An Experimental Study of ATM Capacity

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1 Introduction

Planning, or making decisions for the evolution of the European air traffic management system (EATMS) involves a careful evaluation of alternative scenarios, from various perspectives: technical, operational, economic, or even environmental. This assessment is often carried out through experimentations, in which modeling and simulation contribute significantly, by reducing the turn-around time between the design and the implementation of advanced operational concepts.

We develop below a formalized approach, simulation based planning, to determine the requirements needed to accomplish efficient air traffic services, and to assess how well proposed operational scenarios meet those requirements. This determination follows a logical top down approach to EATMS concept assessment by identifying - at different time frames - key factors that affect system performance and permit a preliminary evaluation of these concepts.

We argue that air traffic control modeling and simulation techniques must inter-operate to yield supportive evidence and justification for proceeding with new operational concepts, and for addressing the complexity of the assessment of alternative airspace organizations, controller working methods, and automation strategies. Although numerous mathematical models and fast time simulation facilities are already being used to assess the performance of the European airspace system (NASPAC, EAM, TAAM, RAMS, ARC2000, RAMS, ERATO, SPECTRA), recent review studies ([Sof96b, Sof96c, NAS96]) highlighted also their lack of flexibility to cope with new concepts, with complex dynamics of the ATM system, with large scale uncertainty factors, and with simulation software complexity.

To support this simulation based planning methodology, we develop a general purpose en-route air traffic simulator, connected to other modules which act as filters to organize traffic demand and match ATM resources to this demand. Filters operate at different time frames (strategic, pre-tactical, tactical) to model key components of the EATMS: the work schedule of controllers, the flexible use of airspace, the central flow management unit, the actions of planning and executive air traffic controllers, the airborne separation assurance and short term collision avoidance systems.

Flexibility is a key feature of the simulator as new filters are easily introduced, and tuned to model specific features of an operational scenario. The core of the traffic simulator is small and easy to maintain. It is less than 3,000 lines of ML code. It works with classical aircraft performances, with real airspace designs and operational constraints. Furthermore, it provides a practical framework for thorough mathematical model development, for route network and sector design, air traffic assignment, conflict resolution, ground holding, real-time route allocation or speed control strategies.

Flight, sector, and airport statistics are output from the simulator. Flight statistics include aircraft trajectories, flight duration, fuel burn, detected and resolved conflicts, number and type of maneuvers, passenger delay (ground hold), oper-

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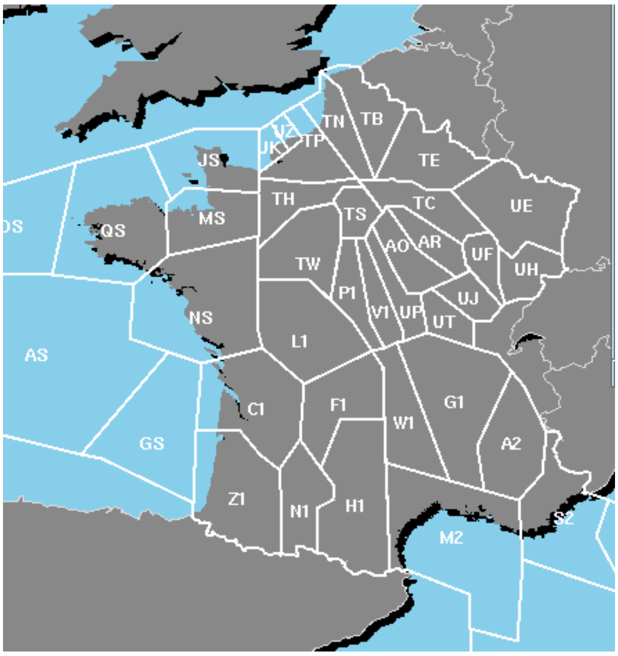

Figure 1: French airspace

ational delay (airborne and ground hold). Sector statistics include sector entry and exit time for each aircraft, controller maneuvers, traffic throughput, etc. Airport statistics include runway capacity utilization, hold-stack delays and departure delays.

This paper is organized as follows. First, the simulation based planning methodology is developed. The needs for advanced ATM concept assessment described in the literature are then briefly reviewed. The hierarchical simulation based planner is presented in the third section. We illustrate its adequacy for concept assessment with a study of new operational procedures, based on the reduction of vertical separation minima to 1,000 feet above FL195.

2 Simulation based planning

Simulation is the discipline of designing a model, executing the model on a digital computer and analyzing the results ([Fis95]). It embodies the principle of learning by doing, whereby to learn about a system, we build a model of some sort and then operate - simulate - the model. We define *simulation based planning* as the use of simulation to aid in the decision making process. It relies on a basic iterative approach where a model of an action is executed to determine the efficiency of an input or control decision within the given situation.

Planning occurs over several different time scales depending on the amount of time that one has to plan prior to committing to a particular plan. Regardless of the specific domain, it involves three components: 1) model type, 2) plan set, 3) plan evaluation. The first step consists in selecting the modeling language to describe a plan, using rules, predicate logic, fuzzy sets, petri nets, graphs, queuing models. The next step is to create a set of candidate plans, or alternative options. The third and key step simulates the different elements of each plan to determine the best.

To apply simulation based planning to the EATMS operational process, we identify key elements of the system at specific time frames. Each of them addresses a problem, described with its input and output parameters, and has a solution procedure to resolve it. Plans are then evaluated not only individually, but also with respect to each other, according to global operational objectives: capacity, safety, cost-effectiveness.

Plans may operate at different levels of abstraction: system capacity, traffic flow, aircraft trajectory, terminal area traffic. Plans can be described with analytical models, or heuristics in the form of operators and rules. Rules can use uncertainty factors or fuzzy sets. If time is of the essence, aggregate models will need to be simulated. For example, to plan and organize air traffic demand, if one has the costs a flight imposes on others by using a small part of the ATC resources, a mathematical programming approach can be used to minimize the overall social cost of air transportation. Unfortunately, such costs are often unknown, and more detailed models must be used instead. As the modeling complexity increases, with dynamics involved, it is valuable to use computer simulation to obtain an answer to the question “Which is the best approach to take given and all currently available knowledge ?" Indeed, the simulation technique is generally useful to answer such "what if" scenarios.

Our approach is to gather the combined effects at the required level of detail of key EATMS components, to assess advanced ATM concepts related to automation, airspace organization and operational procedures. We explore several levels of planning strategies, walking the narrow line separating mathematical modeling and air traffic control fast time simulation.

3 Assessment of ATM concepts

Decision making and planning are critical operations for safe and efficient air traffic services. Available forecast of air transport demand in the next decades and associated congestion costs already call for a complete rethinking of the European ATM business strategy. Foreseen technological developments in communication, navigation, surveillance, avionics and human-machine interfaces are augmented with even greater harmonization and integration efforts by the member states of the European Civil Aviation Conference (ECAC), the European Organization for the Safety of Air Navigation (EUROCONTROL), the Joint Aviation Authorities (JAA), and the European Union (EU) ([ECA97, Com96, Jos96, JAA96]).

To meet the requirements of future air transport, several concept studies have been initiated to analyze new operational concepts, to propose scenarios for the evolution of the current system to the target EATMS. To name a few, studies included ATLAS with its Single Unified Air Traffic Management System (SU-ATMS) scenario, AEGIS with its GIANT scenario, Free-Routes (the European equivalent of Free-flight from the Federal Aviation Administration), or Testing Operational Scenarios for Concepts in ATM (TOSCA) from EUROCONTROL ([ATL93, AEG94]). The European Union in its fourth framework programme is also promoting research on ATM operational concept assessment with studies like New Approaches in Air Traffic Flow Management (NOAA), Model Use of Fast Time Simulation (MUFTIS), or Development of Functional Concepts from the EATMS Operational Requirements (FACTOR) ([Sof96c, Sof96b, Sof96a]).

These scenarios develop different philosophies, are based on different ATM design structures, automation, air space management and air/ground task sharing strategies. For example, developments in ATM might allow the introduction of free routes above a certain level, of 4D ATM, of precision area navigation in terminal areas, of dedicated routes between major airport platforms, or of real-time market based slot allocation.

However, the operational scenarios sketched in these concept studies need to be carefully assessed, technically and operationally, before being implemented, as delicate interdependencies prevail between the technical features of the EATMS and the working methods of both clients and service providers. The scenario's options as well as each transition step towards the target system need to be validated and demonstrated.

Recurrent key issues of these studies relate to:

- work schedule of air traffic controllers;
- flexible use of airspace;
- new route networks;
- air traffic flow management strategies;
- departure slot, route allocation strategies;
- multi-sector planning strategies;
- free flight and free route airspace;
- automation level: delegation, 4D profile;
- cost/benefit analysis;

Similar efforts to assess the system wide impacts of changes of individual components of the ATM system are being undertaken by the Federal Aviation Administration (FAA) with its National Simulation Capability programme. The National Aeronautics and Space Agency (NASA) has also launched an Advanced Air Transportation Technologies programme to address these issues.

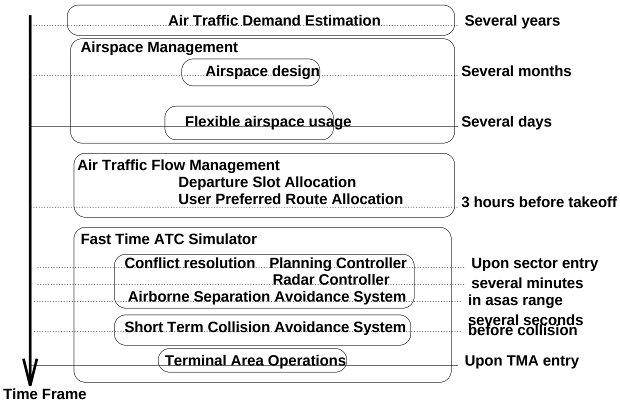

Figure 2: Outil de Planification ATM et Simulation

4 Air Traffic Management Filters

The OPAS[1] system models the operational EATMS process to match traffic demand and system capacity. It comprises several modules, connected to each other. Each module is described below, with input, output, problem addressed, and solution procedure. We refer the reader to cited references for further modeling details on each technique. Two modules, for route allocation and airspace design using genetic algorithms ([DASF94, All96]) are not yet integrated in the system are thus left out here.

4.1 Traffic demand estimation

This filter models traffic demand for a time period in the future, tailored to fast time simulations studies.

Input: a large traffic database of filled and actual flight plans (5 millions), a forecast of traffic growth rates for the main flows.

Problem statement: estimate a forecast sample taking into account daily, weekly, or monthly seasonal effects.

Output: a set of ICAO flight plans to be used in a fast time simulation.

Solution procedure: time series stochastic sampling. Described in [Mau95]

Time frame: traffic estimation is carried out several years in advance.

4.2 Pre-tactical flow management

This filter models airspace management operational procedures carried several days in advance. It matches airspace capacity to air traffic demand, taking into account both civil and military requirements.

Input: controller availability, estimated traffic throughput over all sectors, capacity of sectors, feasible sector combinations, a schedule of airspace requirements from military users possibly offering some flexibility.

Problem statement: combine sectors and assign air traffic controllers to work duty periods, to minimize ground holding delays. Possibly optimize the time periods for the activation of military areas.

Output: schedule of active combined sectors, schedule of active military areas.

Solution procedure: combinatorial optimization, described in [Mau95]

Time frame: the schedule of combined sector is decided one day in advance in the operational process.

4.3 Tactical flow management

This filter models tactical airspace management procedures and specifically the activities of the central flow management unit (CFMU) which match air traffic demand to system capacity.

Input: a schedule of active combined sectors with their capacities, a traffic sample.

Problem statement: assign ground delays to flights such that the flow of aircraft trough a sector does not exceed its capacity.

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[1] Outil de Planification ATM et Simulation (OPAS).

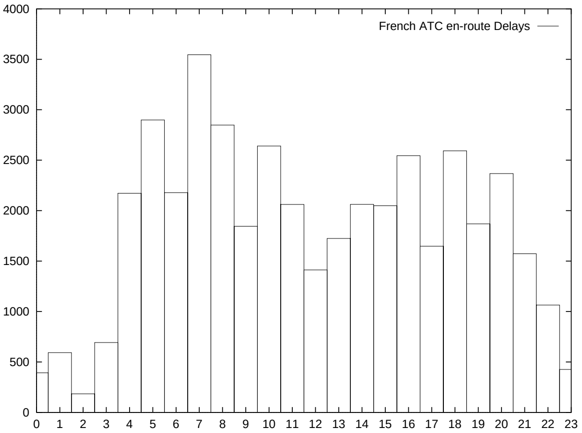


Figure 3: Estimated en-route delays (in seconds) for the French airspace system, on September 27, 1996

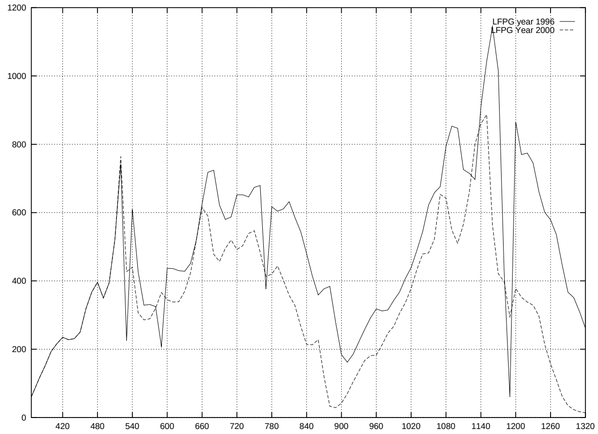


Figure 4: Estimated Delays for Paris Airports, September 27, 1996

Output: ground hold for each flight.

Solution procedure: 6 slot delay models are included in the system:

- 1 (default) model based on the TACT/CASA system based on first planned, first served principle, using 2 time bands to distribute equitably delays between long haul and short haul traffic;
- 3 models based on constraint satisfaction techniques: using CLP(FD), INRIA/Eclipse, and ILOG/Solver.
- 1 model based on linear and integer programming, which yields optimal results;
- 1 model based on advances in scheduling theory with cumulative constraints, which yields high quality and very fast results.

Time frame: Ground delay assignment is typically carried out three hours in advance before take-off.

Essential to delay analysis ([Jai91]), we treat uncertainty factors related to the time of estimated departure and sector entry as stochastic variables and perform n slot allocations to estimate average delay build-up. Different random number streams are used for each run so that the results are independent across runs. For n sufficiently large, due to the *central limit theorem* ([All90]), the average sum of delays is normally distributed, which allows the use of the confidence interval analysis.

For example, the total average en-route delays for September 27, 1996 (Figure 3), was estimated (with $n = 500$) to 9058 ± 26 minutes of delays at the 99% confidence level. Such a simulation was carried out with a real traffic sample and sector opening schedule, in less than 2 minutes of computing time. Delay models have being validated with respect to operational delays enforced by the Central Flow Management Unit ([Mau95, MP96]).

4.4 Terminal and airport modeling

The objective of the TMA and airport filter module is to estimate arrival and departure delays based on various runway configurations, in-trail separations on final approach due to wake vortex turbulences, and/or hourly runway capacity (Figures 5,6) ([Erz95]).

Airport runways are thus modeled as a set of queues, with finite capacity. Aircraft entering the TMA are not subject conflict detection and resolution: given their TMA entry time and aircraft type, a landing sequence is computed, an arrival queue is selected. If time separa-

Year	Airport	Arr/h	Dep/h	Tot/h
1996	LFPG	45	47	84
1996	LFPO	34	36	70
2000	LFPG	52	57	96

Figure 5: Paris airports hourly capacities

	trailing heavy jet	trailing large jet	trailing large turboprop
leading heavy jet	113	135	170
leading large jet	89	89	110
leading large turboprop	83	83	94

Figure 6: Minimum separation time matrix for pairs of aircraft on final approach in seconds.

tion between two consecutive aircraft cannot be achieved by speed control or rerouting measures, the aircraft is put on a hold stack. Transit time in the TMA is either computed with the aircraft simulator, using standard procedures, or given as a probability distribution with mean and variance, as in arrival traffic managers like the French MAESTRO system.

Input: TMA entry times of incoming traffic, gate departure times of outgoing traffic, in-trail time separations minima for different aircraft categories, runway capacities.

Problem statement: estimate average airborne and departure delay;

Output: landing time of each flight on the runway, runway utilization;

Solution procedure: queue modeling and Monte-Carlo discrete event simulation ([Dou87]);

Time frame: several minutes before landing/departure.

Again, we use repeated simulations to take into account stochastic uncertainties of arrival and departure times. In Figure 4, delays for Paris airports are estimated with $n = 500$ simulation runs. Note that these delay estimates were compared with those produced by airport monitoring tools like the "Outil de Reboublage des Crénaux Aéroportuaires" (ORCA), and are considered valid.

4.5 Conflict detection and resolution

Conflicts correspond to horizontal and vertical separation minima infringements: typically, two aircraft conflict when they are separated vertically by less than 1,000 feet and horizontally by less than 5nm. Inter-related conflicting aircraft form a conflict cluster.

To prevent conflicts from occurring, three types of resolution rules are applicable:

1. radar: five minutes before the conflict;
2. procedural: level change are applied when an aircraft enter a sector;
3. on-board: an airborne separation assurance and collision avoidance logic (ACAS/ASAS) is applied to aircraft to prevent conflicts.

The radar conflict resolution algorithm is able - alone - to resolve all conflicts that occur higher than FL100 with current traffic levels, with 5 minutes of advance notice. It relies on thorough mathematical optimization with genetic algorithms, and takes into account convex uncertainties on speed (vertical and horizontal) ([DCA96, All96]).

The procedural level change are applicable upon sector entry. When a flight enters a sector, a cleared flight level (CFL) is decided in order to prevent conflicts. The algorithm is straightforward in that each sector maintains a list of occupied levels, and the CFL is chosen accordingly. This procedure does not solve all conflicts, but seeks to prevent them by using unoccupied levels.

In contrast to the above two operational procedures which rely on air traffic controllers, the airborne separation and collision avoidance system procedure models more autonomous aircraft. All conflicts above FL100 are resolved with such on-board ACAS-III type systems, even without the use to radar and procedural rules. An aircraft reacts to others that are within range (15nm by default). The intensity of this reaction depends on

1. the reaction time left before the two aircraft loose standard separation;
2. the aircraft relative position and speed;
3. the time needed to perform evasive maneuvers.

Aircraft turn under full control of a reactive force, summed over all neighbor aircraft. Horizontal turn rate is limited to 3 degrees per second. Formally, the force F exerted by an intruder Q on a reference aircraft P includes a repulsive and sliding component, and is computed as follows (Figure 7):

$$F = \frac{\lambda v}{(pq - hsep - 1)}(J + (\frac{1}{cos\ \alpha} - 1)I) \qquad (1)$$

$$\lambda = \begin{cases} 1 \text{ if } PQ.V \geq 0; \\ -1 \text{ otherwise }; \end{cases} \qquad (2)$$

$$cos\ \alpha = \frac{-V.I}{v} \qquad (3)$$

I is a unit vector with the same orientation as the reference aircraft, and J the unit vector directly normal to I. V is the speed vector of Q relative to P (norm v, in kts) and PQ the position vector of Q relative to P (norm pq, in nm). Let $hsep$ be the horizontal separation norm (.i.e: 5nm) If the aircraft Q is within ACAS range of P ($pq < 15nm$), and Q is closing on P ($PQ.V > 0$).

Reactions are applied in the horizontal plane while aircraft are separated, and vertically if they loose separation.

4.6 En-route traffic simulation engine

The core of the OPAS system is an en-route traffic simulation engine. It is based on a discrete, fixed time slice execution model: the position and velocities of aircraft are computed at fixed time steps, usually every 5 or 10 seconds.

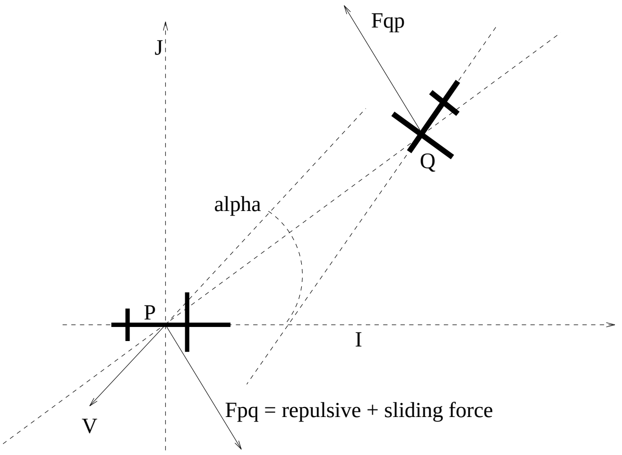


Figure 7: Model for ACAS III logic

Aircraft performances are in tabulated form describing ground speed, vertical speed, and fuel burn as a function of altitude, aircraft type and flight segment (cruise, climb or descent.) Two main datasets for aircraft flight performance are used:

- CAUTRA / ENAC aircraft performance tables, extracted from the French flight data processing system;
- Base of aircraft data (BADA) performance summary tables derived from the total energy model of EUROCONTROL. 69 different aircraft types are described. Synonym aircraft are used to model the rest of the fleet. The Airbus A320 (EA32) is used as default aircraft.

Aircraft use different navigation modes: they can fly direct routes to their destination, or follow the sequence of navigation aids described in their flight plan. An upcoming filter will allow aircraft to use optimized routes to avoid congested areas and minimize delays. Although there is no route orientation scheme explicitly defined for the air traffic network, aircraft may use one level out of two based on its heading (north/south or east/west route orientation). Every four levels can be also used based on the

(NE,SE,SW,NW) aircraft's orientation (quadruple alternate).

When available, operational constraints such as the forced profiles of the EURO-NASPAC simulation system are also taken into account. These include climb, descent, or cruise limitations at specific fixes, for particular traffic flows.

5 Simulation output and ATM work load indexes

Undoubtedly, air traffic controller work load, delays, aircraft operator costs, aircraft safety, and overall ATM system capacity are the cornerstone of en-route simulations with OPAS. The simulation system records and computes the following output variables:

- instantaneous aircraft count per sector;
- aircraft flow rates trough sectors;
- airborne separation and collision avoidance system statistics (number, duration, type of maneuvers);
- conflict statistics (geometry, aircraft maneuvers, duration, etc);
- statistics from other filters such as ground delays, runway capacity utilization are also available.

For example, 5 controller work load indicators are used to characterize a pair of conflicting aircraft, based on the relative angle of the conflict, the relative horizontal speed of the aircraft, the relative vertical speed of the aircraft, and the duration of the conflict.

Controller work load and capacity analysis are carried out with a simple model, based on weighted sum of these indicators, which can be measured by simulation. This modeling strategy is much in the spirit of the classical MBB or DORA operator models ([Spa92, Tof93]), or of the Eurocontrol airspace model and capacity analyzer. Subjective elements related to stress, psychological work load, are not considered explicitly.

6 Assessment of RVSM procedures

This section describes preliminary results for assessing the introduction of reduced vertical separation minima procedures ([Int92]) in continental airspace above flight level FL290. We use the OPAS simulation based planner to study three main RVSM airspace organizations, with the primary objective of estimating potential benefits on conflict work load, and a secondary objective of comparing these alternative organizations according to the density of potential conflicts.

6.1 Scenario description

With current ICAO vertical separation minima, aircraft must be separated by at least 2,000 feet above FL195. Furthermore, aircraft cruise at levels that are compatible with the orientation of the route network: in specific airspace areas, aircraft flying north must fly at odd levels, and aircraft flying south must fly at even levels. Under ICAO rules, FL290 is odd, and all levels above alternate: FL310 is even, FL330 is odd, FL350 is even, etc. This type of flight level orientation scheme (FLOS), which may correspond to either east-west orientation, or north-south orientation, is adapted by each air traffic control center (ACC), and thus not enforced "as is" throughout the ECAC area. Letters of agreement between ACCs specify the entry and exit conditions for flights that are handed over between them.

Four organizations are simulated, which differ by the vertical separation minima used above FL290, and the flight level orientation schemes selected:

The reference scenario use 2,000 feet separation and standard ICAO flight level orientation scheme. The geographical area of the simulation covers the the 6 French ACCs. The simulated traffic sample is extracted from French traffic archives, and comprises 353,741 filled and actual flight plans of September 1996 (Figure 8). Airspace operational constraints were not taken into account due to their unavailability at the

Reference ICAO	p	RVSM RFL
RFL=280	1/6	RFL+30
RFL=280	5/6	RFL
RFL=290	1/6	RFL+30
RFL=290	5/6	RFL
RFL>290	1/8	RFL+30
RFL>290	3/8	RFL-10
RFL>290	4/8	RFL

Figure 9: Modeling double alternate traffic

Reference ICAO	p	RVSM RFL
RFL=290	1/3	RFL+20
RFL=290	2/3	RFL
odd(RFL)	1/4	RFL+20
odd(RFL)	1/4	RFL-20
odd(RFL)	2/4	RFL
even(RFL)	1/2	RFL-10
even(RFL)	1/2	RFL+10

Figure 10: Modeling single alternate traffic

time of the study. RVSM scenarios use 1,000 feet of vertical separations minima, as follows:

1. ICAO - 1,000 feet below FL195, 2,000 feet above FL195 for vertical separations;
2. RVSM - single alternate: all levels are odd or even based on the second digit of the level: i.e FL330 is odd, FL320 is even.
3. RVSM - double alternate: ICAO levels keep their orientations, new intermediate levels have the same orientation of the ICAO level immediately higher.
4. RVSM - quadruple alternate: one out of four levels is used according to the north-east, north-west, south-west or south-east orientation of the route.

To model an RVSM traffic demand, we redistribute the flight plans' requested flight levels (RFL). Given a flight's RFL in the reference traffic, we give the probability p of the flight to use another level for the double and the single alternate scenario in (Figures 9,10).

Reference ICAO	p	RVSM RFL
RFL < 290	1/2	RFL
RFL < 290	1/4	RFL + 10
RFL < 290	1/4	RFL + 10
RFL = 290	1/6	RFL - 10
RFL = 290	1/3	RFL
RFL = 290	1/3	RFL + 10
RFL = 290	1/6	RFL + 20
RFL > 290	1/8	RFL - 20
RFL > 290	1/4	RFL - 10
RFL > 290	1/4	RFL
RFL > 290	1/4	RFL + 10
RFL > 290	1/8	RFL + 20

Figure 11: Rules for quadruple alternate

Name	Ref	Single	Double	Quad.
G2	21.37	26.92	25.78	23.860
G3	34.72	29.37	30.30	32.533

Figure 12: Average rate of traffic per hour for peak hours of September 1996

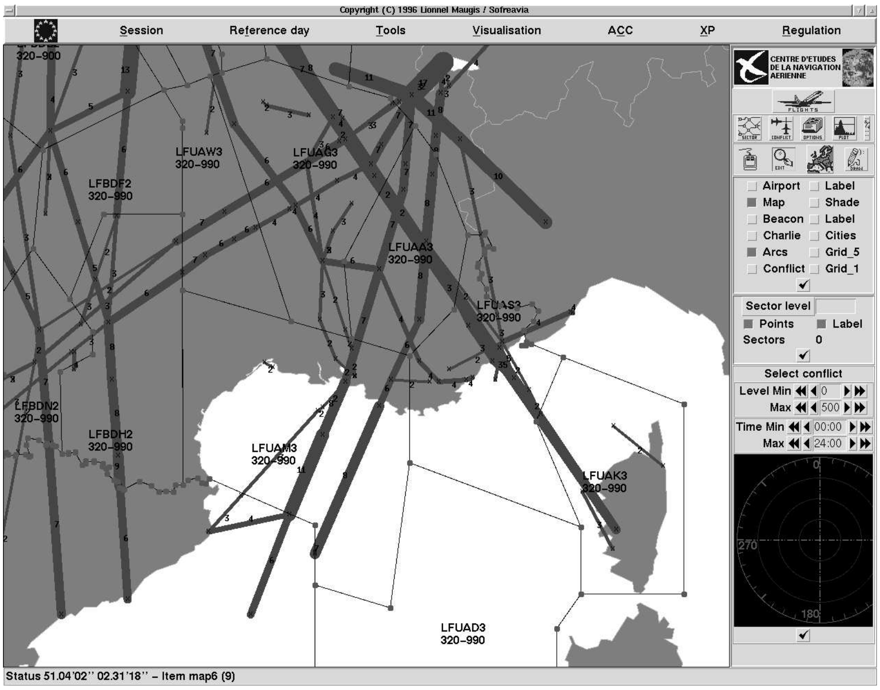
To model quadruple alternate traffic, we apply a similar rule to estimate the flight's optimum levels (Figure 11), and then select the closest level with a correct route orientation.

6.2 Results

To evaluate the various options of the scenario, we simulated more than 5 millions flights: 30 days of traffic $*$ 2 traffic demand types (filled and actual flight plans) $*$ 6,000 flight plans per day $*$ 14 options. These simulations were performed overnight in 10 hours of computing time on the workstation cluster at CENA, with 30 machines. We analyze below the statistics output from the simulations both at the sector level with sectors G2 and G3 of Aix-en-Provence ACC, and at the overall airspace system level.

6.3 Traffic work load

At the sector level, we focus on sectors G2 and G3, which are defined respectively between FL275-FL320, and FL320-FL900. The average rate of traffic flow past these sectors during peak



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Level Min 0
Max 500
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Figure 8: Traffic flows for September 1996, for ACC at Aix-en-Provence

Figure 13: throughput of sector G2 (hourly rate of traffic flow)

periods of the month (Thursdays and Fridays: 37,543 flights plans) is given in Figure 12.

The analysis of sector throughput (Figure 13,14) and work load (instantaneous aircraft count, Figures 15,16) show a transfer of traffic (20%) between G3 and G2 with the RVSM single alternate. In other words, with RVSM, the traffic is no longer equitably partitioned between the two sectors. They might have to be re-designed

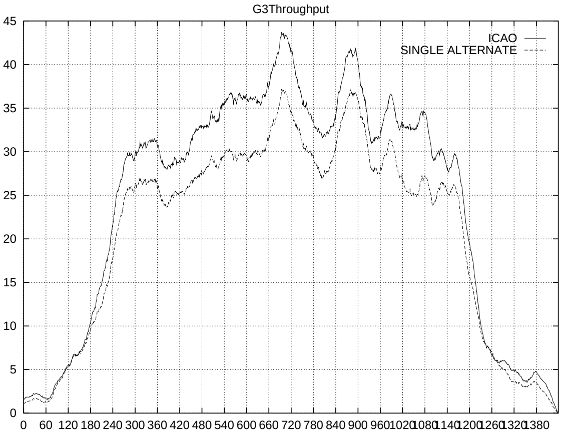

Figure 14: throughput of sector G3 (hourly rate of traffic flow)

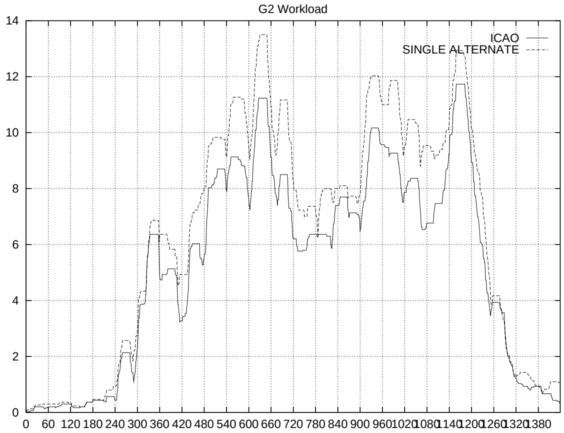

Figure 15: work load of sector G2 (maximum instantaneous number of aircraft)

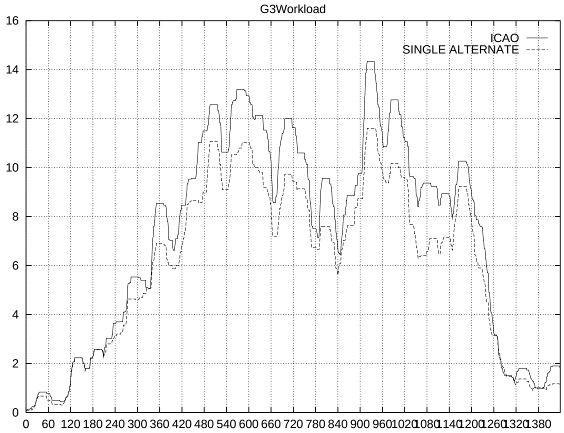

Figure 16: work load of sector G3 (maximum instantaneous number of aircraft)

vertically.

6.4 Conflict work load

We define conflict work load[2] as the average number of separation minima infringements per sector. For sectors G2 and G3, it is described in Figure 19, for peak hours of September 1996.

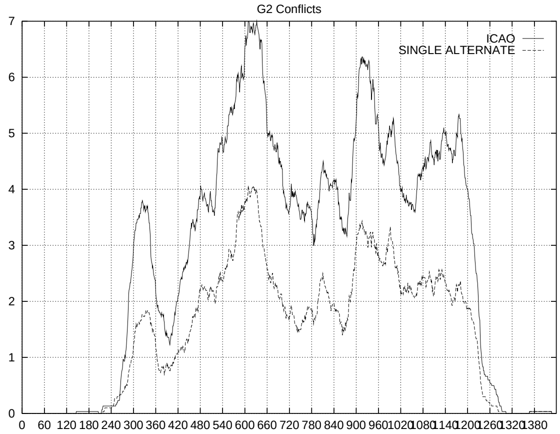

Figure 17: number of conflicts per hour for sector G2

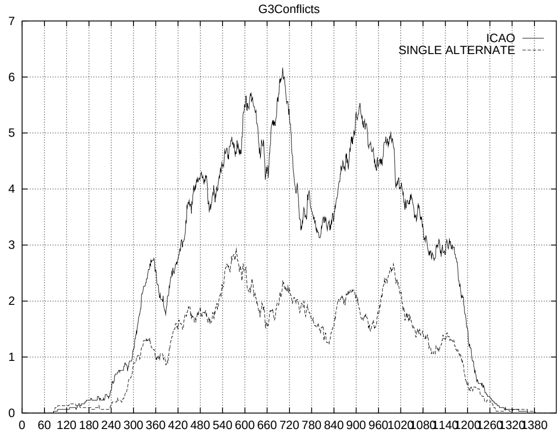

Figure 18: number of conflicts per hour for sector G3

Sector	Ref	Single	Double	Quad.
G2	4.048	2.212	2.356	1.926
G3	4.154	1.962	2.048	2.014

Figure 19: Average number of conflicts per hour computed for peak hours of September 1996

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[2] We assume that safety, defined as the probability of collision per hour of flight, is not affected by the introduction of RVSM. Safety issues are addressed with specific analytical models ([Int92]). Indeed, it is inherently difficult to estimate by simulation the distribution of mid-air collisions, due to their high improbability. We do measure however the risk of conflict as a controller work load indicator.

Traffic	Ref	Single	Double	Quad.
Filled	0.491	0.284	0.278	0.268
Actual	0.444	0.247	0.240	0.233

Figure 20: Conflict risk levels for proposed RVSM organizations and impact of traffic flow regulation

Traffic	Risk	Variation
	0.491	
+20%	0.571	+16%
+50%	0.698	+42%
+100%	0.901	+83%
+200%	1.295	+163%

Figure 21: Impact of density factor on risk level

It is depicted along the day in (Figures 17,18). With RVSM, conflict rates are reduced in average by 50%. Despite traffic flow increases in G2, the conflict rate is reduced by 40%. Other conflict related indictators are in similar plight.

At the system level, we estimate (Figure 20) the impact of RVSM organizations on conflict density with a conflict risk indicator: the number of conflict per hour of flight, for all conflicts above FL100, and for all the simulated traffic sample (353,741 flight plans).

The overall impact of RVSM on conflict work load is clearly significant, much higher than the impact of traffic flow regulation. Furthermore, there is no clear benefits between the proposed RVSM options (single or double alternate). Bias due to traffic sample estimation procedures need to be further analyzed. At this point, operational considerations such as transition steps prevail over the choice of either RVSM options.

6.5 Traffic density

We estimated the impact of traffic density on the overall risk level by taking the same traffic sample and compressing the flights' entry time in the simulation (divided by two to double the density). Standard air route network and vertical separation minima was used. (Figure 21)

	Organization	Risk	ACAS
DIRECT	ICAO	0.275	0
+ACAS	ICAO	0	9.51
+ACAS	SINGLE	0	4.81

Figure 22: Impact of RVSM on Free Flight Traffic

Traffic	ACAS
	4.97
+20%	6.20
+50%	7.54
+100%	9.79
+200%	14.45

Figure 23: Impact of density factor on acas work load.

6.6 Use of direct routes and ACAS work load

Finally, we analyzed the impact of RVSM and density factors with a hypothetical free-flight scenario: all military restricted areas are inactive, all aircraft are equipped with ASAS type systems, and fly almost direct - orthodromic - routes to their destinations.

We define as ACAS work load for an aircraft the *interaction time* in seconds needed to perform evasive maneuvers in order to prevent conflicts. If aircraft A is in interaction with B,C, and D, during one second, this counts as 3 seconds of ACAS work load for A. Note that all conflicts were resolved with the proposed ACAS model.

Figure 22 shows that the use of direct routes (no military areas) and standard vertical separations yields the same overall conflict risk levels as the standard route network and RVSM vertical separations. Furthermore, the average ACAS work load is reduced by half with RVSM: qualitatively, the impact of RVSM on free-flight traffic is significant.

We can also measure that in high density traffic areas such in France, it becomes more and more difficult to resolve conflicts with only ACAS type systems: the average ACAS work load per aircraft increases much higher than the density factor (Figure 23).

7 Description of traffic

The simulator has been used to study various global traffic parameters. The traffic sample used for simulation includes all controlled flights in the French airspace for a particular day. Most tests used a sample from December 11, 1992 (Friday). The flights can follow their scheduled route, or fly directly to their destination. The simulator provides realistic control-free flight profiles.

A traffic increase can be simulated by dividing all take-off times by a constant factor (as a side effect, the duration of the day is divided by the same factor). During time periods where traffic is stable, there is a very strict correlation between the number of aircraft in flight and that factor, which therefore represents global traffic density (the density of the original sample being equal to 1). Flight levels can be randomly reallocated in order to increase the number of available levels when vertical separation is altered.

We used the simulator in order to evaluate the influence of various parameters on the number of conflicts and clusters. The values used for the parameters were :

- horizontal separations (NM) : 1, 2, 4, 6, 8, 10
- vertical separations (ft) : 300, 500, 800, 1000, 1300, 1500, 1800, 2000 (no increase above FL295)
- time compression : 1, 1.25, 1.5, 1.75, 2, 2.5, 4

The corresponding simulations were performed with standard routes, straight routes without resolution, and straight routes with resolution.

Moreover, in order to study the influence of the time horizon, we used a variable-length time window (ranging between 10 and 60 mn).

Figure 24 shows the distribution of flights by flight level, with the original sample, with RVSM (single alternate), and with 500 ft vertical separation.

7.1 Results

The results observed in standard and straight (free) routes are presented in tables 1 (current traffic) and 2 (traffic increased by 150%). The last two columns give the difference (in percentage) between normal and straight routes. Regarding straight routes, the following points can be observed :

- Traffic density decreases by 6 or 7%, because of the induced reduction of flight times (6,4% on average).
- The numbers of conflicts and clusters decrease dramatically.
- The size of clusters (number of aircraft and number of conflicts) decreases.

It is generally admitted that structured traffic (following a route network, with semi-circular rule) reduces the number of conflicts. Some additional results regarding semi-circular rule are given below. In the present case, one must consider that with straight routes the whole french airspace can be used. Even though some areas are still heavily loaded, the overall traffic density is reduced, which is probably one of the main causes of the reduction of the number of conflicts.

The reduction of the number of flights in the window induced by RVSM can be explained by the way flight levels are reallocated in the simulation : on average new levels are slightly lower than initial ones. Therefore climb and descent phases, during which speed is lower that cruise speed, are reduced, which induces a slight reduction of flight times, and therefore a reduction of the number of aircraft simultaneously in flight. This phenomenon is not significant. On the other hand, there is a significant reduction of the number of conflicts because the busiest flight levels are above FL295 (cf. figure 24). As one could expect, this reduction mainly concerns cruise flights.

Suppression of semi-circular rule : Some simulations have been made without taking into

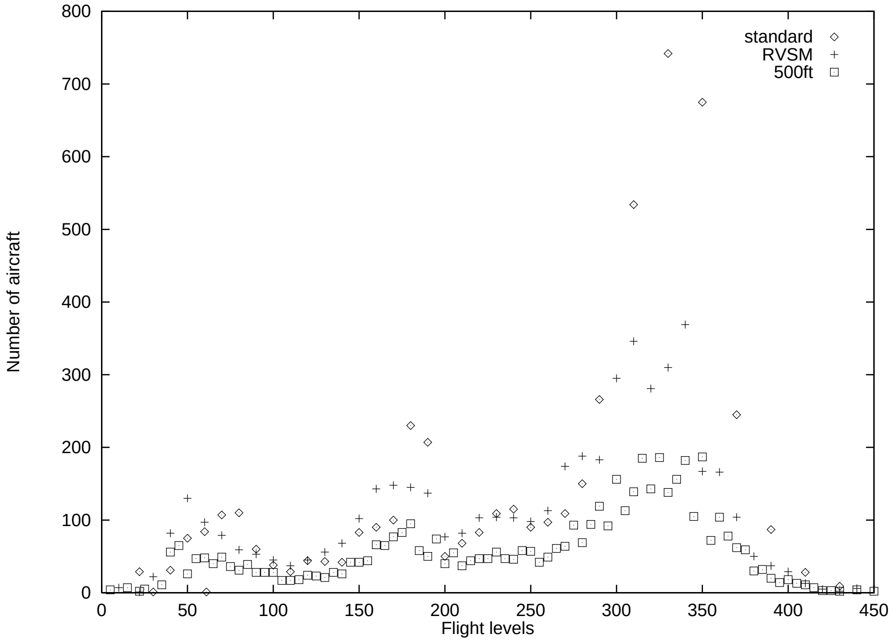

Figure 24: Traffic distribution

Routes	std		straight		diff (%)	
Vertical separation	STD	RVSM	STD	RVSM	STD	RVSM
Nb of flight in the window	220	215	205	200	-6.8	-7.0
Nb of clusters	48	42	35	28	-27	-33
Nb of conflicts	77	61	43	32	-44	-48
2 a/c level	20	6	15	4	-25	-33
1 a/c level	38	37	20	20	-47	-46
0 a/c level	19	18	8	8	-58	-56
Avg nb of conflicts per cluster	1.60	1.45	1.23	1.14	-23	-21
Max nb of conflicts per cluster	4	4	3	3	–	–
Avg nb of aircraft per cluster	2.52	2.38	2.17	2.11	-14	-11
Max nb of aircraft per cluster	5	5	3	3	–	–

Table 1: Current traffic.

Routes	std		straight		diff (%)	
Vertical separation	STD	RVSM	STD	RVSM	STD	RVSM
Nb of flight in the window	557	545	522	511	-6.3	-6.2
Nb of clusters	219	200	176	150	-20	-25
Nb of conflicts	500	409	314	243	-37	-40
2 level	160	67	91	35	-43	-48
1 level	216	213	103	105	-52	-41
none level	124	129	120	103	-3	-20
Avg nb of conflicts per cluster	2.28	2.05	1.78	1.62	-22	-21
Max nb of conflicts per cluster	37	23	18	13	-51	-43
Avg nb of aircraft per cluster	3.07	2.89	2.68	2.53	-13	-12
Max nb of aircraft per cluster	33	19	19	10	-42	-47

Table 2: 150% increase.

account the semi-circular rule. In this case a gaussian noise with standard deviation 1500 ft is added to the requested flight level, and the result is then truncated to the level immediately below, whatever its parity may be. Simulations have been made with RVSM in standard and direct routes, with current and increased traffic. Results observed during the whole day are given in table 3, those observed in the usual time window are in table 4 (these last results concern limited numbers of conflicts, therefore the uncertainty is higher).

It appears that semi-circular rule allows a significant decrease of the number of conflicts. Moreover, since it eliminates opposite encounters, it increases the time available for the controller to react. On the other hand, it also increases the number of conflicts with small angle, which are more costly regarding the duration of the maneuvers and the flight time or distance ([Dur96]).

7.2 Modelisation

7.2.1 Traffic density

In all cases (normal or straight routes, with or without resolution), the correlation between time compression and the number of aircraft in flight correspond to the prediction :

$$N_{aircraft} = K_1 C^{\alpha}$$

where $\alpha = 1$, C being the time compression factor. The error on the value of α is approximately 1%, and the correlation coefficient is 99.9%. Therefore the size of the time window has no incidence on the average traffic, which means that the traffic density remains stable throughout the time window, even for large windows with high compression factor.

7.2.2 Conflicts and clusters

We observe that the parameters (separations, time compression and window length) are independent. We can expect that the number of conflicts will increase with each of them, and will be null for a null value of any of them. Therefore we try to model the number of conflicts as follows :

$$N_{conf} = K\, C^c\, H^h\, V^v\, I^i$$

where C is the time compression factor, H the horizontal separation, V the vertical separation, and I the size of the time window.

Standard routes : The results are presented in table 5. The number of conflicts is approximately proportional to the square of traffic density, to horizontal separation, and to the size of the time window.

Regarding vertical separation, models ([Ale70, Bos94]) predict that the increase is proportional to the separation, or to the inverse of the number of available flight levels, which is observed here for conflicts between cruising aircraft. However, a larger separation reduces the number of flight levels that an aircraft crosses during climb or descent, which explains the lower coefficients observed for conflicts with climbing or descending aircraft.

Regarding horizontal separation, a 2-dimensional mathematical model shows a linear increase of the number of conflicts when traffic is totally random (ie, the position of the departure and destination of each flight are random). But when flights are distributed over a few predefined airports, some conflicts remain even with a null horizontal separation. As a consequence, the evolution of the number of conflicts versus horizontal separation should be slightly less than linear, especially with standard routes. Therefore the coefficient obtained for conflicts between level aircraft seems acceptable.

When an aircraft's vertical speed V_z is non-null, its protected surface (πH^2) sweeps a volume equal to $\pi H^2 V_z$, where H is the horizontal separation ([EO83]). A quadratic component of the horizontal separation appears, which explains the higher coefficient for conflicts with one non-level aircraft.

For pairs of climbing or descending aircraft, the average relative vertical speed remains unchanged (compared to the case where only one aircraft not level). This is because the situations

Routes	Current traffic			Increased traffic		
	with 1/2 c.	no 1/2 c.	Increase	with 1/2 c.	no 1/2 c.	Increase
Standard	810	938	16%	2087	2423	16%
Direct	611	712	17%	1434	1764	23%

Table 3: Influence of semi-circular rule on the number of conflicts during the day

Routes	Current traffic			Increased traffic		
	with 1/2 c.	no 1/2 c.	Increase	with 1/2 c.	no 1/2 c.	Increase
Standard	60	68	13%	380	449	18%
Direct	36	44	22%	231	282	22%

Table 4: Influence of semi-circular rule on the number of conflicts in the window

	Conflicts				Clusters
	total	2 level	1 level	0 level	
c	1.97	2.35	1.84	1.95	1.55
h	0.96	0.58	1.17	0.91	0.61
v	0.54	1.12	0.45	0.37	0.38
i	0.89	0.89	1.07	0.67	0.78
r^2	0.98	0.95	0.97	0.96	0.95

Table 5: Conflicts and clusters, standard routes

	Conflicts				Clusters
	total	2 level	1 level	0 level	
c	2.14	2.02	2.09	2.10	1.69
h	1.23	0.77	1.40	1.22	0.88
v	0.59	1.00	0.52	0.40	0.46
i	0.92	0.88	0.97	0.81	0.83
r^2	0.96	0.92	0.95	0.95	0.92

Table 6: Conflicts and clusters, straight routes, no resolution

where the two vertical speeds have the same or opposite direction are equally likely. Therefore, a further increase of the coefficient is not expected, but neither is the observed decrease.

Finally, the low coefficient for the size of the time window may result from the fact that if a conflict goes on after the end of the window, it won't count as an additional conflict when the window is extended.

Straight routes The observed values are presented in table 6. Correlation is still very high, the coefficients and the offsets observed between each type of conflict are similar to those obtained with standard routes. Therefore the same comments apply. The main difference lies with the coefficients on horizontal separation, all of which are slightly higher than their counterparts in standard routes. The phenomenon described above (conflicts remaining with null separation) is reduced, but doesn't disappear completely.

Regarding vertical separation, the coefficient here is slightly higher, maybe because the number of flight levels crossed during climb or descent has a smaller influence (since traffic density is smaller).

Figures 25, 26, 27 and 28 show the evolution of the number of conflicts versus one of the four parameters, the three others remaining unchanged (the fixed values are 1 for time compression, 6 NM for horizontal separation, 1000 ft for vertical separation, and 30 mn for the time window).

Tables 5 and 6 show that the coefficient obtained for the time compression factor is higher in free routes (2.16) than in standard routes (1.95). The number of conflicts increases more rapidly with free routes when traffic increases, which complies with the generally agreed fact that organised traffic is preferable at high density. However, the difference between the two values is too small to be significant, which can

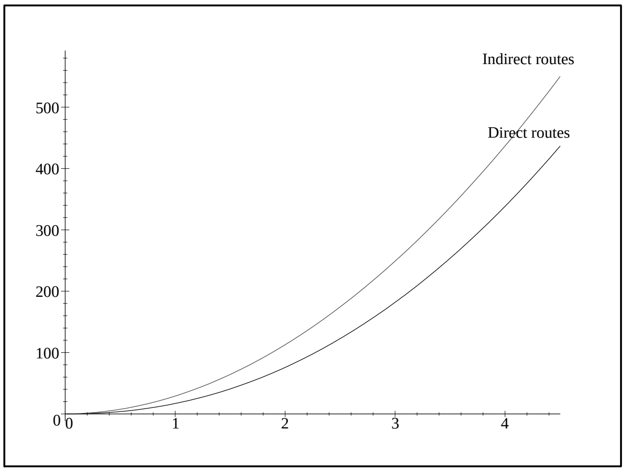

Figure 25: Number of conflicts vs density.

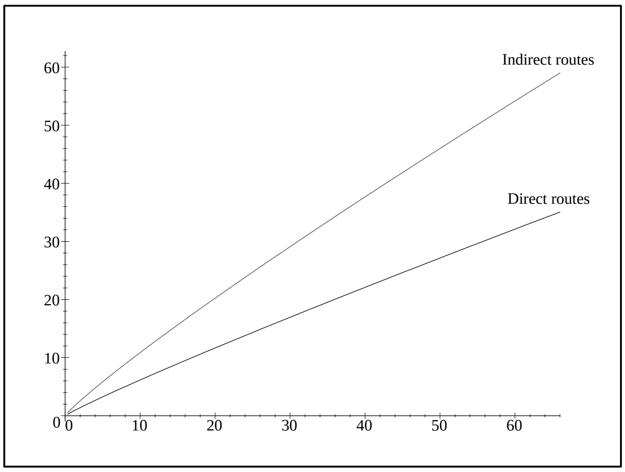

Figure 27: Number of conflicts vs vertical separation.

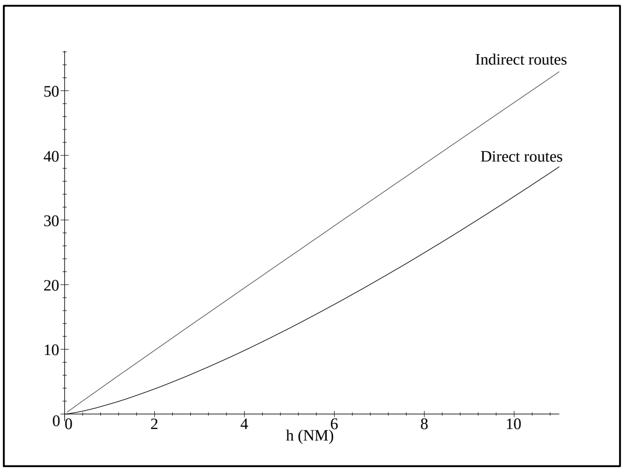

Figure 26: Number of conflicts vs horizontal separation.

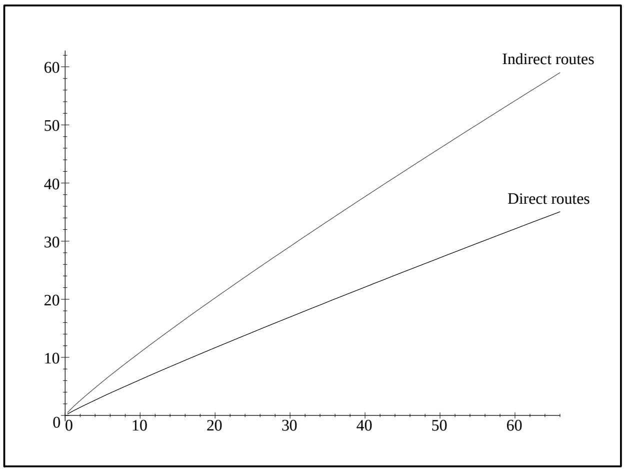

Figure 28: Number of conflicts vs length of the time window.

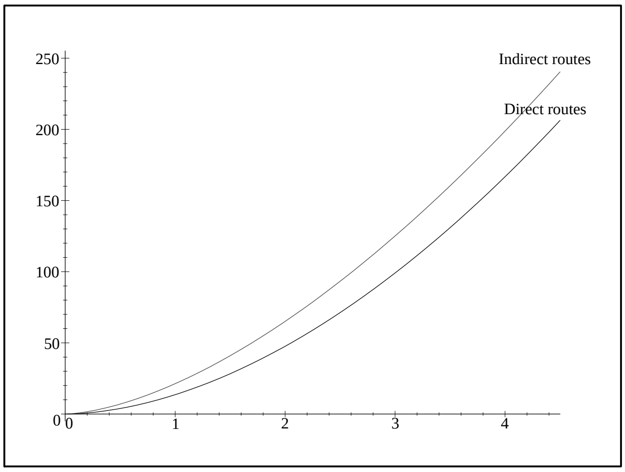

Figure 29: Number of clusters vs density.

probably be explained by the fact that semicircular rule has also been applied in free routes simulations. Therefore traffic remains partially organised, especially considering that even with free routes some high-density flows still appear.

Figures 29, 30, 31 and 32 show the evolution of the number of clusters. The coefficients are similar to those of conflicts, but slightly smaller, because an increase of the number of conflicts generates an increase of both the number and the size of clusters.

7.3 Traffic complexity

A candidate criterium for traffic complexity is the average number of conflicts per cluster. We tried to reproduce a similar situation (same size of clusters) by doubling the number of aircraft and dividing horizontal separation by 2. The area observed must also be divided by 2, which is obtained by dividing the length of the time window by the square root of 2. This can be viewed as a means to increase capacity in an automatized system, provided that the time horizon remains large enough when the area of responsibility is reduced, and that increased coordinations can be handled. We expect that the average size of the clusters will be the same in both situations. The values used for this experiment are :

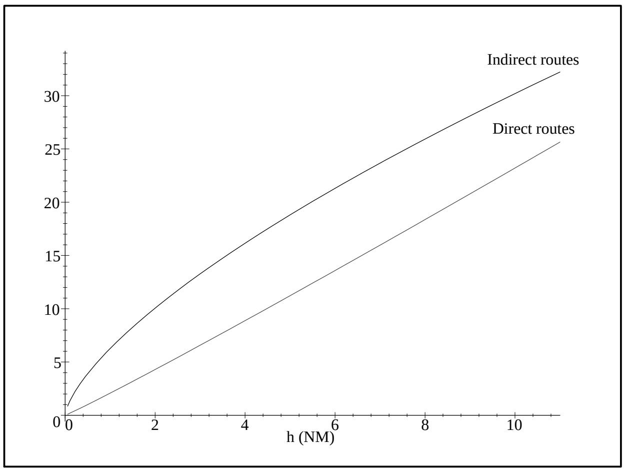

Figure 30: Number of clusters vs horizontal separation.

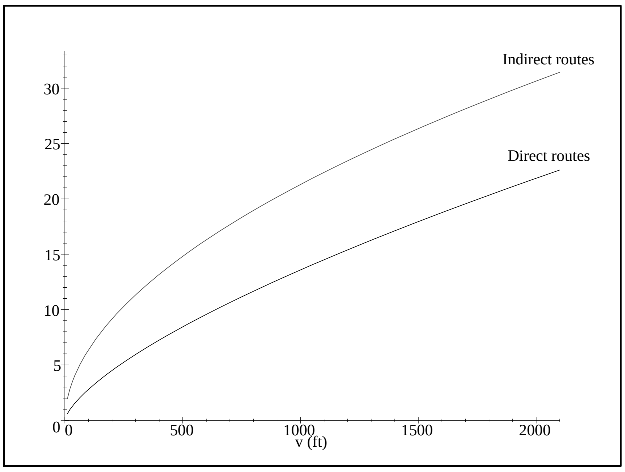

Figure 31: Number of clusters vs vertical separation.

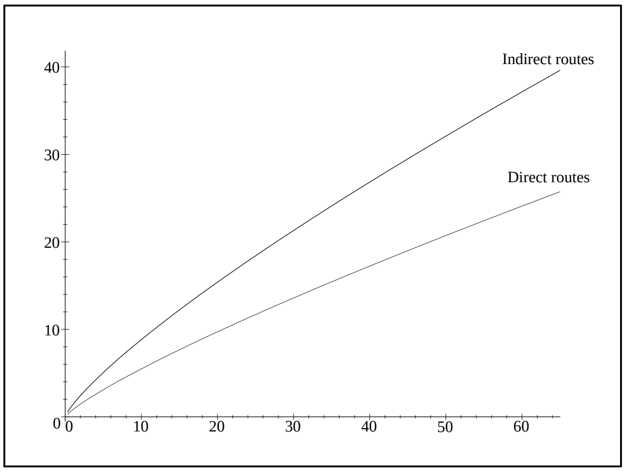

Figure 32: Number of clusters vs length of the time window.

- time compression : 1, 2 and 4,
- horizontal separation : 2, 4 and 8 NM,
- time window : 30, 40 and 60 mn ($\frac{60}{\sqrt{2}} \simeq 40, \frac{40}{\sqrt{2}} \simeq 30$).

Therefore 3 situations are obtained and should give similar results. In each case 8 results corresponding the 8 possible values of the vertical separation are given. Results are shown in figure 33. Each set of connected points corresponds to a particular situation. The 3 series of vertically aligne points show values obtained with all possible combinations of the parameters, in order to provide a scale reference. Each series corresponds to one particular traffic density.

We observe a reduced range of values. However, one must also take into account the fact that extreme situations (high density together with a large separation) are suppressed. Moreover, the values of the first situation (current traffic, 8 NM separation, 60 mn) are slightly higher than those of the two others. The results are as expected, but should be validated with different sets of data.

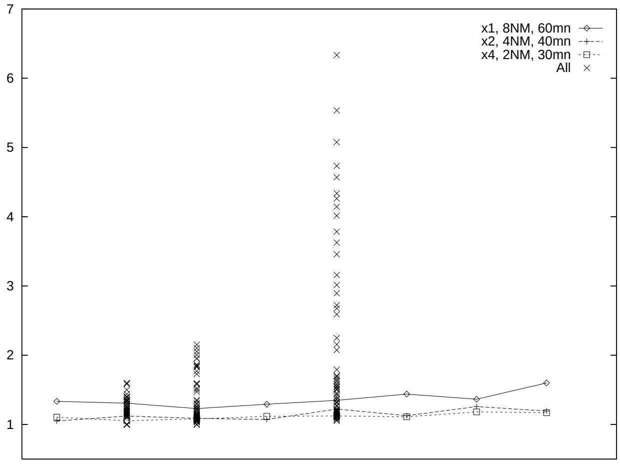

Figure 33: Average number of conflicts per cluster

8 Automatic resolution

Several automatic conflict resolution methods have been implemented on the simulator, in order to develop a tool for studying ATC and to provide a reference for the evaluation of genetic resolution techniques developed by the team.

8.1 Reactive resolution

The methods used are reactive resolution methods similar to those developed by Karim Zeghal ([Zeg93, Zeg94]). Their main advantage is simplicity of development and use, since no extrapolation of trajectories is necessary. The minimal set of information concerning an intruder aircraft is distance, altitude, azimuth, relative speed, and the intruder's type of behaviour (avoidance with an identical or different method, interception). Some additional information, in particular planned changes in course or vertical speed, can be helpful. For the moment automatic resolution is only used with aircraft flying straight routes.

Additional limitations have been put on aircraft maneuvers. Normally, forces can alter aircraft motion in three dimensions. However, commercial aircraft performance in cruise flight is optimized for a particular speed and altitude. Flying at a lower altitude is less efficient, and a higher altitude may be unreachable because of engine limitations. Regarding speed, changes are limited to 2 to 3% of normal cruise speed, and must be planned a very long time ahead in order to produce some effect. Since our studies mainly deal with en-route traffic, we decided to only allow lateral maneuvers. Even though the main reason was simplicity, this restriction is very close to reality.

In order to improve the resolution of conflicts between aircraft following quasi-parallel tracks (pass-over or convergence with a small angle), a repulsive component has been added to the force vector. The repartition between the two components depends on the conflict geometry. The resulting force is purely tangential if both aircraft are on a colliding course and purely repulsive if they fly on parallel tracks.

The intensity of the avoidance force is proportional to the inverse of the time remaining until normal separation will be lost. An attraction towards the aircraft's destination is added to the total force-vector (the current implementation only allows straight route navigation). The aircraft then tries to reach the resulting direction, with a limit of $3^o/s$ on the turning rate.

In most cases this method ensures avoidance and generates smooth trajectories (which however are not flyable by a human pilot since during maneuvers heading changes slightly at every step of computation). Some problems still occur in cases where the angle between the two trajectories is small and the ratio of the speeds is close to 1. These cases are known to be the most difficult to solve, in the sense that the avoidance maneuver takes more time and generates a greater increase of flight time or distance ([Dur94]).

Two different implementations have been tested. One is truly reactive, all intruder aircraft are taken into account, which includes many aircraft that don't really constitute a threat. The only parameters used to distinguish aircraft that may generate a conflict are distance and closing speed, therefore the selection process can't be very efficient.

In the other version, aircraft trajectories are first simulated (without resolution, ie aircraft fly straight to their destination) to detect future conflicts. Typically the simulation occurs every 1 to 5 minutes, and spans over the next 5 to 20 minutes. An increased horizontal separation (usually twice the normal separation) is used in order to take into account aircraft flying near a conflict, which may interfere with the resolution maneuver. Even so this method dramaticallly reduces the number of aircraft pairs to consider. "Clusters" (sets of interfering aircraft) are then determined, and the computation of reactive forces is then only applied to pairs of aircraft belonging to the same cluster. Compared to the purely reactive method, the time of computation is approximately divided by 6, despite the time spent in pre-simulation of trajectories.

The information necessary (knowledge of planned future trajectories) is not available in the current system. However, it may be approximated over a small period of time (eg 5 minutes), provided that planned changes in vertical speed or heading are transmitted between aircraft.

Both versions (i.e., with and without conflict pre-detection) give similar results regarding the number of unsolved conflicts. The knowledge of future trajectories reduces the amount of processing (but the volume of data to transmit is increased), and also the number of useless avoidance maneuvers. The average increase in flight time induced by maneuvers is 0.3% (compared to 1.5% with the purely reactive version). The maneuvering time is approximately 10%.

8.1.1 Results with knowledge of future trajectories

Figure 34 shows the evolution of the number of separation losses versus traffic density, both without (first curve) and with (3 others) conflict resolution. Here resolution is performed with pre-detection of conflicts, with different conditions for each curve : respectively every 5 mn with twice the normal separation, every mn with twice the normal separation, and every 5 mn with one normal separation. A few corresponding values are presented in table 7. Figure 35 shows the percentage of unsolved conflicts relative to the number of separation losses observed

Traffic	std	+50%	+100%	+150%	+300%	+500%
no resol	508	748	962	1266	2071	2953
2 sep, 5 mn	7 (1.4%)	24 (3.2%)	38 (4.0%)	89 (7%)	1487 (72%)	
2 sep, 1 mn	10 (2.0%)		22 (2.3%)		112 (5.4%)	739 (25%)
1 sep, 5 mn	18 (3.5%)		72 (7.5%)		197 (9.5%)	545 (19%)

Table 7: Remaining conflicts.

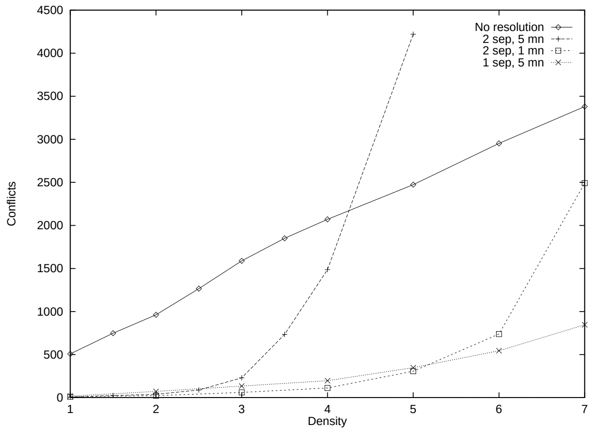

Figure 34: Number of separation losses vs density

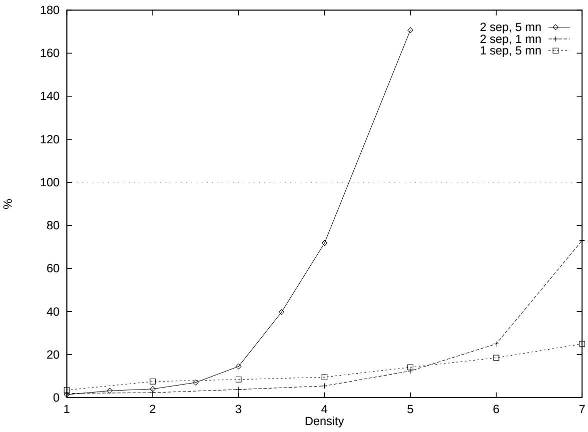

Figure 35: Percentage of unsolved conflicts vs density

without resolution. The results here are observed on the full traffic sample (1 day), which explains the linear shape of the conflict number without resolution. If traffic was stable during the whole simulation, this would be quadratic.

Influence of the horizontal separation used for conflict prediction : An increased horizontal separation is used for detection of future conflicts. Values ranging from 1/3 to 3 times the normal separation have been tested. Values between 1.5 and 3 times the normal separation givie similar results with standard traffic. We retained the value 2, which generates only 4 unexpected conflicts (cases where a maneuvering aircraft conflicts with a non-maneuvering one).

En-route conflicts : Only true "en-route" conflicts are taken into account here. There's a lower bound on altitude (6000 ft), and the first and last 5 mn of each flight are not considered either. This is to suppress problems due to aircraft entering or leaving the simulated airspace at the same point and time. In the first case separation is lost as soon as the planes are created in the simulator, in the second the proximity of the exit point hinders avoidance maneuvers since no sequencing is performed, and we don't want to generate unrealistic maneuvers.

508 "true" en-route conflicts are observed in the original traffic sample, and only 15 remain with automatic resolution, which is 97% of success. The method can be slightly altered to solve 8 more conflicts (98.6% of success), but is then more sensitive to traffic increase. The 7 remaining conflicts have the same geometry (aircraft converging on quasi-parallel tracks). Apart from that, the method can easily handle standard traffic density.

Influence of traffic density : When density is increased, the curve clearly shows the saturation of the resolution method. However, it appears later than with the purely reactive method (no prediction of conflicts). The percentage of unsolved conflicts is pretty good up to density 2.5 (17% unsolved, compared to 25% with the purely reactive method and RVSM), but it increases dramatically when density exceeds 3 (70% unsolved for density 4, compared to 50% without conflict prediction). There is also a rapid increase of the number of unredicted conflicts.

It is possible to delay saturation when density increases. The previous results were obtained with conflict pre-detection performed every 5 mn on a 15 mn period, which is not optimal. A higher frequency allows more accurate updating of clusters, while a shorter period avoids treatment of conflict that are too far ahead in the future. With a frequency of once every mn and a period of 5 mn, performance remains similar at low density, but saturation appears only at densities higher than 5.

Another possibility is to use a smaller horizontal separation for pre-detection. On both figures, curves “1 sep” are obtained with predetection every 5 mn, using the normal horizontal separation. This limits the number of aircraft pairs that are treated simultaneously, which is the cause of saturation. At some point the trajectories of aircraft submitted to multiple forces become so irregular that more conflicts are generated than solved (which doesn't mean that no conflict-free trajectories exist). The curves show that saturation appears much later. However performance is slightly worse at low density (more than twice as many conflicts remain unsolved). This is because with a reduced separation for pre-detection, maneuvering aircraft may create new conflicts with surrounding aircraft not initially involved. Those conflicts won't be treated until the next pre-detection step, which of course is unacceptable in a real system.

Consequences of traffic increase : A sample from June 21, 1996 (also Friday) has been used too. In 1992, 4851 controlled flights were flown, vs 6388 in 1996. Figure 36 shows the distribution of traffic along the day.

The increase of traffic is approximately 30%, and the number of resulting conflicts has been multiplied by 1.6 approximately (table 8).

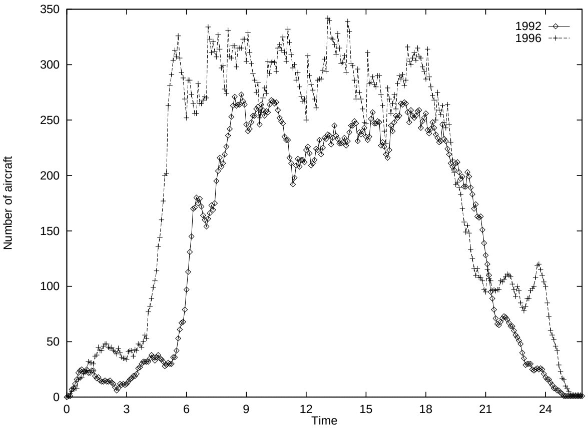

Figure 36: Distribution of traffic

Some simulations were run with the 1992 data set in order to study the effect of traffic increase (which was artificially obtained as explained above). A 25% increase of traffic resulted in 70% increase of the number of conflicts. If we extrapolate this result to 30% traffic increase, and to a full day of traffic (24 hours), we obtain 130% of increase for the total number of conflicts. The difference with the results obtained with the 1996 sample (166%) may be explained by the uneven distribution of additional traffic, and also by the relatively higher number of flight hours.

8.1.2 Results without knowledge of future trajectories

More extensive simulations have been performed with the purely reactive method. There's no detection of future conflicts to select threatening intruders, therefore useless maneuvers may be generated. Moreover all conflicts are taken into account, including those caused by simultaneous entries or exits. It is to be noted that in this case, the performance of the resolution method decreases progressively when traffic or separations are increased. The curves don't clearly show a saturation point as previously observed.

All conflicts (including simultaneous entries or exits) are taken into account. The reactive method solves 92% of the conflicts with cur-

		1992	1996	Increase
	Flights	4851	6338	+31 %
Indirect	Flight hours	3941	5513	+40 %
	Conflicts	1044	2746	+163 %
Direct	Flight hours	3662	5187	+42 %
	Conflicts	731	1942	+166 %
	Maneuv. time	3.2%	4.5%	
	Delays	0.4%	1.0%	

Table 8: Evolution between 1992 and 1996

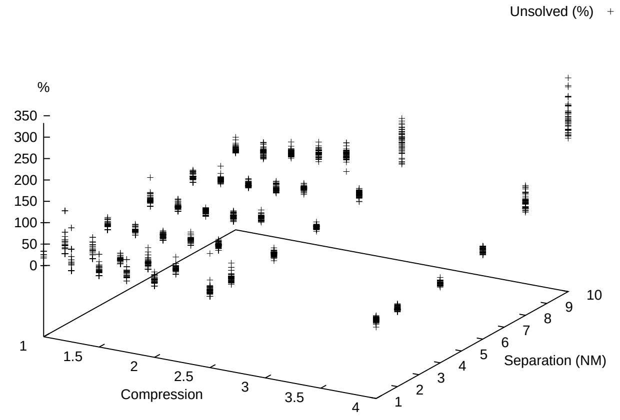

Figure 37: Percentage of remaining conflicts

rent traffic. Figure 37 shows the percentage of remaining conflicts versus horizontal separation and traffic density. The different points appearing for each couple of values correspond to different values of the vertical separation and of the time window.

8.2 Genetic resolution

A resolution method using genetic algorithms has been developped and implemented. Both horizontal and vertical maneuvers are available, and a delaying of take-off time (up to 5 mn) is possible in order to solve simultaneous entries in the airspace. The method solves all conflicts observed in the 1992 and 1996 samples. Maneuvering time is 3.2% of flight time with the 1992 sample, and 4.5% with the 1996 one. Induced delays are respectively 0.4% and 1.0%.

9 Conclusion

Digital (fast and real time) simulation is one of the foremost application areas for computing technology, and is poised to become a dominant and pervasive force to assess advanced EATMS concepts. Modeling and simulation is indeed the only facility to propose a representation of the future system and an evolutionary path to it. We develop the *simulation based planning* methodology to help making decisions in the air traffic management planning process. Operational concepts most fit to relieve bottlenecks hampering the system can be identified, and a large range of options can be assessed, with a level of detail in adequacy to key ATM decision loops.

To support this methodology, we designed a flexible ATM simulation system which models these hierarchical levels of planning: from airspace design to air traffic flow management up to conflict resolution and short term collision avoidance. It is designed for fast performance assessment of the airspace system: capacity, delay, safety and cost effectiveness are the main operational objectives addressed by the model. Several other uses are possible

- For the airspace designer, the system is able to visualize monthly or yearly traffic flows and interactively adjust the sectorisation around the main flows;
- For the airspace management planner, it provides robust delay estimations procedures for en-route traffic and airports, and can suggest optimal regulation plans;
- For the air traffic flow manager, it can

quickly assess various regulation measures such as ground-hold, speed-control, re-routing strategies, or assess demand-capacity imbalance;

- For the policy decision maker, it is a convenient ATM spreadsheet that can estimate traffic revenues (flight-kilometers per country, per sector, per acc), airline direct operational costs (fuel burn, flight time).
- For the researcher, it is a testbed which can be used to *experiment* new algorithms (trajectory prediction, conflict resolution, advanced HMIs) with real traffic.

The OPAS system has been successfully put to practice in the [Sof96c] study, to evaluate various speed control strategies and their interactions with the slot allocation process of the CFMU, in order to smooth north atlantic traffic bound to Paris airports. In this paper, it was used to assess several organisations for the reduction of vertical separation minima in continental airspace. Specifically, it contributed to show that:

1. the introduction of reduced vertical separation minima reduces the average conflict work load by as much as 50%;
2. as more aircraft use FL300, FL320, sectors might have to be redesigned vertically to balance the variations in traffic throughput;
3. there is no clear cut benefits between alternative flight level orientation schemes (FLOS), and operational considerations must be taken into account before proceeding to implementation. These include, but are not limited to, cooperation with military airspace users, consideration of non RVSM traffic, use of in-trail step climb procedures, design of new operational flight level allocation schemes.
4. Even with a direct route network and all aircraft equipped with ACAS type systems, RVSM remains a significant factor to improve system capacity.
5. A simple mathematical model shows that some conflicts are generated even with null separations. These conflicts include in particular pass-overs on the same route. This phenomenon should alter the results of data correlation : when trying to model conflict number as a power of separation, the exponent should be less than expected.
6. The use of free routes over the French airspace causes :
    - 6 to 7% decrease of the number of aircraft simultaneously in flight, because of reduced flight distances,
    - a much larger decrease of the number of conflicts. This is partly explained by the decrease of overall traffic, and also by the decrease of traffic density caused by an increase of available airspace. However, it must be noted that traffic is not evenly distributed, some areas and routes are still very busy.
    - a significant decrease of the size of clusters.

    Moreover, with free routes the number of conflicts increases more rapidly with traffic density. However this is not very significant (extrapolated curves cross at about 15 times the current traffic density).
7. The use of RVSM causes a significant reduction of the number of conflicts (about 20%), both with standard and free routes. Almost only conflicts between level aircraft are involved.
8. Suppressing semi-circular rule increases the number of conflict by 15 to 20%.
9. Regarding correlation of the number of conflicts with the parameters, some differences with the predictions have been observed, and some explanations have been proposed.
    - The number of conflicts between stable aircraft increases linearly with vertical separation.

- When a non-stable aircraft is involved, the increase is slower, probably because a larger separation means that fewer flight levels are crossed during climbs and descents.
- The increase with horizontal separation is less than linear, which can be explained by the phenomenon mentioned at point 5 above.
- For non-stable aircraft, the volume swept by the protection surface has a quadratic component of horizontal separation, therefore the increase is faster than linear ([EO83]).
- The number of clusters varies similarly to the number of conflicts, but with slightly smaller exponents, because an increase of the number of conflicts generates an increase of both the number and the size of clusters.

10. Regarding reactive resolution, unsolved conflicts remaining at low traffic densities are mostly due to conflict geometry. It is clear that at current traffic density the resolution method is far from being overloaded.
11. The genetic resolution method handles correctly the current traffic level, and induces very low delays.

Although still in the research phase, we achieve a high degree of flexibility through the use of modern computing technology and thorough mathematical modeling. For example, we treat uncertainty factors in the planning domain - specifically for en-route and airport delays - as random variates with probability distributions, and use repeated simulation using sampled data in order to perform the proper analysis, which include confidence intervals, about the mean for each result.

While benefits of simulation are known, so are pitfalls in their application. Complicated statistical models may not be understood by the decision-makers, simple assumptions limit their applicability. Simulations are often inadequately accurate, insufficiently evaluated leading to a lack of trust in the results. OPAS is only a decision support tool designed to help ATM analysts: although these difficult issues are left unresolved, their impact are minimized: the simulation based planner is able to evolve smoothly, through the replacement or tuning of individual ATM filter modules.

10 Further research

The main themes of future research with the OPAS system are twofold: model development and model validation.

The ATC simulator is still the focus of core research, to enhance some of its technical features: the radar conflict algorithm is being modified to take into account speed uncertainties of vertical maneuvers. New models for user preferred routing are being designed. Algorithms of efficient multi-sector planning are also sought to prevent the development of large conflict clusters.

In addition, several validation studies are underway. To increase the confidence of ATM analysts with the model, its output results are compared with those produced by other fast time simulators available at CENA: namely, TAAM from the Preston Group, RAMS from Eurocontrol, and Euro-Naspac originally from the Mitre Corporation. Furthermore, the underlying operator model needs to be carefully tuned to estimate accurately sector capacity from the various work load indicators measured during the course of the simulation. Note that this task is endemic to all fast time ATC facilities used for capacity assessment. Indeed, it would be most valuable to use a reference - European - operator model based on the DORA, MBB or [Tof93] model to estimate sector and ACC capacity with such facilities.

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