Redesign of the European route network for sector-less

Thomas Rivière

REDESIGN OF THE EUROPEAN ROUTE NETWORK FOR SECTOR-LESS

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Abstract

The increase in air traffic and the limited capacity of air traffic control services force us to think of a new way in which to control aircraft. An innovative ATM concept, called Sector-Less Air Traffic Management, has been defined by the Eurocontrol Experimental Centre. In this concept the role of the controller is radically different from the current one : instead of having controllers controlling a sector, controllers would be responsible for a certain number of aircraft from departure to arrival in terminal areas.

The aim of this paper is to redesign the European en-route network in order to make this new way of controlling aircraft possible and to provide an aeroplane with the shortest route possible by providing a new route network. The approach proposed here is, starting from scratch, to provide a very simple route network and to improve it by using optimisation algorithm.

A generated route network will be evaluated in terms of length of trajectories weighted by the amount of aeroplanes using them and then compare it with the direct route network and the current one. Using this tool and a fast time air traffic simulator, the Sector-Less concept will be able to be evaluated in terms of capacity and delay due to conflict. This also provides the route density of the network for this concept.

The results of various simulations performed on the best route network generated so far will be presented.

Introduction

The increase in air traffic raises a major concern. How does one simultaneously accommodate increasing numbers of aircraft into an already saturated airspace, whilst maintaining safety at at least current levels, and simultaneously improving the efficiency of Air Traffic Services by reducing delays ? An innovative ATM concept, called *Sector-Less Air Traffic Management*, defined by [2] at the ATM conference, 2001 tries to answer this question.

In this concept the role of the air traffic controller is radically different from the actual one : instead of having two controllers controlling one sector containing *n* aircraft, one controller will be responsible for a number of *m* aircraft, from departure to arrival terminal areas (TMA).

According to [2] the mean number of operations handled by one controller per year does not exceed 650. Mathematically speaking, instead of managing a number of aircraft flying across a number of sectors, requiring the attention of a number of controllers responsible for those sectors, it is not unrealistic to assume that the same number of controllers can handle such numbers of aircraft individually from departure to arrival.

The aim of this paper is to generate a route network which will fit into the *Sector-Less* concept and provide an aeroplane with the shortest route possible. This problem will be approached by generating a suitable simple route network for *Sector-Less* and improved by using optimisation techniques such as *simulated annealing algorithm*.

After having roughly explained the *Sector-Less* concept in the second part, this paper will show how, within this framework, a route network is generated and optimised. Finally the results of simulations, done using a fast time air traffic simulator, on the *best so far* network will be presented.

The *Sector-Less* concept

The concept

This concept has been devised by taking into account one major problem in the current ATC world : traditionally the traffic increase has been accommodated by subdividing highly loaded sectors but nowadays many sectors have become too small to be divided. [2] think that now sectors are therefore a constraint to the increase of air

traffic and that there is obviously a need to explore new practices that could break away from this major constraint.

The paradigm that *Sector-Less* investigates is the trajectory-based individual control as opposed to the airspace-based sector control currently used. The ultimate unknown which this project tries to clarify is whether or not in the future we could remove sectors, as well as their associated constraints, in order to respond to the capacity impasse.

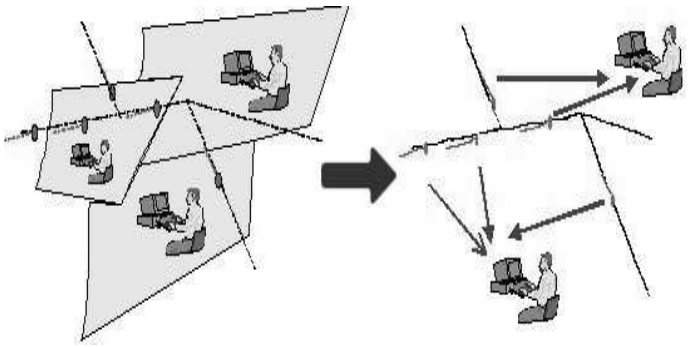

Figure 1. Basic *Sector-Less* concept

The airspace design

According to [2] the generation process of a route network for their concept can be divided into two sub-problems :

- a Trunk Route Network (TRN) in which there will be specific spacing techniques performed whilst avoiding flight level changes and vectoring ;
- a Secondary Route Network (SRN) which will link the TRN to every origin and destination TMA.
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The main airspace design rules of the *Sector-Less* concept are composed of the one which separates flows going in opposite directions and the one which handles the crossing section between two routes. As shown in figure 3, the crossing rule works more or less like a roundabout.

Flows separation

As the concept implies a simplification of the route network, it is possible to think of larger routes than the current one by employing closed parallel tracks. This will allow fast aircraft to overtake slower ones. One can also imagine using tracks to change flight levels without interfering with other flights.

As shown in figure 2, which represents a crossroad of two orthogonal flows, every route is doubled in order to avoid mixing traffic going in opposite parallel directions. In addition to that, every route is comprised of 3 tracks : a main track and two secondary ones, respectively on each side of the main track, used for manoeuvring techniques. Moreover this figure shows two flows going in orthogonal directions and the crossing techniques this concept requires. These techniques will be presented in the next part of this paper.

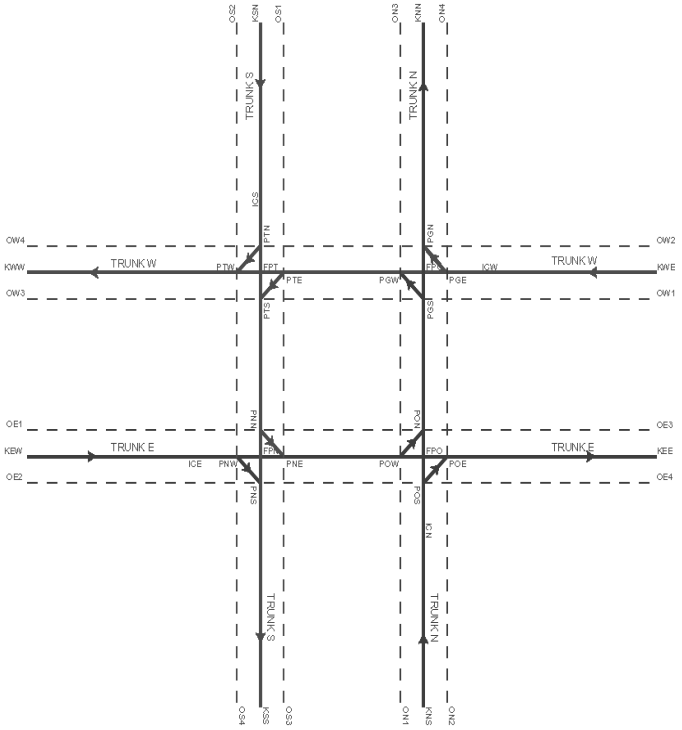

Figure 2. Super-Sector flows separation system

Finally, the rules taken into account for the flows separation are that :

- flows going in opposite directions use parallel routes. Unlike [5] in the *Super-Sector* concept, aircraft going in opposite parallel directions are allowed to use the same flight level but, consequently, parallel routes must be far enough apart in order to respect the separation distance ;

- one route can be divided into several parallel tracks going in the same direction in order to allow faster aeroplanes to overtake slower ones ;
- two crossing routes must be on a different flight level. One can therefore imagine that aircraft taking a directional route East-West bound have an odd flight level so aircraft going in a South-North direction have an even flight level.

Crossing points

In order to make this flows separation rule available, the *Sector-Less* concept defines another important rule on how to handle the crossing section of two flows.

As shown in figure 3, a crossing point in the *Sector-Less* concept works more or less like a roundabout, but uses 3 dimensions.

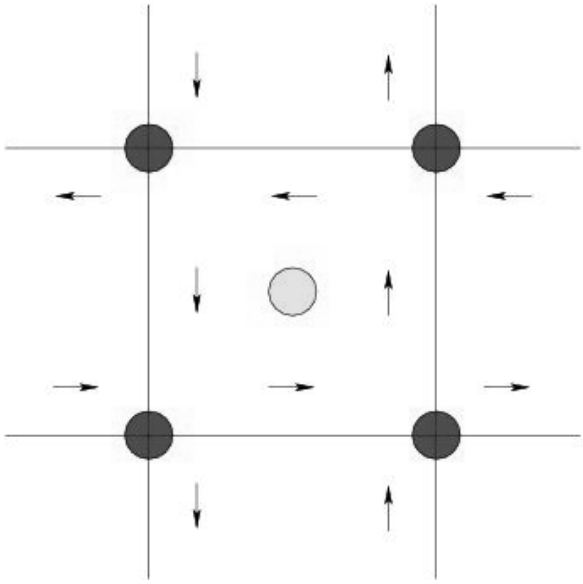

Figure 3. The square crossing

As mentioned in the previous section, two crossing routes must use different flight levels. An aeroplane which is crossing another route has to respect the following rules (see figure 4) :

- any aeroplane passing through without changing direction must stay stable on its flight level ;
- any aeroplane turning right must not cross the route but must change flight level (be that up or down) to reach the flight level of their new trunk route ;
- any aeroplane turning left must cross the route, turn at the opposite corner and change flight level.

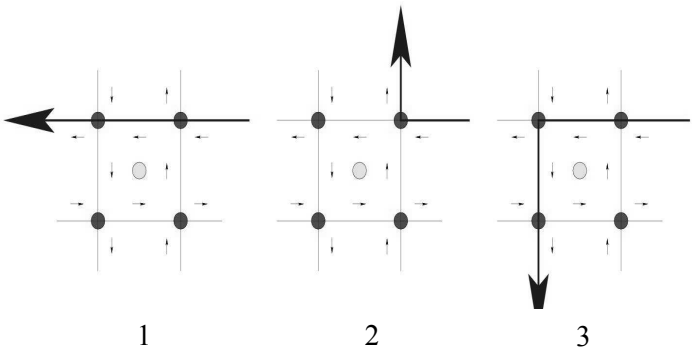

Figure 4. The turning process

According to the rules defined above, it is comprehensible that two main criteria are going to lead the research : these seek to find the shortest path possible and to minimise the number of turning points.

The trunk route generation

As the *Sector-Less* concept is something radically different from the current one, a new route network will be generated for it starting from scratch rather than being an adaptation of the current one. Except for the basic *Air Traffic Management* rules, no technical configuration data concerning the route network has been defined by [2].

The prime concern of this research is to generate the *best* Trunk Route Network possible. The secondary route network has not yet been taken into account so the only way (used in simulation) to reach or leave the trunk route network is by using direct routes.

The initial TRN

The first route network generated is a very simple square grid covering Europe (see figure 5). Every parameter has been decided arbitrarily; future work will be to test different values for each one and find the *best* of these.

The initial TRN has the following characteristics :

- a square 4000 kilometres long;
- two neighbouring crossing points separated by 240 km making 256 crossing points.

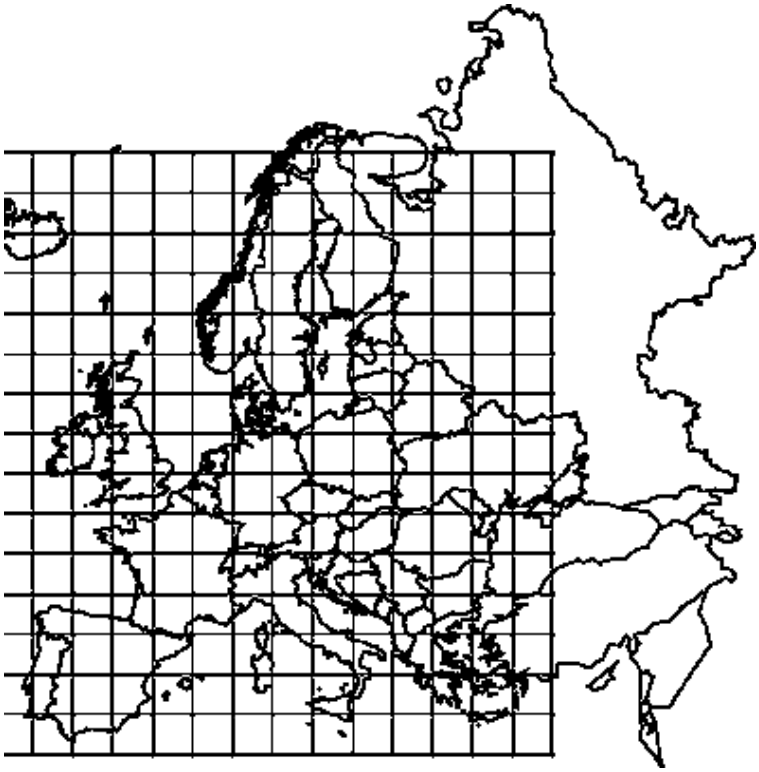

Figure 5. The initial TRN

Grid Bending

The aim of this work is to optimise the basic route network defined previously by bending the grid according to one essential criterion : the average global extension of trajectories in comparison with the length of direct routes.

In the case of the initial TRN, the criterion is worth 32% which means that a trajectory of an aeroplane following the grid is, on average, 32% longer than the direct route.

Simulated annealing and shortest path algorithms

The route network is optimised by using an algorithm based on a simulated annealing algorithm ([6]). Thus, the algorithm :

- chooses one point randomly and moves it in a random direction ;
- evaluates the criterion ;
- rejects or accepts the movement.

The optimisation criterion is based on a Floyd-Warshall shortest path algorithm [3]. It gives the shortest path between every pair of points on the grid. Knowing every air flow possible[1] and the number of aeroplanes using it[2], the average global extension of trajectories (which is the sum of the differences between the length of a trajectory and the corresponding direct route, weighed by the number of aeroplanes using this route) can easily be computed.

Consequently the criteria favours the flows with a high number of flights per day[3].

More details about the algorithm, especially about various heuristics used, have been presented by [8].

Limitations

It is worthwhile noting that some limitations have to be added in order to provide a route network which is potentially valid in reality :

- the distance between two crossing points cannot be smaller than 100 kilometres in order for an aircraft to spend more time on a main trunk than in a crossing area;
- a shortest path cannot include an angle smaller than 90 degrees. This is in order to make turning points feasible. As the criteria favours the main flows, some flows (which are mainly orthogonal to these major flows) with only a few

[1] A departure-arrival pair is considered in this paper as a flow.
[2] Arbitrarily the data of June the 21st which is one of the busiest day of the year 2002 with 10738 flows has been chosen.
[3] In Europe the main flows are Madrid-Barcelona (over 70 aeroplanes a day in each direction), Milan-Rome (about 45 aeroplanes a day), Paris-London (35) or Paris-Toulouse (35).

- aeroplanes a day may have awkward trajectories (see figure 6) with turning angles impossible to manage in reality.

This last limitation tends to smooth trajectories.

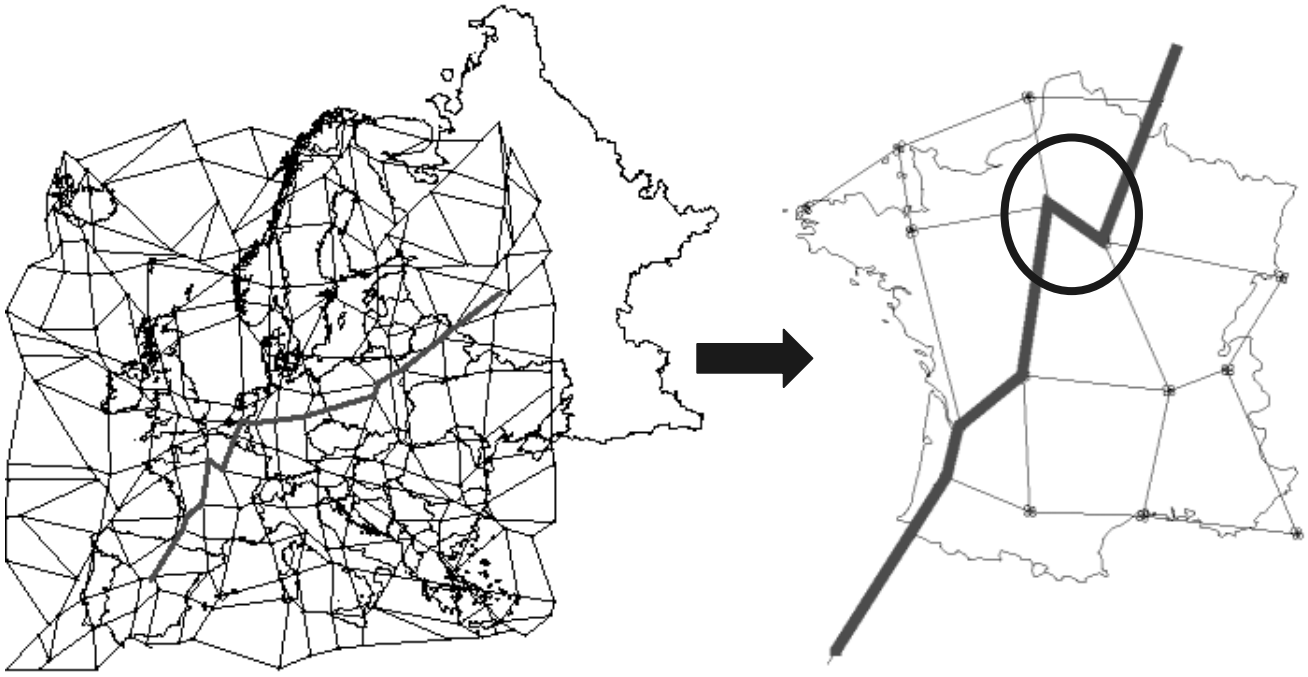

Figure 6. Moscow-Madrid rejected trajectory

Best TRN so far

The best trunk route network obtained so far (figure 7) has been deducted from the initial one presented before using the basic algorithm described previously.

The average global extension of trajectories in comparison with the length of direct routes is worth 16% in this case.

Figure 8 represents the trajectory of an aeroplane going from Reykjavik, Iceland (BIKF) to Palma, Mallorca Island, Spain (LEPA) using this route network.

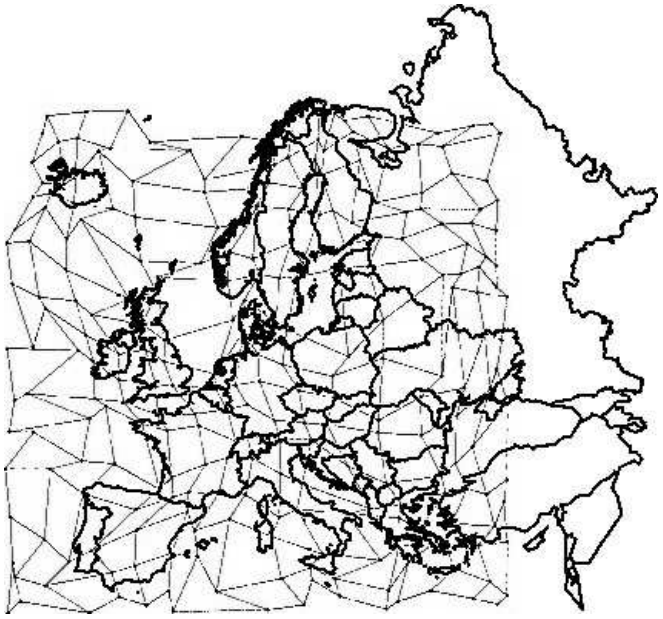

Figure 7. The best TRN so far

Conservation of the airspace design rules

Of course, the fact that the grid is bent has an influence on the airspace design rules defined previously. Even though the bending process does not change anything in the flows separation rule, the shape of the crossing section cannot remain square.

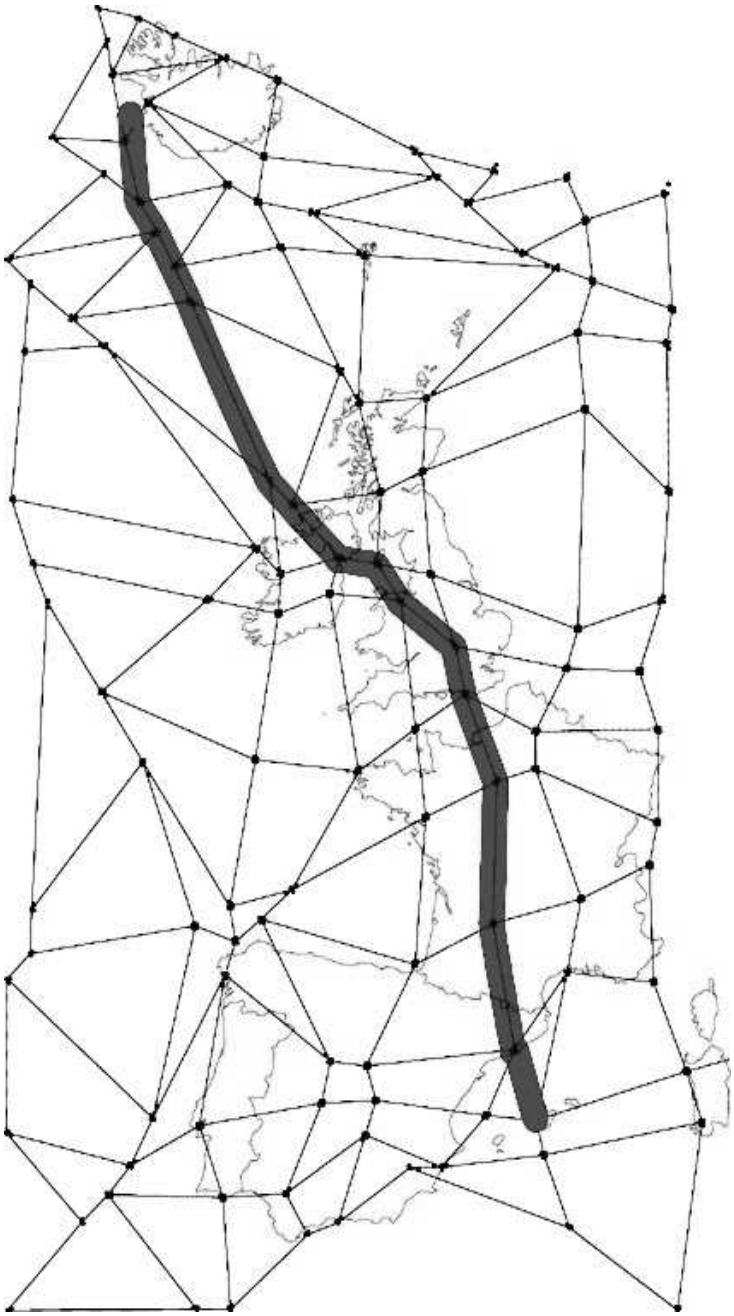

Figure 8. Example of trajectory in the TRN

As presented in figure 9, every crossing section has to be adapted to its new shape. Its size and the relative position of its 4 turning points (with respect to its centre) change. The only parameter which does not change is the distance between two parallel routes.

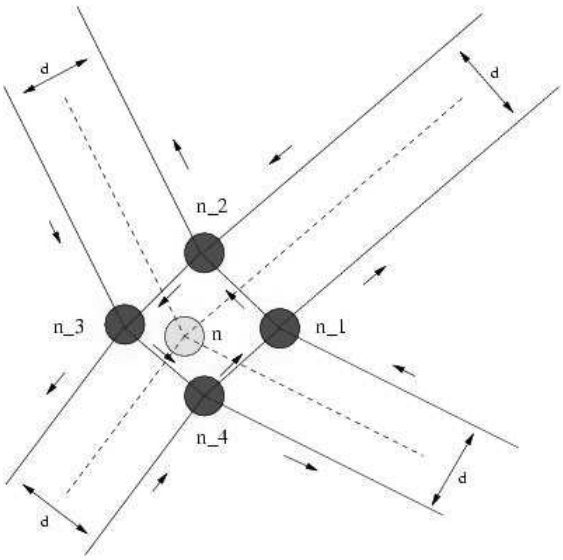

Figure 9. Adaptation of the crossing section

Evaluation

Having generated a *good* route network, the purpose of this study is to evaluate various values for the minimum space between two parallel routes. As previously stated this parameter is the only one not to change whilst the grid is bent.

The value 0 has no meaning in this concept as two aeroplanes going in opposite directions are allowed to use the same flight level. Even so, a wide range of values has been tested from 1 to 100 kilometres.

Three criteria have been taken into account for the evaluation of the network :

- the global number of conflicts[4], in order to find the best value possible from a global point of view ;
- the number of conflicts located in the crossing points, in order to evaluate the distribution of aircraft within the network ;
- the amount of conflicts per crossing point within the next *n* minutes, in order to evaluate the workload of a controller.

[4] There is a conflict between two aircraft when they do not respect the vertical and/or the horizontal separation rules.

Simulations have been performed on a fast time air traffic simulator CATS [1].

Simulation

Every simulation has been performed using real European data from 2002. Arbitrarily the data of June the 21st, which is one of the busiest days of this year with more than 28000 flights[5], has been chosen. Conflicts are detected but unsolved. The separation standards used for the detection are :

- minimum detection flight level : FL 100. Flights under this flight level are considered either as being handled by an approach controller or as non commercial flights. Thus they are not taken into account to avoid too much noise in statistics ;
- horizontal separation standard : 5 NM[6] ;
- vertical separation standard : 800 ft (*The Reduced Vertical Separation Minimum (RVSM)* is taken into account but an error of 400 ft is allowed due to the imprecision of aeroplanes positions of an aircraft during a simulation) ;
- if two aircraft are in conflict more than once, only one is considered if the time between two conflict positions is smaller than 30 seconds.

In order to avoid two aircraft taking off (or landing) at the same time from the same place, the air traffic is regulated by scheduling departure and arrival in every airport with 60 seconds delay[7] (except in Paris' Charles de Gaulle airport where the delay is 30 seconds and Paris' Orly airport where it is 45 seconds).

[5] This data contains 11024 point to point destinations with 1439 of these containing at least 5 aeroplanes, 363 with at least 10 aeroplanes and 68 with at least 20.

[6] The French separation standard is applied to every country in Europe despite the different rules in use in these countries.

[7] It would be possible to adapt the value of each airport but there is a lack of available data. Thus some aeroplane coming or going to or from major airport such as London-Heathrow can be delayed excessively (for sometimes more than an hour sometimes).

Global number of conflicts

The route network has been evaluated in terms of number of conflicts during the day. If this value is not significant enough for the precise evaluation of the workload to be done by controllers, it nonetheless provides an overview of the relevancy of such values (see figure 10).

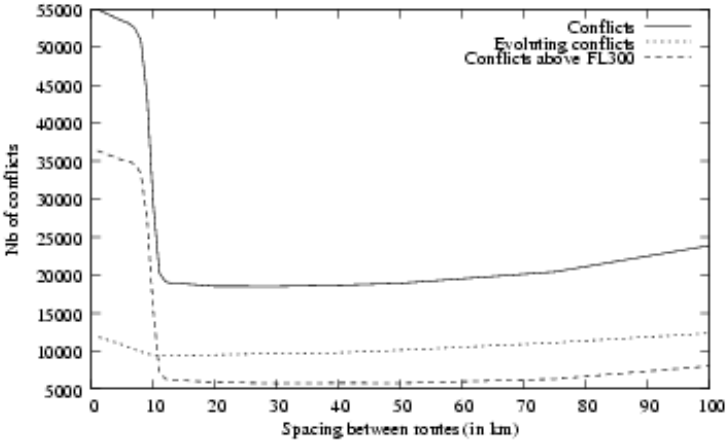

Figure 10: Global number of conflicts

As the horizontal separation distance is 5NM (about 9.3 km), it is not surprising that the amount of conflicts for the small values (less than 10 km) is much higher than with any other one. As expected, a big decrease can be seen between 9 and 10 kilometres due to the fact that two aircraft going in opposite directions on two parallel routes are no longer in conflict. The decrease continue between 10 and 11. This is the result of the position of the aircraft on its trajectory being uncertain. Having a space of 11 kilometres between routes envelopes this uncertainty. For values between 11 and 30 kilometres, the number of conflicts remains stable and begins to increase when the space between two routes is so wide that two crossing points may interfere (see figure 11).

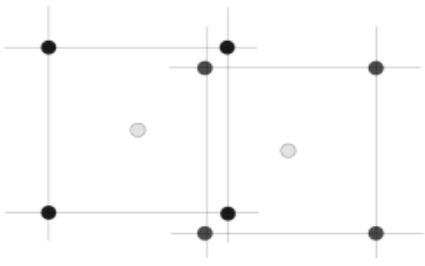

Figure 11: Two crossing points interfering

Number of conflicts per crossing

If the *Sector-Less* concept is the control of an aircraft from departure to arrival, the load of a crossing section gives an idea of the feasibility of the concept in terms of the acceptance of considerable traffic.

If the global number of conflicts gives a rough idea of the best values to use, it is important to understand how these conflicts are distributed. Not taken into consideration are :

- conflicts happening outside the TRN, while an aircraft is reaching or leaving the route network. They are considered as being handled by the approach air traffic control ;
- conflicts on a route going from a crossing section to another. These are only conflicts between overtaking aircraft. They are handled by the system (using speed regulation or parallel tracks).

Only conflicts happening within a crossing section are therefore considered valuable to this study.

Even if the number of crossings with conflicts may change with the different values used for the space between routes, there are about 20 of them (always the same) which have more than a hundred conflicts a day whatever the distance between two tracks. As shown in figure 12, for values between 10 and 30 kilometres, the number of crossings with conflicts and those crossings with more than 100 conflicts does not really depends on route spacing.

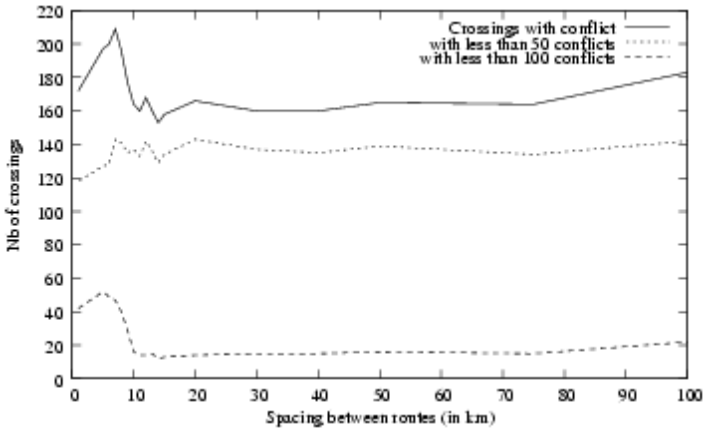

Figure 12: Conflicts in crossing sections

Geographically, the busiest crossing sections are mainly (see figure 13 which represents the number of conflicts per crossing with a 15 kilometre track space) over England, France, Belgium, the Netherlands and Germany. This include one over Spain and few over Italy. This finding was expected as these areas are some of the more crowded area in Europe (usually called the *core area*). Some other busy crossings are situated near the corner of the grid as the simulation approximation (an aeroplane reaches the grid on direct route from its departure) tends to group aeroplanes coming from or going to the rest of the world on few entry/exit points.

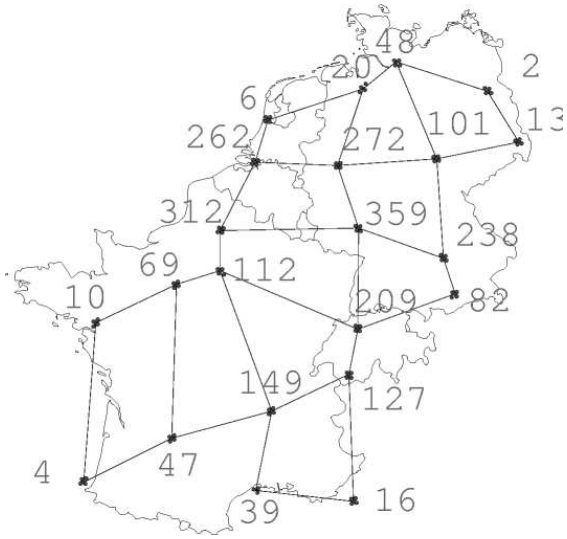

Figure 13 : Number of conflicts per crossing

Number of conflicts per crossing point per hour

According to values in figure 12, the ”best” value between two parallel routes is 15 kilometres. It is this value which will be used in this part. More specifically, four crossings will be considered in detail (see figure 13) :

- One to the west of Paris with 69 conflicts during the day and one over Paris with 112 conflicts. Smaller amounts of conflicts would not be interesting as their density throughout the day would not be sufficient. These two crossings are a good representation of sections which are not too overloaded ;

- One over the north of Switzerland with 209 conflicts and the last one over south-west Germany with 359 conflicts during the day. These two crossings provide good examples for the 20 ”heavy load” sections.

As the busiest crossing points are always the same, it is interesting to evaluate the amount of conflicts to be solved by air traffic controllers. Figure 14 shows when conflicts happen throughout the day for the four selected crossings. The first observation is that the number is mostly equal to 1, especially for those with few conflicts.

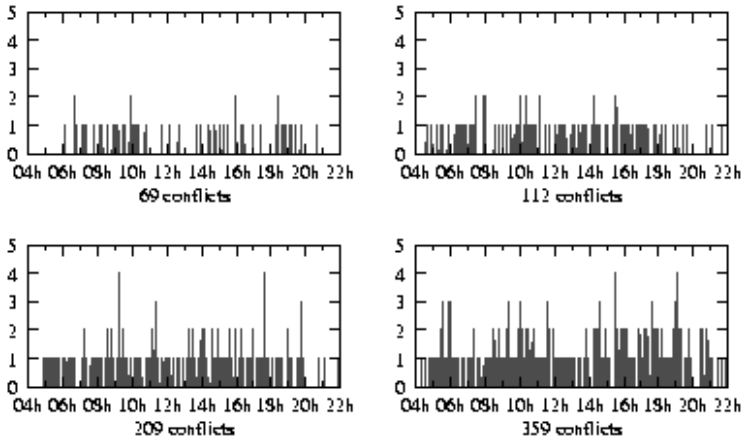

Figure 14: Number of instantaneous conflicts

If the number of conflicts give a rough idea of the work to be done, a better indication is the number of conflicts happening within a certain time. Figure 15 presents the result of this indication on the same four crossings as in figure 14 : the number of conflicts happening within 15 minutes. On the ”few conflict” crossings, the amount of expected conflicts is rarely higher than 5. This suggests show that such an amount of conflicts can be handled by controllers. For the ”lots of conflicts” crossings, the amount of conflicts to come can exceed 15 and is in any case regularly higher than 10.

As the main characteristic of the *Sector-Less* concept is the control of an aircraft from departure to arrival not within a geographical section (one crossing area) a conflict can either be between two aircraft controlled by the same person or by two different controllers. Thus several cases can occur :

1. The controller controls the two aircraft in conflict and these aircraft do not interfere with other aircraft or interfere with aeroplanes controlled by the same person. These sorts of conflicts can be handled without difficulty.
2. The controller controls only one of the two aircraft in conflict or the resolution of the conflict between two aeroplanes controlled by the same person interfere with planes controlled by another controller. The resolution implies a communication between controllers.

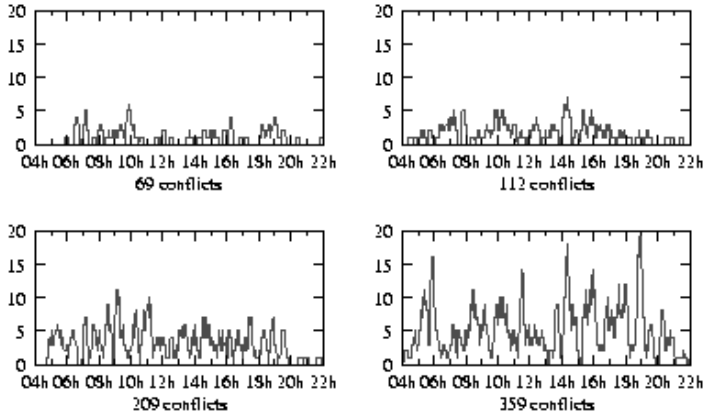

Figure 15: Number of conflicts within the next 15 minutes

Within the ”small” crossings, it is possible to say that the most frequent case will be the first one. Even if the second case occurred, it would probably involve no more than two controllers. Within the ”big” crossings, however, the second case would appear frequently. 10 expected conflicts within the next 15 minutes may imply 5 or more controllers to decide together how to solve the conflict. Of course, this seems impossible with the current equipment controllers use (e.g. voice, telephone).

The main problem in this evaluation is to know how many controllers would be working at the same time and need to interfere. As [2] does not give any details, only a real simulation with controllers could give a value usable to qualify a TRN. Surely, in the TRN presented, some of the most heavily loaded crossings would be impossible to deal with.

Conclusion and Work in Progress

From the route network generation process point of view, the first results are encouraging but a proper evaluation of a trunk route network proves difficult.

The generation process is in its early days and further work will be done. Some other optimisation algorithms such as genetic algorithm (see [7]) could be applied in order to generate the best TRN possible and better heuristics for the choice of the point to move could also be found. Finally, the number of turning points should be minimised.

The evaluation process is more difficult to deal with. Whatever is achieved, without a good idea of what the capacity of a controller would be within this concept, it is hard to say whether or not the traffic on a TRN could be handled by controllers. Even so it seems that some of the crossings are overloaded, especially if the aeroplanes in conflict are not controlled by the same person. Some feature should be added such as the avoidance of too many conflicts having secondary routes for certain point to point destinations or having different flight levels for different routes.

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Biography

Thomas Rivière is a 2nd year Ph.D. student in computer science at the Global Optimisation Laboratory of the French Air Navigation Studies Centre in Toulouse, France. He is currently working on the generation and the optimisation of a route network for the *Sector-Less* concept under the responsibility of Jean-Marc Alliot (CENA) and Vu Duong (EEC).