

## [EN-002] Designing 3D ATC Sectors by using a “Genetic Algorithm”-based methodology

(EIWAC 2010)

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**Abstract:** This paper is focused on the use of Genetic Algorithms for laying out Dynamic 3D ATC Sectors configurations. In 1999, the One Sky European Directive established the requirement of optimising the airspace structure no matter the existing political frontiers. Additionally, because the Air Traffic Control “world” is plenty of particularities e.g. each flight should enter in a sector only one time, each ATC sector is a continuous volume without internal gaps and the number of sectors as well as the maximum ATC workload per sector is as minimum as possible-, this task was traditionally performed manually and focused on a very limited airspace volume. For all these reasons, a GA-based methodology was developed with the aim of having a more objective, automated and extensive way of tackling this work, and to be aligned with the European Directive. Nowadays, this methodology plays an important role in the Airspace Management - Medium Term Planning Phase. It has been already successfully applied to propose a 3D ATC Sector configuration, composed by 70 sectors, optimising around 1200000 km<sup>2</sup> from Ground to FL460 (i.e 46000 feet or around 14000 metres).

**Keywords:** Genetic Algorithm, 3D sector design, airspace management.

### 1. INTRODUCTION

INECO, specifically the Air Navigation Systems Operation Directorate, is in charge of studies and research for improving both the design and management of the Spanish airspace.

Before explaining the mathematical logic, a brief and simplified explanation of some key aspects related to ATC workload. An airspace sector, with its intrinsic characteristics of traffic demand (e.g. 4D trajectory, aircraft performances, etc) and system capabilities (e.g. radar coverage, data-link, etc) is managed by two air traffic controllers: one executive and one planner. The planner one supports to the executive one by performing some tasks that do not imply to communicate with flight crew. For the time being, the planner workload is far of being a bottleneck in the system, for that reason the estimation of its workload is not performed. However, the executive controller is the responsible for safely managing the flights that use a specific ATC sector by performing complex and numerous tasks, most of them requiring to communicate with flight crew. The size and shape of an ATC sector, which may be composed by one or more air space volumes, must be decided by taking into account these tasks, and therefore the workload induced on ATC controller.

The ATC workload can be roughly classified in two fields:

1.- due to 4D flight trajectories existence (fix) and

2.- due to the sector frontiers existence (variable).

The first one, even though being the weightiest workload part, does not depend on how much good or bad the sectorisation is, and there is no room to decrease it. However, although sector design does not impact on this workload type, in vice versus, this workload impacts on the final sectorisation.

Regarding the second one, it can impact on the sectorisation and vice-versus, so it is a variable ATC workload.

Therefore, this GA should distribute equally the global (i.e. the addition of fix plus variable) ATC workload as well as minimise the variable one.

Each control sector is characterised with a capacity figure, whose objective is to protect controller against traffic overloads that would require him performing more tasks than recommended to manage safely flights under his/her responsibility. Neither overloaded sectors nor under loaded sectors is recommended. An ATC sectorisation is composed by sectors that are regrouped if traffic load is low enough.

Traffic flows (i.e. number of flights and planned 4D trajectories) change significantly along the day, depending on the different airline business preferences.

Peak hours, when the workload is higher than other ones, are selected to the design of the optimal ATC sectorisation. Nowadays, it is not feasible to change sector boundaries in real time, so it is assumed that optimal sectors designed to manage peak hours are not

so optimal for peak-off hours. During peak-off periods, there is less induced workload and therefore some sectors can be linked. This group of sectors is controlled by one executive controller.

The design process to obtain the group of sectors required for managing the traffic in a specific airspace volume is currently performed manually, supported by the expertise of controllers and some Fast Time Simulations tools assessments.

Today’s ATM System is very fragmented. It is caused by the fact, that each state has its own airspace which belongs to its national borders.

The new solution is an ambitious proposal from European Commission (1999 - Communication from the Commission to the council and the European parliament - The creation of the single European sky [COM(1999)614]) to reform the outdated architecture of European air traffic control. The project is called Single European Sky [1], and pretends to create one common upper-airspace. Airspace divided into sectors on the base of demands and workload, not on the geographical frontiers as it is in these days.

Aligned with that idea, this paper shows how a Genetic Algorithm, developed in 2000, can help to design 3D ATC sectors

## 2. MODEL

### 2.1 Introduction (about sector design)

Before doing the description of the developed Genetic Algorithm, it is necessary to briefly explain some simplifications, assumptions and decisions that were made as well as an introduction about some sector design constraints.

Firstly, an analysis on how the physical route network is flown concluded that there are many different types of aircrafts (e.g. climb/descent rates), different airline business models (e.g. fuel consumption) and different preferred Cruise Flight Levels. Therefore, it was decided to model 3D scenarios, to obtain an optimal trajectory-based sectorisation by meeting the wide-range behaviour of the traffic.

Nowadays, 5 months is, roughly, the period of time from a new sectorisation is decided until it is really implemented because safety assessments and controllers training, amongst other bureaucratic issues, are strictly mandatory. For that reason, it is not in the scope of this research to offer a real time solution to be implemented “on live”.

### 2.2 Mathematical formulation

#### 2.2.1 The airspace

It is patently obvious that the first item is to specify the 3D limits of the airspace volume to be optimised. Then, this fixed airspace is virtually divided into small cells. The size and shape of cells must be carefully assessed

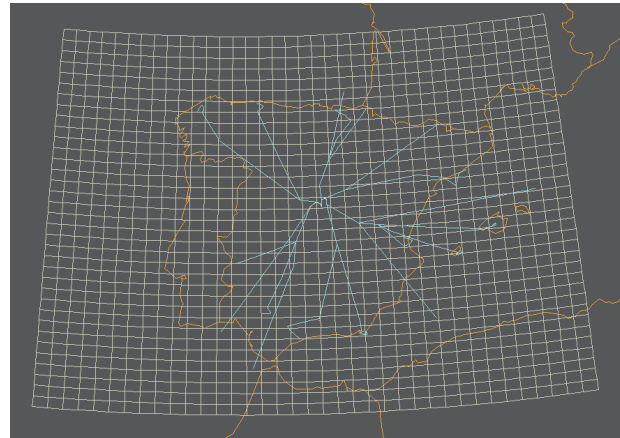


Figure 1 En-route studies - Rectangular cells

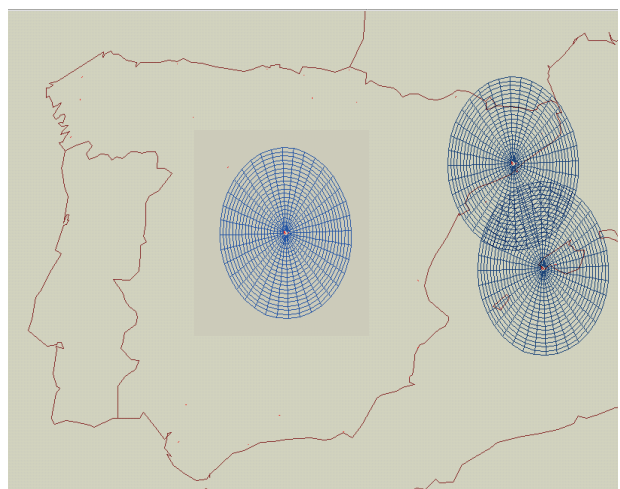


Figure 2 TMA studies – semi-annulus cells

because this decision impacts severely on the length of the chromosome and, therefore on the invested time to obtain the solution, and the ability of meeting some Operational Conditions (see 2.2.3).

“Fig. 1” For En-Route studies, the size goes from 10NM x 10 NM x 40FLs to 20NM x 20NM x 40FLs. The shape of cells is rectangular.

“Fig. 2” For TMA studies, the size is roughly of 5NM x 5NM x 40FLs. The shape of cells is a semi-annulus.

This paper is only focused on En-route researches.

The grid is defined by 3 parameters (X, Y, Z), in which X refers to the number of columns along the Longitudinal axe, Y refers to the number of rows along the Latitude axe and Z the number of vertical layers.

#### 2.2.2 Workload estimation

Although there are quantitative and psychological factors that contributes to the overall ATC workload. Within this method, only the quantitative ones are considered.

The parameters, taken into account to estimate the ATC workload, are the following ones:

- Flights entering into a sector
- Flights exiting from a sector

- Separation losses
- Flight duration

Both flight duration and separation losses induce an amount of workload that remains invariable independently of the layout of the ATC sector configuration.

However, the workload induced by flights being transferred from one sector to other one is directly linked to the 3D sectorisation layout.

2.2.3 Operational conditions

When building ATC sectors, there are some operational conditions that the genetic solution should comply with:

1.- An executive controller must not manage twice the same flight for safety and efficiency reasons. To guarantee that the genetic solution is fully aligned with this condition, it would have been easier by imposing convexity rules in the chromosome building [2]. However, to avoid missing possible solutions due to coding a too strong mathematical constraint, the number of double-entries is captured and then weighted in the fitness function (Fig 3).

2.- An executive controller, in order to safely manage a flight, requires having it under its control enough time (e.g. 2 minutes). So, the number of short-stays is captured and then weighted in the fitness function (Fig 4).

3.- A 3D ATC sector must be spatially continuous, without any disruptions and gaps. This constraint is imposed to the initial population and then, along each iteration, only those crossovers that do not break the continuity are allowed. In addition, each mutation was coded to avoid breaking that continuity (Fig 5).

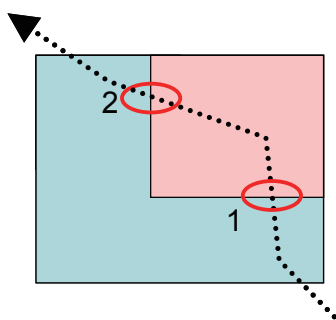


Figure 3 Example of a double-entry

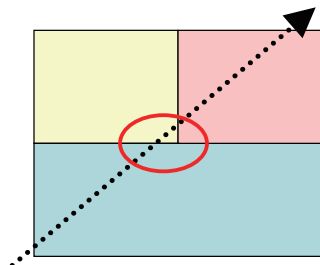


Figure 4 Example of a short-stay

A	A	A	A
A	B	B	B
A	C	A	A
A	C	C	C

Figure 5 Example of an ATC sector with disruptions



Figure 6 Example of a non-cylindrical ATC sector

4.- A 3D ATC sector will be as cylindrical as possible, easing its future operational validation and implementation. A lesson learnt, after many operational validations performed by ATCOs, suggests that non-cylindrical ATC sectors difficult controller-transfer-tasks and increase the probability of incident occurrence (Fig 6).

It is not included in the current GA the ability of rejecting solutions taking into account the ATC zoom constraint. In a controller working position, Air Traffic Controller selects the zoom of his/her Control Display depending on the minimum radar separation in order to manage traffic in a safe way. In those airspace volumes with a very low traffic demand and consequently low ATC workload, the ATC sector likely will result too wide to be adequately managed. This issue will be further addressed in future researches.

3. PRINCIPLE OF RESOLUTION

3.1 Complexity of our problem

The optimal “3D ATC sectors configuration” should come close to this target:

“To provide the optimal set of airspace volumes that allow configuring the minimum number of ATC sectors, without exceeding an admissible workload level to protect the ATC controller role, along every hour in a day meeting the changeable traffic demand.”

According to the size of our scenario (roughly 7000 cells), the combinatorial optimisation is discarded in favour of stochastic optimisation.

This problem may have many solutions than could be considered as optimal and all of them may have many similarities. Genetic Algorithms have been selected as relevant to generate the “3D ATC sectors configuration”, due to their parallelism. GA is travelling in a search space with more different individuals along iterations and they are less likely to get stuck in a local extreme

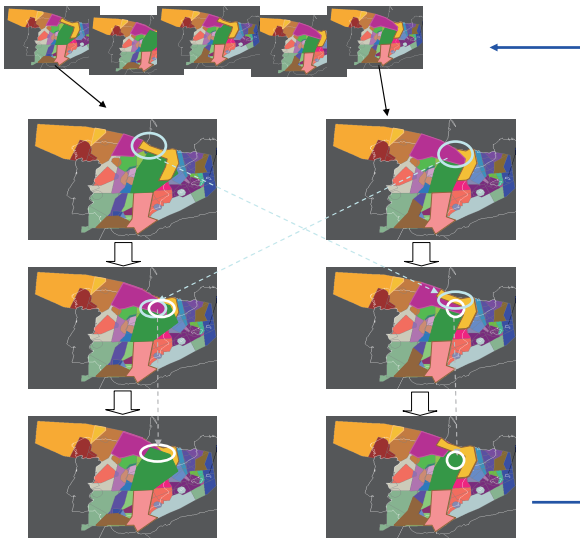


Figure 7 Application of Genetic Algorithm Process

like some other methods. GA leads to several “near optimal” solutions.

### 3.2 The final GA [3]

#### 3.2.1 Encoding

The chromosome is designed taking into account the necessity of the existence of fix limits (from now nodes) that will be used by the crossover process. So each chromosome will be composed of n parts (from now s-gene), where n is the number of sectors of the proposed solution. Each s-gene is composed of m parts (from now gene), that translates each 3D cell in a specific order.

Each gene, representing a specific 3D cell, virtually contains a lot of data referring to different ATC events that are required to estimate workload (see 2.2.2).

Additionally, current real sectorisations suggest some sectors are elongated, adapting to the greatest flows. This is the reason why it was considered relevant to try a different encoding-approach from the one used in other similar studies [2, 4].

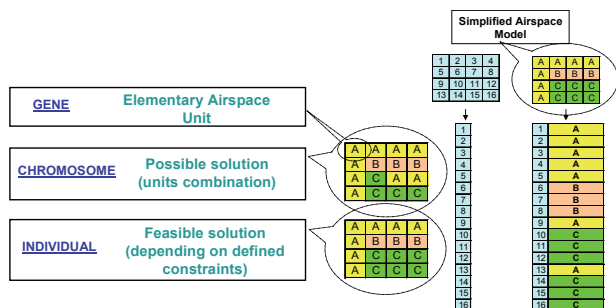


Figure 8 Encoding

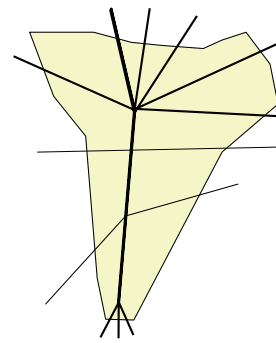


Figure 9 Elongated sector embracing main flows

All these data are obtained by using an ATM-focused Fast Time Simulation Tool called RAMS Plus. The outputs coming from this tool are post-processed by means of automated post-processing modules in order to obtain the required information in the specified format.

#### 3.2.2 Population

The size of the population (i.e. number of chromosomes) is decided taking into consideration the number of different type of mutations and the number of significantly different parallel threads to assure an enough wide search range and to avoid finding a “local extreme” For instance, in already performed assessments, around 200 chromosomes compose the initial population. The initial population is generated imposing that all chromosomes complies 100% with the operational condition number 3.- “A 3D ATC sector must be spatially continuous” in order to speed-up the automated solution finding. (See 2.2.3). Consequently, only crossover and mutation attempts that do not break the spatial continuity will be allowed.

#### 3.2.3 Selection: fitness function

The solution aims to comply with both target and operational conditions, so the following indicators were weighted by means of a fitness function:

- The 24 hour-workload per genetic-sector
- Number of double entries
- Number of short stays
- Number of non-cylindrical sectors

In this GA, in order to avoid losing the best chromosome within population when the iterative crossover and mutation processes are executed, the selection is “elitist”. 10% of chromosomes of each new population are the best found chromosome.

#### 3.2.4 Crossover

From each mother, a sector is selected to be exchanged with the corresponding father. This selected sector is not randomly selected but chosen between those sectors whose workload is close to the safe workload limit. In

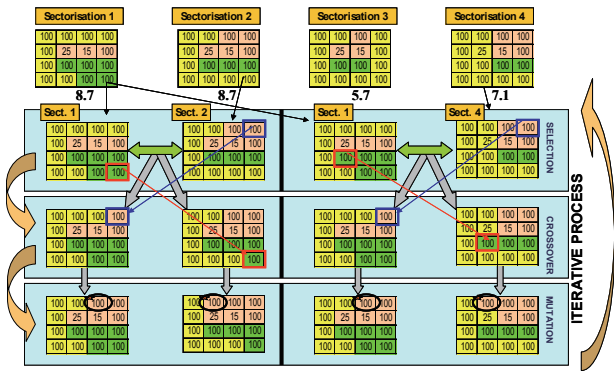


Figure 10 Genetic Algorithm Process

this way, a possible good sector is crossed with other different but good chromosome.

3.2.5 Mutation

One cell of the busiest sector (in workload terms) is removed and aggregated to a collateral sector. This oriented-mutation instead of a random mutation is designed to minimise the convergence time, because by removing airspace from a sector leads, with a higher probability, to a workload reduction.

3.2.6 Loop process

Initially, it is necessary to decide the number of sectors and therefore, the number of partitions to be generated in each chromosome. This initial number is estimated by looking for an over-sized figure. When the standard iterative GA process is finished, a new population is generated taking the previous loop-winner but subtracting one from the previous figure. Therefore, genes belonging to one random sector are allocated to a neighbour one. Finally, other loop can start. The necessity of performing more loops or not will depend on the calculated maximum sector workload at the end of the loop. If this maximum is too close to the admissible limit the loops can stop.

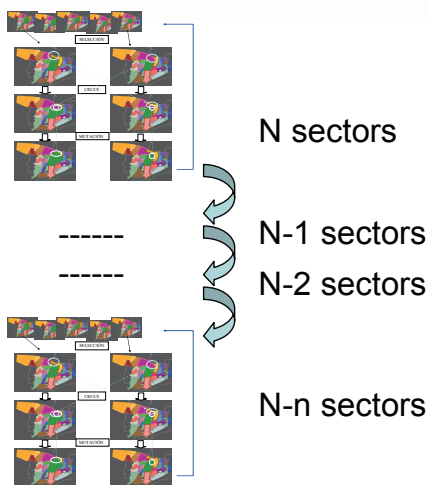


Figure 11 GA Loop

4. RESULTS

This algorithm is being used to perform many studies with the common objective of designing a new ATC sector structure. The size of the airspace volume goes from TMA (12500 NM2 and 24500 feet) to FIR (350000 NM2 and 46000 feet) resulting in from 12 sectors till 70 sectors.

Moreover, a continuous support to ANSPs is carried out by offering objective and alternative designs of ACC and TMA sectorisations complementing the ATS unit proposal ones.

After redesigning different type of scenarios and assessing the obtained results from an operational point of view, the main conclusion obtained was that the genetic solution was too optimal. The genetic sectorisation was too adapted to traffic flows and to descent/climb profiles and consequently many sectors was composed of too many air blocks with too many different FL limits.

For the time being, the sectors activated in the ATS Units are as simple as possible in terms of vertical limits. The operational rationale says that it is not easy to have a clear situational and responsibility awareness by controlling too many air blocks with different vertical limits.

For this reason, along the initial studies, the GA solution was manually simplified to be aligned with the ATC requirement by sacrificing the optimal solutions and by spending extra time to end the process. In other words, some parameters were included within the fitness function to allow that the GA solution was less optimal from the point of view of numeric results but much better from the operational one. It was achieved by weighting in a positive way those solutions with few different vertical limits.

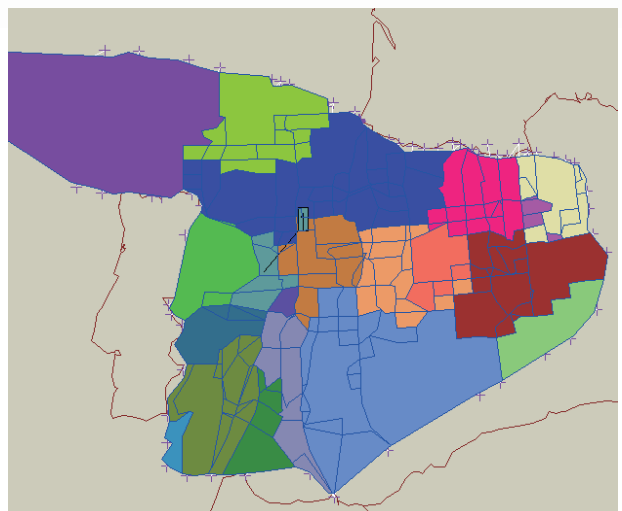


Figure 12 Sample of a pure Genetic 3D ATC Sectorisation



Figure 13 Sample of an operationally tuned-up Genetic 3D ATC Sectorisation

## 5. CONCLUSIONS

This GA is being exploited and it is a relevant and useful piece supporting the whole 3D ATC Sector Design process, by reducing the time and effort in generating different objective proposals that complement other ones coming from the ATS unit experts. These genetic proposals are later validated from the safety and operational point of view before being implemented in real world.

## 6. ACKNOWLEDGEMENTS

The success of this methodology would have not been possible without the non-accidental encouraging atmosphere that can be breathed in INECO. Although belonging to a consultancy company, where the always urgent and sometimes routine tasks must be carried

out, any individual innovative idea is well received and finds the adequate support from the heads.

## 7. REFERENCES

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