

SOP: a decision-aid tool for Global Air Traffic Management System Optimisation

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1. Abstract

SOP (Strategic OPTimisation) is a practical approach for global optimisation of Air Traffic Management Systems. It is oriented to improve the airspace regulation, design and management, with the objective to make the best use, today and in the future, of a single European sky for civil and military, by reducing the imbalance between demand and capacity in a totally safe manner.

Today linked to SAAM, a Eurocontrol quick airspace design evaluation system, SOP is able to provide assistance to managers and designers to make the best decision in a strategic or a tactical environment.

2. Introduction

The annual increase in traffic demand places permanent pressure on the ECAC ATM system to make the best use of existing capacity and, where capacity is insufficient, to develop airspace structures to provide additional capacity to keep pace with demand. The Route Network Development Sub-Group (RNDSG) which is a

sub-group of the Airspace and Navigation Team (ANT) has been engaged in the development of proposals for enhanced capacity for a period of approximately eight years. During this period it has supported the development of Analytical and Evaluation tools in order to have the capability to analyse the current operation of the ATM system at regional and ECAC wide level. The need for such analytical tools becomes apparent when one considers that on any single day up to twenty seven thousand flights will operate through as many as one thousand five hundred sectors in the en-route and terminal ECAC ATM system. The current tool, developed in support of the RNDSG activities, is the System for Assignment and Analysis at a Macroscopic level (SAAM) tool which provides the flexibility, speed, and high quality graphical presentation to carry out analyses at both regional and ECAC wide level.

The SAAM tool consists of a portfolio of functionalities which can provide information on route segment loading and sector loading on the current and proposed route network and sector configuration. A schematic diagram of the SAAM evaluation process is given in figure 1.

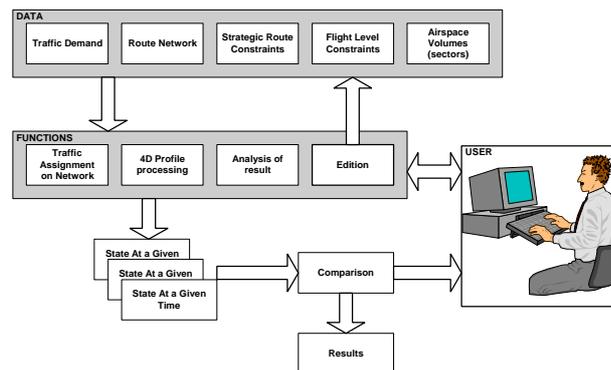


Fig 1: SAAM Evaluation Process

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Up to now, the SAAM tool has been used to provide support in a passive manner to airspace planners to enable them to assess the implication of route changes or sector changes using the “what if” capability of the tool. However, following recent development work an additional functionality has been developed which shows considerable promise in airspace design and ATC capacity utilisation.

The Strategic OPTimisation (SOP) functionality is oriented to improve airspace design and management with the objective of making the best use today, and in the future, of a single European Sky for civil and military airspace users.

3. SOP Process: Underlying Concept and Principles

It is well known that at present, traffic is frequently delayed because of a poor utilisation of capacity or because of a lack of capacity. The key of SOP process is the capability to examine what would happen to the overall ATM performance if the spare capacity is utilised and, if no solution is found, which areas should be examined as a priority to create capacity.

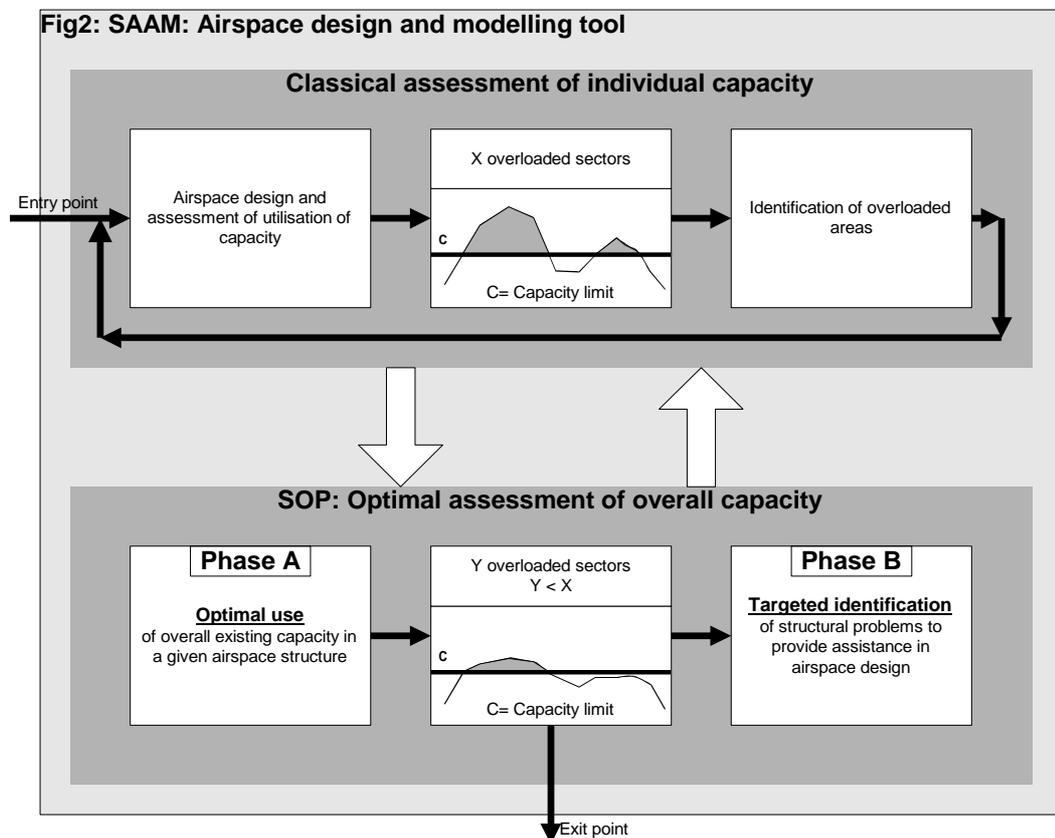
To illustrate the interaction and loops between

the different processes the schema below shows how SAAM is working. In the “Classical assessment of capacity” users can change route and airspace structure and apply traffic on this environment via some rules resulting in compromise between ways of analysing of result and operational expertise, economical pressure and safety requirements.

SOP, embedded into SAAM, is an iterative and incremental process that provides users an “optimal way of assessing overall capacity”. Two phases are necessary: phase A indicates the way to use existing capacity at its best, and then, during phase B, SOP identifies the limiting sectors or areas in the proposed airspace structure. SOP can be seen as a decision aid tool to assist airspace planners to progressively improve airspace structure.

The two phases, A and B, making the Optimal assessment of overall capacity are described in detail below:

Phase A: Optimal use of overall existing capacity in a given airspace structure: investigation with SOP of the optimum use of overall capacity (maximum potential) of a proposed airspace structure utilising the



parameters of route assignment, flight profile and (reasonable) delay. All parameters can be subject to constraint i.e. not more than X additional route length etc.

This optimal use of overall existing capacity is carried out using the following parameters or options:

- Alternative routes: on a given network, each origin/destination presents a possible set of alternative routes, with an extension of less than “x” nautical miles. Each different routing should define a different sequence of crossed sectors and thus determine different sector entry rates or workload.
- Flight levels: each flight presents a variety of possible flight level options around the RFL. The selection of a different FL may impact on sector entry rate or workload (by suppressing or adding conflicts).
- Departure time: research of possible departure time slot allocation that impact on sector entry rate or workload.

One or a combination of these options (2D, 3D or 4D) can be processed for SOP.

The primary aim of the model is to find an assignment of aircraft to routes minimising aircraft operation costs while complying with sector capacity constraints. However, exact satisfaction of all sector capacity constraints is not always possible e.g. when the given sectorisation and/or route network are not well suited to the traffic patterns to be handled (this often occurs in the European “core area”). To cope with such situations the objective function of SOP model incorporates an additional term (a “penalty” term) measuring how difficult it is to satisfy each hourly sector capacity constraint. As explained in section 3 below, this gives rise to large-scale integer programming models.

Phase B: Targeted identification of structural problems to provide assistance in airspace design: using selective indicators, the weaknesses or limits, in terms of route Network and/or sectorisation, of the proposed airspace structure are identified and proposed to designers for corrections. In other words, SOP specifies those sectors for which significant difficulties were encountered to satisfy demand thereby indicating a structural problem in airspace design.

These structural problems should be overcome through:

- Network changes: route re-alignment or route changes (deletion or creation).
- Sector shape changes: re-sizing, collapsing or splitting sectors boundaries and/or sectors division flight levels.

The optimal values of the penalty terms in the objective function of SOP, generated during phase A (and associated to each sector and one-hour time period) are used to determine and prioritise the necessary structural changes such as sector or route network modifications.

4. SOP model

SOP examines the aircraft demand pattern as expressed in a set of four-dimensional (4D) planned flight trajectories from origin to destination or from entry point to exit point in the area of interest.

The model assumes that, for each aircraft i , a list L_i of alternative 4D trajectories for the aircraft is available. (Note that, in practice, many such trajectories may be obtained by choosing combinations of a 2D path on a route network together with a cruise level, an entry time, and a top of descent time.) With each trajectory j in the list L_i there is an associated cost, $\mathbf{g}_{j,i}$ and there is one preferred trajectory which has the least cost.

The model also assumes that there is a certain amount of airspace volumes and runways which have to be used by aircraft trajectories. These airspace volume and runway systems have capacity limits that should not be exceeded.

The proposed model can then be stated as an optimum selection problem: for each aircraft i , select one trajectory x_{ij} , out of the given list L_i , in such a way as to minimise the objective function $z = \sum_{i,j} g_j x_{ij}$, subject to satisfaction of

all capacity constraints C_k .

The SOP model uses sector capacities expressed in terms of hourly entry rates, i.e., for each sector k and each one-hour time period t in the day, the total number of aircraft entering the sector in this period should not exceed a prescribed value $C_{k,t}$. These values may vary slightly from one sector to the next, and, for a given sector, may depend on the time period t . This way of handling sector capacity constraint in our model had been validated through numerous simulations (using the CAPAN and the SAAM simulation tools in use at Eurocontrol) which have shown that a strong correlation exists between entry rates and controller workload.

For each sector k and each one-hour period t , let us denote by $EA(k,t,x)$ the total number of aircraft entering sector k in period t , under trajectory assignment x . It is easily seen that $EA(k,t,x)$ may be expressed as a linear function in terms of the x variables, since:

$$EA(k,t,x) = \sum_{i,j} w_{i,j}(k,t) x_{ij}$$

where the $w_{i,j}(k,t)$ coefficients are defined as:

$$w_{i,j}(k,t) = 1 \text{ if aircraft } i \text{ following trajectory } j \in L_i \text{ crosses sector } k \text{ during time period } t, \\ = 0 \text{ otherwise.}$$

For each constraint of the form $EA(k,t,x) \leq C_{k,t}$ we compute the penalty value :

$$P(k,t,x) = \max\{0; EA(k,t,x) - C_{k,t}\}$$

Then the SOP model is as follows:

$$\left\{ \begin{array}{l} \text{Minimise} \\ \sum_{i,j} g_j x_{ij} + r \sum_k \sum_t P(k,t,x) \\ \text{subject to:} \\ EA(k,t,x) - P(k,t,x) \leq C_{k,t} \\ \text{for each aircraft } i: \sum_{j \in L_i} x_{i,j} = 1 \\ x_{i,j} \in \{0,1\} \text{ for all } i, j \in L_i \end{array} \right.$$

5. AN EXPERIMENTAL SETTING

5.1. Description

To highlight the facilities and the kind of output that are issued from SOP, experiments have been carried out on the most congested airspace in Europe, called the “core area”, from Maastricht sectors (above Belgium) to Geneva/Zurich sectors (above Switzerland).

Because the assessment of capacity has to take into account changes that might occur outside the congested area, 600 sectors, covering all Europe were taken into consideration.

In the congested area specific route segment were locked to the traffic in order to generate alternative route options for the most important city pairs. 50 routes segments were chosen that leads to more than 3000 route options. Each 2D route option is never exceeding more than 50nm of route length extension as compared with the shortest path length, and is individually avoiding on purpose some or several of the congested sectors.

Since SOP works with constraints expressed in terms of sector entry rate, we choose a sector capacity limit of $C_{k,t} = 40$ for each sector (which means no more than 40 aircraft per hour entering a given sector). Of course, this limit can be easily changed, globally or for each of the 600 sectors.

In order to obtain more robust solutions from the model, we consider that each aircraft may be up to 15 minutes late or ahead of time on its calculated exact entry time. This is easily taken into account in the computation of the $w_{i,j}(k,t)$ coefficients.

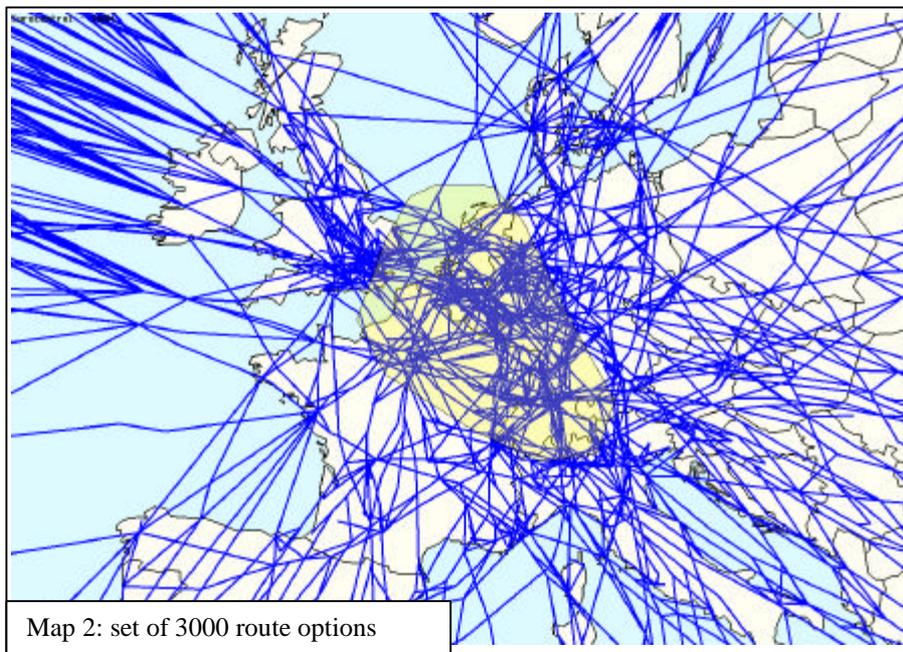
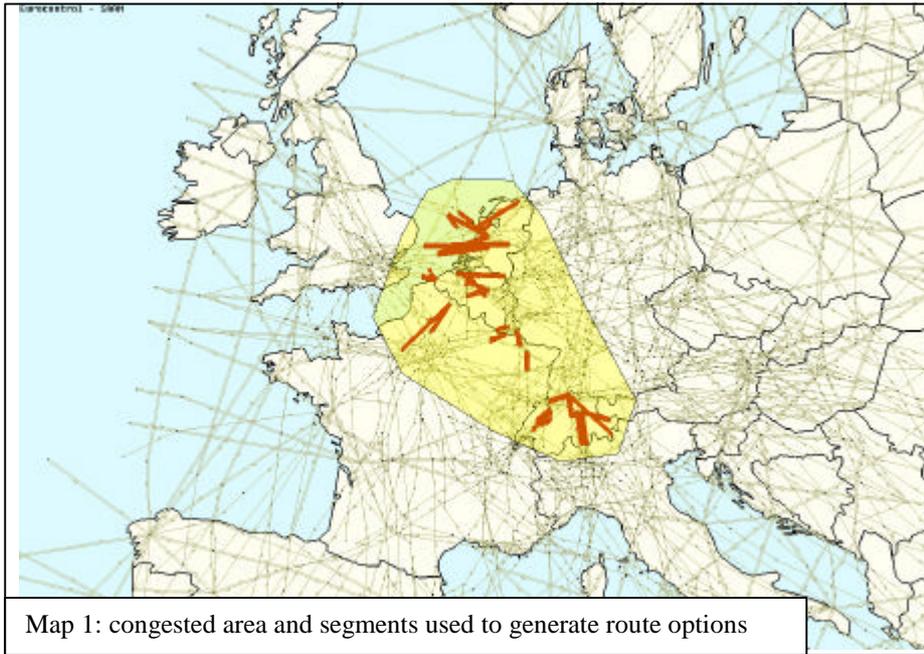
The totality of the traffic of the busiest day of the year 2001 was used (the 29th of June 2001

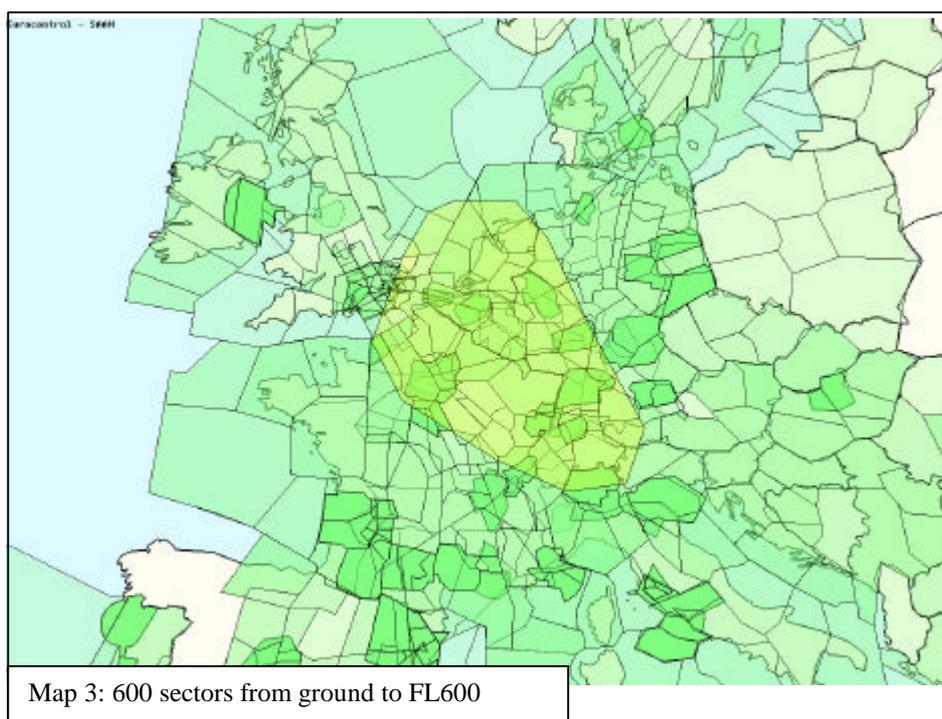
having more than 27000 flights) with the different options, in order to get for each of the 600 sectors a correct entry rate.

The typical size of the linear programming models to be solved corresponds to approximately 6000 binary assignment variables $x_{i,j}$ and more than 100.000 artificial variables, together with more than 100.000 sector capacity constraints. These problems are typically solved

to optimality within minutes using commercial linear programming solver Cplex 7.0.

The maps below shows the extend of the congested area, the location of route segments that were alternatively locked to generate the route options, and a depiction showing the top view of the set of 600 sectors that were taking into account during the optimisation process.





5.2. Analysis of the results

The run of SOP, for the example described in section 4, took approximately 2 minutes on a Windows NT 4.0 computer, equipped with a Pentium II 450Mhz. From the original 3000 route options that were proposed, SOP retains only 1000, which mean that the remaining 2000 options stayed on their original route paths (SOP changes route options only when necessary). The average route extension for these 1000 route options that were changed by SOP represents only an increase of 20nm, which is very low.

Map 4 and 6 show two examples of route options (extracted from the set of 3000 route options) proposed to SOP between two city-pairs: EGCC (Manchester) to LGKR (Kerker) and LEMG (Malaga) to ESSA (Stockolm).

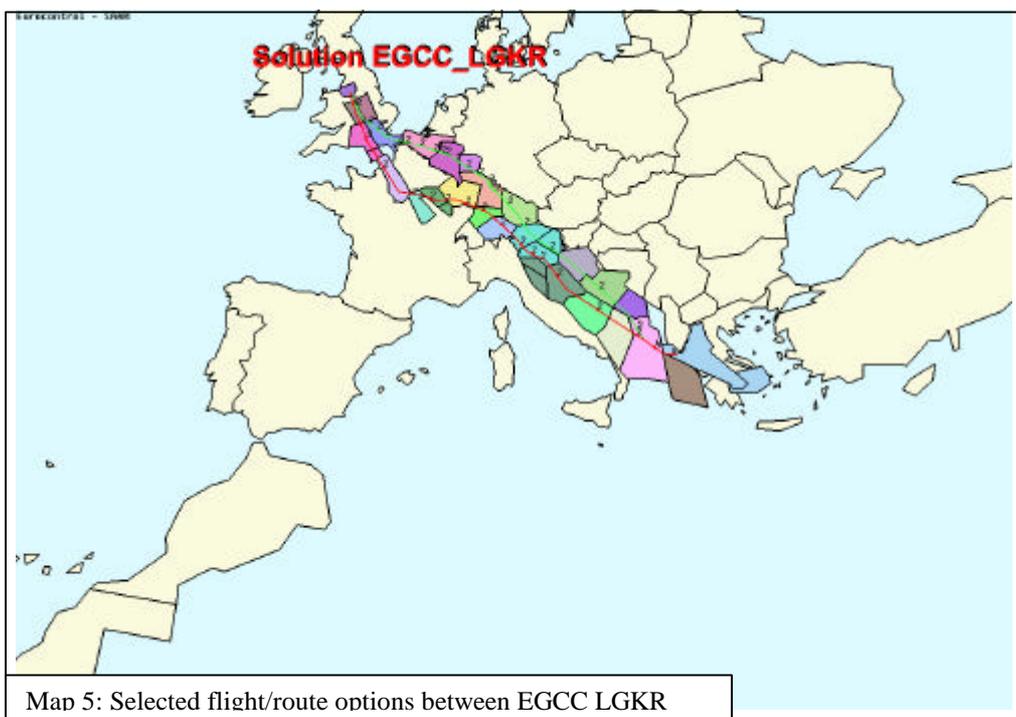
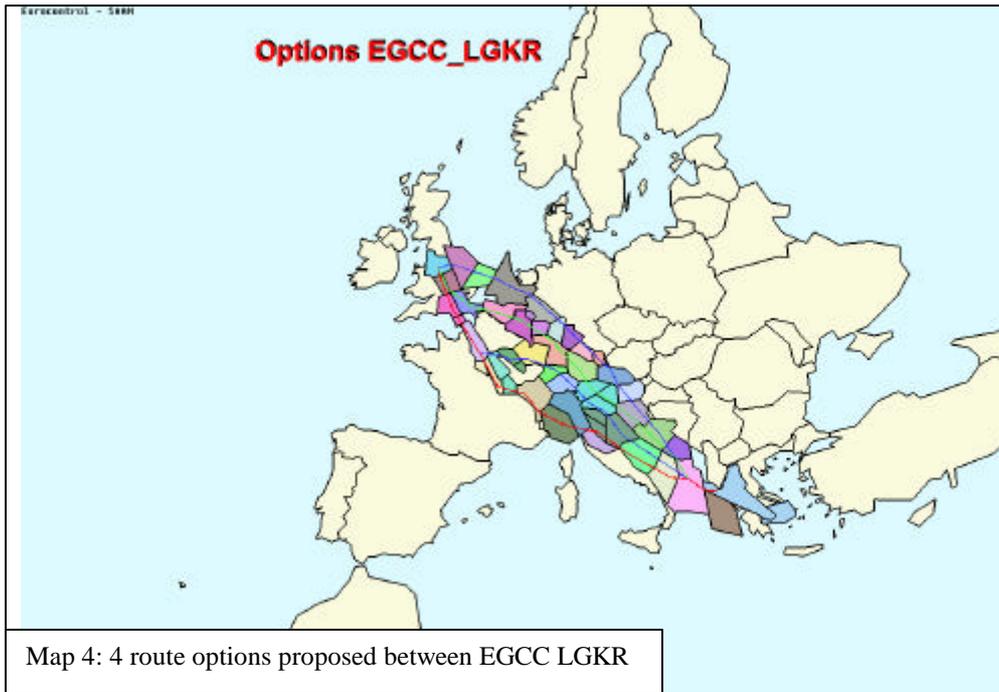
Map 5 and 7 illustrate choices that SOP made from the above examples: optimal distribution of flights on these route options.

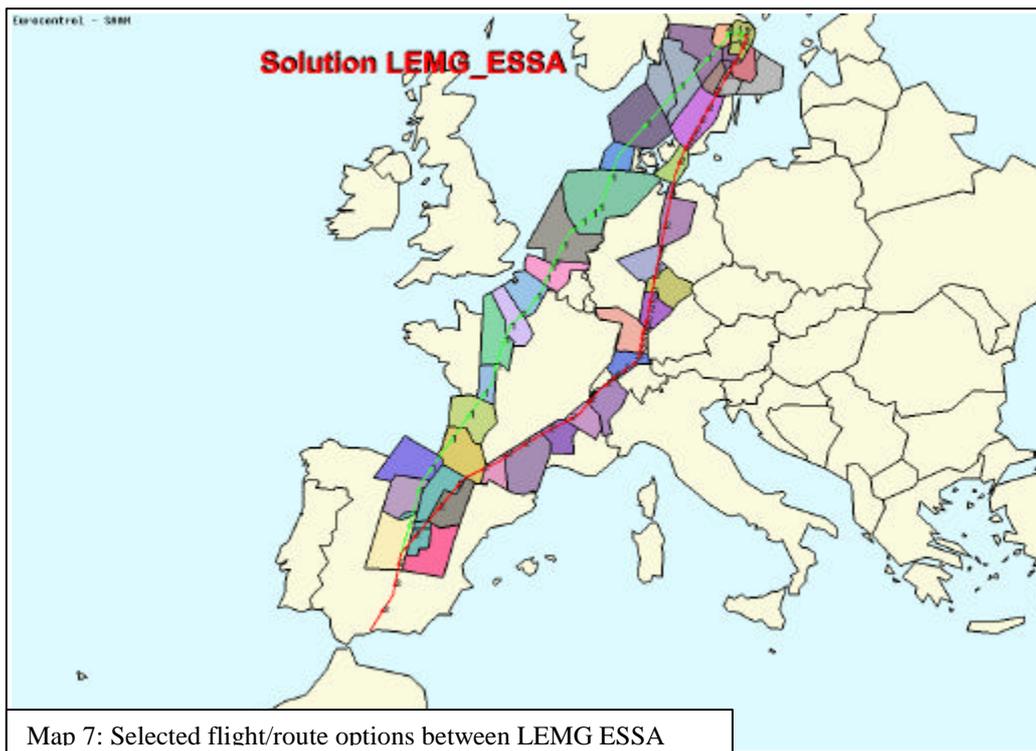
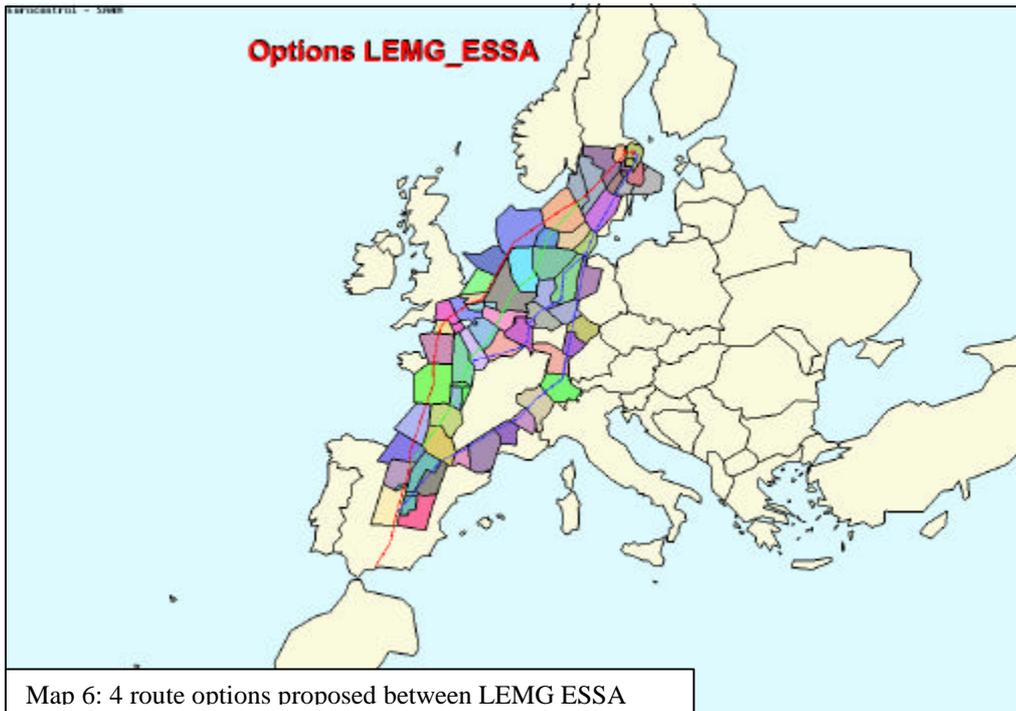
Map 8 shows a global view of the effect of SOP in the congested area via a comparison of traffic density. We can see that traffic crossing

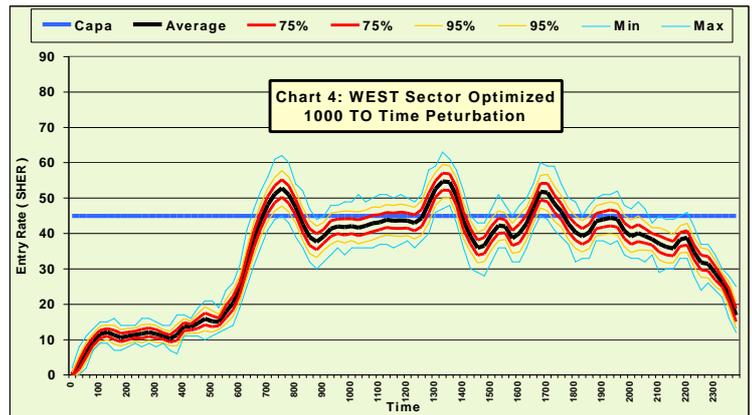
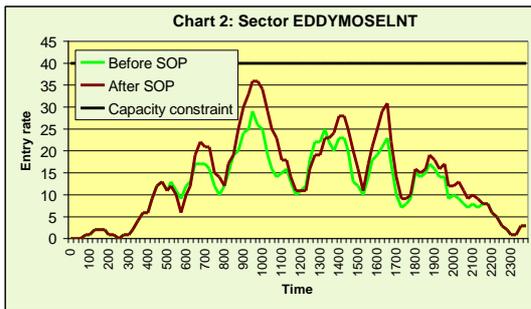
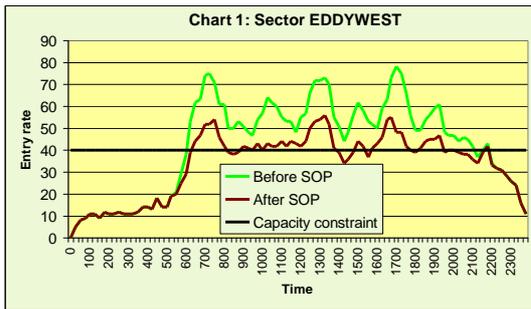
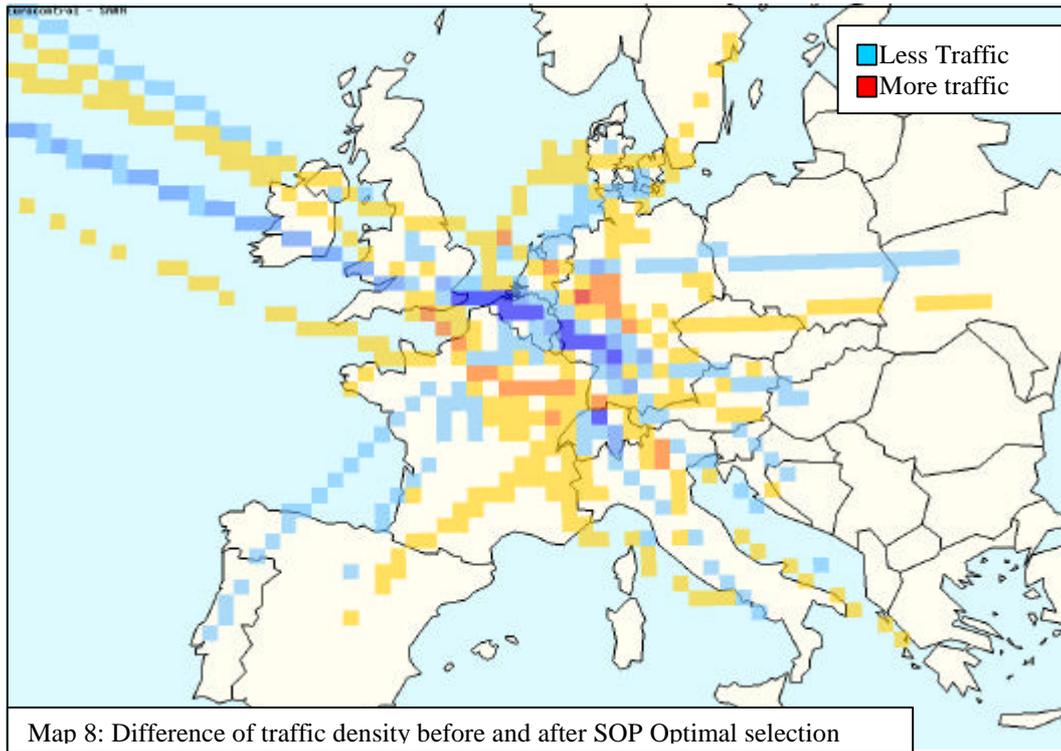
overloaded sectors were, in general, and when possible, pushed around the congested area.

The benefit of SOP are also illustrated with the chart 1 and 2 showing how the entry rate for sectors EDDYWEST (usually congested) and sector EDDYMOSELNT (usually not overloaded) are changed. For EDDYWEST a clear reduction of the entry rate (when it is necessary and possible) is depicted, even if some above capacity peaks are still existing. On the other hand, sector EDDYMOSELNT receives more traffic because its capacity limit allows it. The transfer of traffic from overloaded sectors, to sectors still having capacity, illustrates phase A of SOP. The remaining peaks in sector EDDYWEST have activated the penalty terms of the objective function of SOP for that sector and for these periods of time illustrating phase B of SOP.

Chart 3 and 4 show the robustness of SOP facing heavy perturbations. The same perturbations were applied on sector EDDYWEST before Optimisation (chart 3) and after optimisation (chart 4). We can see that, in any case, the result of SOP remains better than the original situation.





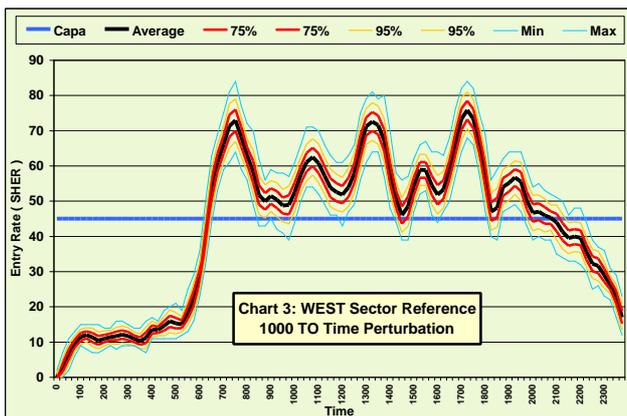


6. CONCLUSIONS

Changing and increased modelling requirements in support of Eurocontrol AMN work have resulted in the development of the SOP/SAAM tool set which extends AMN ability to assess procedural and technological ATM system improvements which are required to keep pace with demand.

Based on an appropriate mathematical model, it provides significantly improved solutions, in terms of ATC Workload.

From the results obtained so far for part of the most busy core of European airspace, it is possible to conclude that there are opportunities to significantly increase airspace system capacity today and in the future.



7. ANNEXES

BIOGRAPHICAL INFORMATION

Thierry Champougny is responsible for the development of SAAM in the Airspace design Evaluation tool service in Eurocontrol's Airspace Management and Navigation Unit.

Alain Duchene is responsible for the coordination of the development of the European Route Network within the Airspace Structure of the Eurocontrol's Airspace Management and Navigation Unit.

Antoine Joubert is consultant in Airspace Modelling Service in Eurocontrol's Airspace Management and Navigation Unit.

Jim Lambert is head of the Airspace Structure in the Eurocontrol's Airspace Management and Navigation Unit.

Michel Minoux is a Professor at University Paris VI (FR). His research interests include Graph Theory, algorithms and mathematical models for system optimisation.

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References:

NIEDRINGHAUS W.P., FROLOW I., CORBIN JC, GISCH A.M., TABER N.J., LEIBER F.H (1983)

“Automated En Route Air Traffic Control Algorithmic specifications”

Technical report DOD/FAA/ES-83/6

DURAND N., ALLIOT J.M. (1997)

“Optimal Resolution of En Route Conflicts”

in Proceedings of Europe-USA Conference on Air Traffic management

AVELLO C.G., SWIERSTRA S. (1997)

“Free Flight until where ... and then ? “

Proceedings 10th European Aerospace Conference on Free Flight, Amsterdam

GARCIA C., SWIERSTRA S (1996)

“Towards Optimum Air Traffic Management”

Proceedings Infautom 96, Toulouse and Eurocontrol DOC 967009

Joubert S. Hockaday M. Minoux (2001)

“Tools for European ATM System Capacity enhancement and the Optimiser example.”

WCTR - Seoul 2001

7.1. Definition of terms

AMN: Airspace Management and Navigation

ATC: Air Traffic Control

ATM: Air Traffic Management

FL: Flight Level

RFL: Requested flight level

RVSM: Reduced Vertical Separation Minima

SAAM: System for traffic Assignment and Analyses at a Macroscopic level

SHER: Sliding hourly entry rate

SOP: Strategic Optimisation