

USING ABSORPTION AREAS TO IMPROVE ATFM

Frédéric Ferchaud, LaBRI/EEC, Talence, France

Vu Duong, EEC, Brétigny sur Orge, France

Cyril Gavaille, Mohamed Mosbah, LaBRI, Talence, France

Abstract

The stochastic nature of Air Traffic Management arises mainly from uncertain operational events. This uncertainty may jeopardize the Central Flow Management Unit (CFMU) planning leading to safety problems and sub optimally used capacity.

An absorption area is defined as one or several free slots in the planning so that the management of uncertainty is easier. Its aim is to compensate the aircraft uncertainty. The issue is to use the free slots in order to absorb uncertainty, and so not modify the initial planning. Finding the best configuration of the absorption areas corresponds to balancing optimally their size with the available capacity in order to absorb uncertainty and minimize "load loss" (unused capacity).

This paper presents the initial results of slot allocation problem incorporating absorption areas: Under some elementary assumptions, the simulations show that, for whatever the rate of uncertainty is, the debit of traffic with absorption areas in slot allocation is always higher than without the absorption areas. A theoretical model is attempted to bring the proof to these empirical results.

Introduction

Basic Air Traffic Control (ATC) organizes air flows to ensure flight safety and to increase the capacity of the route network. Currently, about 8000 flights are registered everyday over France, which is a crossroad for the whole European airspace. This traffic generates a considerable amount of control workload and the airspace is divided into elementary sectors to be manageable by Air Traffic Controllers (ATCOs). For several years, a constant increase of air traffic has induced more and more congestion in the control sectors as traffic encompasses sector capacity. Since the events of 9/11, the traffic growth has diminished reduced, and there has been less and less congestion. But the previous traffic growth will

presuppose future congestion of the air traffic. Two strategies can then be applied to reduce such congestion. Either to adapt the demand to the existing capacity (slot route allocation, collaborative decision making, etc.) or is adapt the capacity to the demand (modification of the route network, of the airspace sectorization, new airports, etc.). For both strategies and to simplify the discussion, we assume that the capacity of a sector is measured by the number of aircraft flying across the sector during a given period of time.

In EUROCONTROL Air Traffic Flow Management (ATFM), the CFMU is in charge of the slot allocation for all flights, elaborates the daily planning of slots. A slot corresponds to a time window (-5 min, +10 min) during which the aircraft can take-off.

Centralized ATFM is in charge of regulating air traffic demands by, among several other strategic or tactical measures, delaying departure slots of the flights that could overload congested sectors. The purpose of delaying is to respect the "en-route" capacity constraints provided by each Air Traffic Control Centre (ATCC). This constraint is represented by the number of aircraft in a sector at one time. The CFMU currently solves this problem in three phases [1]:

1. The **strategic phase** takes place between 19 months and seven days prior to the day of operation and includes research, planning and coordination activities. This phase consists of analysing the evolution of the forecast demand and the identification of potential new problem and in evaluating new solutions. The output of this phase are the capacity plan for the following year, the Route Allocation Plan and sets of other plans than can be activated as necessary during the next phases.
2. The **pre-tactical phase** is applied during six days prior to the day of operation and consists of planning and coordination activities. This phase analyses and decides

on the best way to manage the available capacity resources and on the need for the implementation of flow measures (regulations or routing). The output is the ATFM daily plan published via ATFM notification message and network news.

3. The **tactical phase** is applied on the day of the operation. This phase update the daily plan according to the actual traffic and capacity. The management of the traffic is made through slot allocation and/or ad-hoc rerouting. Basically, CASA¹ computes a list of slots by dividing the time length of the regulated period by its capacity and try to fill each slot according to the estimated arrival time of the flights in the concerned sector. Several revision processes occur when new flight plans are received that may shift all the flights already scheduled during the same period to respect the "first planned-first served" principle. Moreover, the regulation for a given flight is computed with respect to the sector inducing the greatest delay (in case of multiple regulations).

Unfortunately, as a matter of fact, uncertain operational events occur daily and disturb the CFMU planning leading to safety problem and sub optimally used capacity. This issue causes delays. Indeed, dynamic reallocation of slot is required. During congestion period, reallocating flights on the "first served-first planned" principle causes delays on other flight previously allocated with scheduled slots.

This paper focuses on improving ATFM efficiency using a new concept: absorption areas (AA). The aim of the AA is to absorb aircraft losing their slots so that to minimize disturbance on other scheduled slots. For this, one let unfilled slots during the pre-tactical phase in order to use this unfilled slot for delayed flights because of uncertainty. We present the first results obtained with absorption areas according to the actual flow management, and the Slot Allocation Problem (SAP).

¹ Computer Assisted Slot Allocation: Algorithm in charge of the slot allocation in the CFMU

Types of Uncertainty

The ATFM is a daily pre-tactical filter intended to regulate scheduled flight across controlled airspace. Its main aim is to limit the number of aircraft in a given space or period.

If there were not uncertainty in air traffic, such that all flights could be guaranteed to respect all estimated time of arrival at all route segments, one could envisage a situation in which schedules and routes could be designed to allow gate-to-gate flight without any conflict, and would not be necessary for any active intervention by ATCos.

This ideal situation is not yet reachable today; therefore one major issue with ATM is to deal with uncertainty. Current ATM is a complex socio technical system organizes to cope with uncertainty: controllers and pilots frequently make important decisions based on uncertain or incomplete information, especially in non nominal and emergency situation.

The culture of eliminating uncertainty therefore seems quite deeply ingrained in ATM, but may not be sustainable or optimal. New concepts and tools, such as those for planning and conflicts detection, tend to increase the amount of data that can be presented and the degree of reliability placed on predicted information.

There are several definitions of uncertainty. The term uncertainty can include:

- Unexpected weather conditions,
- Unexpected technical failures,
- Unexpected delays cause by passengers,
- etc.

The research problem described in this paper concerns the reduction of disturbance caused by uncertainty in slot allocation. The goal of slot allocation is to guarantee that the ATCos workload will not be overload. Actually, the disturbance in slot allocation problem corresponds to aircraft not taking their slots and requesting new ones. AA is intended to absorb these requests without disturbing the scheduler slots. The issue with AA is that full capacity would not be used in pre-tactical planning. An optional trade-off shall be found in order to maximize capacity while minimizing disturbances.

Experimental Results

A simulator was developed to take into account only the upper airspace area and the “en-route” control for experimental purpose. This simulator randomly creates an upper airspace and air routes. The results obtained were encouraging. Indeed, we can reduce disturbance and also increase the average throughput (number of aircraft in the upper area in the same time) [2].

These empirical results encouraged us to investigate into a theoretical model that could formally confirm the experimental results.

The Slot Allocation Problem

Definition

Let:

- n be the number of slot.
- m be the number of aircraft, $m \leq n$.
- p_i be the allocate slot to flight $i, i \in [1, n]$.
- s_i be the status of the flight i :
 - $= 0 \Leftrightarrow$ flight i does not take p_i .
 - $= 1 \Leftrightarrow$ flight i takes p_i .
- d_j be the slot really taken by flight $j, j \in [1, m]$.

Let us define the Slot Allocation Problem (SAP) as follows:

- The INPUT of SAP is a list of pairs $I = (p_1, s_1), \dots, (p_n, s_n)$ such that $p_i < p_j$ for $i < j$ and $s_i \in \{0, 1, \dots\}$.

SAP is an algorithm producing a list of pair:

- $O = (1, d_1), \dots, (m, d_m)$ subject to: $m \leq n$, $d_i \neq d_j$ for $i \neq j$, $d_i \geq p_i$.

The conditions “ $p_i < p_j$ ” and “ $d_i \neq d_j$ ” imply that there is at most one flight per slot. In each output, $(i, d_i) \in O$, d_i is the real departure time (or slot number) of the flight i .

We note “ $i \in O$ ” if there exists some d_i such that $(i, d_i) \in O$. If $i \notin O$, then flight i is said discard. If $i \in O$ and if $d_i > p_i$, then flight i is said cancelled at time d_i . If $i \in O$ with $d_i = p_i$, then flight i is said to be on-time. So an algorithm solving SAP consists in taking on-time, cancel, or discard decisions for each flight of the input (for on-time and cancel decisions, the departure time d_i must output).

Optimization Problem

The main measure of an algorithm solving SAP is its throughput performance. More precisely, let A be any algorithm solving SAP. The throughput of A on input I is defined by:

$$T_A(I) = \frac{\text{card}(O)}{n}$$

With $\text{card}(O)$ the cardinal of O the output.

Intuitively, this gives the number of aircraft having taken a slot, used by A to solve SAP in comparison to the number of slots (there is at most one flight per slot).

Decomposition of SAP

In order to simplify the complexity of large SAP, one solves it in different cases:

- Using AA in order to show the AA benefits according to the actual system.
- Lost slots reallocation: when an aircraft lost its slot p_i , it can happen that p_i be allocated to flight j .
- All flights are reallocated in a given time.
- Consider only one sector or space time dependencies between sectors

To resolve SAP, we begin by considering fewer constraints, and then we add them successively in order to find the SAP solution and deduce impacts created by AA.

In resume, the case of one sector is demonstrated without considering the reallocation time. Then results with AA and those without AA are compared.

Notations

- Let AA be the case that absorption areas are used.
- Let \overline{AA} be the case that absorption areas are not used.
- Let R be the case that some lost slots are reallocated.
- Let \overline{R} be the case that some lost slots are not reallocated.
- Let D be the case that we consider the delays.
- Let \overline{D} be the case that we do not consider the delays on aircraft having lost their slot.
- Let MS be the case that we take into account the neighbourhood relationship between the sectors.
- Let \overline{MS} be the case we work on one sector, we try to find the best distribution of the absorption areas in one sector.

Graphical Representation of SAP

With the previous notations, we can decompose the SAP into sixteen cases (see Figure 1).

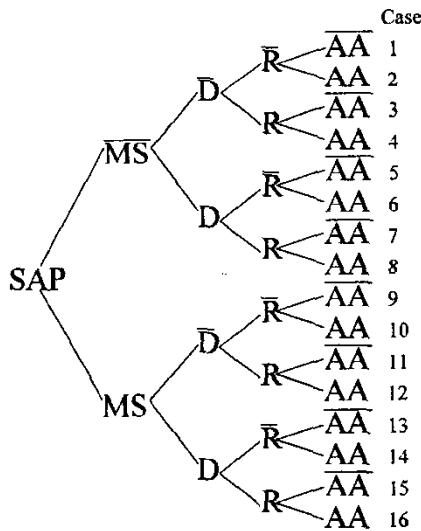


Figure 1. Decomposition of SAP

Resolution of SAP

Let $T_{A_j}(I)$ be the throughput performance of an algorithm resolving the SAP under the case j cases.

The benefits of absorption areas can be demonstrate when $T_{A_{2n+1}}(I) < T_{A_{2n+2}}(I)$. It compares the cases with AA and without AA under the same assumptions.

Let p be the probability that an aircraft takes its slot, and n the number of slots.

Case 1-2

The easiest case to solve is the $\overline{MS}, \overline{D}, \overline{R}$ case (fewer constraints).

This case corresponds to find the best quantity of absorption areas to improve the ATFM without reallocating required of the lost slots.

We obtain an amount of absorption areas equal to $n \frac{1-p}{2-p}$ slots [3].

So with a probability $q \geq 1 - \frac{1}{n^c}$:

$$T_{A_1}(I) > \frac{pn - \sqrt{2c(1-p)n \ln(n)}}{n}$$

For the second case:

$$T_{A_2}(I) > \frac{\frac{n}{2-p} - \sqrt{2c \frac{1-p}{2-p} n \ln(n)}}{n}$$

Figure 2 compares $nT_{A_2}(I)$ with AA (Case 2), and $nT_{A_1}(I)$ without AA (Case 1), for 1000 slots

($n = 1000$) with a probability higher than $\frac{1}{1000^2}$

($c = 2$). p is the probability that an aircraft takes its slot. $nT_{A_j}(I)$ represents the number of aircraft having take-off with n slots.

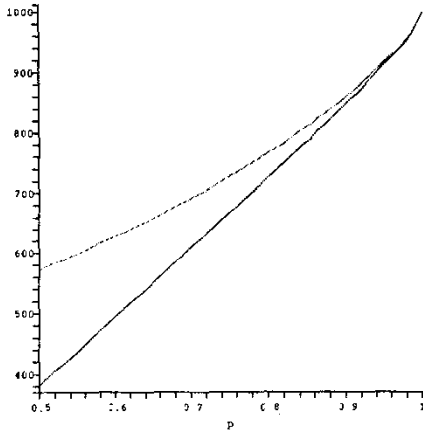


Figure 2. Comparison of Case 2 (Upper Curve) and Case 1.

Figure 2 compares these results and shows the benefits of absorption areas. With AA, whatever the rate of uncertainty is, the obtained throughput is always higher than without AA. Moreover, without AA all slots are allocated but not all aircraft took-off due to safety constraints. In this case, more slots are required or defined capacity must not respect the capacities.

Case 3-4

For the next cases, we add the assumption that we can reallocate some lost slots.

It corresponds to find the best amount of absorption areas we need to improve the ATFM with reallocation of the lost slots.

Let q be the proportion of lost slots we can reallocate, we obtain [3]:

1. An amount of absorption areas equals to:

$$n \frac{(1-p)(1-q)}{1+(1-p)(1-q)}$$

2. An average $T_{A_3}(I)$ and $T_{A_4}(I)$:

$$T_{A_3}(I) = p + (1-p)q$$

$$T_{A_4}(I) = \frac{1}{1+(1-p)(1-q)}$$

3. And we have:

$$T_{A_4}(I) - T_{A_3}(I) = \frac{(1-p)^2(1-q)^2}{1+(1-p)(1-q)} \geq 0$$

The first results theoretically obtained show the benefits of AA.

Future Work

We want to take into account the delays on the aircraft losing their slots. When an aircraft loses its slot we want to guarantee that it will take-off in a given time. In other words (with the SAP notations):

$$T_{A_{2n+1}}(I) < T_{A_{2n+2}}(I)$$

And

$$p_i - d_i \leq r \text{ for all } i \in \{1, \dots, m\}$$

r is the maximal number of slots we can wait for a delayed aircraft. Now we have two variables to compare:

- (i) the number of aircraft taking off under safety condition with n slots,
- (ii) and the average delay.

One other assumption shall be considered in the next step: the neighbourhood relationship between the regulated sectors. If an aircraft loses its slots and requests a new one, we must find a slot in all regulated sectors defined by flight plan.

To solve this problem, our approach uses the Graph Theory. Then the multi-sectors can be solved in SAP.

We think that an optimal number of AA was found through a distribution of AA as a function of delays.

Conclusion

The first results obtained shown the benefits of absorption areas to improve the ATFM. Each new assumption reduces these benefits, because in each case we increase the load loss (unused slots). We want to find an algorithm, according to the probability of the uncertainty, which guarantees that we can improve the slot allocation. Our experimental results shown that such algorithm must exist. Moreover, the declared capacities are lower than the real capacities, in order to have a safety margin. So the AA are already used with this

safety margin, but not considered by the CFMU. This safety margin is given according to the ATCos but not according to the uncertainty. It corresponds to a continuous AA; each hour, we can add the same number of aircraft. We want to distribute these unfilled slots more efficiently in the sectors in order to minimize the load loss.

Another interest of absorption areas is that if we find an algorithm giving a good distribution of unfilled slots, then its implementation will neither change sectors topologies, nor controller's work nor flight plans submission procedure.

References

- [1] Eurocontrol, ATFM Users Manual, edition n°9.0, April 2003.
- [2] Ferchaud Frédéric, *Gestion de flux du trafic aérien: un modèle de graphe évolutif*. Master Thesis, University of Bordeaux 1, June 2003.
- [3] Duong, Ferchaud, Gavaille, Mosbah. A New Slot Allocation for ATFM. *In Proceedings of the 7th International Conference on Intelligent Transport Systems*, Washington D.C., Oct. 2004.