

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 incentivises 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 considered 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-resources 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

B. Passengers itineraries

Individual passenger itineraries are modelled for each flight based on anonymous airport connection data. These contain also an 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 2σ 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.

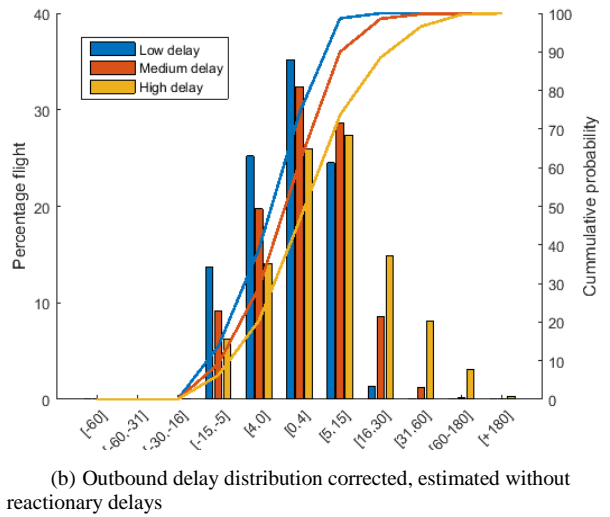
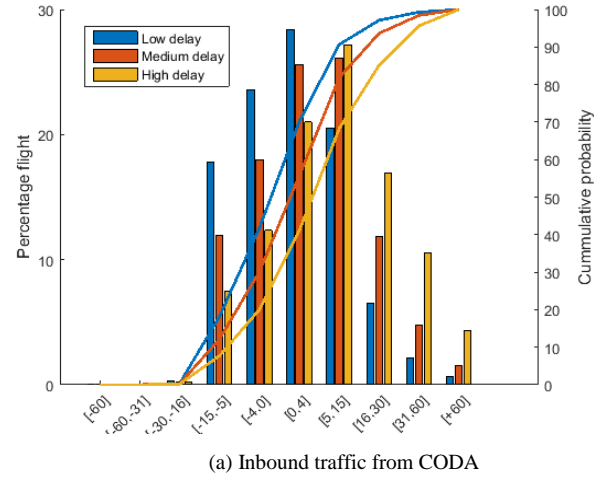


Figure 5. Delay for inbound and outbound traffic

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

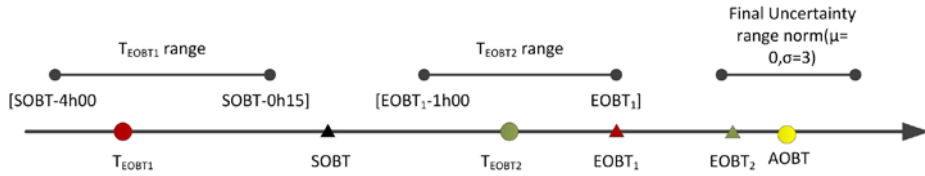


Figure 7. - Initial delay generation and awareness for outbound flight

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 $[\text{SOBT}-4\text{h}00$ and $\text{SOBT}-0\text{h}15]$, the EOBT of the airline is estimated to be EOBT_1 , then this estimated departure time is modified at a time between $[\text{EOBT}_1-1\text{h}00$ and $\text{EOBT}_1]$ leading to the actual EOBT_2 , which in turn has some final uncertainty following a normal distribution of $\mu=\text{EOBT}_2$ and $\sigma=3$ 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 flight 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.

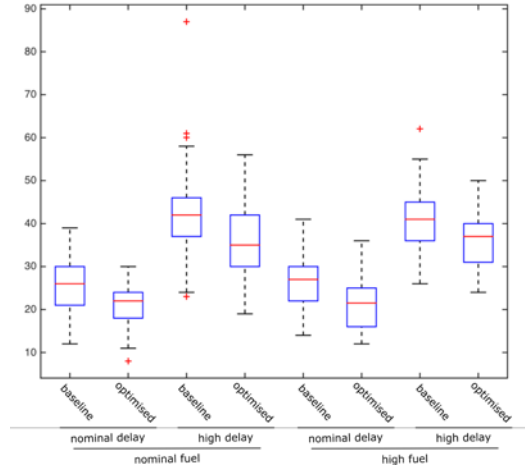


Figure 6. Missed connections at the hub

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%

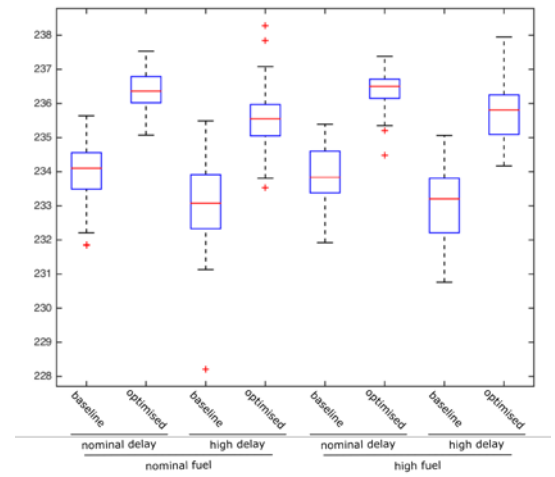
and 17.5%. However, as presented in Figure 8(a), the average gate-to-gate time increases for the passengers (in average around 1.1%). This increment is the result of a trade-off between connecting and non-connecting passengers as shown in Figure 8(b) and 8(c). For non-connecting passengers the gate-to-gate 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.

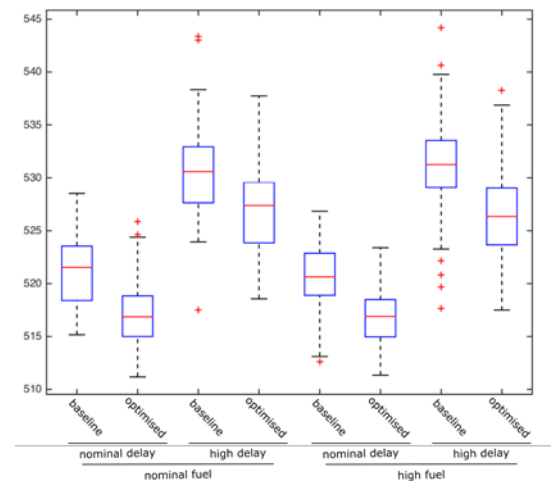
As presented in Figure 10, the number of flights that realise speed variations increases with the optimisation, but the average variation on speed is similar or generally lower than in the non-optimised case. This is related to the fact that the total cost is considered, i.e., taking into account the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

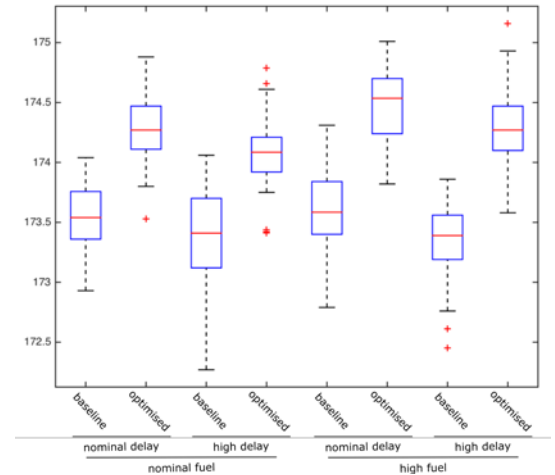
The efficiency at the AMAN in terms of delay and fuel cost generated is presented in Figure 11. As shown, in the optimised strategy, more delay is generated at the AMAN than at the baseline scenarios. However, a reduction on fuel usage is appreciated. The underlying reason is that on the optimised strategy, 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

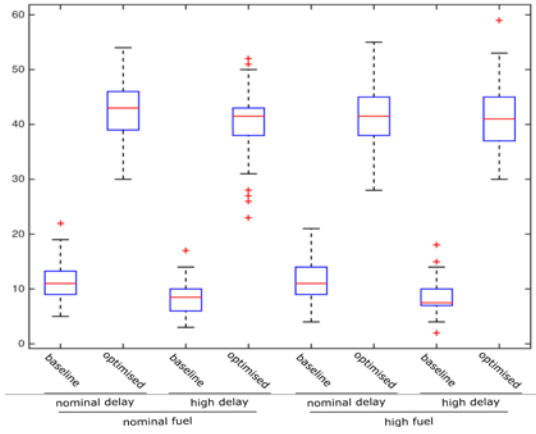


(b) connecting passengers

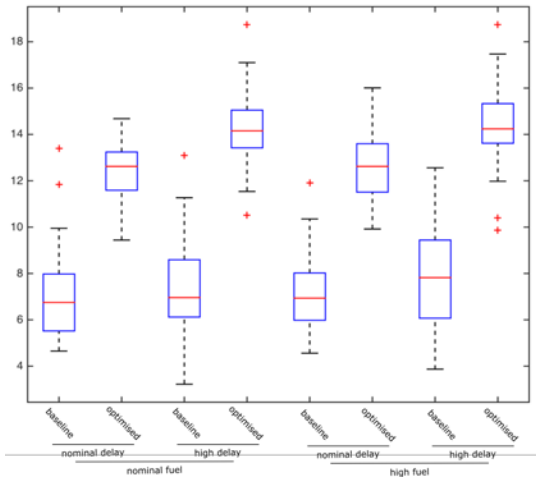


(c) non-connecting passengers

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



(a) number of flights waiting for passengers



(b) average waiting time (min)

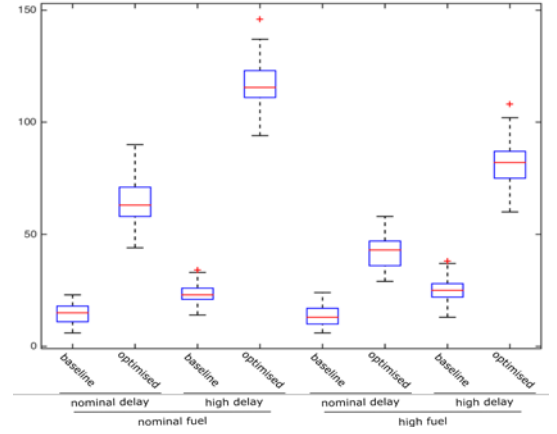
Figure 9. Wait-for-passengers at hub

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.

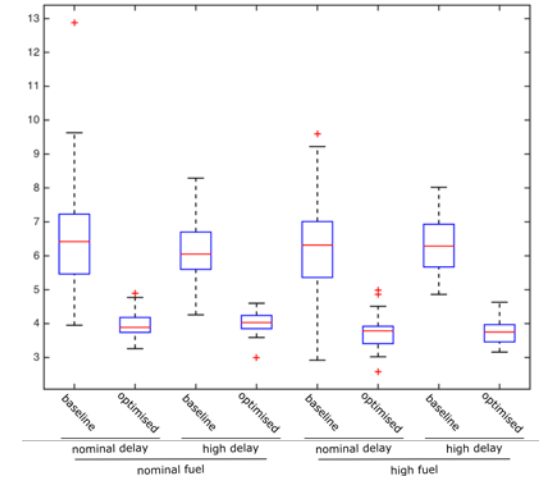
VII. CONCLUSIONS AND FURTHER WORK

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.



(a) number of flights performing speed variations



(b) average percentage variations

Figure 10. Speed variations at top of climb

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.

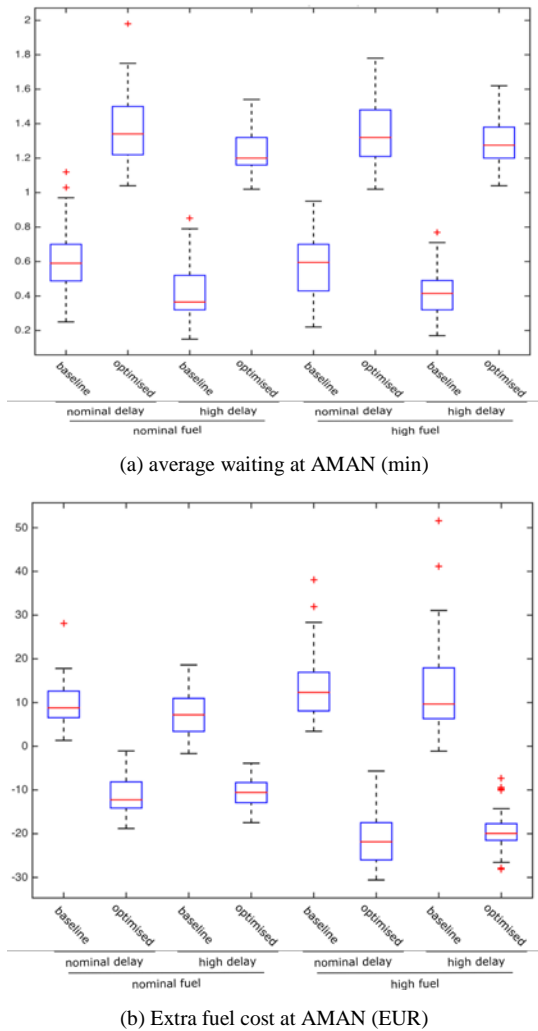


Figure 11. Variations at AMAN

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 towards 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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