Building and evaluating a minimal regulation scheme

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Abstract

The airspace that we consider is a volume without hole made up of sub-volumes. A capacity, described by a maximum throughput, is calculated in cooperation with ATC controllers several months before the day of operations. It is assigned for each sub-volume. A sub-volume is called a sector or a group of sectors.

According to the predicted traffic and the available staff of controllers, sub-volumes number and capacity vary throughout the day and define a scheme for armed control positions, what we call the opening schedule.

Depending on the opening schedule and on the predicted traffic sample, it is necessary to apply a set of regulation measures to avoid remaining sectors overloads. A regulation measure is described by a sector or a group of sectors, a time period and a capacity.

A flight passes through 7 sectors or groups of sectors in France on average (13 in Europe). Hence, a single regulation measure may protect several sectors or groups of sectors. Knowing that the French control system manages up to 8000 flights per day (27 000 in Europe), it would be very effective to reduce as much as possible the number of treated regulation measures.

In this document, we define a working methodology which aims at reducing the size of the regulation scheme.

Simulations were carried out with SHAMAN experimental platform. Constraints programming was used to solve the problem.

CENA

CENA is in charge of studies related to air traffic management in order to support French and European Air Traffic Control (ATC) in an international cooperation.

One domain of division RFM of CENA is to design and to implement mock-ups, prototypes and simulators for airspace and air traffic flow managers (ASM & ATFM respectively). SHAMAN is one of them.

Introduction

Overview

Before the ATFM tactical phase, the FMP prepares its ACC's schedule (that we call opening schedule) for controlled sectors or groups of sectors, taking into account a predicted traffic sample and the available staff of controllers. The goal is to make this scheme as capacitive as possible and to define a set of regulation measures to protect every sector of the ACC.

The FMP then transmits the opening schedule and the temporary protection requests for airspace volumes that might be critical, to the CFMU executive unit (CEU). The opening schedule and the requested measures of protections are indissociable. This work is done locally in the ACC and does not take into account the capacities of the other ACCs' sectors.
The CEU collects the opening schedule and the associated requests for protection coming from the different FMPs. It must make it consistent for all the ECAC zone. Considering the number of interdependent regulations and some other phenomena consecutive with exploitation of such a mosaic of capacities in the air route network, it is difficult to find a consistent scheme with appropriate protections for airspace volumes. Let us keep in mind that a flight passes through 7 en-route sectors on average in the French airspace and through 13 in Europe.
Today, identification of the most penalizing volumes is made by a simple comparison between traffic demand and sectors capacities. This static identification highlights more sectors than necessary, i.e. regulation scheme may contain redundant regulations.

Goal

ATFM tactical process complexity (slot allocation and real time supervision) depends on the number of capacity constraints treated, knowing that they are interdependent. Decreasing the number of treated constraints allows:

- to simplify the process by suppressing redundant regulations: benefits for ATFM;
- to reduce total delay: benefits for companies.

The objective of this study is to address and validate a working methodology that allows flow managers to easily work out a minimal regulation scheme using a tool with an integrated take-off-slot allocation module. First, this tool will help the flow managers to identify the airspace volumes that take part in the slot allocation process. Then it will help them to extract only those which generate high delays during short periods or low delays during large periods.

Proposed method

We recommend the following working method to build the minimal regulation scheme :

- **Step 1** Identification of participating airspace volumes

  The flow manager starts a slot allocation that treats every capacity constraint for all airspace volumes. This results in a list of airspace volumes, each of them beeing characterized by the individual delay it generated.

- **Step 2** Minimal regulation scheme elaboration

  The flow manager chooses a "participation threshold" i.e. a minimal value of the ratio *airspace volume individual delay generated / total generated delay*. The airspace volumes and periods during which they must be protected derive from it.

- **Step 3** Minimal regulation scheme validation

  The flow manager starts a slot allocation process taking into consideration the only capacity constraints given by the minimal regulation scheme. Since all the capacity constraints are not treated, the remaining sectors overloads have to be quantified. If these traffic overloads are unacceptable in quality and/or in quantity (the cost function is presented in the "Protocol" of the technical validation part), step 2 must be reiterated with a smaller participation threshold. If not, the regulation scheme can be forwarded to the CEU.

Participation threshold definition

The aim is to find a relevant parameter that allows the flow manager to highlight critical airspace volumes.

In step 1, the slot allocation process treating all airspace volumes capacity constraints generates a total delay D_T and the list of airspace volumes that generated delays. Let D_V the delay generated by airspace volume V during the regulated period.

Among volumes that may need regulation ($D_V \neq 0$), some are characterized by a large delay generation during a short time period and others by a short delay during a long time period.

Let us first define τ, the individual participation of V in the total delay D_T generated during the regulated period:

If D_V is the total delay generated by V, then $\tau = \frac{D_V}{D_T}$

At first glance, it seems easy for flow managers to set a minimal participation threshold τ_0 because they have a good knowledge of τ from their own experience and thanks to the weekly and monthly reports published by SCTA and CFMU. But in fact, this is not enough : volumes that ponctually generate delays are not highlighted.

Let us refine this criterion with the average delay generated by a capacity constraint of 30 minutes on V:

$$\bar{d} = \frac{D_V}{N_V} = \frac{D_V}{D_T}\frac{D_T}{N_V} = \frac{\tau D_T}{N_V}$$

where N_V is the number of 30-minute capacity period relative to V during the regulated period. For example, if V is "armed" between 04h00 and 11h00, and then between 17h00 and 20h00, then the number of 30-minute capacity constraints (corresponding to the allocation step) is $N_V = 20$. Moreover, if we decide to solve the problem between 4h00 and 22h00 (peak traffic), therefore $N_T = 36$.

Let d_0 the minimal participation delay:

$$\bar{d} = \frac{\tau D_T}{N_V} \geq \frac{\tau_0 D_T}{N_V} \geq \frac{\tau_0 D_T}{N_T} = \tau_0 \bar{D} = d_0$$

The minimal regulation scheme will be reduced to the airspace volumes which generate delays above minimal delay d_0 on a given 30-minute period.

In practice, the flow manager chooses τ_0; the system uses d_0:

$$\frac{\tau_0 D_T}{N_T} = \tau_0 \bar{D} = d_0$$

τ_0 is called " participation threshold ".

We show that $\bar{d}$, therefore d_0 with constant τ_0 doesn't increase significantly with N_T. For instance, the day of 02/06/1995 has given following results:

D_T *(min)*	capa width *(min)*	N_T	$d_0 \mapsto \tau_0 = 1\%$ *(min)*
4900	60	4	12
10000	30	8	13
15500	20	12	13
33000	10	24	14

where "capa width" is the width, in minutes, of a section of capacity.

Thus, the flow manager does not need to modify τ_0 even if the allocation step is changed.

Simulations

Data sample

The data sample we use relates to the French airspace.

Flight plans come from the French initial flight plan data processing system (STIP) archives. Regulation names and delays came from CFMU figures.

We measured traffic overloads (difference between traffic and capacity).

1997	C1 Nb flights	C2 Overloads with initial traffic	C3 Overloads after operations
06/06	6372	790	577
13/06	6306	709	568
20/06	6234	633	558
27/06	6378	696	479
05/09	6433	682	640
12/09	6429	720	599
19/09	6383	735	622
26/09	6332	683	555
average	6358	706	575
std. dev.	62	43	46

Column C2 indicates the traffic overloads which would have occurred if initial demand had not been regulated at all. The capacity figures taken into account result from opening schedules prepared by ACCs.

Column C3 indicates the traffic overloads that occured after CFMU slot allocation and operational disturbances.

Regulation reduces the traffic overloads by 19% in spite of the variations over the CFMU calculated take-off times due to operational disturbances.

Hypothesis

Following referenced hours are UTC hours.

Simulations are carried out from 4h00 to 22h00.

Considered counts and capacities are values for a 60-minute fixed slice.

A slot allocation consists in satisfaying 30-minute capacity constraints (maximal rate of entering flights per 30 minutes) coming from ACCs' opening schedules.

A slot allocation module integrated in SHAMAN is used. The slot allocation strategy is: "first in the most saturated constraint, first served" (close to the CASA slot allocation strategy of CFMU).

This type of strategy leads to a total generated delay reduction compared to a FIFO strategy based on the departure hours.

Slot allocation treating all capacity constraints

There are 1944 30-minute capacity constraints on average ($std.dev. = 21$).

The total delay average is 55295 minutes ($std.dev. = 7109$, $min = 42770$ for the 20/06, $max = 65083$ for the 27/06) after a slot allocation that treats all capacity constraints.

The average execution time of a slot allocation with *2000* constraints is about *1* min *10* sec. *20* sec are spent to generate constraints and *50* sec to find a solution, on a *SUN ULTRA SPARC* workstation using about *20* Mo on average.

The following table gives, for each day of traffic studied, the number of airspace volumes that need protections according to τ, after a slot allocation treating all capacity constraints.

	τ (%)										
1997	=0	0	0.5	1.0	1.5	2.0	2.5	3.0	5.0	>7	total
06/06	31	45	7	9	2	2	2	3	2	4	107
13/06	40	49	5	6	6	2	2	4	0	6	120
20/06	42	55	4	5	2	1	2	4	2	3	120
27/06	29	51	10	6	2	4	1	3	3	2	111
05/09	29	56	7	1	5	2	0	3	2	6	111
12/09	36	44	10	3	2	4	1	4	1	3	108
19/09	40	45	9	2	6	2	2	1	2	4	113
26/09	42	47	2	8	0	2	3	3	2	3	112

The "=0" column contains the number of airspace volumes that do not generate delays.

The "0" column contains the number of airspace volumes which participated in strictly more than 0% and in less than 0.5% of the total delay ($0\% < \tau \leq 0.5\%$) and so on for the other values of τ.

It appears that on average, 35% of the airspace volumes do not participate to the ATFM process. For ($\tau > 1.0\%$), only 19% of capacity constraints are treated.

Technical validation of minimal regulation scheme definition

Presentation of the simulation

Protocol The simulation process goes through the following steps:

- slot allocation with all capacity constraints;
- definition of a reduced set of capacity constraints (minimal regulation scheme) with d_0 values based respectively on different τ_0 values;
- slot allocation based on the respect of this reduced set of capacity constraints;
- study of remaining traffic overloads after slot allocation based on the respect of this reduced set of capacity constraints;

  The following rates of remaining traffic overloads are considered:

  - between 0% and 10% over the capacity: admissible regarding safety aspect;
  - between 10% and 20% over the capacity: admissible regarding safety aspect only if they are ponctual.
  - 20% over the capacity: inadmissible or non valid declared capacity for airspace volume.

To check that a solution based on a minimal regulation scheme provides better protections of airspace volumes even if some traffic overloads remain (which is the case with CFMU), the following traffic overloads can be compared:

- initial traffic overloads (initial demand);
- remaining traffic overloads with allocated traffic after:
  - a slot allocation respecting all capacity constraints
  - applying a noise to the allocated departure hours;
- remaining traffic overloads with allocated traffic after:
  - a slot allocation respecting capacity constraints of a minimal regulation scheme
  - applying a noise to the allocated departure hours;
- remaining traffic overloads after operations.

Noise Adding a noise aims at simulating operational disturbances which affect allocated departure hours (bad meteorological conditions, delay at boarding, uncertainty on rolling time, ...).
A Gaussian noise with a mean delay of 5 minutes and a standard deviation of 16 minutes is applied to allocated departure hours. These parameters were provided by a statistical study based on STIP and CFMU inputs. Standard deviation is consistent with the window allowed by CFMU to take off (window of $-5,\ +10\ min$ around each departure hour). In fact, departure hours variation is more complex: there is a main traffic peak at $-5\ min$, a secondary one at 0 and a last one at $+10\ min$. Choosing a Gaussian variation of departure hours (i.e. adding to an initial entry time of flights in airspace volume a calculated variation) is practical: it provides an entering traffic curve in airspace volume that is close to the observed one.
First, for each studied sample, the initial traffic demand is treated with the SHAMAN slot allocation module (all capacity constraints are respected or only minimal regulation scheme constraints are respected according to each simulation). Then 50 pseudo allocated samples are created by applying Gaussian noise. This number of experiments is sufficient according to the standard deviation on number of remaining traffic overloads (the standard deviation is less than 10% of the average).

Results Simulations are made with different τ_0 values: 0%, 1%, 1.5%, 2%, 2.5%, 3%, 5%.
Figure 1 represents a number of traffic overloads of $x\%$ over the capacity (before noise) according to the number of treated capacity constraints (only 29% of the 30-minute capacity constraints generate the total delay).

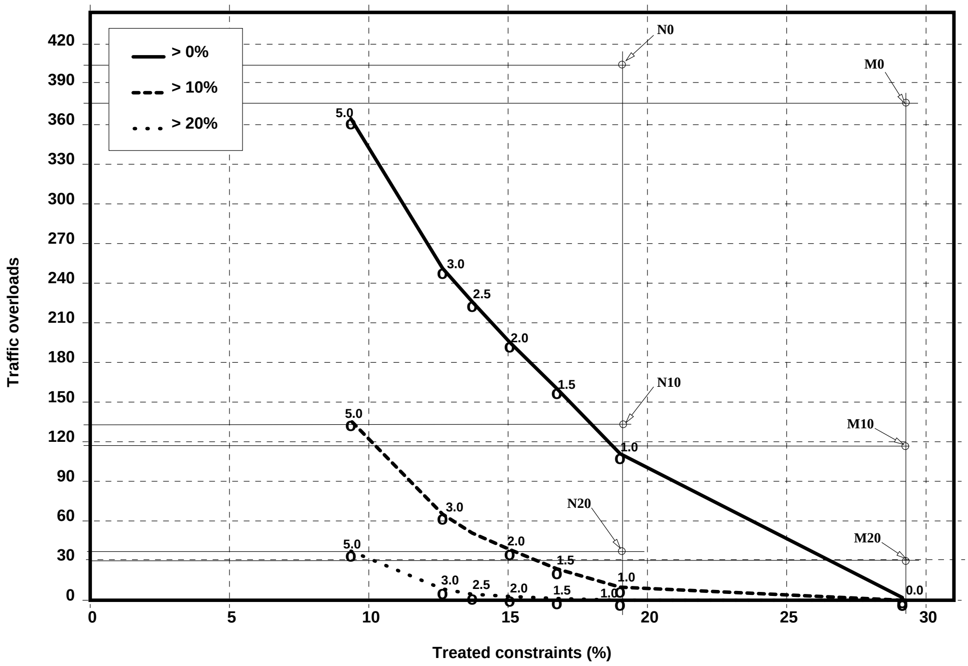

Figure 1: Influence of d_0 on the number of capacity constraints and on the mean number of traffic overloads

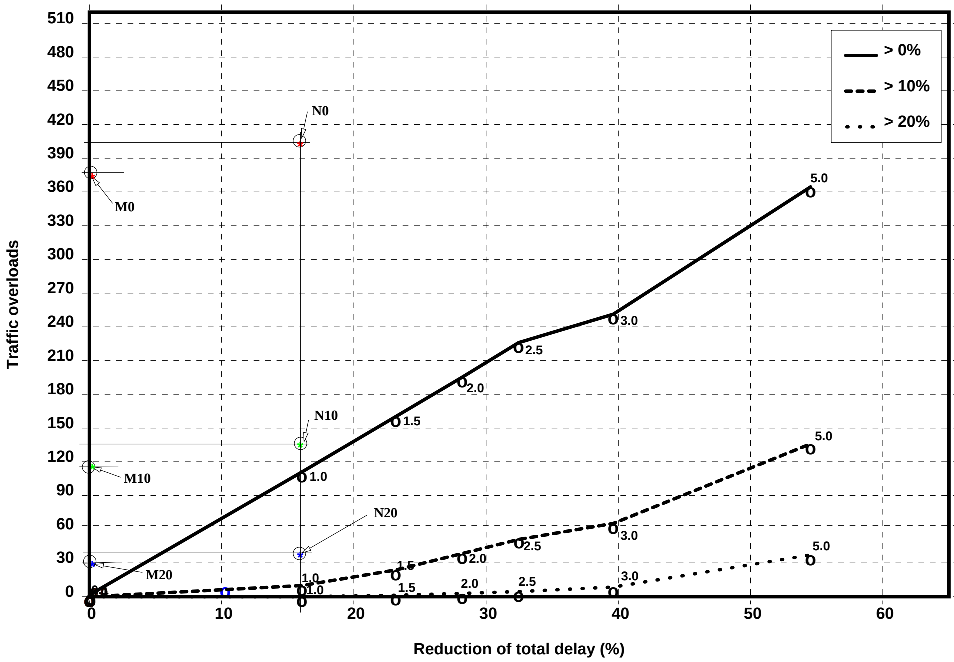

Figure 2: Influence of d_0 on the reduction of the total delay and on the mean number of traffic overloads

Figure 2 represents a number of traffic overloads of $x\%$ over the capacity (before noise) according to the decrease of generated total delay. The origine represents 100% of the total delay generated when all capacity constraints are treated.

Each point of a given curve corresponds to a number of traffic overloads (before noise) for a given τ_0. For example, for d_0 corresponding to $\tau_0 = 1\%$ (noted $d_0 \mapsto \tau_0 = 1\%$),

- only 18% of constraints need to be treated;
- total delay is reduced to 16%;
- the number of remaining traffic overloads is not very high: only about 100 flights.

Points on the figures (not on the curves) represent the remaining traffic overloads after slot allocation respecting all capacity constraints, followed by a Gaussian noise (0% and 1%) applied to calculated departure hours.

The points are called $M0$ and $N0$, $M10$ and $N10$, and $M20$ and $N20$ when they represent respectively traffic overloads between 0% and 10%, 10% and 20%, and over 20%, over the capacity.

First global quantitative results about constraints and delays show that for $d_0 \mapsto \tau_0 = 1\%$, after slot allocation and noise beeing applied, remaining traffic overloads are very small.

The mean numbers of remaining traffic overloads are mentioned in the table 1 and in figures 1 and 2. They can be compared to the traffic overloads after slot allocation respecting all capacity constraints and noise beeing applied.

In all cases, traffic overloads are lower than remaining traffic overloads observed in the traffic after operation, especially concerning traffic overloads 20% over the capacity.

Qualitative results about minimal regulation scheme show that the number of regulations of minimal regulation scheme is close to the number published by CFMU.

Morover, the regulations deduced by this technique correspond to the ones published by CFMU.

Table 1: Traffic overloads before and after slot allocation (CFMU, noise)

	initial	after ops	noised 0%	noised 1%
Overloads	706	575	376	403
Overloads capa+10%	355	272	118	134
Overloads capa+20%	165	165	29	35

Case studies

Validation of the reference day

During the pretactical phase (2 days before the day of operations D), the flow manager knows 60% to 90% of the traffic. Since regulation problems are due to around 10% of the traffic, the pretactical preparation of the regulation scheme uses a predicted traffic. Generally, a good approximation of the traffic of day D is the traffic of day $D-7$ which is called the reference day.

The simulations we present now aim at verifying that this method for choosing the reference day is valid.

A slot allocation called $\frac{D}{D}$ is applied to the traffic of day D. The set of capacity constraints that allocation has to respect derives from the regulations of the minimal regulation scheme, with:

- $d_0 \mapsto \tau_0 = 1\%$;
- slot allocation with the traffic of day D and the opening scheme of day D.

A slot allocation called $\frac{D-7}{D}$ is applied to the traffic of day D. The set of capacity constraints that allocation has to respect due to regulations induced by minimal regulation scheme when:

- $d_0 \mapsto \tau_0 = 1\%$;
- slot allocation with the traffic of day $D-7$ and the opening scheme of day D.

The results of these two simulations can be compared. The mean number of remaining traffic overloads resulting of slot allocation $\frac{D-7}{D}$ is compared to the mean number of remaining traffic overloads resulting of slot allocation $\frac{D}{D}$.

Table 2: Overloads before and after slot allocation

	initial	after ops.	$\frac{D-7}{D}$	$\frac{D}{D}$
Overloads	706	575	288	111
Overloads capa+10%	355	272	118	10
Overloads capa+20%	165	165	51	0

The characteristics (volume, time period during which the regulation is valid, ...) of regulations of the minimal regulation scheme $\frac{D=D-7}{D}$ ($d_0 \mapsto \tau_0 = 1\%$) are compared to the characteristics of regulations induced by the minimal regulation scheme $\frac{D}{D}$ ($d_0 \mapsto \tau_0 = 1\%$).

Table 3: Regulations $\frac{D-7}{D}$

$\frac{D-7}{D}$	Aix	Bord.	Brest	PE	PW	Reims
$\bar{x}$	77	73	74	66	70	70
$std.dev.$	7	7	16	17	15	11

First results show that more than 70% of regulations of the minimal regulation scheme $\frac{D-7}{D}$ are the same than the minimal regulation scheme $\frac{D}{D}$ ones. The minimal regulation scheme $\frac{D-7}{D}$ offers a good protection of the sectors even if some variations concerning regulation periods are noticed. However, the number of remaining traffic overloads of 20% over the capacity, resulting from slot allocation $\frac{D-7}{D}$ is too big.

Validation of the local preparation of regulation measures

Each FMP prepares locally i.e. independently of others ACCs, its regulation measures. CFMU collects all regulation measures and merges them together trying to take into account the network effect between capacity constraints.

This operational process is simulated: for each ACC i.e. for each ACC's opening schedule, a slot allocation is applied. Critical airspace volumes are identified and a local minimal regulation scheme is elaborated for each ACC. Then, local minimal regulation schemes are merged together in a minimal compiled regulation scheme. A slot allocation based on this compiled regulation scheme is performed to identify the regulation measures that generate no delay due to the network effect. Finally, these regulation measures are removed from the compiled minimal regulation scheme. This final scheme is called the compiled minimal regulation scheme.

The compiled minimal regulation scheme is compared to the minimal regulation scheme. If they are close enough (number of regulations, names of regulations, periods of regulations...), then the proposed method of regulation measures preparation is applicable. An efficient coordination supposes that locally defined regulation schemes are changed as less as possible because of the consolidation achieved by CFMU.

The common part between the two regulation schemes for each ACC is given in the following table:

ACC	Minimal reg. scheme / Compiled min. reg. scheme % common
Aix	90
Bordeaux	95
Brest	88
Paris est	77
Paris ouest	89
Reims	89

First results show that the percentage is rather high on average. It should not be penalizing that each FMP prepares its own set of local regulation measures if the method we present is applied.

Conclusion

The complexity of the ATFM tactical process (slot allocation and real time supervision) can be lowered, the total delay generated by the ATFM slot allocation decreased, and finally the safety increased (number of potential remaining traffic overloads reduction), by defining a minimal regulation scheme. This requires the use of a fast pretactical ATFM simulator.
The operational start-up of such a method should be easy because no modification of the actual working method is needed (local preparation of regulation measures and synthesis performed by the CEU).

References

[KMP97a] Ph. Kerlirzin, S. Manchon, and C. Plusquellec. Evaluating the cost of ASM/ATFM measures Technical report, CENA, 1997.

[CDKM94] D. Chemla, D. Diaz, P. Kerlirzin, and S. Manchon. Using clp(fd) to support air traffic flow management. Technical report, CENA-SYSECA-INRIA, Ithaca (NY), Novembre 1994. Séminaire ILPS.

[Col95] D. Colin de Verdière. Adaptation de la demande à la capacité disponible de la piste et de l'espace aérien. Technical Report NT95.928, CENA, Paris, Novembre 1995. Séminaire Aéroports du futur.

[Die95] P. Dieben. *Tactical System Software Requirements*. EUROCONTROL-CFMU, Bruxelles, 1.301 edition, Juillet 1995. TACT/SRD/DOC-1.

[DKM97] É. Deloche, Ph. Kerlirzin, and S. Manchon. Influence de l'activation de la zone C2 sur le secteur TE. Technical Report NT97.117, CENA, 1997.

[M99] S. Manchon. Le Bourget 1999 Technical Report NT99, CENA, 1999.

[GM96] C. Gobier and S. Manchon. Une approche du contrôle généralisé en vitesse dans shaman. Technical Report NT96.058, CENA, 1996.

[KMP97] Ph. Kerlirzin, S. Manchon, and C. Plusquellec. Étude des problèmes structurels de l'espace aérien francais. Technical Report NT97.072, CENA, 1997.

[Man95] S. Manchon. Évaluation rapide d'un changement de capacité du secteur TE. Technical Report NT95.241, CENA, 1995.

[Mau96] L. Maugis. Mathematical Programming for the Air Traffic Flow Management Problem with En-Route Capacities. Technical report, CENA-SOFREAVIA, Vancouver, Juillet 1996. Séminaire IFORS 96.

[Nad89] B.A. Nadel. Constraint satisfaction algorithms. *Computational Intelligence*, (5):188–224, 1989.

[Plu97] C. Plusquellec. Description du module d'allocation de créneaux utilisant la programmation par contraintes implanté dans shaman. Technical Report NT97.105, CENA, 1997.

[SD88] P. Siarry and G. Dreyfus. *La méthode du recuit simulé : théorie et applications*. I. D. S. E. T, Paris, 1988.