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, $S = \{S_i\}_{i=1..10}$

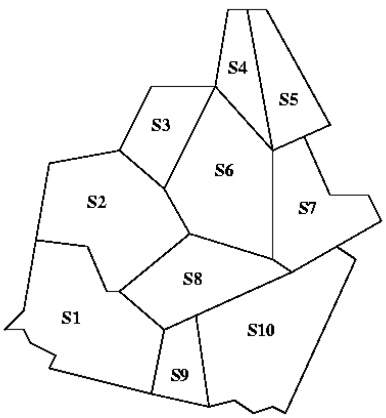


Figure 1: Bordeaux ACC

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).

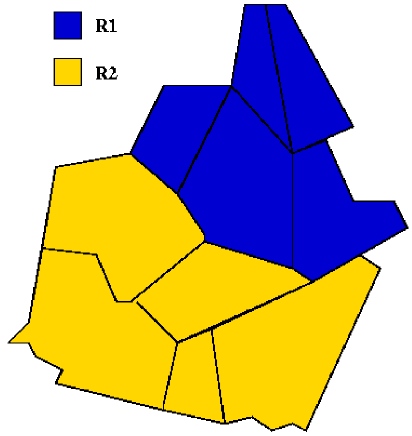


Figure 2: layout l_1 with 2 working positions

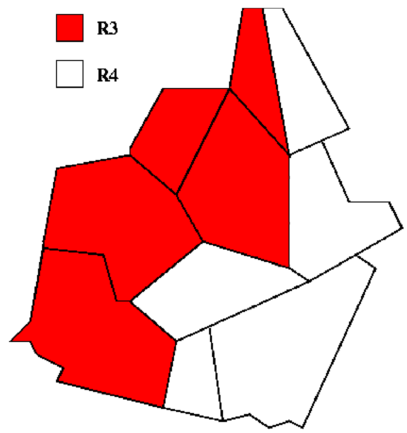


Figure 3: layout l_2 with 2 working positions

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.

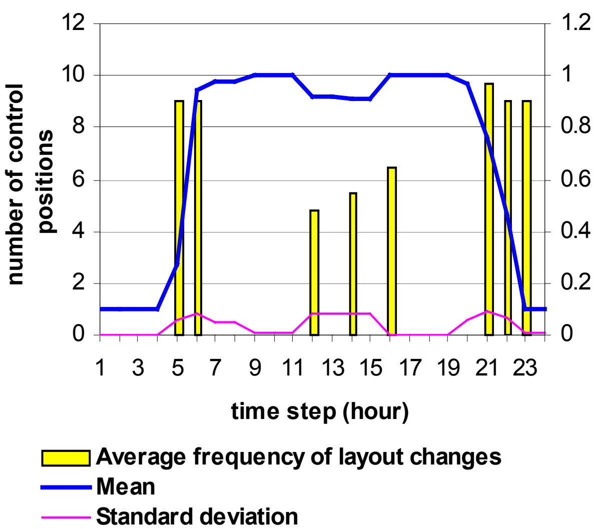
3 Problem formulation

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 $d_{\min(i)}$ [3]. 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:

$P_1 = [0..12[$ and $d_{\min(1)} = 6$

$P_2 = [12..20[$ and $d_{\min(2)} = 1$

$P_3 = [20..36[$ and $d_{\min(3)} = 4$

$P_4 = [36..40[$ and $d_{\min(4)} = 1$

$P_5 = [40..48[$ and $d_{\min(5)} = 6$

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*.

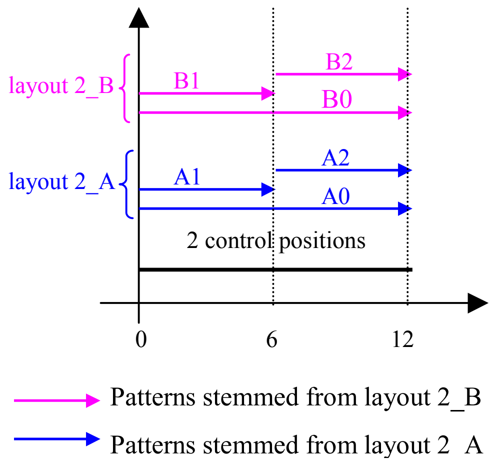
- a pattern *p* is defined from a layout *l*. It can be represented by a couple (h_p, d_p) where h_p and d_p are respectively the hour of beginning of the pattern and its duration. By construction, the duration of a pattern cannot exceed the duration of the layout it is stemmed from:
  $\forall p, \quad d_p \le d_l$.
- a pattern is constructed differently following the period in which it is defined. We have:
  $\forall p, \quad \text{if } h_p \in P_i \text{ then } d_p \ge d_{\min(i)}$
  $\forall p, \quad d_p \bmod (d_{\min(i)}) = 0$
  $\forall p, \quad h_l \le h_p \le h_l + d_l$

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:

[3] 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
$z^{-}(e,t)$ ≥ 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)

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

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

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

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

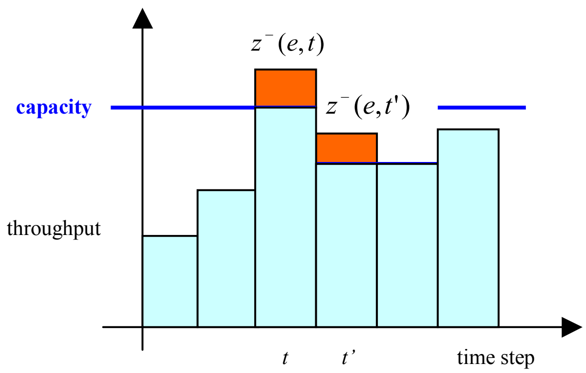
But, with this criterion, we can have equivalent solutions (in term of delays) like:
- solution S_1 with pattern A0.
- solution S_2 with patterns A1 and A2.

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 ε 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_2)

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:

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

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 $\boldsymbol{g^+(e,t)}$ and $\boldsymbol{g^-(e,t)}$; the model becomes:

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

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

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

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

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

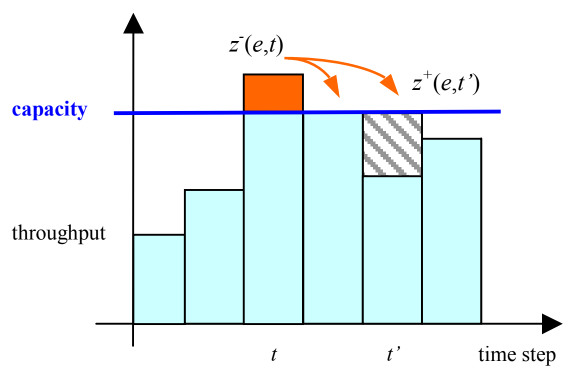
- the deficits of capacity that could not be transferred; C is a constant cost greater than the cost of the longest transfer (the cost of an excess of capacity is null).
- the duration of transfers. The more the transfer is late, the more it is expensive.
- the number of patterns.

(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_3)

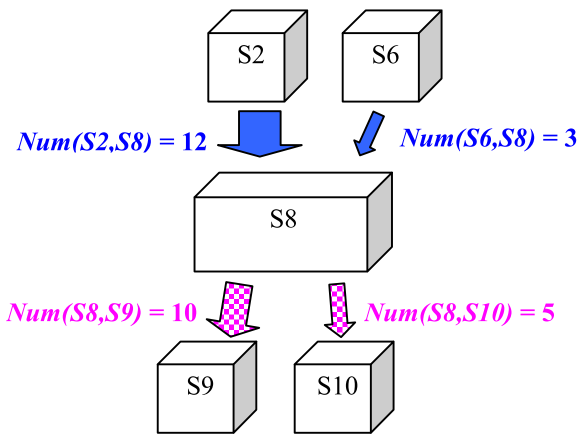
Coupling constraints between airspace entities are statistically generated which makes ACCs inter-connected. This is an evolution of model M_2 in the way that capacity overloads are spread on next capacity slots in time and **space**. This is explained below:

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.

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

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



Then, *deg*(S2,S8) = 12/12×100
= 100 %
deg(S6,S8) = 3/3×100
= 100 %
deg(S8,S9) = 10/15×100
= 66.66 %
deg(S8,S10)= 5/15×100
= 33.33 %

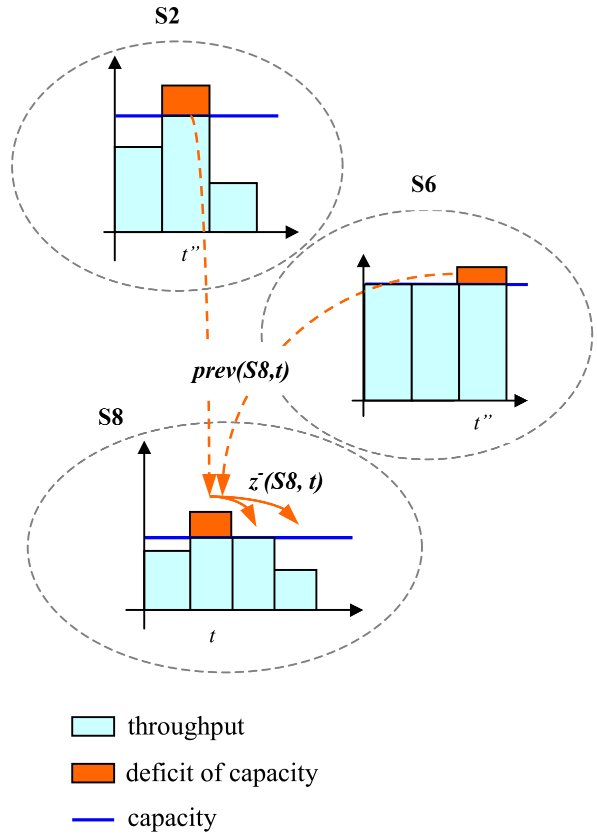
Let $\boldsymbol{prev(e,t)} = \sum_{e \in succ(e''), t > t''} \boldsymbol{y(e'',t'',t)} \times deg(e'',e)$ be the sum of delays transferred from the entities *e''* such as *e''* are geographical predecessors of *e* proportionally to their degree of dependence.

The capacity constraints of the previous model become:

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

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[4] (branch and bound algorithm).

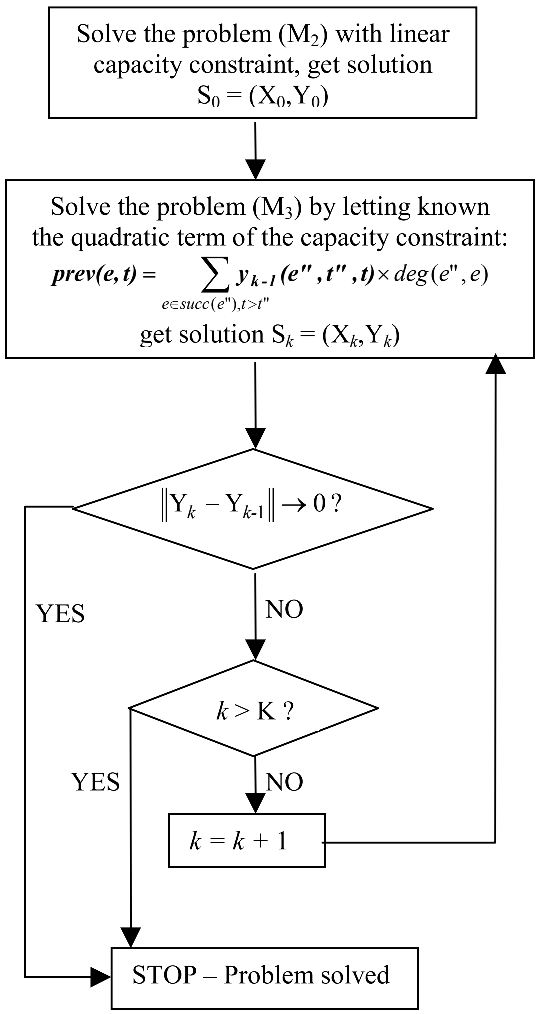
Solving a greater area, even limited to the whole French airspace, is a much more difficult problem (second model yields about 100 000 variables and 6 200 constraints on a heavy traffic day). The problem remains feasible yielding though long calculation times (50 min to 75 min). Optimality cannot be 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.

[4] 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 (LFBBACC), 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:

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

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

$P_1 = [0..6[$ and $d_{min(1)} = 6$.
$P_2 = [6..16[$ and $d_{min(2)} = 1$.
$P_3 = [16..30[$ and $d_{min(3)} = 2$.
$P_4 = [30..46[$ and $d_{min(6)} = 1$.
$P_5 = [46..48[$ 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_1	M_2
Sept/Oct 2000	Number of variables	Min	450	6000
		Max	3500	15100
	Number of constraints	Min	430	430
		Max	900	900
May/June 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_1, M_2 and M_3 has been guided by 2 approaches (local one for M_1 and M_2, global one for M_3), 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

	(HH)		(STAT)	
S1,S2	M_1	M_2	M_1	M_2
Sept/Oct 2000	21,6	29,4	25,7	26
May/June 2001	33	27,2	28,6	25

	(HH)		
S3	M_1	M_2	M_3
Sept/Oct 2000	33,2	40,1	40,1
May/June 2001	41,7	39,3	39,4

CPU time (in seconds)

		(HH)		(STAT)	
S1,S2		M_1	M_2	M_1	M_2
Sept/Oct 2000	Min	1	2	1	2
	Max	7	150	7	151
May/June 2001	Min	1	2	1	2
	Max	18	950	5	176

S3		(HH) M_1	M_2	M_3
Sept/Oct 2000	Min	1	1	1
	Max	18	195	253
May/June 2001	Min	1	1	1
	Max	40	440	816

Comparison M_1/M_2: the model (M_1) 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_2 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_3: as model M_2, M_3 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_1	M_2	M_3
Sept/Oct 2000	49,93	50,3	50,25
May/June 2001	23,97	20,89	21,3

CPU time (in seconds)

S3		(HH) M_1	M_2	M_3
Sept/Oct 2000	Min	18	1	195
	Max	32	194	610
May/June 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_1 gives good results and fast CPU times. Models M_2 and M_3 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_3 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_3 appears not to be necessary for getting effective opening schemes for a set of ACCs. Model M_1 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

	S1, S2		(HH)		(STAT)	
ACC	**20001006**	**Reference**	**M_1**	**M_2**	**M_1**	**M_2**
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

			(HH)		
GLOBAL	**S3**	**Reference**	**M_1**	**M_2**	**M_3**
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

References

[1] E. Jacquet-Lagrèze, "Programmation linéaire – Modélisation et mise en œuvre informatique", P.I.Q. Poche

[2] P. Leal de Matos, R. Ormerod, "The application of operational research to European air traffic flow management – understanding the context", European Journal of Operational Research 123 (200) 125-144.

[3] P. Leal de Matos, " The Development of Decision Support Models for European Air Traffic Flow Management ", PhD 1998.

[4] AEA, "Benchmarking of Air Traffic Control Centres", June 1998.

[5] EEC, "Medium-term Capacity Shortfalls 2003-2005", October 1999.

[6] CENA, Sofréavia, "Techniques de détermination de la capacité des secteurs de contrôle de l'espace aérien : statistiques et simulations. Application et mise en oeuvre de la RVSM", December 1997.

[7] EEC, NATS, "Investigating the Air Traffic complexity", July 2000.

[8] Ph. Kerlirzin, S.Manchon, Ch. Plusquellec (CENA), "Evaluating the cost of ASM/ATFM measures", 1st US/Europe ATM Seminar, June 1997.

[9] Ph. Kerlirzin, S.Manchon, Ch. Plusquellec, JB. Gotteland (CENA), "Building and evaluating a minimal regulation scheme", 3rd International Seminar on ATM R&D, July 2000.

Authors biographies

Céline Verlhac was graduated master in optimization of the Paris VI University Pierre & Marie Curie in 1999. She is an operational research engineer of **EURODECISION**. She has been working for the Eurocontrol Experimental Center in the "Performance, Flow and Economics" business area for 10 months.

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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.