Hub operations delay recovery based on cost optimisation - Dynamic cost indexing and waiting for passengers strategies

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Hub Operations Delay Recovery based on Cost Optimisation

Dynamic Cost Indexing and Waiting for Passengers Strategies

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***Abstract*— In this paper, two strategies for airlines' operations at a hub are combined and analysed: dynamic cost indexing, to recover delay, and waiting for connecting passengers at the hub. Agent Based Modelling techniques have been used to model the airlines' operations considering detailed passenger's itineraries, an extended arrival manager operation with slot negotiation, and delay and uncertainty at different phases of the flights. Results show that, when optimising the total cost, there is a trade-off between connecting and non-connecting passengers with respect to the gate to gate trip time. Waiting for passengers arises as an interesting technique when minimising airline operating costs.**

Keywords- Multiagent Systems, Collaborative Decision Making, Airline Delay Recovery, Dynamic Cost Index, Wait For Passenger

I. INTRODUCTION

Airlines operations at hub require maintaining flights on schedule while managing not only flight delay but also passengers' connections and delay. In this paper, two options are considered: reducing flights' delay by modifying their cost index (CI), which will have an impact on the fuel usage, and/or wait-for-passengers (WFP), i.e., deciding to actively delay outbound flights at the hub to ensure that connecting passengers do not miss their connections. Current low levels of fuel cost might incentivise airlines to use higher cost indexes to recover delay, however, other costs should also be considered, such as the impact of passengers' compensation Regulation 261, maintenance or crew costs [1,2]. The introduction of extended-arrival managers (E-AMAN) also allows the negotiation of arrival slots reducing the arrival uncertainty and potentially incentives a better fuel and delay management strategy [3]. This paper presents, for the 2010 traffic environment, part of the results of DCI-4HD2D project focusing on the use of these techniques, CI management during the cruise phase and WFP and CI optimisation for outbound flights.

Section II presents the description and complexity of the problem. The model and the datasets and data assumptions are described in Section III and IV respectively. The case of study considered is presented in Section V, followed by the main results in Section VI. The paper finishes with the conclusions and further work.

II. PROBLEM DESCRIPTION

Cost index in a flight management system (FMS) represents the relationship between cost of time and cost of fuel used for a given flight. A low cost index, therefore, instructs the aircraft to follow a trajectory that minimises fuel consumption; while higher values, conversely, reduce time even at expenses of using more fuel [4]. The concept of dynamic cost indexing (DCI) entails modifying the value of this parameter during the different flight phases as a function of the current situation [1]. This dynamic optimisation can be considered when managing operations at a hub in order to minimise total operational costs.

As presented in Figure 1, when an inbound flight faces delay there is a set of options available in terms of CI to be selected recovering different amounts of delays, i.e., modifying its Estimated In-bound Time (EIBT). Each option involves different costs in terms of fuel and delay. Passenger connectivity with other flights along with their minimum connecting time at the hub (MCT) should be considering during this optimisation. Therefore, for each inbound flight that is delayed, the strategy for the outbound connecting flights should also be analysed. In some cases, the most economical option might involve delaying one or several outbound flights to wait for connecting passengers, i.e., modifying the Estimated Outbound Time (EOBT), and to apply, in their turn, a CI modification as necessary to minimise outbound delay costs.

For each inbound flight with connecting passengers there are a set of outbound flights to which those passengers connect, and for each outbound flight, there are a set of inbound flights feeding the outbound flight with connecting passengers. These relationships imply that deciding for each flight the optimal strategy in terms of delay recovery and wait-for-passenger rules is a very complex task from a computational point of view. Moreover, the system has uncertainties and limits on the re-sources available, e.g., landing slots. For this reason, instead of an analytical optimal solution, modelling with an agent-based architecture is preferred. This paper focuses on the optimisation of the abovementioned problem at a given hub.

The use of E-AMAN is also considered in this research. E-AMAN leads to reductions on fuel and emissions along with improved en-route capacity. Airports such as Heathrow, Rome

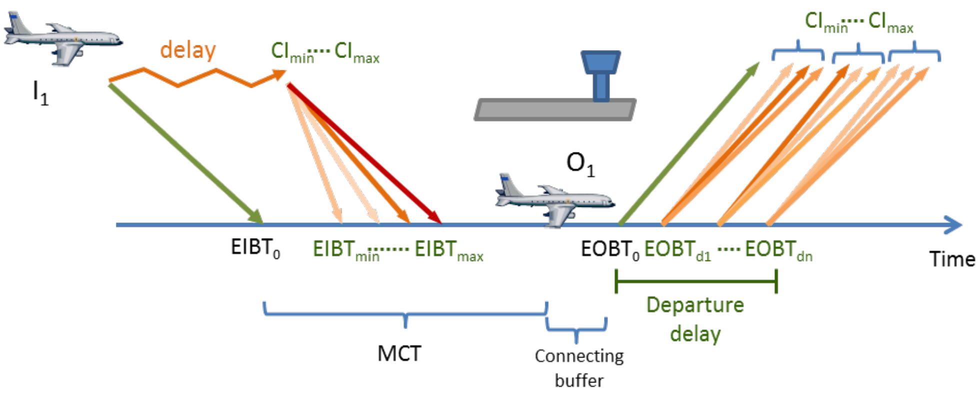


Figure 1. Diagram of DCI usage (SESAR, 2014)

or Stockholm are already implementing this technology with a 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 [3]. Previous research, such as [5] focuses on the mathematical optimisation of arrivals, however, in this paper, a collaborative decision making process is modelled to assign slots taking into consideration airlines' preferences during their operations.

III. Model Description

A. Agent based modelling

Agent based modelling (ABM) allows us to describe the behaviour of the different agents at the hub in a detailed manner. When running the simulations with the different agents and their individual behaviour, a global emergent behaviour of the system is obtained. Figure 2 presents the different agents that are modelled and their interactions, these agents have been implemented using JADEX [6,7]. The different roles played by the agents are defined as follows:

- Aircraft operator centre (AOC): centralises airlines' decisions during the simulation.
- Inbound flight (IF): implements the DCI strategy defined by the AOC.
- Outbound flight (OF): implements the DCI and the WFP strategy defined by the AOC.

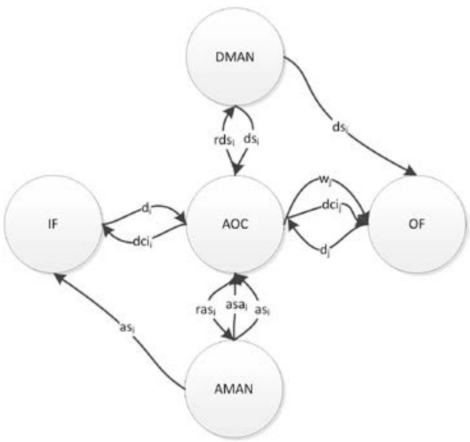


Figure 2. Diagram of agents and their interaction.

- AMAN: is an extended arrival manager, which manages the arrival traffic to meet the airport arrival capacity by assigning flights to slots based on the airlines' requests.
- DMAN: assigns slots to departing traffic to meet the airport capacity on a first come first served basis.

Each inbound flight updates its EIBT at different stages during the flight: when reaching the top of climb (TOC) and when entering the action radius of the E-AMAN.

At the TOC, the flight communicates its current delay to the AOC (d_i). The AOC assesses the situation and computes the CI that the inbound flight should select (dci_i). For each outbound flight that has connecting passengers with this delayed inbound flight, the AOC reassesses if a wait-for-passenger should be implemented (w_j) and the subsequent optimal CI for that outbound flight (dci_j). For in-bound flights, the CI is hence optimised during the cruise phase.

When the flight enters in the action region of the AMAN, 60 minutes before the passing time over the initial approach fix (PTI), there is a request of arrival slots available to the AMAN (asa_i). The AOC prioritises the slots considering the total cost and sends this prioritisation to the AMAN (ras_i). Then the AMAN solves the slot assignment taking into account the requests from different flights/aircraft operators and a slot is assigned to the flight (as_i). At this time, the AOC updates the wait-for-passengers and the CI for the outbound flights connected to that inbound flight.

For each outbound flight the WFP and DCI strategy is hence updated each time an inbound flight with connecting passenger modifies their EIBT, which might lead to new w_j and dci_j values. The out-bound flight might be delayed for reasons independent of the WFP strategy (d_j). Each time there is an update on the delay of the outbound flight, the AOC is notified so it can take into consideration when following inbound flights are delayed, e.g., no need to increase CI as outbound connecting flight al-ready delayed and passengers do not miss their connections.

When the outbound flight is ready for departure, a request of departure slot is submitted to the DMAN (rds_j), which will provide a departure slot (ds_j). Finally, when the outbound flight reaches the TOC, a final update on its CI is carried out by the AOC.

B. Fuel estimation

Fuel consumption is estimated based on BADA 4.0 [8]. For the aircraft types for which BADA 4.0 performances were not available (35% of the total traffic), BADA 3 performances have been considered. Note that part of this traffic corresponds to non-passenger flights (e.g. freight) which are excluded from the optimisation.

A 4th degree polynomial is approximated to the fuel consumption of each flight considering the aircraft type and flight plan distance. The FL and average cruise weight is estimated for each flight. This estimation is based on historical FL selected by same aircraft type with similar flight plan distances and on the specific fuel consumption at those FLs at nominal speed. For some long-haul flights, the weight and flight level are adjusted to consider the effect of cruise climb steps.

The flight envelope of each aircraft type is computed assuming a load factor of 1.3 g, in accordance to the regulation [9], ensuring that the selected speeds are within the aircraft performance limits (avoiding selecting speeds faster than the maximum allowed by the thrust nor too slow causing the aircraft to stall).

C. Costs

One of the main costs to consider is the cost of fuel. The cost of fuel has decreased significantly in the recent year; for this reason, in this research, two values are considered: nominal (0.5 EUR/kg) and high (0.8 EUR/kg) [10].

Besides fuel, other non-passenger and passengers' costs are considered and estimated at different phases for inbound and outbound flights. Maintenance and crew costs are estimated based on the maximum take-off weight (MTOW) of the aircraft. These non-passenger costs are computed for the taxi in and out, the en-route, and the arrival manager delay. Crew costs are computed considering the arrival delay of the flight.

For passenger costs, both hard and soft costs are modelled. Hard costs include provision, compensation and transfer fees. Provision costs are generated due to departing delay due to the care of duty. These costs are variable as a function of the airline model (full service (FSC), low-cost (LLC), charter (CHT) or regional (REG)) and the passenger fare type (premium or standard). Compensation costs are based on Regulation 261 scheme on arrival delay [2]. Not all passengers seek compensation, e.g. due to lack of awareness of their entitlement. It is estimated that 11% of passengers currently apply for compensation [11]. Considering the trend on compensation claims, a scenario where this value has been increased to 50% (increased passenger claim uptake) has also been modelled. Finally, if a passenger misses its connection, an optimisation is done to re-allocate the passenger to a following flight considering alliances and passenger fares types. This might lead to a cost to the airline in terms of transfer costs. For the soft costs, the total arrival delay is considered within an estimation of the propagation of the delay. Soft cost computations are based on the cost of delay reported in [11].

D. Metrics

For each flight in the model, 140 indicators are estimated including flight and passenger metric (e.g., selected speed, actual reaching top of climb time). Passenger-centric metrics should be considered as well as flight-centric metrics in order to understand the system performances, as reported in [12]. To help with the analysis of the results, a total of 22 performance indicators are computed (e.g. flight departure delay, passenger delay, aircraft operator costs) with different aggregators (e.g. average, count, percentile 90) applying different restrictors (e.g. considering all flights, only full service carriers' flights). All these combinations provide us a total of 381 metrics.

The 22 performance indicators are divided into three categories: delay, costs and efficiency. Delay performance indicators are divided between flight and passenger performance, including delay recovery and wait-for-passenger metrics. Costs are considered for the different carriers in the model and for hub and non-hub operators. Finally, to understand the complexity of the scenarios and other parameters, efficiency factors are computed: passenger performance (missed connections), complexity (number of changes on the decisions), emissions and holding at the AMAN.

IV. Datasets

A. Traffic data

1) Flight plan data

The original traffic data is based on a busy Friday of 2010 (20th August 2010) with flights to-from a hub airport. The traffic data has been generated combining different data sources. In total there are 676 flights (336 inbound and 340 outbound) and a total of 61,446 passengers from which 11,570 are connecting at the hub. The hub has been selected considering data availability, the number of short haul flights to-from the hub is relatively high.

Flight schedules are obtained from PRISME dataset (scheduled outbound time (SOBT) and scheduled inbound time (SIBT)). The flight trajectory and flight phases (climb, cruise and descent) are estimated based on so6 data file.

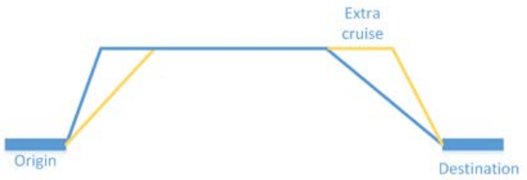
2) Taxi times estimation

For each taxi time (taxi in and taxi out) two different reference values are required. The first one is the taxi time that the airline uses to estimate the taxi times at planning stage, the second one is the actual taxi time experienced by the flights.

The estimated taxi times are based on CFMU taxi times, but modified (considering average reported taxi times and airline schedule buffers) to be as close as possible to the airlines' working taxi times. Note that these values are used when estimating the arrival time at the destination gate and there-fore estimating the delay of the flight to decide the DCI strategy to use.

The taxi out is estimated considering the difference between the duration of the flight plan from take-off to landing with respect to the duration of the flight plan from the estimated off-block time (EOBT). This taxi out time is generally close to the reported CFMU taxi time. For the taxi in, it is worth noticing that for some airports there is a systematic overestimation of the taxi times reported by the CFMU and the ones provided at post-operations by the airlines. It is reasonable to consider that airlines will take this average taxi estimation error when defining their internal taxi times.

(a) full trajectory modified



(b) same cruise flight level maintained

Figure 3. Effect of increasing cost index on trajectory

During the simulation, the actual taxi times that each individual flight experienced are modelled based on the taxi out and taxi in data provided by airlines to CODA. These actual taxi time values are based on reported taxi times but at an aggregated level. Uncertainty is added as explained in section IV.C.1.

3) Arrival buffers

The arrival buffers are defined as the difference between the scheduled block times (SIBT - SOBT) and the planned gate-to-gate flights (estimated taxi out + flight plan duration + estimated taxi in). In general, airlines plan a shorter gate-to-gate trip than their published scheduled times. This creates a buffer to deal with uncertainties and delay [13,14]. If these buffers are not modelled each minute of delay would be considered as arrival delay triggering, in some cases, unnecessary delay recovery. In our analysis, in 72% of the flights some positive buffer exists. There are some flights, 28%, that would arrive delayed even if on time, this might be due to operational constraints during the route, note that only 2.7% of the flights would arrive with a delay greater than 15 minutes.

4) Turn around

A minimum turnaround time (MTT) is defined for each aircraft type based on the airline type, the wake turbulence of the aircraft, i.e., size, and if the airline is the hub airline [15]. In this paper, these values are based on the ones estimated in [16] with a lower limit of 20 minutes.

The turnaround buffers were defined as the time between an SIBT and a subsequent SOBT for the same aircraft type considering the MTT, i.e., subsequent SOBT - arrival SIBT - MTT. These buffers reduce the propagation of delay, i.e., reactionary delay, at the airport. For flights in the hub the median value of the buffer is 28 minutes with values ranging between 53 and 19 minutes (75th and 25th per-centile respectively), for turnaround outside the hub the median is 18 minutes with values between 28 and 13 minutes (75th and 25th percentile respectively).

5) Cruise speed and wind estimation

If the average ground speed is considered as the nominal true airspeed during the cruise, 19.0% of flights (129 flights) would be operating faster than their VMO (maximum operating

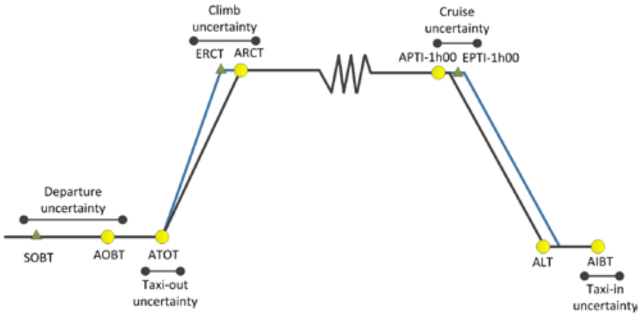


Figure 4. Flight delay and uncertainty modelled

speed) and 5.7% of the flights (39 flights) would be cruising slower than their minimum operating speed. For this rea-son, instead of using the average cruise speed as the true airspeed, the nominal airspeed as indicated by BADA is considered. This nominal airspeed is indicated as a Mach number and hence for very short flights, using a very low flight level, the airspeed in knots has been adjusted to ensure that the operations are within the aerodynamic domain of the aircraft (avoid speeds faster than the VMO).

By comparing the average ground speed and the estimated true airspeed, the average cruise wind component is estimated. These winds estimations range between about 100 kts tailwind to about 100 kts headwind.

6) Trajectory modification due to DCI

When the cost index of a flight is increased, not only the cruise airspeed is modified but also the whole trajectory might be affected. As depicted in Figure 3, a higher cost index, leads to a less steep climb, a sharper descent and, generally, a longer cruise phase. In some cases, it can even have an impact on the optimal flight level; generally, a lower flight level is preferred (see Figure 3(a)). In this research, the decision of increasing the airspeed to recover delay is executed once the flight reaches its TOC, the option of selecting a different altitude than the nominal is not considered. However, as shown in Figure 3(b), if the cost index is increased, there will be an extra cruise length that could be used to recovered delay. The descent speeds would also be modified, but at that point the AMAN negotiation will be carried out and therefore that phase is not considered in the delay recovery strategy. Note that due to the aircraft performance and flight characteristics, i.e. length of the flights, a significant part of the delay that can be recovered is achieved by the reduction of the slow descent for faster cruise by extending the cruise length, hence the importance of modelling this cruise extension.

Using Airbus Flight Plan Performance Engineering Program, flight plans are computed for the different flights in the model (same altitude, distance, weight and cruise speed) and the same flight plans are computed considering a maximum cost index. An estimation of the extra cruise distance is computed by comparing those two flight plans and it is approximated by a normal distribution of parameters μ=7.60 NM and σ=2.15 NM. These extra cruising distances are bounded by a minimum of 2 NM and a maximum of 18 NM. These values are reduced from the descent phase, which is hence shortened. If the extra cruise distance estimated is longer than the descent distance, then it is bounded by half of the descent distance available.

B. Passengers itineraries

Individual passenger itineraries are modelled for each flight based on anonymous airport connection data. These contain also and estimation of the minimum connecting time required. In general passenger's connections tend to be longer than the MCT, having some buffer to realise the connection. On [17] less than 1% of connections were found to be shorter than 40 minutes (which was the declared MCT for the airport under study).

C. Uncertainties and delay

Besides the departure delay, uncertainties are modelled for the different phases of the flight. As shown in Figure 4, there is uncertainty with respect to the actual off block time (AOBT) that might be delayed with respect to the SOBT. Once the flight is in the air, the climb phase suffers from performance uncertainties and from the effects of the departure TMA leading to some variability on the arrival to the reaching of the cruise (ARCT) that might differ from the estimated time to reach the cruise (ERCT). During the cruise, there is uncertainty due to meteorological conditions and flight path modifications, which lead to uncertainty on the time when the aircraft enters the AMAN scope, i.e., 1h00 before the passing time over IAF (initial approach fix) (EPTI).

Finally, uncertainty on the taxi times is also modelled, i.e., difference between scheduled and actual taxi times. This leads to uncertainties on the actual take of time (ATOT) and the actual inbound time (AIBT), being ATOT the AOBT + taxi out and the AIBT the actual time of arrival (ATA) + taxi in.

1) Taxi uncertainty

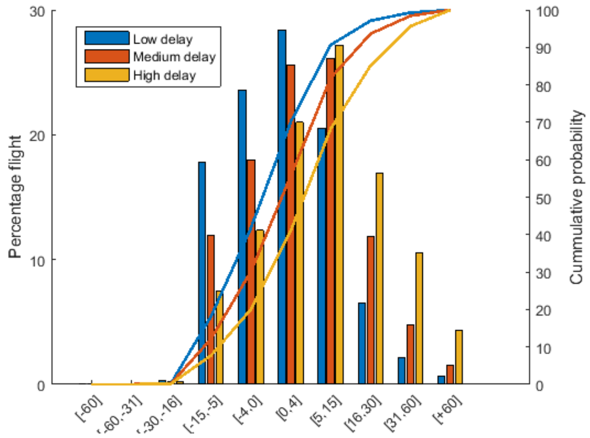
For each taxi time at the execution stage, a deviation is added. This deviation is based on the standard deviations (σ) reported by IATA for inbound and outbound taxi times for the airports. For out-bound flights, this deviation is aircraft category-dependent (heavy or medium). For taxi-in, this deviation is airport-dependent. Thus, for each flight, a normal distribution centred at the execution taxi time with standard deviation from the reported by IATA is used to estimate the actual taxi times. The minimum and maximum taxi times are bounded by a minimum of 2 mins and a maximum of 2 σ to avoid too small or too long taxi times.

2) Airborne uncertainty

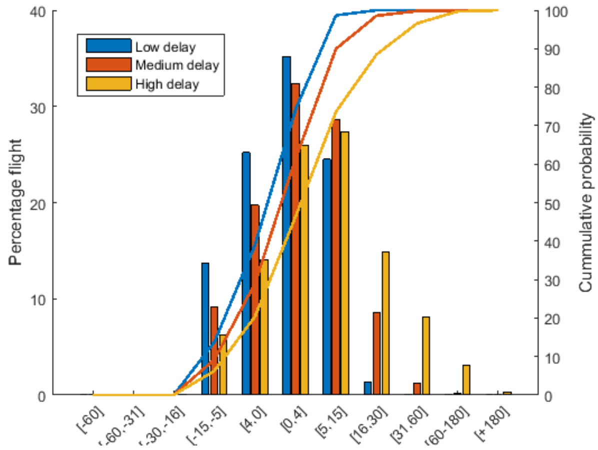
Once the aircraft is airborne there are two stages where uncertainty is modelled: the actual reaching cruise time (ARTC), where a new CI could be assigned, and the actual passing time over IAF - 1h00 (APTI-1h00), when the aircraft enters the AMAN scope.

a) Climb uncertainty

In order to generate the uncertainties during the climb phase, the difference between the estimated time required from take-off to reaching FL180 according to the finally submitted flight plan and the actual time required to reach FL180 from departure, for all the flights going to the hub, during the period AIRAC 1313 to AIRAC 1413 (i.e., 12 December 2013 to 07 January 2015), are analysed and approximated to a normal distribution.



(a) Inbound traffic from CODA



(b) Outbound delay distribution corrected, estimated without reactionary delays

Figure 5. Delay for inbound and outbound traffic

b) Cruise uncertainty

A comparison between the distances of the finally submitted flight plan and the actual flown trajectory for all the flights inbound to the hub between reaching FL180 in climb until reaching FL180 on descent during the period AIRAC 1313 to AIRAC 1413 period provides the cruise uncertainty. These distance differences are approximated with a normal distribution.

3) Off-block delays

For each flight, the airline considers the schedule off block time (SOBT), however, the estimation of the off block time (EOBT) changes as the flight is affected by delay leading to the actual off block time (AOBT). In this research three different delay scenarios are modelled: low, medium and high delay for the inbound and outbound traffic. To estimate the departure delay CODA data are analysed. CODA data contains the information of the difference between the SOBT and the AOBT.

The data of all the flights arriving and departing from the hub during 2014 have been analysed. For each day the average delay per flight (considering inbound and outbound flights) is computed. The different days are grouped in three categories: days within the 25 quantile of average delay per flight (low

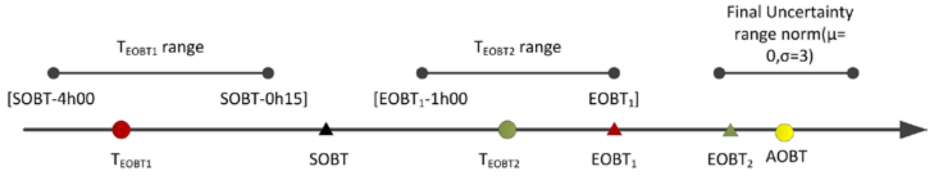


Figure 7. - Initial delay generation and awareness for outbound flight

delay days), days within the 25 and 75 quantile (medium delay days) and days over the 75 quantile (high delay).

Figure 5(a) presents the frequency of inbound flights to the hub for the three categories of day with the experimental cumulative distribution.

For the outbound delay, the data from CODA is not directly used as these include the reactionary de-lay that is explicitly modelled in this research. To avoid this double counting, from the distribution of outbound delay, the reactionary delay (codes 91-96) are removed, leading to the frequency and distributions presented in Figure 5(b). These distributions do not consider the reactionary delay and therefore for outbound flights the delay considered is the maximum between the delay following these distributions and the potential reactionary delay experienced by the flights.

The departing delays are fitted with Burr distributions and bounded in the [-30, 240] min range (p-values < 0.01 with 2 samples Kolmogorov-Smirnov test). The model also considers the fact that the aircraft operator might get the information of the delay that a given flight experience at different stages, having in this manner uncertainty on the final departing delay that a given flight might experience.

Figure 6 presents the different stages on which the delay is communicated to the airline for its out-bound flights. The total delay is computed for each flight and the AOBT is calculated, but this information is not fed instantly to the aircraft operator agent. At a given time between [SOBT-4h00 and SOBT-0h15], the EOBT of the airline is estimated to be EOBT1, then this estimated departure time is modified at a time between [EOBT1-1h00 and EOBT1] leading to the actual EOBT2, which in turn has some final uncertainty following a normal distribution of μ=EOBT2 and σ=3 min.

For the outbound flights, this modelling gives a more realistic approach for the DCI and WFP decision-making process. If the airline already knows that a connecting outbound fight is delayed there might not be an incentive to increase the cost index on a delayed inbound flight; this information of the departure delay is refined as the actual departure time is closer in time.

D. Capacity model

After analysing the arrival and departure planned demand at the hub, a capacity of 20 acc/30 min for departure and arrival is selected. If the demand is significantly higher than the capacity an ATFM regulation would be implemented adjusting the demand; as these types of regulations at the hub are not considered in this research, the capacity is selected to be high enough to prevent unrealistic tactical delay generation.

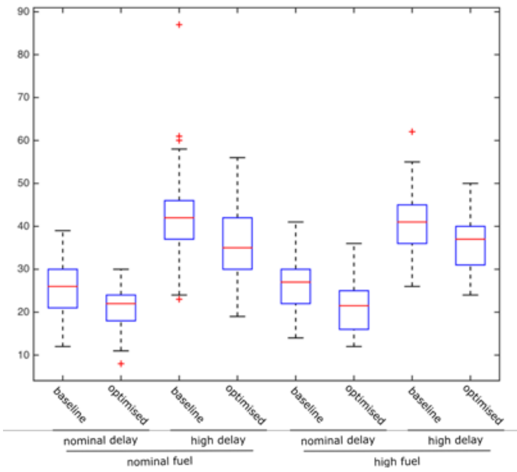


Figure 6. Missed connections at the hub

V. CASE OF STUDY

Two strategies have been modelled: a baseline strategy modelling the current operations and a cost optimised strategy where the cost index and WFP are managed considering the costs.

On the baseline strategy, a simple rule to recover delay is implemented. For 10% of the flights, if the estimated delay is more than 15 minute, the flight tries to recover it up to a remaining of 5 min. An outbound flight only waits for connecting passengers' if the total waiting time required is up to 20 min and the inbound flight with connecting passengers is already speeding up to recover part of the delay.

On the cost optimised strategy, the decision to speed up is based on the estimated total cost. DCI is considered for all delayed flights at top of climb. Costs are assessed for each of the different DCI options and the minimum cost decision taken. The outbound flights wait for connecting passengers based on the overall total costs.

The combination of the different uncertainty and initial delay (low, medium and high delay), costs (nominal and high fuel costs, and nominal and high passenger compensation claim uptake) and strategies (baseline and optimised) defines the scenarios to be tested. The results of each evaluated scenario are the result of analysing 50 independent runs.

VI. RESULTS

The delays generated on the low delay scenarios are too low, and therefore only results for nominal and high cases are presented.

As shown in Figure 7, the number of passengers missing connections is reduced when the optimisation strategy is implemented. This reduction, in average ranges between 14.4%

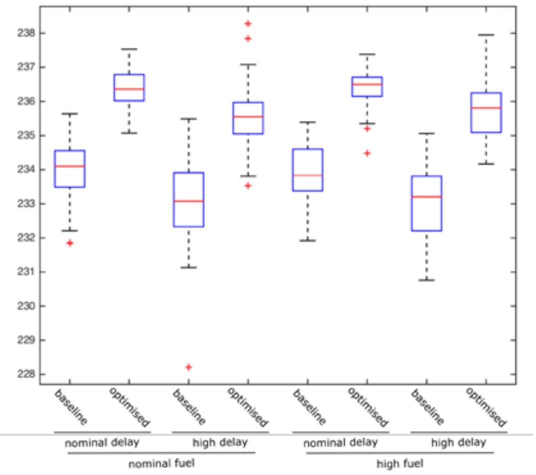
and 17.5%. However, as presented in Figure 8(a), the average gate-to-gate time increases for the passengers (in average around 1.1%). This increment is the result of a trade-off between connecting and non-connecting passengers as shown in Figure 8(b) and 8(c). For non-connecting passengers the gate-to-gate time increases by 0.4% in average, while connecting passengers decrease their gate-to-gate time by 0.8% for nominal delay and by 0.6% for high delay scenarios. This trade-off effect is more significant in airlines with connecting passengers (e.g., FSC) rather than in airlines with few connecting passengers' itineraries (e.g., LCCs). The cost of a small delay for direct flight passengers is traded for the potential cost of connecting passengers missing their connections at the hub.

Outbound flights waiting at the hub for connecting passengers increase significantly when optimised strategy is implemented: an increase on number of flight WFP greater than 270%, see Figure 9(a), and the waiting time is also higher: average waiting time increases from 7 min to 13-14 min, see Figure 9(b). The waiting times at airport for connecting passengers decreases (in average by 1.6%) when the cost optimisation strategy is followed by the airlines.

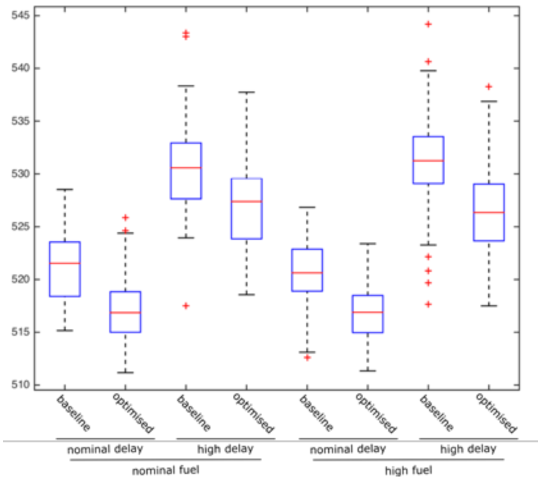
As presented in Figure 10, the number of flights that realise speed variations increases with the optimisation, but the average variation on speed is similar or generally lower than in the non-optimised case. This is related to the fact that the total cost is considered, i.e., taking into account the fuel cost.

An increment in fuel cost leads to lower emissions. In nominal conditions (nominal delay) with air-lines optimising their strategies, the increment in fuel cost produces a reduction on the number of flights that decide to increase their speed of 30-35%, and the aircraft fly slower (on average there is a reduction of the speed selected of 5-7%). This leads to a reduction on fuel consumption and emissions by approximately 25%. In general, passenger metrics are not significantly affected due to the limited amount of delay that is recovered during the cruise phase.

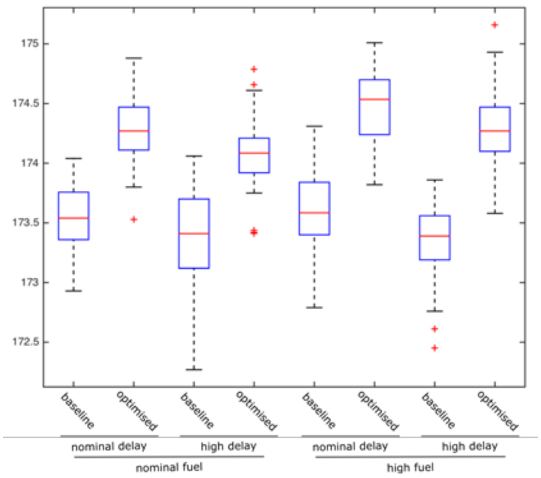
The efficiency at the AMAN in terms of delay and fuel cost generated is presented in Figure 11. As shown, in the optimised strategy, more delay is generated at the AMAN than at the baseline scenarios. However, a reduction on fuel usage is appreciated. The underlying reason is that on the optimised strategy, the selected slot is the one which is expected to minimise the cost of the inbound flight and its connections. Therefore, in some cases, it is worth it to select a later slot that will represent some fuel savings if the connections are already ensured.



(a) all passengers

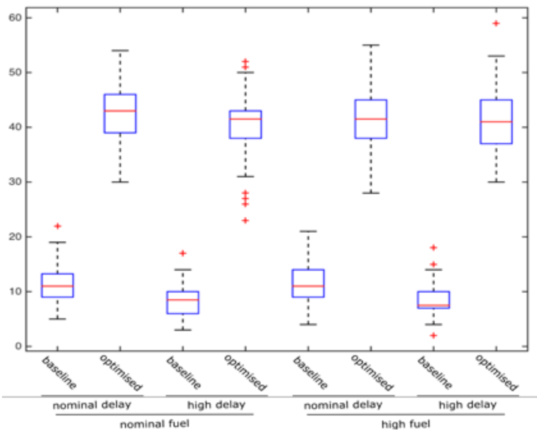


(b) connecting passengers

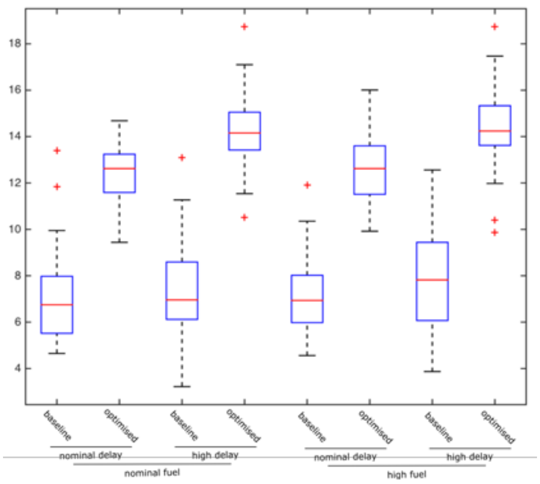


(c) non-connecting passengers

Figure 8. Average gate-to-gate passenger time (min)

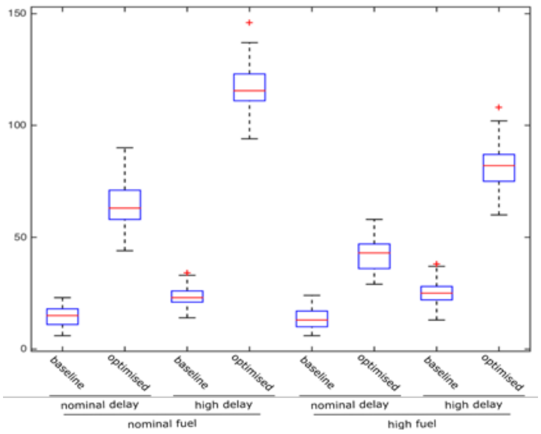


(a) number of flights waiting for passengers

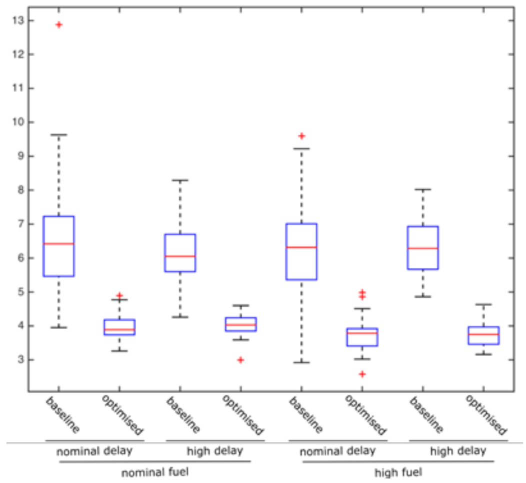


(b) average waiting time (min)

Figure 9. Wait-for-passengers at hub



(a) number of flights performing speed variations



(b) average percentage variations

Figure 10. Speed variations at top of climb

With the optimisation strategy the total costs are reduced by a small percentage. There is an improvement on the costs in average of 0.7% for nominal delay. This benefit is partially achieved by reducing the passenger costs and in particular the passengers' reactionary costs. In high delay scenarios, airlines benefits decrease to around 0.5%. Increasing the number of passengers claiming compensation (from 11% to 50%) slightly reduce the benefit of the optimised strategy.

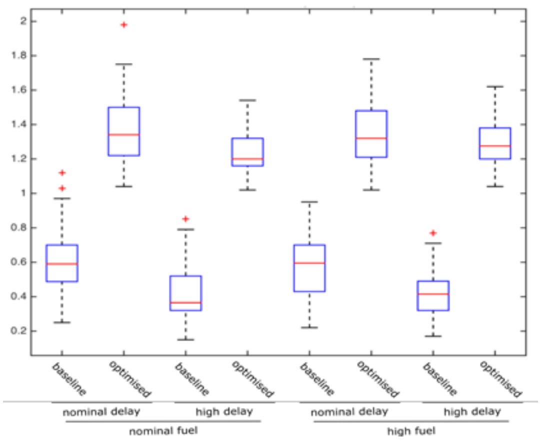
VII. Conclusions and Further Work

Hub operations have been modelled, including:

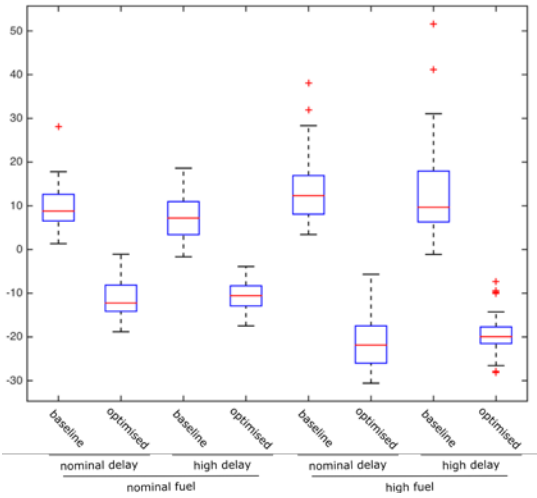
- Dynamic cost indexing,
- Wait-for-passenger rules,
- SESAR objectives such as extended approach manager and collaborative decision making pro-cesses,
- Passenger gate-to-gate times, especially transit passengers in the context of the 4 hours door-to-door challenge,
- Future passenger compensation regulations uptake and
- Airline schedule recovery strategies considering passenger connectivity as well as hard and soft passenger costs.

Each flight in the model does not just compute its cost index dynamically, but in collaboration with the rest of the flights; which in turn update their own strategies. In this sense, flights under the same operator act as a network, or rather as a system of systems. On top of that, since decisions and proposals are continuously shared and updated between flights sharing passengers, feedback loops appear increasing the system's complexity. ABM has proven a suitable tool to capture these interactions and ultimately reveal some emergent behaviour not expected from the initial strategies, such an increase on outbound flights waiting for connecting passengers.

The results and conclusions presented in this paper are airport dependent as they are based on one particular hub with a relatively high number of short flights. The main characteristics of an airport that affect the efficiency of DCI and WFP strategies are the number of connections and the flight plan distances, i.e., the potential possibility of recovery delay with DCI. For this reason, the distribution of flight plan distances at major hubs in Europe during one year have been analysed. Results show that airports such as LTBA or EGLL could be better candidate to implement DCI strategies while other air-ports, such as LIRF, LEMD or LSZH, even if served with some long haul flights, the majority of the traffic is relatively short not allowing to exploit the potential of delay recovery through DCI and, possibly, WFP will play a higher role on them.



(a) average waiting at AMAN (min)



(b) Extra fuel cost at AMAN (EUR)

Figure 11. Variations at AMAN

The conclusions can be summarised in three categories: cost, delay and efficiency.

A. Cost

Application of cost optimisation strategies would reduce airline cost by around 0.7%. This reduction is observed to be obtained by increasing the number of outbound connecting flight performing wait-for-passengers and the duration of the waiting time to avoid passengers missing connections. When the amount of passengers claiming compensation increases, the optimised strategy benefit is reduced to around 0.5%.

The initial delay in the system plays an important role on the total cost that airlines experience: the savings in fuel that are observed during the AMAN phase decrease as the initial delay is increased. Similarly, the extra costs in fuel and passenger costs increase when the system has higher delay.

Higher fuel costs leads to fewer flights deciding to increase the speed. However, the total delay experienced is similar and the passenger costs do not increase.

B. Delay

The application of airline cost optimisation strategy increases gate-to-gate time in average 1.1%. However, there is a trade-off between the types of passengers: the optimisation strategy increases non-connecting gate-to-gate time by 0.4%, as there is an increase of wait-for-passengers time, which translates into a reduction of 0.6-0.8% for connecting passengers due to a reduction of passengers missing connections. These missed connections would increase the total passenger delay, compensation and costs higher than the penalisation for small delays on non-connecting passengers.

The number of aircraft waiting for passengers and the time they wait increase significantly when the optimisation is applied. Outbound flights waiting for passengers benefit from the possibility of applying DCI on their turn. This shows that unexpectedly, the benefit of the DCI strategy combined with the WFP is mainly achieved by the later strategy. Airlines, sometimes, dismiss this approach as it might lead to lower on-time flight performance and potentially higher probability of getting extra undesired delay due to ATFM regulations. This is something that should be considered when working to-wards a more passenger and cost-centric solution.

When optimising costs, flights prefer to save fuel than delay during the AMAN phase as with the WFP strategy connections can still be achieved providing, overall, some savings.

Increasing the number of passengers claiming compensation reduces the amount of passengers missing connections (by 8.5% in nominal delay and by 15% in high delay).

C. Efficiency

In nominal conditions (nominal delay) with airlines optimising their strategies, the increment in fuel cost makes airlines to fly slower, reducing fuel consumption and emissions by approximately 25%.

An optimisation that allows speed variations leads to lower emissions (i.e., lower fuel consumption) than current operations. The main reason for this is that the optimisation is considering the total cost, including fuel consumption, while in the current operations, even if a few flights recover delay, there is no assessment on the fuel that that recovery will represent. Moreover, in the optimised strategy wait-for-passengers seems to be playing a role as important as speed variations to minimise air-line operations costs.

Higher initial delays lead to lower holding delay but the biggest difference is between current and optimised strategies. In the optimised strategy the delay increases significantly at the AMAN, part of the reason is due to the speed selected to save fuel. This might be the reason behind why not extra delay is saved on the optimised strategy. In the modelling of current operations, the first slot available is assigned to the arriving flights regardless of the potential fuel usage.

D. Further work

Other metric dependencies among the existing indicators could be explored. Further analysis could be conducted to study the sensitivity and stability of the solutions to the confidence level of the input factors. For example, the capacity of the airport could be modified to see how higher delays affect to the optimised solutions.

The decision of the strategy follow by each flight is reassessed at different points during the flight, therefore, there is a difference between the expected and the actual cost experienced. This could be explored to include some learning process and enhanced decision making process by selecting the option that provides a higher probability of delivering a lower cost.

The conclusions of the model invite to explore in further detail the efficiency of the AMAN. Its time horizon could be extended further than 60 minutes. This would entail designing new algorithms to better negotiate the arrival time of the flights and maintain the flexibility required for last minute changes, especially for those flights which are close to the destination airport, which need an arrival slot subject to change.

Currently, the optimisation strategy considers modifying the arrival times of flights in a downstream manner, i.e., when an inbound flight is delayed the outbound reassess their strategy. It could be possible to dynamically modify the decision of an inbound flight when an outbound flight is delayed. This, however, would create a ripple effect, as there is a dependency between inbound and outbound flights, which entails a computational challenge for the model.

The cost distribution for the different airlines is usually quite different; therefore, it would seem appropriate to include differences on the strategies based on the operator classification. Note also that the current operation strategy could be modified to better represent the current practices, such as limiting the speed increment based on forecast fuel consumption.

It would be interesting to assess this strategy at different hubs to see if the traffic pattern delivers different operational strategies. Other airports with a greater component of long-haul flights which can potentially recover more delay might be more suitable for DCI strategies finding, for example a reduction on the number of outbound flights waiting for passengers.

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