MANAGING NETWORK FLIGHT DELAYS THROUGH COLLABORATIVE DECISION MAKING

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ABSTRACT

This communication considers the operation of domestic airlines and more particularly the delay propagation along their operated network. In this communication is first introduced a modelling approach which allows to assess the consequences of perturbations, in general flight delays, on the operation of the network operated by the airline. An optimization process is introduced so that AIRLINES can update on-line and in a global way their flight schedules by performing optimally in-flight delay absorption. Then an ATC procedure is presented to assign time arrival slots to delayed aircraft according to the value of their network arrival delay index. A similar procedure, run by AIRPORT, is used to assign time departure slots at runway to departing aircraft. The whole process configurates a collaborative decision making (CDM) scheme devoted to managing efficiently network flight delays.

Keywords: air transportation networks, delay propagation, collaborative decision making, flight schedules, delay mitigation.

1. INTRODUCTION

This paper considers the operation of flights operated by airlines in a domestic network and develops a collaborative scheme to face delays generated during operation. In general, domestic airlines try at the same time to offer an on-time air transport service to potential passengers and to maximize the use of their fleet of aircraft. These are contradictory objectives and when a tight flight schedule, with as many flights as possible, has been adopted by an airline, the occurrence of any delay on a flight, either at departure or arrival, may impact on the remaining flights of the day. This can be in terms of delayed or cancelled flights, with a high impact on the quality of service. The Collaborative Decision Making (CDM) concept has been developed recently to deal with the coordination of activities addressed to the processing of aircraft during their whole operation (flights and airport operations). This concept favors overall efficiency by implementing on-time communication of information and predictions between the different operators which process aircraft in the airspace as well as at airports.

In this communication is first introduced a graph framework which allows to assess the consequences of perturbations, in general flight delays, on the operation of the network operated by the different airlines. An optimization process is introduced so that AIRLINES can update on-line and in a global way their flights schedule by performing optimally in-flight delay absorption. Then an ATC procedure is presented to assign time arrival slots to delayed aircraft according to the value of their network arrival delay index. A similar procedure run by AIRPORT is used to assign time departure slots at runway to departing aircraft. The whole process configurates a Collaborative Decision Making scheme devoted to managing efficiently network flight delays.

The paper is organized as follows: in section 2 elements about network delays are introduced and compose the background of the problem, then is section 3 a directed graph is introduced to represent the sequencing constraints between flights. In section 4 is considered, based on the proposed graph representation, the feasibility and the cost efficiency of flight schedules. Section 5 considers the in-flight delay absorption by airlines through the repeated resolution of NCIO, a global cost-effective optimization module. Section 6 introduces a sequencing procedure at landing, ASATS, which allows to implement priority policies for delayed aircraft. Section 7 considers from the airport side priority policies for departing aircraft with delays, the ASDTS procedure is then introduced. Finally, in the conclusion the whole collaborative scheme is displayed.

2. FLIGHT DELAYS IN AIR TRANSPORTATION

Delay is the time duration which appears when a planned event does not happen at the planned time, but later. In air transportation two planned events are of main interest: planned departure time and planned arrival time. A departure delay is the difference between a scheduled time of departure for a flight as informed to passengers and its actual off-block time. An arrival delay is the difference between a scheduled time of arrival for a flight and the actual on-block time at the destination airport. Arrival delay is important for passenger connectivity (and crew and aircraft connectivity) and is now becoming a more important issue for the airlines because of the costs of passenger compensation in case of long delay. Many causes may induce delays in airlines operations. These can be classified in different ways: internal or external reasons with respect to the airline, ground (airport) or in-flight reasons, common or exceptional reasons. Delays can be classified as primary or reactionary, where reactionary delays are the result of a late arrival of an aircraft, crew, passengers or loads from an anterior flight, while primary delays are all the other delays which take place during the commercial operation of the aircraft. It appears that along a day of operation the proportion of primary and reactionary delays varies with in general an accumulation of reactionary delays by the end of the operations period. Figure 1 displays the evolution of the shares of delay causes by

hour of the day reported by airlines in Europe for 2017.

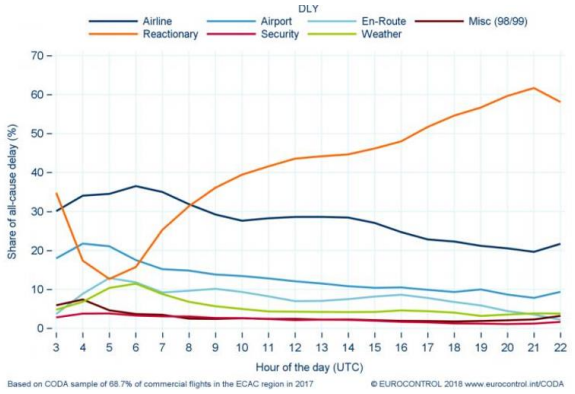


Figure 1: Hourly evolution of shares of delay causes in 2017

In Europe the percentage of flights with an actual block time which exceeded the scheduled block time for 2017 was 27% while for the US domestic airlines, 20% of the flights were delayed (meaning at least 15 minutes delay).

Delays forecast is considered from an European perspective in Eurocontrol's last study published earlier in 2018: despite the 16% planned improvement in airport capacity (111 airports, 84% of flights), the most likely scenario in 2040 shows a shortage of 1.5 million flights, which is 8% of the underlying demand or 160 million passengers unable to fly [7]. That would mean that the average delay would be 20 minutes per flight (year 2040) compared to 12 minutes per flight today (2018).

3. FLIGHT SCHEDULES AND TRANSFER GRAPHS

In this section is introduced a mathematical representation of the flight schedule of an airline to enable the computation of cumulative effects in network delays. Here the daily operation of an airline is seen as a set of elementary tasks, the flights, performed sequentially or in parallel, using resources such as aircraft and crews as well as air traffic and airport facilities. Then let F_α be the set of flights $f \in F_\alpha$ offered by a given airline α, $\alpha \in A$, where A is the set of considered airlines. Let V_α be the set of operated aircraft, $C_{T\alpha}$ is the set of technical crew and $C_{C\alpha}$ is the set of commercial crew for airline α on a standard day of operation. Let $F_{\alpha v}$ be the set of flights operated by aircraft v of airline α. Then, sequential time constraints between the flight legs of $F_{\alpha v}$ take place according to the order in which these flights are planned to be operated by the airline. Let this sequence be given by $\left(f_1^v, \cdots, f_k^v, \cdots, f_{|F_v|}^v\right)$, then between flights k and k+1 of this sequence, time constraints such as:

$$t_d^{pf_k^v} + DF_{f_k^v} + GAD_{f_k^v f_{k+1}^v} \leq t_d^{pf_{k+1}^v} \quad (1)$$

should be satisfied. Here t_d^{pf} is the planned or published departure time for flight f, DF_f is the nominal duration of flight f, $GAD_{ff'}$ is the overall duration of ground handling activities for successive flights f and f'. The difference between the RHS and the LHS of relation (1) represents the buffer which could compensate for a delay at departure of flight f_k^v, for a delay during the flight f_k^v or during ground handling tasks at arrival of flight f_k^v or departure of flight f_{k+1}^v. When a connection from flight f to flight $f'$is planned, this introduces a succession constraint. Let X be the set of planned flight connections, then:

$$t_d^{pf} + DF_f + T_{ff'} \leq t_d^{pf'} \quad \forall (f, f') \in X \quad (2)$$

where $T_{ff'}$is the transfer time (passengers and luggage) from flight f to flight f'. The flights offered by an airline may be linked between themselves by flight connections which introduce sequential constraints between flights, these constraints are effective if passengers can use these connections. To each departing flight f of airline α can be attached a set of predecessor flights Φ_f^α which satisfy different constraints such as same airlines group, same airport, passenger transfer is feasible and waiting time is acceptable. Among the daily operated flights, source and end flights can be identified. The set of daily source flights for airline α, S_α, is composed of its flights with no predecessor that day and the set of daily end flights for airline α, E_α.

Let $\Phi^\alpha = \bigcup_{f \in F_\alpha} \Phi_f^\alpha$, the pair $[F_\alpha, \Phi^\alpha]$ built up for each airline α a directed graph G_α, the Flight Transfer Graph, whose vertices are the

flights operated and the arcs are associated with the precedence constraints. This directed graph without circuits links the sources flights S_α to the end flights E_α through intermediate connected flights with $|S_\alpha| = |E_\alpha| = |V_\alpha|$. Let also G_α^f be the transitive closure of vertice *f* in G_α. Let Γ_f be the set of arcs leading to the vertice associated to flight *f* and Γ^f the set of arcs leaving the vertice associated with flight *f* in graph G_α . Then it is possible to assign in an increasing way, a rank r_f to each flight *f* of F_α with a maximum rank $r_{max} = \max_{f \in E_\alpha} r_f$. Then, between the source flights and the end flights, the different possible paths, or *cross paths*, composed of successively connected flights, can be defined. Let P_α be the number of these paths, the p^{th} path will be composed of a source flight f_p^s, n_p intermediate flights, $f_n^p, n = 1\ to\ n_p$ and an end flight f_p^e.

4. FEASIBLE DEPARTURE FLIGHT PLANS

For each flight *f* in S_α is attached an earliest starting time t_d^{Ef} which corresponds to the earliest time at which all resources for this flight can be made available at its departure airport. For each flight *f* in E_α is attached a latest starting time t_d^{Lf} which corresponds to the latest time at which all resources for this flight can be made available at its departure and arrival airports. Then, beginning from the earliest starting times of flights in S_α it is possible to compute by increasing rank in G_α for each remaining flight an earliest starting time t_d^{Ef} given for $f \in F_\alpha - S_\alpha$ by:

$$t_d^{Ef} = max_{\varphi \in \Phi_f^\alpha} \left\{ t_d^{E\varphi} + DF_\varphi + GAD_{\varphi f} + T_{\varphi f} \right\} \quad (3)$$

where $T_{\varphi f}$ is the transfer time from flight φ to flight *f*. Then, beginning from the latest starting times of flights in E_a, it is possible to compute through decreasing rank for each remaining flight a latest starting time t_d^{Lf} given for $f \in F_\alpha - E_\alpha$ by:

$$t_d^{Lf} = min_{\varphi \in (\Phi_f^\alpha)^{-1}} \left\{ t_d^{L\varphi} - DF_f - GAD_{f\varphi} - T_{f\varphi} \right\} \quad (4)$$

Then a feasible flight programs will exist if for each flight *f*, t_d^{Ef} is inferior or equal to t_d^{Lf} and then for each flight $f \in F_a$, the feasible period for departure is such as $t_d^{pf} \in \left[t_d^{Ef}, t_d^{Lf} \right]$. When there a no feasible departure time window, the question which arises is whether or not it is possible to turn it feasible by modifying the duration of some flights. If this is not possible, the frame of the flight program must be modified either by deleting some flights or by introducing new airplanes and crews.

The duration of a flight *f*, DF_f, covers here taxi-out, take-off and climb, cruise, approach, descent, landing and taxi-in. The duration of the climb, cruise, descent and approach phases depends of the flight plan adopted by the airline through the choice of tactical parameters such as the cost index for its flight management programme which corresponds to a relative weight of the cost of fly time with respect to the and cost of fuel. The other phases of the trip, taxi-out, take-off, landing and taxi-in, are considered to have durations which cannot be changed by the airline even if a limited choice can exist with respect to parking positions. Then the cost of a flight for an airline can be written as:

$$C_f(DF_f) = C_f^{cst} + C_f^{var}(DF_f)$$
$$\text{with} \quad DF_f^{min} \le DF_f \le DF_f^{max} \quad (5)$$

where C_f^{var} is a decreasing function of DF_f, DF_f^{min} corresponds to a maximum value of the cost index and DF_f^{max} corresponds to a minimum value of the cost index.

The set of flight succession constraints (1) and (2) will be satisfied if cross paths of G_α are such as for $p \in [1, \dots, P_\alpha]$:

$$t_d^{Ef_p^s} + \sum_{n=1}^{n_p} (DF_{f_n^p} + GAD_{f_n^p f_{n+1}^p} + T_{f_n^p f_{n+1}^p}) \le t_d^{Lf_p^e} \quad (6)$$

If constraints (6) are satisfied adopting the maximum duration for each flight, the proposed flight plan is loose enough for each flight be operated at minimum flight cost. If it is not the case but constraints (6) are satisfied adopting the minimum duration for each flight, it will be necessary to find feasible flight durations so that condition (6) are satisfied at the minimum total operating cost. What will be of interest for the airline will be

to set the flight durations to minimize the total flight cost. This lead to formulate the following convex optimization problem with linear constraints, called here NCIO (Network Cost Index Optimization):

$$min \sum_{f \in F_\alpha} C_f(DF_f) \qquad (7)$$

under constraints (5) and (6) . Then , the concept of *network cost index* appears, where to each flight corresponds a globally optimal cost index according to (7): the choice of cost index is no more independent from one flight to the next when flight scheduling is too tight. In the case of a loose flight schedule for flight *f*, the natural solution will be: $DF_f^* = DF_f^{max}$. Observe that problem (7) is a linear convex mathematical programming problem with well known solution algorithms such as the convex simplex.

5. FACING DELAYED OPERATIONS FROM AIRLINES

Here it is considered that once flight delays appear, airlines try to update their flights plan so that they remain feasible and when flight schedules become too tight, they have to adopt global scheduling solutions for the now interdependent flights. Also, it is considered useful to compute for each remaining flight a frequently updated estimation of its induced delays on the remaining of the flights either at arrival or departure, allowing to point out delay critical flights. In this study reductions of ground-handling or transfer durations is not developed but could be easily introduced in the analysis when potential benefits appear possible.

Let $S_{\alpha d}(t)$ be the set of flights of airline α which have already departed at that time t , either on time or not. Then the current ***e****xpected* earlier departure of flights ϕ of $F_\alpha - S_{\alpha d}(t)$ will be $t_d^{e\phi}(t,0)$ given through increasing rank as for $\phi \in F_\alpha - S_{\alpha d}(t)$:

$$t_d^{e\phi}(t,0) = \max\left\{t_d^{p\phi}, max_{g \in \Phi_\phi}\left\{\begin{matrix} t_d^{eg}(t,0) + \\ DF_g + GAD_{gf} + T_{gf} \end{matrix}\right\}\right\} \qquad (8)$$

while for flights of $S_{\alpha d}(t)$, $t_d^{e\phi}(t,0)$ is equal to the ***e****ffective* departing time of flight ϕ. A similar notation is adopted for arrival times for $\phi \in F_\alpha - S_{\alpha d}(t)$:

$$t_a^{e\phi}(t,0) = t_d^{e\phi}(t,0) + DF_\phi \qquad (9)$$

Let expression (10) be the set of constraints corresponding to the constraints (6) reduced to the remaining flights, $p \in [1, \dots, P_\alpha]$:

$$t_d^{ef_p(t)} + \sum_{f_n \in \pi_p(t)} \left(\begin{matrix} DF_{f_n^p} + \\ GAD_{f_n^p f_{n+1}^p} + T_{f_n^p f_{n+1}^p} \end{matrix} \right) \leq t_d^{Lf_p^e} \qquad (10)$$

where $f_p(t)$ is the current operated flight of cross path *p* at time *t*, while $\pi_p(t)$ is the set of the remaining flights of cross path *p* which have not started at time *t*. Then, the tactical duration of flight plans can be updated by solving the updated version of NCIO, relation (6):

$$min \sum_{f \in F_\alpha - S_{\alpha d}(t)} C_f^{var}(DF_f) \qquad (11)$$

under constraints (5) and (10). The solution of problem (11) results in the desired flight durations at time *t*: $DF_f^*(t)$, $f \in F_\alpha - S_{\alpha d}(t)$.

Then, to know at current time *t* the expected network effect of a delay δ at departure time of flight *f*, the computation of the departure times for the flights belonging to the transitive closure of flight f in G_α , G_α^f, should be updated starting with $t_d^{ef}(t,\delta) = t_d^{ef}(t,0) + \delta$ and by increasing rank order:

$$\forall f \in F_\alpha - S_{\alpha d}(t): \forall \phi \in G_\alpha^f:$$

$$t_d^{e\phi}(t,\delta) = \max\left\{t_d^{p\phi}, max_{g \in \Phi_\phi}\left\{\begin{matrix} t_d^{eg}(t,\delta) \\ +DF_g^*(t) + GAD_{g\phi} \end{matrix}\right\}\right\} \qquad (12)$$

and $$t_a^{e\phi}(t,\delta) = t_d^{e\phi}(t,\delta) + DF_\phi^*(t) \qquad (13)$$

Then the total induced arrival delay estimated at time *t* and resulting from a departure delay δ for flight *f* of airline α will be given by:

$$T_{\alpha f}^a(t,\delta) = \sum_{\varphi \in G_\alpha^f} \left(t_a^{e\varphi}(t,\delta) - t_a^{e\varphi}(t,0) \right) \qquad (14)$$

While the total induced departure delay estimated at time *t* and resulting from a departure delay δ for flight *f* of airline α will be given by:

$$T_{\alpha f}^d(t,\delta) = \sum_{\varphi \in G_\alpha^f} \left(t_d^{e\varphi}(t,\delta) - t_d^{e\varphi}(t,0) \right) \qquad (15)$$

Here according to the way departure times are computed, $T_{\alpha f}(\delta)$ should be an increasing piecewise linear function of δ. This computation can be performed for different values of δ over a given time span The maximum sustainable value of δ for flight *f*, written $\delta^{ft}_{\alpha\max}$ at time *t*, corresponds to the value of δ beyond which it becomes no more possible to comply with the upper limit for departure for some of the flights of the transitive closure of *f* in G_α . This maximum value is given by:

$$\delta^{ft}_{\alpha max} = min\{\delta / \exists \varphi \in G^f_\alpha : t^{e\varphi}_d(t,\delta) = t^{L\varphi}_d\} \quad (16)$$

Then for a departure delay for flight *f* greater than $\delta^{ft}_{\alpha max}$, the remaining flight program is no more feasible and must be revised at period *t*: flights or connections must be cancelled.

6. FACING DELAYED OPERATIONS FROM ATC

It is assumed here that no trading process takes place for arrival slot ownership or allocation, the only objective, beyond safety being to mitigate congestion effects on traffic, i.e. delays. It is also assumed that collaboration between airlines through aircraft, ATC and airport operations takes place, fully endorsed by ad-hoc regulations. This paragraph proposes a collaboration scheme between these actors which is developed according to a tempo based on different time scales.

It is supposed that a landing runway and an arrival time slot are assigned to each arriving aircraft before TOD (Top of Descent) on a first come-first served basis mixed with priority, so that aircraft have a stable scenario to optimize their descent and satisfy overfly and noise constraints. This will take place roughly between 30 min and 20 min before landing (Δ=10 min for decision making + about 20 min for descent). The common arrival time slot duration δ_S for all operated aircraft, about 2 min, covers final approach, landing and roll-out until exit from runway.

Then when flight *f* reaches its top of descent point TOD at time t^f_{TOD}, an arrival time slot chosen between $t^f_{min} = t^{e\varphi}_d(t^f_{TOD} - \Delta,0) - \Delta^f_{min}$ and $t^f_{max} = t^{e\varphi}_d(t^f_{TOD} - \Delta,0) - \Delta^f_{max}$ must have been assigned to it during decision period $[t^f_{TOD} - \Delta, t^f_{TOD}]$ by ATC. Here Δ^f_{min} represents for the aircraft operating flight *f* the maximum feasible descent shortening while Δ^f_{max} represents the maximum feasible descent extension. Let $s^f_1, s^f_2, \ldots, s^f_{n_f}$ be the successive reachable arrival time slots for flight *f* at time $t^f_{TOD} - \Delta$, with $[t^f_{min}, t^f_{max}] = [s^f_1, s^f_{n_f} + \delta_S]$. To each of these time slots can be attached an extended arrival delay for flight *f* :

$$EAD^f_n(\delta^f_n) = \begin{pmatrix} (t^{ef}_a(t^f_{TOD} - \Delta,0) - t^{pf}_a) \\ +\delta^f_n + T^a_{af}(t^f_{TOD} - \Delta, \delta^f_n) \end{pmatrix} \quad (17)$$

$$\text{with} \quad \delta^f_n = s^f_n - t^{ef}_a(t^f_{TOD} - \Delta,0) \quad (18)$$

$EAD^f_n(\delta^f_n)$ defined by relation (18) represents the addition of the estimated delay of flight *f* at time $t^f_{TOD} - \Delta$, of the supplementary delay (δ^f_n which can be positive or negative) associated to the assigned arrival time slot and the induced delay on successive flights. There is no distinction between on time and delayed flights so that compression effects can be introduced to diminish the presence of unused arrival time slots.

First, arrival capacity is checked for period $[t^f_{min}, t^f_{max}]$ at time $t^f_{TOD} - \Delta$: If the number of arriving flights during period $[t^f_{min}, t^f_{max}]$ is superior to n_f, choose among these arriving flights φ with $t^\varphi_{TOD} > t^f_{TOD} - \Delta$ (this includes *f*), the one with smaller extended delay and assign it a delayed trajectory or holding position and a new TOD, repeat this until capacity matches non delayed arrivals.

Then, the assignment procedure, ASATS, activated for flight *f* when *t* =$t^f_{TOD} - \Delta$ or when its assigned arrival time slot has been reassigned to another flight, is a greedy on-line heuristic algorithm given by:

ASATS (f, $t^f_{TOD} - \Delta$):

n:=1

iter:

if s^f_n is free, assign slot n to flight f: $t^{ef}_a(t^f_{TOD}, 0) = s^f_n + \delta_S$, end.

if s^f_n is already assigned to a flight φ:

if $t^\varphi_{TOD} \le t^f_{TOD} - \Delta$, assignment is frozen to flight φ, do $n = n+1$ and go back to iter;

if $t^\varphi_{TOD} > t^f_{TOD} - \Delta$, compare extended arrival delays of flight f and φ :

if $EAD^f_n(\delta^f_n) \le EAD^\varphi_n(\delta^\varphi_n)$ do $n = n+1$ and go to iter;

if $EAD^f_n(\delta^f_n) > EAD^\varphi_n(\delta^\varphi_n)$: unassign slot n to flight φ, free slot s^f_n and go to iter;

At time t^f_{TOD}, the estimated time of arrival, including the assigned arrival time slot, is frozen for the descent phase: $t^{ef}_a(t) = t^{ef}_a(t^f_{TOD}, 0)$ for $t^f_{TOD} \leq t \leq t^{ef}_a(t^f_{TOD}, 0)$. The first goal of the proposed on-line heuristic is to assign to a flight the first reachable free arrival time slot, this should limit additional delays. The second goal, when a reachable slot is already assigned but not already frozen, is to assign that slot the more delay critical competing flight, so that over delays is not generated for some flights. A different choice can be done at this stage inverting the two last inequalities, leading now to disturb as less as possible not delayed or slightly delayed flights. So another layer could be added to the ASATS procedure by checking if concurrent aircraft *f* and φ are from the same airline group or not. In the first case, delays impacts will be shared and in the second case, they will remain segregated.

7. FACING DELAYED OPERATIONS FROM AIRPORT

It is assumed here also that no trading process takes place for departure slot ownership or allocation, the only objective, beyond safety, being to manage efficiently airport capacity for flight departures. It is also assumed that collaboration between airlines, ATC and airport operations takes place through an Airport Collaborative Decision Making process easing exchange of flow information and coordination of the different processing stages of aircraft associated with arriving and then departure flights.

Once flight *f* has arrived, its effective arrival time (it is the "in-block time (AIBT)" of A-CDM) can be written $t^{ef}_a(t)$. Once aircraft is ready for next flight *f'*, start up is requested at time $t^{f'}_{dr}$ to control tower ("Start up request time (ASRT)" of A-CDM) . At this point, the start up approval process ("Start up approved time, ASAT" of A-CDM) can either generate new delays or on the contrary, reduce existing delays. Remembering that in this study the duration of a flight covers also taxi-out and take-off , if start up approval is immediate for flight *f'*, its departure delay will be given by $t^{f'}_{dr} - t^{pf'}_d$. Here also, total induced delay can be computed by the airline operating flight *f'*.

Let $P^{f'}_\alpha$ bet the set of cross paths to which flight *f'* belongs, then expression (18) be the set of constraints corresponding to constraints (6) reduced to the remaining flights:

$$t^{f'}_{dr} + \sum_{f_n \in \pi_p(t)} \begin{pmatrix} (DF_{f^p_n} + \\ GAD_{f^p_n f^p_{n+1}} + T_{f^p_n f^p_{n+1}}) \end{pmatrix} \leq t^{Lf^e_p}_d \quad p \in P^{f'}_\alpha \qquad (19)$$

The current tactical duration of flight plans can be computed by solving the updated version of NCIO , relation (8):

$$min \sum_{f \in \pi_p\left(t^{f'}_{dr}\right), p \in P^{f'}_\alpha} C^{var}_f(DF_f) \qquad (20)$$

with constraints (6) and (19).

The solution of problem (20) results in the desired flight durations at time $t^{f'}_{dr}$: $DF^*_f(t^{f'}_{dr})$, $f \in \pi_p\left(t^{f'}_{dr}\right), p \in P^{f'}_\alpha$. Then, at time $t^{f'}_{dr}$, to estimate the expected network effect of a delay δ at departure time of flight *f'*, the computation of the departure times for the flights belonging to the transitive closure of flight *f'* in G_α , $G^{f'}_\alpha$, should be updated starting with $t^{ef}_d(t^{f'}_{dr}, \delta) = t^{f'}_{dr} + \delta$ and by increasing rank order:

$$t^{e\phi}_d\left(t^{f'}_{dr}, \delta\right) = \max\left\{ t^{p\phi}_d, max_{g \in \Phi_\phi} \begin{Bmatrix} t^{eg}_d\left(t^{f'}_{dr}, \delta\right) \\ +DF^*_g(t^{f'}_{dr}) + GAD_{g\phi} \end{Bmatrix} \right\} \quad p \in P^{f'}_\alpha \qquad (21)$$

and

$$t^{e\phi}_a(t^{f'}_{dr}, \delta) = t^{e\phi}_d(t^{f'}_{dr}, \delta) + DF^*_\phi(t^{f'}_{dr}) \qquad (22)$$

Then the total induced arrival and departure delays estimated at time $t^{f'}_{dr}$ and resulting from a departure delay δ for flight *f'* of airline α ,respectively $T^a_{\alpha f'}(t^{f'}_{dr}, \delta)$ and $T^a_{\alpha f'}(t^{f'}_{dr}, \delta)$, are given by:

$$T^a_{\alpha f'}(t^{f'}_{dr}, \delta) = \sum_{\varphi \in G^{f'}_\alpha} \left(t^{e\varphi}_a(t^{f'}_{dr}, \delta) - t^{e\varphi}_a(t^{f'}_{dr}, 0)\right) \qquad (23)$$

and

$$T^d_{\alpha f'}(t^{f'}_{dr}, \delta) = \sum_{\varphi \in G^{f'}_\alpha} \left(t^{e\varphi}_d(t^{f'}_{dr}, \delta) - t^{e\varphi}_d(t^{f'}_{dr}, 0)\right) \qquad (24)$$

When start up for flight f' is delayed of δ, it can be attached to flight f' at time $t_{dr}^{f'}$, an extended departure delay:

$$EDD_n^f(\delta) = (t_{dr}^{f'} - t_d^{pf'}) + \delta + T_{af'}^d(t_{dr}^{f'}, \delta) \quad (25)$$

Let $\sigma_1^{f'}, \sigma_2^{f'}, \ldots, \sigma_{n_d}^{f'}$ be the successive reachable departure time slots at the runway for flight f' at time $t_{dr}^{f'}$. To each of these departure time slots at the runway, is attached a start up time (including engines warm up) at the gate: $t_{d1}^{f'} < t_{d2}^{f'} < \ldots < t_{dn_d}^{f'}$ corresponding to departure delays $\delta_i^{f'} = t_{di}^{f'} - t_{dr}^{f'}, i = 1, \ldots, n_d$.
Then, the assignment procedure, ASDTS, activated for flight f' at ASRT or when its assigned departure time slot has been reassigned to another flight, is a greedy on-line heuristic algorithm given by:

ASDTS (f', $t_{dr}^{f'}$)

n:=1
iter:
if $\sigma_n^{f'}$ is free, assign departure slot $\sigma_n^{f'}$ to flight f': $t_a^{ef}(t_{dr}^{f'}, 0) = t_{dn}^{f'}$, end.
if $\sigma_n^{f'}$ is already assigned to a flight φ but it start up
request has not been still approved,
    if the corresponding start up time for φ has been approved,
    do $n = n+1$ and go back to iter;
    otherwise, compare extended departure delays of flight f' and φ :
        if $EDD_n^{f'} \leq EDD_n^{\varphi}$ do $n = n+1$ and go to iter;
        if $EDD_n^{f'} > EDD_n^{\varphi}$: unassign slot $\sigma_n^{f'}$ to flight φ,
        free slot $\sigma_n^{f'}$ and go to iter;

Then, once approved, departure time for flight f' is: $t_d^{ef'} = t_{dn}^{f'}$. If delay for start up approval is important, problem (19) with updated constraint (18) can be run to get updated previsions of arrival times of flights $f' \cup G_{\alpha}^{f'}$.

8. CONCLUSION

This communication has considered the operation of a domestic air transportation network and more particularly the management of flight delays which propagate along the networks operated by the different airlines. In the proposed scheme in-flight delays can be treated during cruise in a global way by airlines, arrival delays are processed by ATC up to TOD time while the processing of departure delays is under responsibility of airport tower. The flows of information within the CDM scheme is sketched in figure 2 where different milestones are introduced (ALDT: estimated landing time, AIBT: estimated block in time, ASRT: estimated start up request time, ASAT: start up approved, ATOT: estimated take off time).

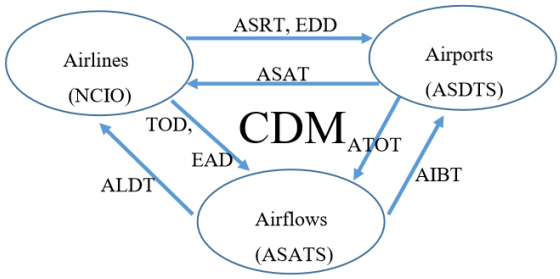


Figure 2: Global view of proposed CDM scheme

Coordinated decisions of the different actors will contribute to reduce the effect of primary delays. It is worth to be observed that both procedures ASATS and ASDTS can be easily modified to integrate ground delay programs when next destinations are known to be saturated, so *no need to hurry* policies can be implemented by modifying accordingly the EAD and EDD indexes of concerned flights. However in some cases with large disruptions, flight rescheduling will be necessary. In that cases, new decision tools should be developed for the different actors of air transport operation.

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