

# Optimization of opening schemes

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## 1 Summary

Air traffic increases in the ECAC (European Civil Aviation Conference) area; as the capacity of air traffic control (ATC) does not have uniformly the same growth, airports and airspace areas are congested.

The effect of this congestion is an important increase of delays on flights. To face these problems and handle traffic demand, many measures can be taken during the air traffic flow management (ATFM) pre-tactical phase (two days before the day of operations), from ground delay to re-routing of flights.

Above all, the ATFM process includes actions that aim at adapting the ATC capacity to the traffic demand, ATFM flow restrictions being the ultimate actions that have to be defined to handle safely traffic demand. Particularly, during the ATFM pre-tactical phase, flow managers try to improve the sharing out of human resources (air traffic controllers) according to a predicted traffic demand. This is possible having a large set of individual sectors which, operationally, is very effective in the way that it allows dynamic adaptation to the traffic demand according to flow weights and time. But, opening all ATC working positions all along the day would not be cost effective.

This study which comes within the **COSAAC** (COMmon Simulator to Asses ATFM Concepts, see p.11) project, aims at describing three optimization models to solve this problem of one-day ACCs (Air Control Centers) configuration definition and to illustrate them with practical applications.

## 2 Problem definition

### 2.1 Context

To provide an efficient ATFM process by centralizing and harmonizing ATFM measures over the ECAC area, the central flow management unit (CFMU) has been created. The ATFM process can be described in 3 phases:

- a strategic phase that takes place several months to 2 days before the day of operations (flights take-off day).
- a pre-tactical phase that begins 2 days before the day of operations.
- a tactical phase which consists of 2 sub processes: the real time supervision process (monitoring of the effects of flow management measures on traffic volumes loads and on delays) and the slot allocation process (ground delays).

Our study concentrates on the ATFM pre-tactical planning. 2 days before the day of operations, flow managers identify congested areas taking into account a predicted traffic demand, the ATC capacity, events that can have exceptional impact on traffic (like the Olympic Games) and the ATFM regulation plan (set of restrictions) of the same day of the previous week considering the related operational log.

At this moment, they can define measures to alleviate overloads by taking preventive measures: first, by adapting the ATC capacity to the predicted traffic demand, then by defining flow management restrictions to use as best as possible the ATC capacity.

### 2.2 Definitions

In order to understand better the problem we focus on, the following definitions are given:

- The airspace is divided in **ACCs** and each ACC is subdivided in areas called **sectors**. A country of the ECAC area can manage several ACCs: for example, there are 5 ACCs in France – 2 of them are subdivided in 2 (Paris East/West and Aix East/West) – and 106 sectors which makes 15 sectors on average per ACC.
- Some sectors can be grouped. A group of sectors is called a **collapsed set of sectors** or **collapsed sectors**. Collapsed sectors are defined during the strategic phase i.e. this is not a dynamic process.
- Here, there is no need to differentiate a sector and a collapsed sector ; both are **airspace entities** defined with a static shape and a control capacity (see next definition) depending on ATC controllers manpower.

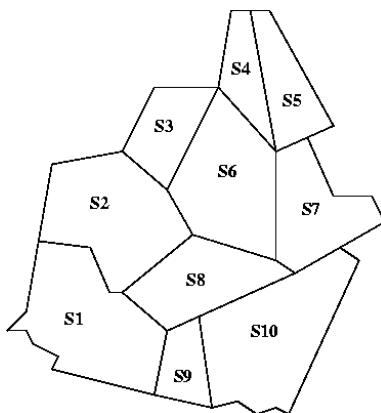
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- The *capacity* of an airspace entity is the maximum entering throughput during one hour. The capacity can be reduced following traffic complexity, in case of military activity in one region, for example.
- An ACC has a maximal number of control positions defined per period of time during the pre-tactical phase.
- A *layout* (or a configuration) for a center is a partition in  $k$ -control positions of one center.

Illustration with Bordeaux ACC (10 sectors):

Let  $S$  be the set of sectors,  $S = \{S_i\}_{i=1..10}$



**Figure 1: Bordeaux ACC**

Let  $R1, R2, R3, R4$  and  $R5$  be group of sectors such as:

$$R1 = \{S3, S4, S5, S6, S7\}$$

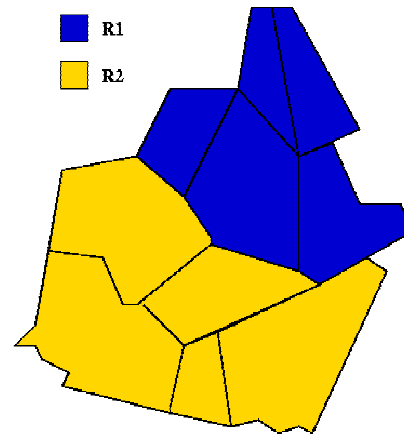
$$R2 = \{S1, S2, S8, S9, S10\}$$

$$R3 = \{S1, S2, S3, S4, S6\}$$

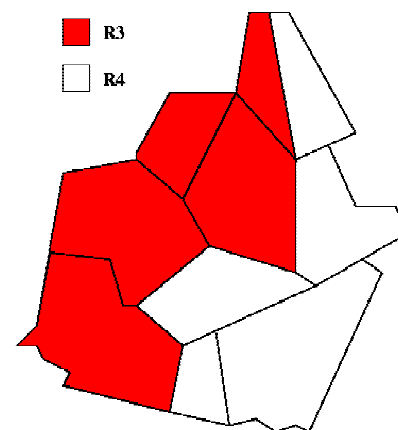
$$R4 = \{S5, S7, S8, S9, S10\}$$

$$R5 = \{S1, S2, S3, S4, S5, S6, S7, S8, S9, S10\}$$

Then, layouts with a potential of 2 control positions are  $l_1 = \{R1, R2\}$  and  $l_2 = \{R3, R4\}$  (see next figures).



**Figure 2: layout  $l_1$  with 2 working positions**



**Figure 3: layout  $l_2$  with 2 working positions**

If there is only one control position then the single layout is  $l_3 = \{R5\}$ , the whole airspace of the ACC.

A layout is defined over a time period characterized by a potential; for example, if Bordeaux ACC has a potential of 2 control positions during the night duty (0h – 6h) then layouts  $l_1$  and  $l_2$  are candidates layouts for this period.

- An *opening scheme* is the description of the different ACC's layouts during a day.

We are interested in optimizing the opening schemes for all ACCs of the ECAC area i.e. in defining the different layouts that best suit the predicted traffic demand according to the maximal number of working positions that can be manned during each time period of a day.

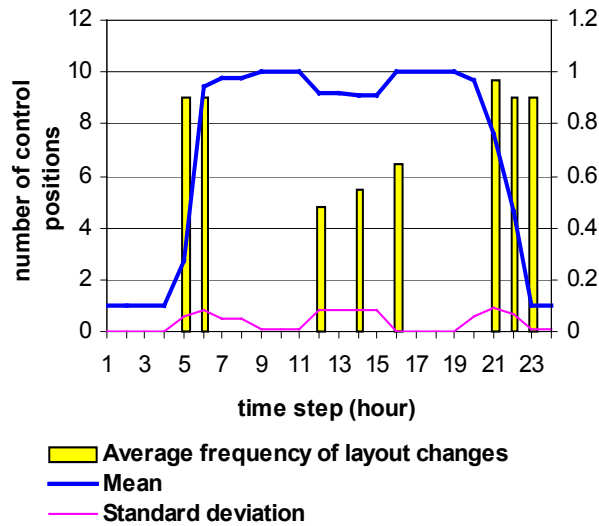
### 3 Problem formulation

#### 3.1 An operational approach

We have carried out statistics on frequency of layout changes (time period and average duration of a layout) in order to build models able to generate viable operational opening schemes. We perceived that generally, the minimal duration of validity of a layout is half an hour. So we can discretize time space in time step of half an hour. Let  $t$  be the time step such:  $t \in T = [0..48[$ .

In a first step, we have considered that the number of control positions is an input data that had to be satisfied. The average variation of the number of control positions (in October 2000) in one ACC during a day is illustrated on this figure:

The number of working positions follows traffic



growth with the objective of adapting capacity to demand. For example, the quick growth of traffic in the morning requires a continuous adaptation of ACCs configurations. This is illustrated by the impulses on the diagram: in the morning, the average frequency of layout changes is around 80%.

To a given number of control positions corresponds a set of layouts. Obviously, there is a layout change when the number of control positions varies. But, for one potential, we can have multiple changes of layout.

Generally speaking, we observed these frequencies of layout changes:

- during night duty, none or few changes.
- during periods of come on/off duty, full changes.
- during daytime, few changes.

Let  $P_i$  be a *period* of duration  $d(P_i)$  in which a layout will have a minimum duration  $d_{\min(i)}$ <sup>3</sup>. Then,

during a period, we can change at most  $\left\lceil \frac{d(P_i)}{d_{\min(i)}} \right\rceil - 1$  times of layout.

Example:

$$\begin{aligned} P_1 &= [0..12[ & \text{and} & d_{\min(1)} = 6 \\ P_2 &= [12..20[ & \text{and} & d_{\min(2)} = 1 \\ P_3 &= [20..36[ & \text{and} & d_{\min(3)} = 4 \\ P_4 &= [36..40[ & \text{and} & d_{\min(4)} = 1 \\ P_5 &= [40..48[ & \text{and} & d_{\min(5)} = 6 \end{aligned}$$

During  $P_3$  we can change  $\left\lceil \frac{36 - 20}{4} \right\rceil - 1 = 3$  times of layout.

Let us introduce the notion of *pattern*.

Let  $d_l$  be the duration of the layout  $l$ .

- a pattern  $p$  is defined from a layout  $l$ . It can be represented by a couple  $(h_p, d_p)$  where  $h_p$  and  $d_p$  are respectively the hour of beginning of the pattern and its duration. By construction, the duration of a pattern cannot exceed the duration of the layout it is stemmed from:

$$\forall p, \quad d_p \leq d_l.$$

- a pattern is constructed differently following the period in which it is defined. We have:

$$\forall p, \quad \text{if } h_p \in P_i \text{ then } d_p \geq d_{\min(i)}$$

$$\forall p, \quad d_p \bmod(d_{\min(i)}) = 0$$

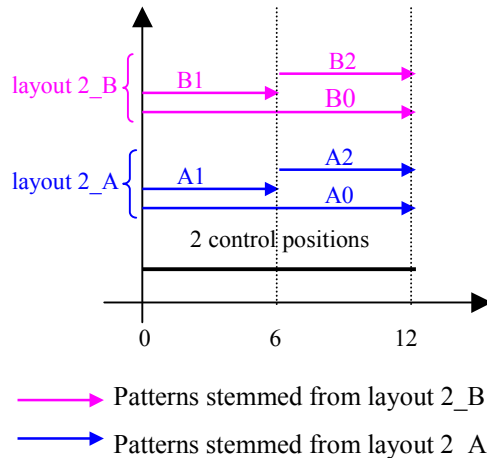
$$\forall p, \quad h_l \leq h_p \leq h_l + d_l$$

As an example, if we have 2 layouts named 2\_A and 2\_B corresponding to a potential of 2 control positions during the time period  $P_1$ , each layout having a minimal duration of 6 time steps, then the following 6 patterns can be generated:

<sup>3</sup> time units are defined in number of time steps

| Layout | Pattern | $(h_j, d_{jl})$ |
|--------|---------|-----------------|
| 2_A    | A0      | (0,12)          |
| 2_A    | A1      | (0,6)           |
| 2_A    | A2      | (6,12)          |
| 2_B    | B0      | (0,12)          |
| 2_B    | B1      | (0,6)           |
| 2_B    | B2      | (6,12)          |

Illustration of these patterns:



This principle of construction allows us to have only one layout change with patterns [A1,B2] and [B1,A2] or no change at all with pattern [A0] or [B0].

We shall keep in mind that each layout is characterized by a set of airspace entities which, according to their capacities (maximal hourly throughputs), must give the ACC the ability to handle the traffic demand at low cost (minimal ground delay). This highlights the relevance of modeling the problem using patterns.

### 3.2 Models

#### Indices

$e$  is an airspace entity

$t$  is the time step,  $t \in T$

$l$  is a layout

$p$  is a pattern stemmed from the layout  $l$  with the couple  $(h_p, d_p)$  as feature

#### Data

$N(e,t)$  is the number of flights crossing the airspace entity  $e$  at time step  $t$

$capa(e,t)$  is the capacity of airspace entity  $e$  during time step  $t$

#### Variables

$x(l,p) = 1$  if pattern  $p$  of layout  $l$  is chosen  
 $= 0$  else

$z^-(e,t) \geq 0$  variable that expresses a deficit of capacity of an airspace entity  $e$

Our modelization has been oriented on 2 approaches:

- a **local resolution** i.e. ACC by ACC approach (models  $M_1$  and  $M_2$ ).
- a **global resolution** i.e. a multi-ACC approach (model  $M_3$ ).

#### 3.1.1 First model ( $M_1$ )

$$\text{Min} \quad \sum_{(e,t)} z^-(e,t) + \sum_{(l,p)} \varepsilon \times x(l,p) \quad (1)$$

$$\sum_{(l,p)/t} [capa(e,t) - N(e,t)] \times x(l,p) + z^-(e,t) \geq 0, \forall e,t \quad (2)$$

$$\sum_{(l,p)/t} x(l,p) = 1, \forall t \quad (3)$$

(1) Objective function: as we are interested in minimizing the deficits of capacity, the first objective function criterion is:  $\text{Min} \sum_{(e,t)} z^-(e,t)$

But, with this criterion, we can have equivalent solutions (in term of delays) like:

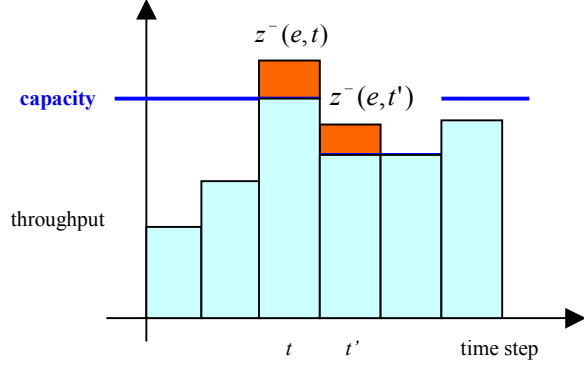
- solution  $S_1$  with pattern A0.
- solution  $S_2$  with patterns A1 and A2.

The change of pattern in the solution  $S_2$  does not impact on a change of layout (it is still layout 2\_A); we would prefer then, the simplest solution  $S_1$ . In this intention, we add a small penalization on the number of patterns that is an  $\varepsilon$  on variables  $x(l,p)$ .

(2) Capacity constraints: traffic demand cannot exceed ATC capacity for each airspace entity and each time step of the day studied.

(3) Pattern unicity constraints: for each time step, only one pattern of a layout can be chosen.

Illustration of capacity constraints on an entity  $e$ :



■ overload of traffic: generation of the variable  $z^-$

### 3.1.2 Evolution of the model (M<sub>2</sub>)

Instead of just taking into account deficits of capacity at each time step, this model simulates the phenomenon of regulation; we try to transfer delays created in a time step to its following time steps.

One notes  $y(e, t, t')$  the quantity of deficit of capacity at the moment  $t$  for entity  $e$  which will refer to the moment  $t'$ . Then, at each time step, we take into account deficits or excesses of capacity as flights delayed from previous time steps and flights being delayed on following time steps. The constraint capacity of the previous model can now be written as follow:

$$\sum_{(l,p)/t} [capa(e, t) - N(e, t)] \times x(l, p) - \sum_{t > t''} y(e, t'', t) + \sum_{t' > t} y(e, t, t') = 0, \forall e, t$$

This constraint can make the model infeasible if deficits or excesses of capacity could not be transferred or do not need to be transferred. A way to relieve this is to introduce goal variables noted  $g^+(e, t)$  and  $g^-(e, t)$ ; the model becomes:

$$\begin{aligned} \text{Min} \sum_{(e,t)} C \times g^-(e, t) + \sum_{(e,t,t')} (t'-t) \times y(e, t, t') \\ + \sum_{(l,p)} \varepsilon \times x(l, p) \end{aligned} \quad (4)$$

$$\begin{aligned} \sum_{(l,p)/t} [capa(e, t) - N(e, t)] \times x(l, p) - \sum_{t > t''} y(e, t'', t) \\ + \sum_{t' > t} y(e, t, t') + g^-(e, t) - g^+(e, t) = 0, \forall e, t \end{aligned} \quad (5)$$

$$\sum_{(l,p)/t} x(l, p) = 1, \forall t \quad (6)$$

$$x \in \{0,1\}, y \geq 0, g^- \geq 0, g^+ \geq 0 \quad (7)$$

4) The objective function is multi-criterion, we penalize:

- the deficits of capacity that could not be transferred;  $C$  is a constant cost greater than the cost of the longest transfer (the cost of an excess of capacity is null).
- the duration of transfers. The more the transfer is late, the more it is expensive.
- the number of patterns.

(5) Capacity constraints

(6) Pattern unicity constraints

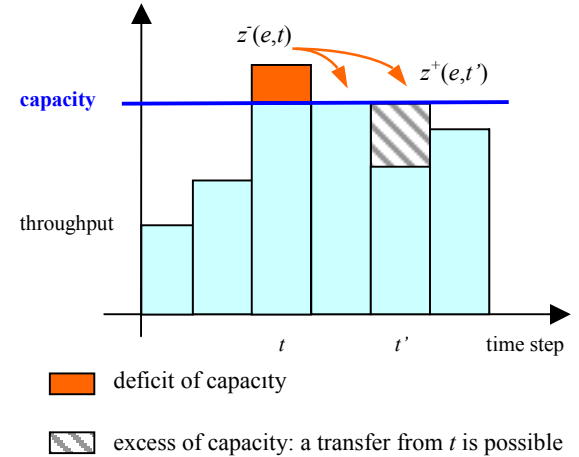
(7) We could also define a threshold of maximum delay in order to give a limit to the variable  $y$  ( $0 \leq y \leq M$  where  $M$  is a constant).

Let us introduce these notations:

$$z^-(e, t) = \sum_{t' > t} y(e, t, t')$$

$$z^+(e, t') = \sum_{t > t''} y(e, t'', t')$$

Then, we can illustrate the mechanism of transfer by the scheme below:



■ deficit of capacity

■ excess of capacity: a transfer from  $t$  is possible

### 3.1.3 Third model (M<sub>3</sub>)

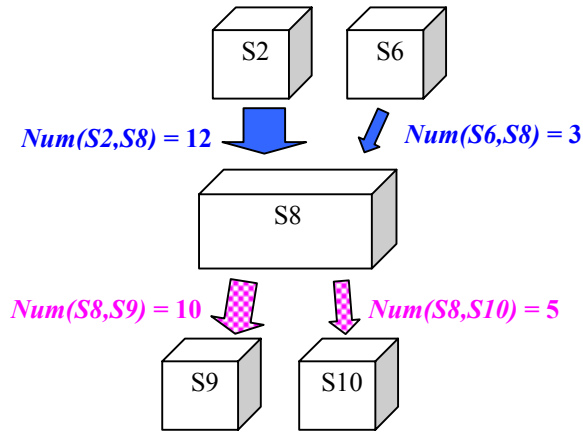
Coupling constraints between airspace entities are statistically generated which makes ACCs interconnected. This is an evolution of model M<sub>2</sub> in the way that capacity overloads are spread on next capacity slots in time and **space**. This is explained below:

Let  $succ(e)$  be the set of the successors of entity  $e$ , and  $Num(e, e')$  be the number of flights going from the entity  $e$  to the entity  $e'$  such as  $e' \in succ(e)$ .

We define a *degree of dependence* between 2 airspace entities  $e$  and  $e'$  as a ratio between  $Num(e, e')$  and the total number of flights outgoing from the entity  $e$  i.e.

$$deg(e, e') = \frac{Num(e, e')}{\sum_{e'=succ(e)} Num(e, e')}$$

Going back to the previous example with Bordeaux ACC (see Figure 1) we could have:



$$\text{Then, } deg(S2, S8) = \frac{12}{12+3} \times 100 = 100\%$$

$$deg(S6, S8) = \frac{3}{12+3} \times 100 = 20\%$$

$$deg(S8, S9) = \frac{10}{10+5} \times 100 = 66.66\%$$

$$deg(S8, S10) = \frac{5}{10+5} \times 100 = 33.33\%$$

Let  $prev(e, t) = \sum_{e'' \in succ(e''), t > t''} y(e'', t'') \times deg(e'', e)$  be the sum

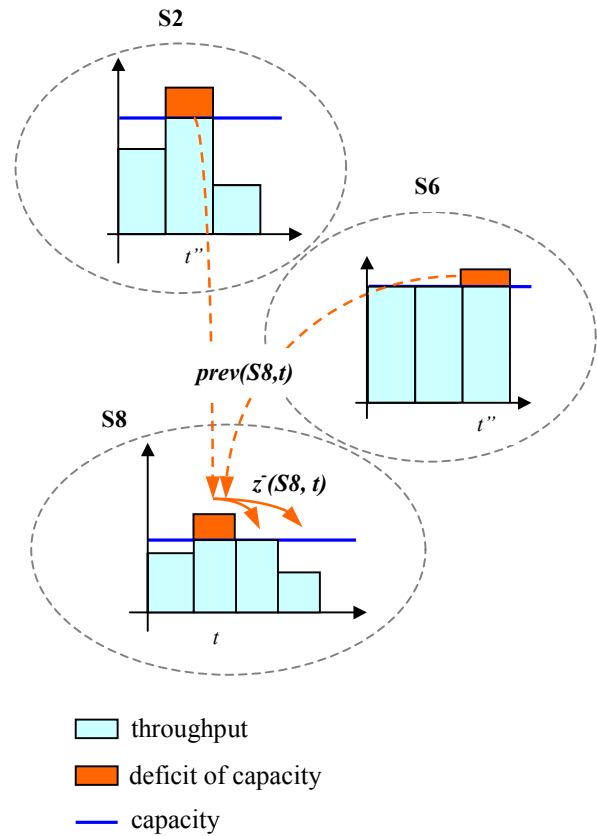
of delays transferred from the entities  $e''$  such as  $e''$  are geographical predecessors of  $e$  proportionally to their degree of dependence.

The capacity constraints of the previous model become:

$$\sum_{(l,p)/t} [capa(e, t) - N(e, t) - prev(e, t)] \times x(l, p) - \sum_{t \geq t''} y(e, t'') + \sum_{t' > t} y(e, t, t') + g^-(e, t) - g^+(e, t) = 0, \forall e, t$$

This model simulates a kind of macroscopic slot allocation process working on the basis of traffic flows instead of individual aircraft.

Then, the new representation of the transfer is:



### 3.3 Combinatorial complexity

$M_1$  and  $M_2$  are *mix integer* large scale linear programs.  $M_3$  is a quadratic model. Problem's difficulty depends on the number of ACCs considered.

For both first and second model, a single ACC is solved in less than 15 minutes and the solution can easily be proven **optimal using standard MIP procedure** included in CPLEX<sup>4</sup> (branch and bound algorithm).

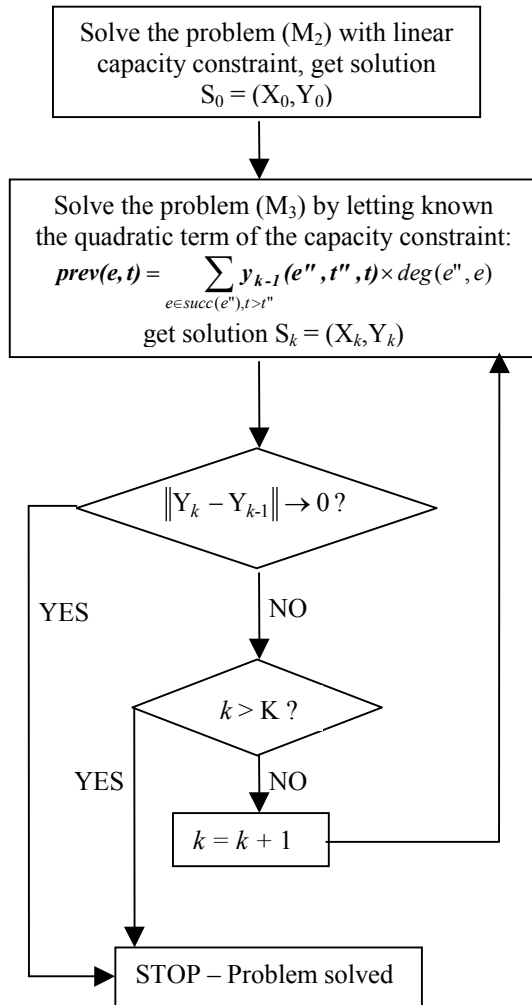
Solving a greater area, even limited to the whole French airspace, is a much more difficult problem (second model yields about 100 000 variables and 6 200 constraints on a heavy traffic day). The problem remains feasible yielding though long calculation times (50 min to 75 min). Optimality cannot be proven anymore even if the best integer solution produced in the constraint of 5000 nodes is not too far from the relaxed solution (2%).

Finally, the strategy adopted to solve the problem on a set of ACCs results in a succession of single ACC optimization.

<sup>4</sup> CPLEX 7.0 is an ILOG product

Moreover, the same optimum is reached because no coupling constraints between ACCs or airspace entities are defined in those models.

On the other hand, the third model has coupling constraints that do not allow us to use the CPLEX branch and bound algorithm. So, we use an iterative algorithm which is described as follow:



Where  $K$  is a constant and  $X, Y$  are respectively the sets of variables  $x$  and  $y$ .

This algorithm is **not an exact algorithm**, theoretically the optimum can be reached when at iteration  $k$ , the quadratic norm  $\|Y_k - Y_{k-1}\|$  converges to zero; practically, we stop the algorithm when a maximum ( $K$ ) of iteration has been reached.

## 4 Results

### 4.1 Input data

- ACCs considered: Aix-East (LFMACCE), Aix-West (LFMACCW), Barcelona (LECBACC), Bordeaux (LFBACC), Brest (LFRRACC), Geneva (LSAGACC), Paris-East (LFFACCE), Paris-West (LFFACCW), Reims (LFEEACC), Zurich (LSAZACC).
- sets of layouts and capacities of airspace entities (updated every cycle of 28 days; we used 4 cycles of data: 2000/09/07, 2000/10/05, 2001/05/17, 2001/06/14).
- variation of the number of control positions.
- 27 heavy traffic samples

### 4.2 Parameters

Let **(HH)** be the notation for tests parameterized with a single period all over the day, with a minimal duration of half an hour whatever the pattern:

$$P_1 = [0..48[, d_{\min(1)} = 1 \text{ time step of 30 min.}$$

And, let **(STAT)** be the notation for tests parameterized with statistical definition of periods:

$$P_1 = [0..6[ \quad \text{and } d_{\min(1)} = 6.$$

$$P_2 = [6..16[ \quad \text{and } d_{\min(2)} = 1.$$

$$P_3 = [16..30[ \quad \text{and } d_{\min(3)} = 2.$$

$$P_4 = [30..46[ \quad \text{and } d_{\min(6)} = 1.$$

$$P_5 = [46..48[ \quad \text{and } d_{\min(6)} = 2.$$

Parameterization (HH) seems to be relevant since such every 30-minute operational layout changes can be observed during growing and falling traffic. Moreover, changing of configuration when traffic volume stability has been reached, appears more feasible.

### 4.3 Tests procedure

These tests have been completed on a HP 9000-700 workstation.

To each traffic day corresponds a succession of optimizations (depending on the number of ACCs considered). After each optimization, the quality of the opening schemes has been assessed – in term of total ground delay generated by each ACC – by performing the CFMU slot allocation process using the **ISACASA** (see p.11) tool developed by Eurocontrol Experimental Center. This module is connected to our simulation platform COSAAC.

Moreover, a first slot allocation has been worked out taking into account the actual opening schemes that have been filed by all ACCs.

3 sequences of optimization have been done:

- two of them – **S1** and **S2** – have been done respectively on (HH) and (STAT) parameterization, over the French airspace (7 ACCs) taking into account the filled flight plans of the 27 traffic days. Models M1 and M2 have been solved.
- the third one – **S3** – has been done on (HH) parameterization over 6 ACCs: LFMACCE, LFMACCW, LFEEACC, LSAGACC, LSAZACC, LECBACC taking into account the actual final traffic demand of the 27 days. The three models M1, M2 and M3 have been solved.

#### 4.4 Computational results

Here is a rough estimate of the combinatory of the models on one ACC:

| S1, S2           | (HH)                  |     | M <sub>1</sub> | M <sub>2</sub> |
|------------------|-----------------------|-----|----------------|----------------|
| Sept/Oct<br>2000 | Number of variables   | Min | 450            | 6000           |
|                  |                       | Max | 3500           | 15100          |
|                  | Number of constraints | Min | 430            | 430            |
|                  |                       | Max | 900            | 900            |
| May/June<br>2001 | Number of variables   | Min | 400            | 6000           |
|                  |                       | Max | 8200           | 22000          |
|                  | Number of constraints | Min | 410            | 410            |
|                  |                       | Max | 1000           | 1000           |

- We have a significant difference between 2000 data and 2001 data; indeed, the combinatory is higher on 2001 data than to 2000 one and this has an impact on the behavior of the models.
- ACCs which have small sets of layouts at a given number of working positions can only take a small advantage of the optimization process (weak combinatorial problem).

#### Remark

Only cautious analysis of results should be done. Capacities declared by ACCs are sometimes misleading:

- Some ACCs give the capacity value assigned to a subset of one airspace entity (some traffic flows being excluded from the global traffic managed by the airspace entity) instead of the actual capacity figure that should be published for the entire traffic handled by this airspace entity.
- Capacity values are sometimes different in the filed opening scheme than what can be found in

the official database of the ACC. This happens, for example, when a military activity is planned (lower capacity value) or the contrary, depending on what is the standard situation.

This does not change the way the problem is solved since it does not apply on degrees of dependence between airspace entities but it makes the models more constrained and comparison between actual opening scheme (or reference scheme) and optimized opening scheme is more delicate.

Even if the modelization of M<sub>1</sub>, M<sub>2</sub> and M<sub>3</sub> has been guided by 2 approaches (local one for M<sub>1</sub> and M<sub>2</sub>, global one for M<sub>3</sub>), it is interesting to compare the profits (in term of delay generated by a slot allocation process) by each of these models in both cases i.e. on the local approach – ACC point of view – and on the global approach – multi-ACC point of view.

#### LOCAL APPROACH (see examples on p.10)

The profit in p.c. for one ACC, is the variation of the delay generated by a slot allocation process respectively applied to the reference scheme and to the optimized opening scheme for this ACC, then this represents a **local profit only**.

#### Mean profit in p.c. for each model

| S1,S2            | (HH)           |                | (STAT)         |                |
|------------------|----------------|----------------|----------------|----------------|
|                  | M <sub>1</sub> | M <sub>2</sub> | M <sub>1</sub> | M <sub>2</sub> |
| Sept/Oct<br>2000 | 21,6           | 29,4           | 25,7           | 26             |
| May/June<br>2001 | 33             | 27,2           | 28,6           | 25             |

| S3               | (HH)           |                |                |
|------------------|----------------|----------------|----------------|
|                  | M <sub>1</sub> | M <sub>2</sub> | M <sub>3</sub> |
| Sept/Oct<br>2000 | 33,2           | 40,1           | 40,1           |
| May/June<br>2001 | 41,7           | 39,3           | 39,4           |

#### CPU time (in seconds)

| S1,S2            |     | (HH)           |                | (STAT)         |                |
|------------------|-----|----------------|----------------|----------------|----------------|
|                  |     | M <sub>1</sub> | M <sub>2</sub> | M <sub>1</sub> | M <sub>2</sub> |
| Sept/Oct<br>2000 | Min | 1              | 2              | 1              | 2              |
|                  | Max | 7              | 150            | 7              | 151            |
| May/June<br>2001 | Min | 1              | 2              | 1              | 2              |
|                  | Max | 18             | 950            | 5              | 176            |

| S3               |     | (HH)           |                |                |
|------------------|-----|----------------|----------------|----------------|
|                  |     | M <sub>1</sub> | M <sub>2</sub> | M <sub>3</sub> |
| Sept/Oct<br>2000 | Min | 1              | 1              | 1              |
|                  | Max | 18             | 195            | 253            |
| May/June<br>2001 | Min | 1              | 1              | 1              |
|                  | Max | 40             | 440            | 816            |

**Comparison M<sub>1</sub>/M<sub>2</sub>:** the model (M<sub>1</sub>) gives good results (gains around 30%) whatever the traffic day and the parameterization; moreover the computing time is very efficient (less than 40s). Nevertheless, the model M<sub>2</sub> is more effective than the first one on September and October 2000 cycles of data; indeed, the combinatory for these 2 cycles is lower than 2001 cycles.

**M<sub>3</sub>:** as model M<sub>2</sub>, M<sub>3</sub> provides good solutions even if it is a global oriented approach resolution model. However, the CPU time is long.

**Comparison (HH)/(STAT):** (HH) parameterization (a single period all over the day, with a minimal duration of half an hour whatever the pattern) is more flexible than (STAT) that is why it generally gives better results. However, (HH) parameterization generates more layouts changes, particularly between 8h and 15h UTC, but at a frequency which is of the same magnitude than what can be observed today when traffic demand grows in the morning or declines at the end of the day. If necessary, the rhythm of layout changes can be satisfied applying the (STAT) parameterization.

#### GLOBAL APPROACH (see examples on p.10)

The profit in p.c. for a set of ACCs is the variation of the total delay generated by a slot allocation process respectively applied to all reference schemes and to all optimized opening schemes, then this represents a **global profit on the area studied**.

| S3               |  | (HH)           |                |                |
|------------------|--|----------------|----------------|----------------|
|                  |  | M <sub>1</sub> | M <sub>2</sub> | M <sub>3</sub> |
| Sept/Oct<br>2000 |  | 49,93          | 50,3           | 50,25          |
|                  |  | 23,97          | 20,89          | 21,3           |

#### CPU time (in seconds)

| S3               |     | (HH)           |                |                |
|------------------|-----|----------------|----------------|----------------|
|                  |     | M <sub>1</sub> | M <sub>2</sub> | M <sub>3</sub> |
| Sept/Oct<br>2000 | Min | 18             | 1              | 195            |
|                  | Max | 32             | 194            | 610            |
| May/June<br>2001 | Min | 15             | 41             | 99             |
|                  | Max | 67             | 527            | 1066           |

The local approach analysis of the model's behavior is still true for the global approach: the model M<sub>1</sub> gives good results and fast CPU times. Models M<sub>2</sub> and M<sub>3</sub> are also effective, their calculation time can reach 18 min but over 6 ACCs it seems to be acceptable. The third model is especially long due to the resolution algorithm.

We expected model M<sub>3</sub> being more efficient than the other ones – because of coupling constraints on airspace entities that should give a continuity of capacity between layouts which could have been very efficient at first sight – but this is not the case for most of traffic days.

The overall results are good especially for 2000 data.

## 5 Conclusion

Even if some results are biased by input data, these results show the feasibility of working out usually more efficient opening schemes compared to handmade actual ones.

The global resolution with model M<sub>3</sub> appears not to be necessary for getting effective opening schemes for a set of ACCs. Model M<sub>1</sub> is simple, quick and very efficient and could be used by ACC flow manager positions. But, the set of restrictions which are derived from the different opening schemes would still have to be handled by the CFMU for harmonization between capacity constraints due to the network effect. Even if the continuity of capacity were guaranteed along one flow, one constraint capacity at least would be more saturated than the others and would only require activating a single flow management restriction.

The modelization with patterns has the advantage of keeping close to operational activity. It is true that one can parameter the frequency of layout changes and the optimization period in the models. This kind of optimization could be a good decision aid tool.

We could also imagine to extend these models to the tactical ATFM phase by continuously adapting the ACCs configurations to a changing traffic demand according to operational disturbances.

**LOCAL APPROACH (see p.8)**

Examples of results obtained on the 2000/10/06 traffic day for Aix-West (LFMACCW), Paris-West (LFFACCW) and Reims (LFEEACC) ACCs

| ACC     | S1, S2                    |       | Reference | (HH)           |                | (STAT)         |                |
|---------|---------------------------|-------|-----------|----------------|----------------|----------------|----------------|
|         | 20001006                  |       |           | M <sub>1</sub> | M <sub>2</sub> | M <sub>1</sub> | M <sub>2</sub> |
| LFMACCW | Number of patterns        |       | 10        | 14             | 17             | 12             | 15             |
|         | CPU time                  |       |           | 2              | 15             | 1              | 22             |
|         | Delay generated           | 4301  |           | 2360           | 2422           | 2632           | 2750           |
|         | Number of flights delayed | 408   |           | 314            | 294            | 336            | 304            |
|         | Profit percentage         |       |           | 45,13          | 43,69          | 38,80          | 36,06          |
| LFFACCW | Number of patterns        |       | 9         | 11             | 12             | 10             | 11             |
|         | CPU time                  |       |           | 1              | 6              | 1              | 5              |
|         | Delay generated           | 5396  |           | 4185           | 3984           | 4243           | 4049           |
|         | Number of flights delayed | 500   |           | 416            | 396            | 420            | 403            |
|         | Profit percentage         |       |           | 22,44          | 26,17          | 21,37          | 24,96          |
| LFEEACC | Number of patterns        |       | 12        | 14             | 18             | 12             | 17             |
|         | CPU time                  |       |           | 3              | 29             | 1              | 12             |
|         | Delay generated           | 25608 |           | 25608          | 24229          | 25632          | 24247          |
|         | Number of flights delayed | 1186  |           | 1233           | 1173           | 1174           | 1152           |
|         | Profit percentage         |       |           | 0,00           | 5,39           | -0,09          | 5,31           |

**GLOBAL APPROACH (see p.9)**

Examples of optimization results on 6 ACCs: Aix-East, Aix-West, Barcelona, Geneva, Reims, Zurich and for 4 traffic days

| GLOBAL     | S3                        | Reference | (HH)           |                |                |
|------------|---------------------------|-----------|----------------|----------------|----------------|
|            |                           |           | M <sub>1</sub> | M <sub>2</sub> | M <sub>3</sub> |
| 2000/09/29 | CPU time                  |           | 22             | 67             | 204            |
|            | Delay generated           | 114357    | 63858          | 63226          | 65302          |
|            | Number of flights delayed | 3786      | 3480           | 3453           | 3489           |
|            | Profit percentage         |           | 44,16          | 44,71          | 42,90          |
| 2000/10/02 | CPU time                  |           | 28             | 99             | 361            |
|            | Delay generated           | 45530     | 22186          | 20728          | 21317          |
|            | Number of flights delayed | 2500      | 1949           | 1944           | 2021           |
|            | Profit percentage         |           | 51,27          | 54,47          | 53,18          |
| 2000/10/06 | CPU time                  |           | 18             | 145            | 283            |
|            | Delay generated           | 107111    | 52373          | 51979          | 51436          |
|            | Number of flights delayed | 3477      | 3005           | 3002           | 2985           |
|            | Profit percentage         |           | 51,10          | 51,47          | 51,98          |
| 2001/06/25 | CPU time                  |           | 18             | 124            | 182            |
|            | Delay generated           | 28169     | 18555          | 20897          | 18562          |
|            | Number of flights delayed | 2212      | 1794           | 1918           | 1802           |
|            | Profit percentage         |           | 34,13          | 25,82          | 34,10          |

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## Authors biographies

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## Annex – Presentation of tools

### COSAAC

COSAAC is an ATFM simulator adapted to strategic and pre-tactical studies and simulations in the fields of airspace design, airspace management and ATFM. COSAAC is co-developed by EEC and CENA (Centre d’Etudes de la Navigation Aérienne) in a context of a close co-operation between them.

This tool is characterized by a user-friendly GUI which enables accurate analysis of traffic demand at the level of the whole ECAC airspace down to individual aircraft via ACC and sector levels.

Being a simulator, COSAAC includes essential actions that can be applied to traffic flows such as rerouting, traffic growth, slot allocation and operational disturbances on departure hours application.

### ISACASA

ISA is a generic software tool that can be used to model a wide range of slot allocation strategies using any specific algorithm and a number of different optimization techniques. Programming techniques include constraint programming and linear programming. ISACASA is the slot allocation module which produces accurately the actual operational slot allocation process of the CFMU, called CASA.