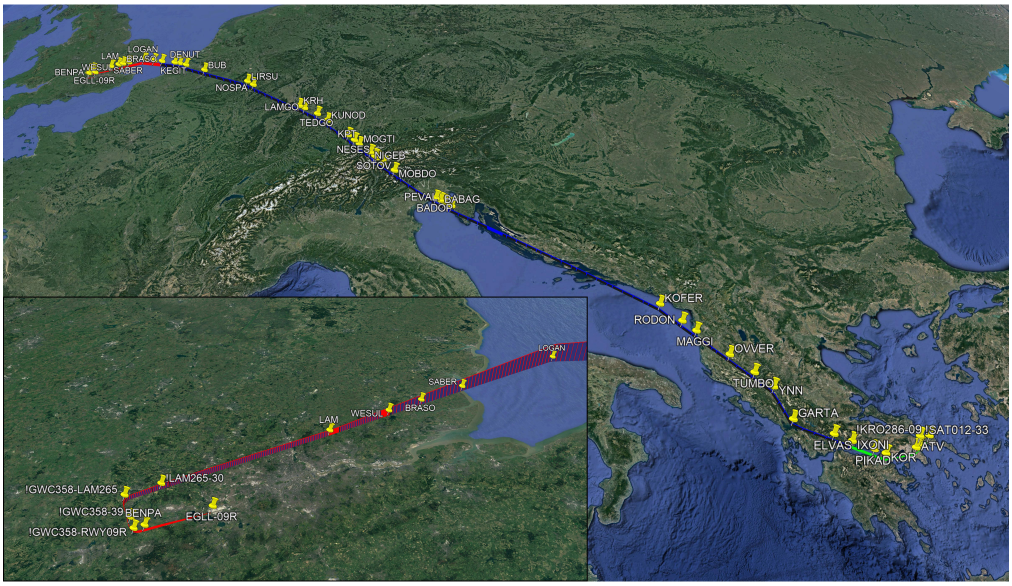


Fig. 3 OFP route: Horizontal trajectory profile. Detail of the descent trajectory in the lower-left side.

ings at arrival with different degree of certainty. For this purpose, a flight from Athens (LGAV) to London Heathrow (EGLL) has been selected taking into account the flight schedule, dispatch and operational considerations summarised in Table 1.

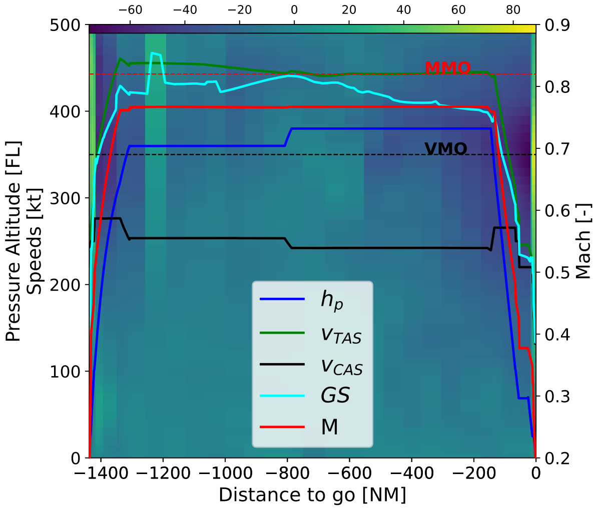
Individual passenger itineraries (with their connections) are modelled based on historical data from IATA's PaxIS and Global distribution Systems datasets, as in previous research projects.[17] Figure 2 shows the different passenger groups with connections at EGLL for the flight under study. The number of passengers of each group is indicated along the time where their connecting flight is scheduled to depart. Note how some passengers have a large waiting time at EGLL before their subsequent flight, *i.e.*, their connection will not be missed even if some arrival delay is experienced. However, the first passenger group with a connection is for a flight scheduled at 10h50 (recall that the SIBT of the LGAV-EGLL flight is 9h10). Considering a standard minimum connecting time of 84 minutes at EGLL,[17] some passenger groups will start missing connections with an arrival delay greater than just 16 minutes. As it will be presented in section 4., the fact that passenger miss connections do not necessarily increase significantly the expected cost of delay if, for example, they can be re-accommodated and arrive to their final destination before being entitled to compensation due to Regulation 261, if entitled to this.

3.1. Operational flight plan (OFP)

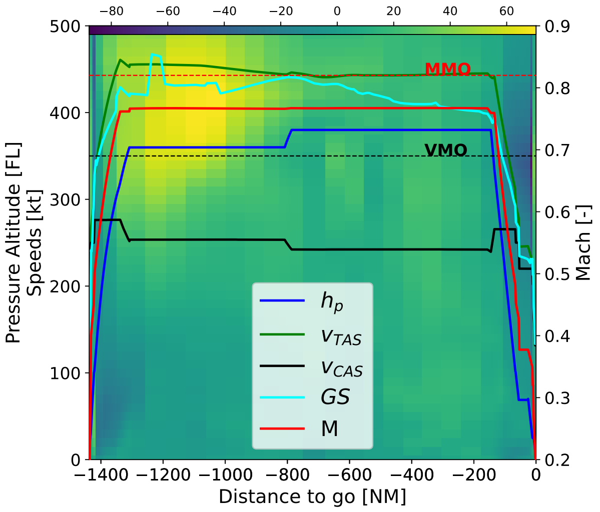
Considering the scenario depicted in Table 1, the OFP has been generated as follows: The route (*i.e.*, sequence of waypoints) is obtained from EUROCONTROL's Demand Data Repository 2 (DDR2);[18] then the vertical (and speed) trajectory profile is optimised with Dynamo,[15] using aircraft performance data from EUROCONTROL's BADA v4.2[19] and weather forecast from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 *. The optimisation criterion for this optimisation is the standard DOC function, assuming that the cruise Mach is kept constant for a given cruise flight level.

Figure 3 presents the OFP trajectory with the climb, cruise and descent phases represented, respectively, by green, blue and red segments. Figure 4 shows the resulting vertical and speed profiles of the OFP trajectory with the along-track and cross-wind components at different altitudes (coloured backgrounds). In these plots, pressure altitude (hp) for the whole trajectory is depicted together with Mach number (M), calibrated airspeed (CAS), true airspeed (TAS) and ground speed (GS). It is worth mentioning that the (apparently) sudden changes in ground speed of these figures (such as observed at around 1300 NM from the destination airport) are due to track changes in the lateral route, which change the relative wind direction along and cross-track and therefore the resulting ground speed. These plots also depict the maximum operational speeds for that aircraft type: MMO (maximum Mach in operation) and VMO (maximum CAS in operation). Is it worth noting that pressure and temperature data given in the ERA5 weather forecast are

*https://www.ecmwf.int/



(a) Background colour: along-track wind.



(b) Background colour: cross-track wind.

Fig. 4 OFP vertical and speed trajectory profiles.

also considered in the optimisation process. The impact of temperature, for instance on the optimisation is analysed in more detail in another publication.[16]

As shown in Figure 4, the OFP for this scenario consists on an initial cruise at FL360 followed by a step-climb to FL380 at around 850 NM from the destination airport. The optimal cruise speed resulting for this OFP is M0.77. The first half of the cruise is mainly affected by a relative strong crosswind component (around 60 kt), while a relative mild headwind and crosswind components dominate the remaining cruise.

Arrival procedures at EGLL are obtained from the UK AIP,[20] AIRAC 2111 (issued on Nov 4th 2021). The arrival procedure LOGAN 2H, which ends at Lambourne fix (LAM) is used. This is the fix where the holding pattern is located. For flight and fuel planning purposes (*i.e.*, to compute the OFP), the approach to runway 09R is chosen, since it is the longest possible.

3.2. Definition of case studies

This paper explores systematically different departure delays and expected holdings at the London TMA. All case studies consider that Pilot3 is triggered when reaching the top of climb (TOC). At that moment, it is assumed that the aircraft crew evaluates the status of the flight with respect to time adherence.

A flight might depart late for a combination of factors: leaving the gate with a deviation with respect to the schedule, a taxi-out time different than planned, route shortcuts (or path stretching) in the departure phase, etc. These factors eventually materialise into deviations of the time of arrival at the TOC, if compared with the OFP. In order to cover a range of operational departures, delays from -10 to 180 minutes at the TOC, at 5 minutes intervals are simulated.

Regarding holding at arrival, we explore a range between 0 to 25 minutes of holding, at 5 minutes intervals, being these common holding times at EGLL. This delay might not be known by the crew (as it will be experienced at arrival) and we will analyse the impact of considering it by the system, *e.g.* with the use of an estimator able to predict them.

For all case studies it is considered that all passengers are entitled to Regulation 261 compensation if delay thresholds at their final destination are met.[11] Note that passengers are only entitled to this compensation if the airline is deemed responsible for their delay.

4. Results

This section presents the results for the scenario and case studies presented in previous section.

The optimisation performed by Pilot3 is compared in terms of expected total cost (EUR), fuel (kg) and time deviation (min) with respect to the default alternative of maintaining the operational flight plan (OFP).

4.1. Cost function

Figure 5 shows the breakdown for the expected cost of delay as a function of the arrival time at the gate (in blue). As observed, the cost of delay consists of different components involving IROPs costs (*e.g.* passenger compensation costs, assuming that passengers are entitled to compensation due to Regulation 261 if delay thresholds are passed) and other costs (*i.e.*, reactionary delay, crew, and maintenance related costs).

As observed in the Figure, costs are dominated by other costs, with reactionary costs (propagated in subsequent rotations) as the main driver. For this flight,

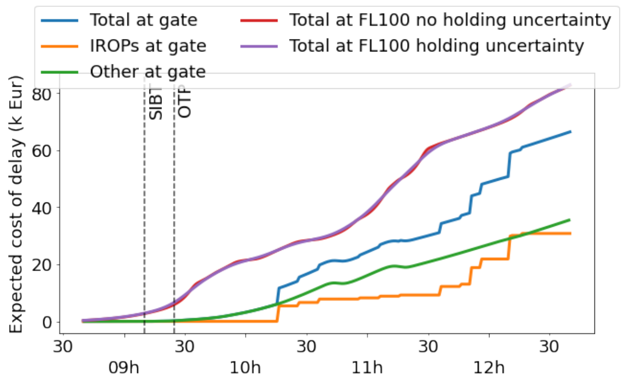


Fig. 5. Expected total cost of delay (and components) as a function of arrival time (at gate and at FL100).

the time allowed for rotations is relatively tight: the aircraft has 40 minutes for the rotation at EGLL before departing to LIRF. Therefore, if the arrival to EGLL is delayed, the probability of delay being propagated to LIRF (and to subsequent flights) is high.

Recall from section 3. that this flight has a relative tight buffer at arrival with only 9 minutes for taxi-in and padding (*i.e.*, the difference between the estimated landing time and the SIBT) and that some passenger groups will start missing connections with an arrival delay greater than just 16 minutes. However, as observed in the cost function (Figure 5), cost associated to these missed connections will not have a significant impact until around 1 hour of delay when, as shown in Figure 2 a group with 9 passengers will miss their connection. This is due to the fact that in some cases, if passengers can be reaccomodated into subsequent flights arriving to their destination before Regulation 261 threshold the cost for the airline for these missed connections can be rather low even if delay can be attributed to the airline. However, once compensations, and duty of care, *e.g.* waiting until next day for a flight, are due, cost increase in sharp steps.

Finally, and as explained in section 2.1., considering the arrival processes with their uncertainties (*i.e.*, holding, sequencing and merging and taxi-in), the expected cost of delay can be expressed as a function of the arrival time at FL100. These arrival processes will be translated into a shift of the cost function to be used by Pilot3 optimiser. This shift will be the addition of the expected times of these arrival processes. For the particular example of Figure 5 46.3 minutes are obtained, resulting from holding (20 minutes), sequencing and merging (17.7 minutes) and taxi-in (8.6 minutes).

In Figure 5 two cost as a function of arrival time at FL100 are presented, both consider an expected holding of 20 minutes, but in one case no uncertainty is considered (in red) while in the other a normal distribution with a sigma of 6 minutes is used (in purple). Note how uncertainty *smooths* the expected cost function. Yet, the two cost curves overlap as, in this example, the expected time of the holding does not change. For the results presented in the next section no holding uncertainty will be considered.

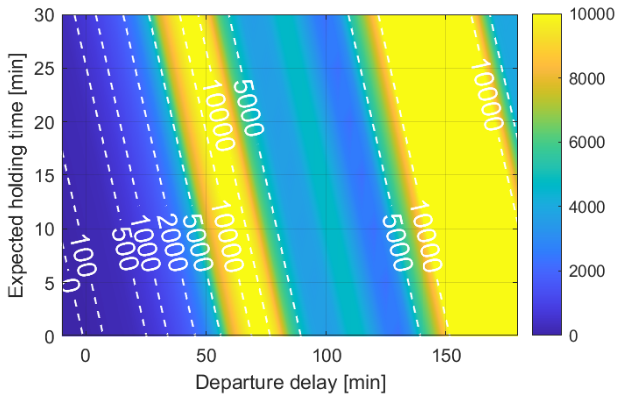
4.2. Analysis of Pilot3 optimised trajectories

Figure 6 presents the results of the optimisation of Pilot3 for the range of departing delays and holding times explained in section 3.2.. Three different results are shown: expected costs savings of the optimised trajectory with respect to maintaining the OFP (Figure 6(a)); expected delay to be recovered by the optimised trajectory (Figure 6(b)); and finally, the variation on fuel consumption (Figure 6(c)).

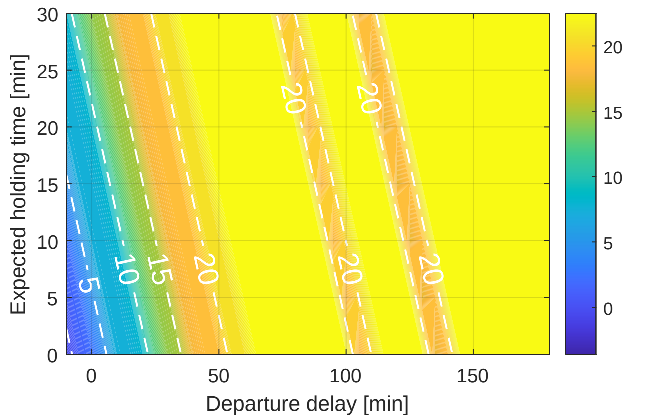
The first aspect to notice is that in both trajectories under comparison (optimised and OFP), the arrival processes are modelled in the same manner. This means that the fuel (and time) required to reach the gate from FL100 will be the same on both cases, as both will model the same holding, final arrival and taxi-in processes.

As we are assuming that the estimation of the holding time is deterministic, and this is translated into a shift of the cost function to be used by the optimiser as previously shown, the result obtained in the optimisation depends just on the total delay expected (departure plus holding), and not on how this delay is shared among them. This can be observed in Figure 6. Nevertheless, the division between both sources of delay are kept independent in the Figure as this facilitates a more operational analysis. For example, if departing on time, crew would usually not consider to recover any delay. Yet, if the expected holding delay is 15 minutes a recovery of around 5 minutes will represent savings close to 100 EUR. In current operations, crew will rely on their expertise on previous operations to decide if delay should be recovered without having a clear view on the impact of theses decisions on the expected costs for the airline.

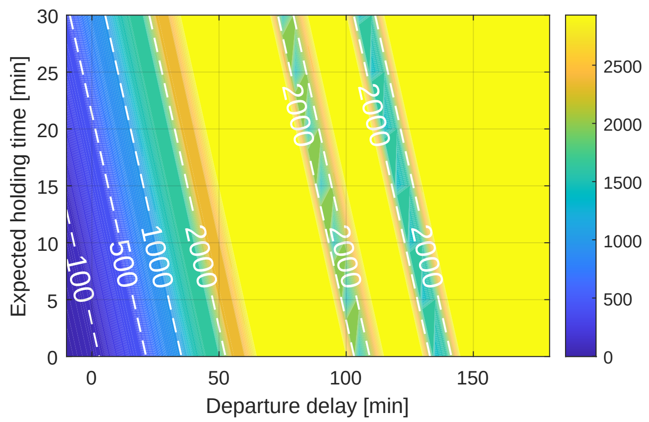
Figure 6(b) shows how there is a maximum amount of delay that can be recovered for this flight (22.5 minutes). As expected as the departure delay (and expected holding) increases the amount of delay to be recovered also increases. It is worth noticing, however, how contrary to simple rules of thumb there are regions where recovering less than the maximum possible delay is more suitable even at high initial delays, *e.g.* if the



(a) Expected costs savings (Eur)



(b) Delay recovered (min)



(c) Extra fuel usage (kg)

Fig. 6. Results of Pilot3 optimisation for the different departure delays and expected holding times

expected arrival delay (departure delay and holding) is 105 minutes the delay recovered by the optimised trajectory is 17.8 minutes instead of the maximum of 22.5 minutes. In a similar manner, the savings obtained do not evolve in a monotonous way as a function of the total expected delay. As expected from the cost function (recall Figure 5), the cost of delay is non-linear

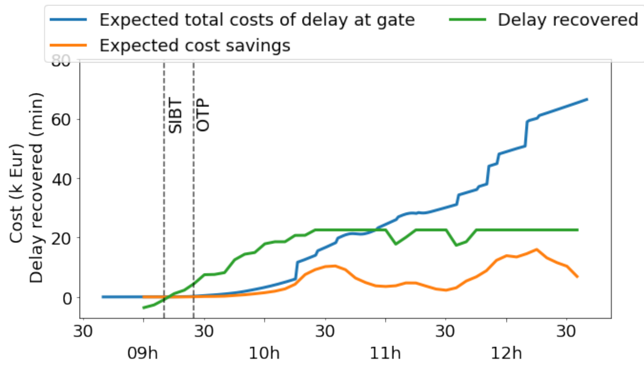


Fig. 7. Expected total cost of delay as a function of the arrival time at the gate if keep flying the OFP. For each of these arrival times the delay recovered and expected cost savings of the Plot3 solution is also given.

and presents regions where higher benefits by recovering delay can be achieved than others. If the event which triggers a given cost is non-recoverable, *e.g.* even with the maximum possible recovery passengers will miss their connection, it might be worth it to recover less delay and save fuel.

To simplify the analysis of the impact of the cost function on the behaviour of the optimiser, Figure 7 presents the cost function at the gate as a function of the expected arrival time at the gate by keep flying the OFP (*i.e.*, when actions to recover departure delay or expected arrival holdings are not taken). For each of these arrival times, the delay recovered and expected cost savings of the Plot3 solution is also given (*i.e.*, comparing with the trajectory resulting of keep flying the OFP).

First, it is worth noticing how if the expected arrival time at the destination gate is before the SIBT, Pilot3 will generate a trajectory that slows down the flight with respect to the OFP, as the extra delay generated will be compensated with fuel savings. Then, as the expected arrival time increases the delay recovered tends to increase, but as previously mentioned, this is not monotonically increasing (recall from previous discussion that recovering the maximum amount of delay is not always the optimal decision). Finally, note how the cost savings are closely related to locations in the cost function when sharp increments are observed, *i.e.*, linked with passengers missed connections.

5. Conclusions

Operations in the terminal maneuvering area (TMA) may induce a negative effect on the performance of a flight, by mainly extending the total flight duration and increasing its fuel consumption. Even if a flight has departed on time (or even earlier than expected), the uncertainties ahead might require some apparently counter intuitive reactions, such as speeding up the flight. The departing delay is known by the crew but considering uncertainties ahead (and holding in particular) is critical to avoid sub-optimal decisions. This paper has introduced the holding uncertainty in TMA in the optimisation process of aircraft trajectories in the execution phase of the flight.

As presented, if holdings could be estimated with a high accuracy, considering them is equivalent as assuming a later departure. However, the consideration of the expected cost of delay produces results which are more complex than rules of thumb. The amount of delay to be recovered not only depends on the departure delay but on the expected holding and on the characteristics of the cost of delay for each particular flight. Adding uncertainties on the predictions modifies the shape of the cost function used by the optimiser making it *smoother* and providing solutions which would be closer to average behaviours, however it is expected a small impact on the results. However, the actual prediction of holding can be critical in situations where the expected arrival time is close to events which trigger costs such as potential passenger missed connections.

Future work should focus on the prediction of holdings and the impact of inaccuracies of these predictions on the performance obtained by the optimiser. The work presented in this paper could also be relevant on other operational contexts, such as Urban Air Mobility.

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