Air Traffic Flow Management  
Pre-tactical Planning  
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Abstract—This paper presents a new architecture for the process of Air Traffic Flow Management. Its main advantage is to help undertaking a reliable regulation in presence of uncertainties corrupting the real air traffic. We focused on delay propagation through aircraft daily schedule of flights, as an example of the interactions that our pre-filter shall detect. We proposed mathematical models to perform this task as well as decision on delay allocation which becomes necessarily stochastic. Up-to-date results are encouraging but a global simulation is still required to validate the improvement of the process.

Index Terms—Aircraft Lifecycle, Airline Operations Control, Air Traffic Flow Management, Delay Propagation, Regulation

I. INTRODUCTION

Air Traffic Management is a broadly defined function which includes airspace management (ASM), air traffic control (ATC) and air traffic flow management (ATFM). Its objective is to enable aircraft operators to meet their planned schedules of arrival and departure and adhere to preferred flight profiles.

Air Traffic Flow Management (ATFM) is an important service, it aims to ensure an optimum flow of air traffic to or through airspaces during times when demand exceeds, or is expected to exceed, available capacity of the air traffic control (ATC) system. The term ATFM is used to embrace any activity concerned with the organization and handling of the flow of air traffic in such a way that, while ensuring the safe, orderly and expeditious flight of individual aircraft, the totality of the traffic handled at any given point or in any area is compatible with the capacity of the ATC system. The term ATC capacity reflects the ability of the ATC system or any of its subsystems or operating positions to provide service to aircraft during normal activities, and is expressed in numbers of aircraft entering a specified portion of the airspace in a given period of time. The maximum peak capacity which may be achieved for short periods may be appreciably higher than the sustainable capacity. ATFM supports ATC in meeting its main objectives of preventing collisions between aircraft, expediting and maintaining an orderly flow of air traffic, as well as of achieving the most efficient utilization of available airport and airspace capacity.

The most efficient utilization of available airport and airspace capacity can be achieved only if all relevant elements of the air traffic system had been considered during the planning stage, applying a systems approach. The flow of traffic is hampered by bottlenecks in the system; a constraint anywhere in the system will contribute to capacity limitations. For that reason, neither the airport system nor the air navigation system should be considered separately in planning system improvements. Present-day airspace utilization is not seen as being optimal and/or flexible in the broadest sense because of the existing discrepancy between ATC capacity and users’ demands, particularly during peak traffic periods. Moreover, operational events lead to situations where air traffic flows exceed the capacity of ATC system, which pose a threat to ATM system safety, in a context characterized by a continuous growth of demand.

In this study, we are interested in the current ATM system shortcomings related to ATFM planning. So we describe the implemented process for ATFM, the nature of perturbations and interactions that contribute to balance failure. Then we propose another design for the process, more appropriate for anticipating changes in flight demand. Finally, we shed light on the transition from deterministic regulation to fuzzy and/or stochastic decision.

II. CURRENT IMPLEMENTATION

Balancing in the European ATM system consists in ground delay programs, aircraft may be affected by regulation delay at departure airports in order to satisfy capacity constraints of arrival airport and airspace sectors throughout the trajectory. The Central Flow Management Unit, located in Brussels, uses the flight plans already submitted to measure magnitudes of traffic volumes in the system then generates the required amounts of delay.

Flight plans are submitted at least three hours before the estimated off-block time, when regulation starts at about two hours before off-block time, the required delay is continuously (i.e. periodically) updated according to the global air traffic demands and the capacity limitations activated by ATC. Priority is given to the first aircraft planned to enter the sector,
as equity suggests.

With operational events of air traffic, the process loses its ability to ensure ATC requirements and traffic volumes can exceed capacity levels. In such situations, en-route controllers change their opening scheme configuration and may require the CFMU to activate some constraints on some specific flows. There is a trade-off between under use of system resources (i.e. keeping margin in occupancy rate) and real-time constraint satisfaction (i.e. real air traffic compatible with ATC needs).

![FIG. 1 CURRENT IMPLEMENTATION OF ATFM](image)

Previous description is depicted in Figure 1, now there are two important remarks:

1. Perturbations are not independent from the input signal. In fact airlines use aircraft in a series of flight services, if an aircraft has a mechanical failure, all that flights planned to be accomplished by this aircraft will be subjected to uncertainty. Passengers connection problems related to hub and spokes strategy provide another example where uncertainty is quite dependent of traffic demand.

2. Regulation is made on the basis of flight plans already submitted, under assumption that the flights are all on time (or have negligible delay). This leads generally to bad estimation of traffic volumes in airspace sectors. Let’s consider a two hours flight from 12:00 to 14:00, at 11:30 the flight is still confronted to flights such those taking-off from its arrival airport at about 13:30, counting cannot be reliable with no a priori information about aircraft punctuality.

![FIG. 2 AIRLINE OPERATION EFFECT ON ATFM](image)

III. PERTURBATIONS AND INTERACTIONS

The primary purpose of aircraft operations control is to ensure the optimum operation of flights planned for a certain defined period ahead of departure and until their completion, and to coordinate with all concerned and finally and disseminate information about any measures taken in case of irregularities. Within an airline organization, this centralized function is carried out by the Airline Operations Center (AOC) and its main objectives are: to keep the flight program as close as possible to the published schedule; and minimize the effects of any irregularities in accordance with company policy. In so doing, the AOC will keep the various operational departments concerned informed about the movement of aircraft, e.g., flight operations, engineering control, passenger and airport.

Accurate and timely information concerning aircraft departures and arrivals, and variations to the planned flight programs, such as delays, diversion, cancellations, re-routings, and change of aircraft type, will enable the operational departments to coordinate their activities in the best interests of airline customers, thereby enhancing flight safety, punctuality and regularity, and reducing costs.

To control effectively a large fleet of aircraft for a worldwide operation is a very complex undertaking. Today, computerized systems process and organize the immense amount of data involved and provide the Airline Operations Centers with a better knowledge of the total situation and the likely consequences involved. As a result, this improves the operational decision-making process which, in turn, can contribute significantly to efficiency and profitability of airline operations [2].
Uncertainty is inherent in Air Traffic Management, if it’s impossible to foresee an aircraft failure or to prevent bad meteorological conditions, delays spoiling the series of flights because of propagation and airline operational control policies can be estimated by modeling the behavior of dispatchers. The role of the pre-filter is to compensate the disruptions resulting from OCC tactical actions.

Because of the complexity of this task, we restrict the scope to the phenomenon of delay propagation throughout the daily schedule of an aircraft, as follows.

Pre-filtering needs to have knowledge of the allocation between aircraft and flights, flights A and B of figure 4 relate to the same plane. It’s a pity that flight plans mention call signs with aircraft types but no information about aircraft tail numbers. Since that’s how it is, airline are able to substitute for aircraft of the same type in order to minimize the costs of delays without filing new flight plans, imperiously three hours before the estimated off-block times. A peaceful way to undertake this problem consists in trying to match the flights accomplished by the same aircraft on the basis of flight plans data.

For the purpose of clarity, we are going to provide a real example of pre-filtering based on coupling departure with arrival flights. However the general inference process remains beyond the scope of this paper as mentioned before, because of the diversity of phenomena, airlines characteristics and behaviors. The matter is still under investigation.

V. Example of Correction

A. Sample of Data

1) Day, Airline and Airport

We have chosen the flights of Air France (AFR) to and from Frankfurt airport (EDDF) on Thursday March 10th 2005. As with other airlines, the Air Traffic Controller’s strike is likely to disrupt the Air France flight schedule. Such a day is full of uncertainty and inconvenience, up with civil service trade unions. Frankfurt has one of the most crowded airports in Europe, Air France schedules ten round trip flights per day between this destination and Paris Charles-de-Gaulle airport. This is the archetypal behavior of foreign airlines, its aircraft come then return to its basis.

2) Key of Figure 5

Call signs (i.e. AFR1618) are replaced on the schedule of flights by numbers in order to lighten the picture. Each color depicts an aircraft type (i.e. A320 for airbus 320 and E145 for Embraer 145). Vertical lines corresponds to times for runways movements, landing and take-off times are on opposite sides of the time axis. Finally the filed flight demand is shown in the upper part of the figure, whilst the current air traffic occupies the lower one.

B. Coupling Flights

1) Principle

Using flight plans of all the flights an airline wishes to make to and from a given airport during the day, we want to find the pairs of flights completed by the same aircraft. Information contained in flight plans consists of scheduled take-off or landing times, types of aircraft, destination or origin airports and call signs. An aircraft landing at an airport can take-off after a span sufficient to unload luggage and passengers, refueling, catering, cleaning, load new luggage and passengers and taxiing towards the runway. A set of pairs is feasible if it satisfies this minimum time for ground operations. From all that feasible solutions, the right one, which corresponds to the reality, shall be of cardinal maximum as commercial airlines would rather do.

2) Case of Figure 5

The pairs are: (3-6), (0-4), (7-5), (12-10), (8-14), (9-11), (13-15), (16-17) and (18-19).

1 Touch-and-go movements are not considered. In some airports, training pilots take-off before a complete stop on the runway.
If we choose (8-11) (9-14) instead of (8-14) (9-11), the solution becomes unfeasible. Indeed there is not enough time between landing 9 and take-off 14. Air France don’t use absorber margins in ground time, the 1h30 span for Airbus and 1h only for Embraer are cutting it a bit fine.

Assume aircraft belongs to a civilian operator, foreign to airport’s country and the flights are with a single destination, the following reasoning is correct: few aircraft may spend the night at the airport and take-off in the morning, what remains can be put in chronological order and matched with FIFO discipline within each class of aircraft types. There is a small exception in case of multiple flight plans, in fact airline may submit a new (delayed version) of a flight plan, so if there are two or more flight plans with same call sign in the same day: that’s one flight.

Notice that this reasoning becomes false if the assumptions don’t hold. Anyway, we are proposing a classical graph modeling for the matching problem and a linear programming approach for its resolution. The previous reasoning is only useful in inference rules at pre-filtering level.

C. Air Traffic Short-Time Correction

1) Qualitative Analysis

Flight AFR1318 corresponding to landing 12 was cancelled, take-off 10 is then impossible. The same thing for the flights related respectively to take-off 14, 11 and 15 for Airbus 319 and 6 and 5 for Airbus 320.

Embraer aircraft has arrived late (landing 16), with no absorber its next scheduled departure (take-off 17) has kept the same delay. We are going to perform a quantitative analysis for this aircraft in the section.

In spite of 3 hours late arrival (landing 0 and 18), airbus aircraft have taken off with slight delays, this is due to the wide spans between scheduled consecutive movements of these aircraft on the runway, fortunately to passengers because the airline is not used to absorbers.

At the origin airport, which is here Paris Charles-de-Gaulle, prediction is possible from the estimated off-block time. More accuracy is get as soon as aircraft start moving. With roughly one hour spent in the air and one other hour on ground, aircraft takes-off once in an interval of two hours, which means information about its next scheduled flight i.e. return from Frankfurt is available two hours before getting in the sky. 2 hours is the magnitude of time the Central Flow Management Unit begins to apply regulation process.

2) Quantitative Analysis

We focus here on the Embraer aircraft which served the flights AFR251E (landing 16) and AFR519T (take-off 17). As depicted in Figure 6, this aircraft have taken off with 51 minutes of delay, because of the regulation FRPAE10N (controllers strike drawbacks). The expected time on flight was 51 minutes; the aircraft made only 48 minutes and hence decreased the delay to 48 minutes. With no margin in the in-block period on ground, the aircraft taken-off from Frankfurt with 46 minutes of delay, it has woned 2 minutes again when being airborne just 42 minutes before landing in Paris with a delay of 44 minutes.

In brief, even with a coarse inference like supposing the delayed aircraft can make up for 5 minutes with no absorber, the prediction magnitude sounds fair. Moreover, the actual off-block time of AFR251E in Paris was 2h15 earlier than take-off time of AFR519T.

Different from the opposite way, routes are not in both directions.
VI. Mathematical Resolution

Flight coupling problem can be modeled using graph theory.

A. Graph Vertices and Edges

In the sequel, $G = (V, E)$ denotes the graph representing the schedule of airline’s flights at the airport, completed by the same type of aircraft. Otherwise $G$ will have as many connected components as types of aircraft in use.

$V$ is the set of vertices, constituted of both arrival and departure flights.

$E$ is the set of edges. $(v_1, v_2)$ is element of $E$ if and only if $v_1$ is an arrival, $v_2$ a departure and the landing time of $v_1$ is less than take-off time of $v_2$, as mentioned in the filed flight plans. $G$ is indeed a directed graph.

The graph $G$ is valuated on its edges by a function $T$

$$T(v_1, v_2)$$ is simply the difference between $v_2$’s take-off time and $v_1$’s landing time.

As noticed, the graph could be chosen as a clique (i.e. each vertex has an edge all other vertices) then the edges with negative value will be ignored. Graph problems are normally NP-complete, so there is no need to increase the size of the problem. It is recommended for limiting the degree of vertices (i.e. the number of edges it have) under a threshold by removing vertices of small positive values then keeping the first ones, however one has got to be careful because the required minimum separation time may be over-evaluated and the threshold under-evaluated, see figure 7.

B. Problem to Resolve

We want to find a set of maximum number of pairs satisfying the minimum separation constraint. If the value of this minimum separation is well known, all solutions become feasible if we devote $G$ to the edges of greater values.

Remark: a set of coupling of maximum cardinal is required because commercial strategy is to keep aircraft in the air insofar as possible for profit. Data of the fleet McDonnell Douglas C-17 Globemaster III, belonging to operator RCH (Reach, USAF, Rhein-Main air base) proved to us that military operations are totally different.

C. Linear Programming Approach

The following program resolves the maxim coupling problem:

- For all edges $(i, j) \in E$, $X(i, j) = 0$ or $1$.
- For all vertices $k \in V$, $\sum_{(i, j) \in E} X(i, j) \leq 1$. s.t. $i = k$ or $j = k$

This constraint means no multiple affectations to vertices.

- Criterion, $\arg \max_{(i, j) \in E} \sum w(i, j) X(i, j)$

The weight $w(i, j)$ is equal to $1$ if $T(i, j) > \text{min, } 0$ otherwise. This means that we are looking to a set of couples arrival / departure that satisfy minimum separation constraint.

This physical problem has always solutions, but uniqueness is not guaranteed.

D. Auto Correlation Approach

If the previous problem has an optimal solution which violate FIFO order, i.e. it contains two edges $e_1 = (\text{Arr}1, \text{Dep}1)$ and $e_2 = (\text{Arr}2, \text{Dep}2)$ such that: Land (Arr1) < Land (Arr2) < Take-off (Dep2) < Take-off (Dep1), as described in Figure 8; then the set of couples with the same elements except $e_1 = (\text{Arr}1, \text{Dep}2)$ and $e_2 = (\text{Arr}2, \text{Dep}1)$ instead of $e_1$ and $e_2$ is also feasible and with same cardinal. By recurrence, there is always an optimal solution which does not violate FIFO order.

FIG. 6 Take-off and landing times of E145 aircraft

FIG. 7 Hazard of graph shortening

FIG. 8 Case of FIFO order violation
The one of maximum cardinal of couples satisfying minimum constraints is an optimal solution to the problem.

E. Uniqueness Problem

In reality, when an airline schedules two aircraft of the same type to take-off from the same airport at closer instants, we shall consider them as one entity. It is the flight having less cost which is cancelled or delayed, regardless the planned allocation between aircraft and flights. Some airlines choose its slots at airports in this way especially to do such management in case of disruptions.

VII. DECISION

After presenting a full example of prediction in Part V and a way to automate the process in Part VI, we will tackle the problem of decision in this section. In most of cases, the punctuality of aircraft stay in airspace sectors is quite well assessed; however there are cases where decision becomes faulty.

In the enlightening case of Part V- section E, if the aircraft are planning to fly in opposite directions (e.g. north/south), even if we know that only one of the two flights is on time and the other will have one hour of delay because of late arrival, we cannot guess which one. For that reason the counting is to likely to be either fuzzy or stochastic [3].

In our context, regulation delays are to be allocated to aircraft in order to ensure ATC capacity constraints, on the basis of fuzzy or stochastic traffic volumes. Anyhow, it is better than current counting which doesn’t keep pace with air traffic dynamics.

A. Deterministic Regulation Model

Let’s consider regulation policy that minimizes a global cost of the system such as total ATFM delay. This can be achieved by different variant formulations, like the following one:

- For all aircraft \( i \in A \), \( T(i) \geq 0 \) indicates the corresponding ATFM delay required.
- For each sector \( k \in S \) of capacity \( C(k) \), for each aircraft \( i \) and \( j \) planning to enter the area \( k \) at estimated time over \( ETO(k, i) \) and \( ETO(k, j) \), we shall have:
  \[
  [ETO(k, i) + T(i)] - [ETO(k, j) + T(j)] \geq 60 / C(k)
  \]

This means that one aircraft is allowed to enter sector \( k \) at a span period of 60 / \( C(k) \), so this ensures an input flow less or equal to \( C(k) \) aircraft per hour.
- Criterion, \( \argmin \sum w(i) T(i) \) for all \( k \in S \):
  for all \( (i,j) \in CA \), \( T(i) - T(j) \geq 60/C(k) + ETO(k, j) - ETO(k, i) \) This is a minimization of a linear criterion under linear constraints. It’s a linear program, of the general form
  \[
  \argmin \sum w(i) T(i) \quad ; w(i) \text{ is a weight for all } i, \sum A(i, j) T(j) \leq b(i)
  \]

B. Stochastic Regulation Model

Starting from regulation model of constraint satisfaction (with FIFO priority rule), the amount of delay required to an aircraft \( i \in CA \) is stochastic (i.e. variable) because the assessed traffic volumes in airspace sectors are variable. This ATFM delay \( T(i) \) is associated to a weight \( w(i) \).

With vector notation, the formulation of last paragraph becomes a linear programming minimization with a stochastic weight \( \langle w, T \rangle \) in the objective function. For simplicity, let’s suppose that the weight vector has a mean value \( \mu \) and a covariance matrix \( K = E [(w-\mu) (w-\mu)^T] \).

The expectation of the objective function is \( E (wT) = \mu T \) and its variance is (scalar) variance is \( \text{var} (wT) = T^T KT \). A good idea is to minimize the composite function: \( E (wT) + \lambda \text{var} (wT) \) under the constraints \( AT \leq b \). The risk-sensitive criterion is then:

\[
\argmin \lambda \mu T + \lambda T^T KT
\]

It’s a quadratic (derivable) program, with a symmetric positive definite matrix, because \( K \) is a covariance.

VIII. CONCLUSION

The suggested design for ATFM control loop is helpful for avoiding propagation effects and disruption of air traffic resulting from the action of airline operation centers along with air traffic operational events. The pre-filter succeeds in giving a reliable idea about traffic volumes in the airspace, but there is a variable depicting our lack of information. Regulation can still be accomplished using the same principles, despite the change in program formulation, it remains solvable.

A global simulation is required to assess the performance of the study, and to compare it with concurrent philosophies such as collaborative decision making (CDM).

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REFERENCES


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