SUSTAINABLE AIR TRAFFIC MANAGEMENT SYSTEM DEVELOPMENT METHODOLOGY

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ABSTRACT

As it is defined in ATM 2000+ Strategy (Eurocontrol 2001), the mission of the Air Traffic Management (ATM) System is: “For all the phases of a flight, the ATM system should facilitate a **safe**, **efficient**, and **expedite** traffic flow, through the provision of adaptable ATM services that can be dimensioned in relation to the requirements of all the users and areas of the European air space. The ATM services should comply with the demand, be compatible, operate under uniform principles, respect the environment and satisfy the national security requirements.”

The objective of this paper is to present a methodology designed to evaluate the **status of the ATM system** in terms of the relationship between the offered capacity and traffic demand, identifying weakness areas and proposing solutions. The first part of the methodology relates to the characterization and evaluation of the current system, while a second part proposes an approach to analyze the possible development limit.

As part of the work, general criteria are established to define the framework in which the analysis and diagnostic methodology presented is placed. They are: the use of Air Traffic Control (ATC) sectors as analysis unit, the presence of network effects, the tactical focus, the relative character of the analysis, objectivity and a high level assessment that allows assumptions on the human and Communications, Navigation and Surveillance (CNS) elements, considered as the typical high density air traffic resources.

The steps followed by the methodology start with the definition of indicators and metrics, like the nominal criticality or the nominal efficiency of a sector; scenario characterization where the necessary data is collected; network effects analysis to study the relations among the constitutive elements of the ATC system; diagnostic by means of the “System Status Diagram”; analytical study of the ATC system development limit; and finally, formulation of conclusions and proposal for improvement.

This methodology was employed by Aena (Spanish Airports Manager and Air Navigation Service Provider) and INECO (Spanish Transport Engineering Company) in the analysis of the Spanish ATM System in the frame of the Spanish airspace capacity sustainability program, although it could be applied elsewhere.

KEY WORDS

ATM, ATC, Indicator, Performance, Sector, Capacity, Network

1. INTRODUCTION.

In 1999, one in every three flights in Europe was delayed. Although there were various reasons for this, half of the delays that occurred were attributed to ATM causes (Eurocontrol 1999b). Since then, mayor efforts have been devoted at European level to develop strategies and to settle processes "to provide sufficient capacity to accommodate the demand in typical hour periods, without imposing significant operational, economic or environmental penalties under normal circumstances".(Eurocontrol 2000a)

In particular a Capacity Planning process is coordinated at European level, based on a performance-driven approach, in the context of the European Convergence and Implementation Plan, which sets quantified and measurable performance targets to be achieved in the medium-term. Within this framework Eurocontrol Provisional Council agreed to established as objective an average ATFM en-route delay target of 1 minute per flight for Summer 2006 and beyond, 2.1 minutes including airport delay (Eurocontrol 2007c). As a prove of the good results of this kind of capacity management processes implemented at network level the actual average ATFM delay for the Summer 2006 was 2.2 minutes per flight, with the en-route average ATC delay 1.4 minutes per flight, in line with the delay forecast. (Eurocontrol 2007a).

Nevertheless generating extra capacity is a complex issue and involves change in a number of different but inter-related fields - infrastructure, airspace, operational procedures, staffing, rule-making, institutional arrangements, etc. This all takes time and extra capacity is quite expensive and cannot be conjured up overnight. (Dreyfuss 2007, Zografos 2001) .

In this context the determination of the current status of the ATM system in terms of the relationship between the offered capacity and the traffic demand becomes a crucial step into the capacity planning continuous process. The knowledge of the strengths and weakness of the system, in particular the identification of the most critical capacity deficits or bottle necks sectors (that can jeopardize and limit the potential capacity of the ATM system) and possible capacity surpluses (if any) becomes important. Actual knowledge of bottle necks, networks effects, sector improvement potentiality and possible development limit will help ATM service providers to propose solutions and to prioritize strategies in an optimum way.

Although the literature provides a broad number of methods related with capacity planning, no systematic performance-driven methodology is available for ATM service providers to evaluate the ATC system current status in order to take decision on how to use capacity surpluses to compensate identified deficits, and to prioritize ATC evolution strategies.

There are several methods to evaluate current ACC and sector group capacity. Highly remarkable are the ones knows as Reverse CASA, NEVAC, and ACCESS (Eurocontrol 2007b). These have been developed and improved over a number of years, but their suitability and effectiveness depends on whether or not the ACC being measured generates a significant amount of ATFM (Air Traffic Flow Management) delay. Additionally they require extensive iterative time consuming ATFM simulation, do not take into account network effects or can not measure offered capacity (only potential). This methodologies have been used in the overall coordination proceeds at European level but are not appropriate for the characterisation and optimisation of the status of an ATM Service Provider sectors network.

Others authors have tried different techniques and heuristics to build optimal sectors configurations considering the input traffic flows, the airspace capacity constrains and the maximum number of control position that can be manned at each time of the day (Gianazza 2002, Christien 2003, Flynn 2003, Verlhac 2005, Degtyarev). Nevertheless those methods are more oriented to the tactical schedule of the Air Traffic Control Center and only consider subset of possible ways to combine sectors. Those methods do not identify strengths and weakness of the systems and are not useful to make proposals on how to take advantage of possible capacity surpluses in order to compensate identified deficits. Additionally most of them do not take into consideration network effects.

On the other hand there are some authors that have concentrated their efforts on assessing the network effects having place between the ATC sectors (Soufian 2006, Manchon 2007a, Manchon 2007b). Nevertheless, up to this moment these works have only study the propagation of effects through the network of sectors, but none of them provide criteria or guidance on how to alleviate derived problems, how to assess the most critical element or how to identify development limit of a certain sector configuration.

Taken into account the previous considerations a clear place has been identified for a methodology specifically devoted to help Air Traffic Management Service Providers in the optimization of its own internal capacity management planning process.

2. OBJECTIVE AND SCOPE.

The objective of this paper is to present a methodology developed by the Technic University of Madrid supported by Aena (Spanish Air Traffic Service Provider) and INECO within the framework of the Spanish airspace capacity sustainability program. The methodology have been designed to evaluate the **status of the ATM system** in terms of the relationship between the offered capacity and traffic demand, identifying weakness areas and proposing solutions.

For accomplish this goal, the first part of the methodology involves the characterization of the current system. Such characterization is achieved by means of specific purpose oriented indicators and metrics and by the obtention of all the necessary data from the scenario.

The second part of the methodology is devoted to the evaluation and diagnosis of the system. The system evaluation is supported by the three following ad-hoc specifically developed tools:

- the analysis of the network effects and relations among the constitutive elements of the ATC system,
- the preparation of a “System Status Diagram” that represents the situation of each ATC constitutive element as a function of a combined analysis of their physical characteristics, the traffic nature and demand and their declared capacities, and
- the evaluation of the ATM system development limit without modifying the current operational concept.

All these steps will conclude with the formulation of conclusions, the development of a simplified CBA (Cost Benefit Analysis) and the proposal of solutions to the detected problems.

The methodology is integrated as a key element into the capacity strategic planning continuous process, which ultimate goal is to ensure that the capacity of the system is adapted to match the air traffic demand, well in advance. The capacity strategic plannign process considers that three main types of actions can be performed to accommodate the system capacity to an increasing demand (as indicated on figure 1)

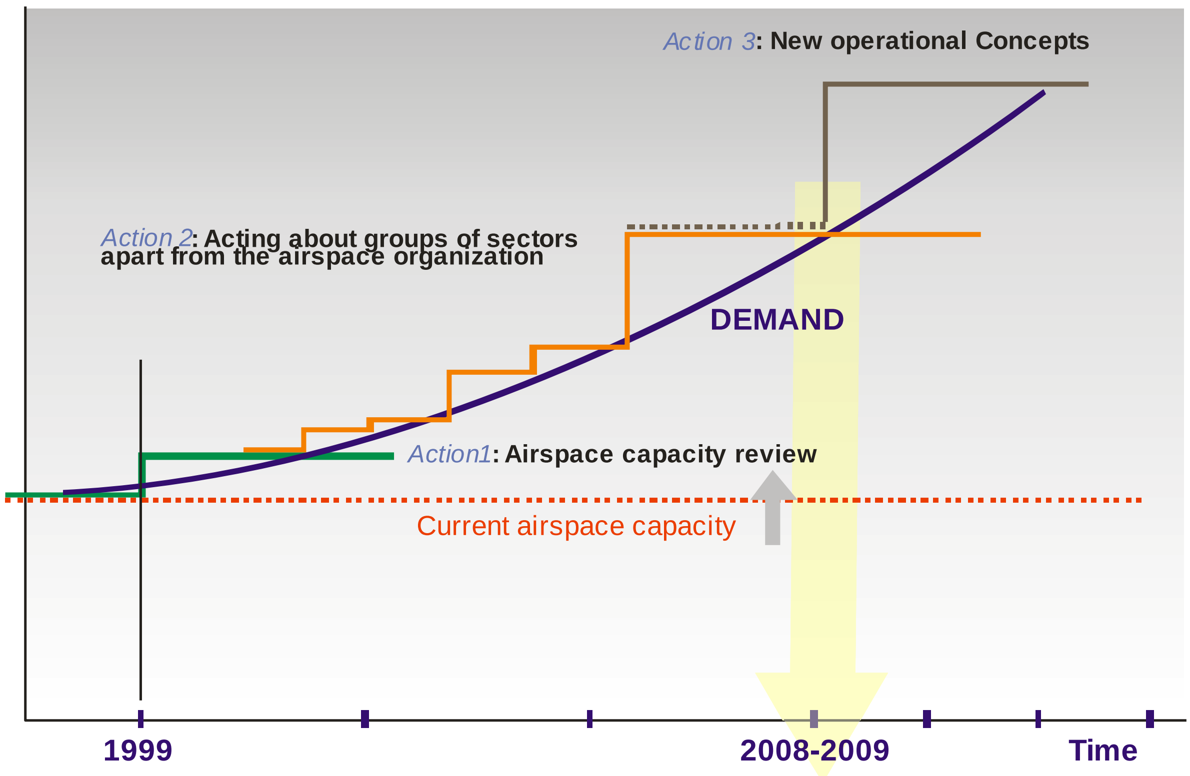


Figure 1. Actuations to adapt capacity to demand.

To develop this methodology, an analytical or inductive method was followed, where the data used and the assumed hypothesis play an essential role to obtain the results, avoiding specific evaluations that could bias the results towards subjective estimations. For the purpose of simplicity the analysis scenario presented in this paper is limited to the en-route ATC system. The figures and tables used as examples to describe the methodology correspond to part of the results of the Spanish Air Navigation Capacity Increasing program.

This methodology was developed taking into account previous work carried out across the aeronautical international community regarding this subject, in particular the FAP (Future ATM Profile) methodology developed by Eurocontrol to project ATM performance indicators into the future. Eurocontrol FAP methodology is just based on simulations, and the methodology presented here is purely analitical. Nvertheless, both methods are intended to identify and quantify capacity shortfalls of the ATM system in an anticipate way, so capacity management and associated decisions processes will progressively move from retro-active to pro-active by forecasting system performances. Also important were references from the PRC´s European ATM performance measurement system with respect to the definition of the performance metrics proposed to evaluate the “system status”.

2.1. General criteria considered in the methodological approach.

The present methodology is based on a set of general criteria presented below. These criteria are supported in the following assumptions that are related to the diagnostics procedure proposed for the short and medium term.

- **ATC Sector:** The analysis uses the ATC sector as the basic capacity reference and as the most elemental operational component of ATC (Eurocontrol 1999b). This election is based on the fact that the sector is the only ATC domain for which a system performance value in terms of capacity/hour has been specified quantitatively. Because ATC sector is selected as basic reference unit in this study the estimation of reliable sector capacity figures becomes a key issue for ATC status determination. The reduced number of methods used in the sector capacity estimation makes the capacity determination process quite homogeneous between the different countries, and facilitates the possible extension of the method proposed in this study to different countries. Figure 2 shows the route ATC sector in Spain for which the study was developed.

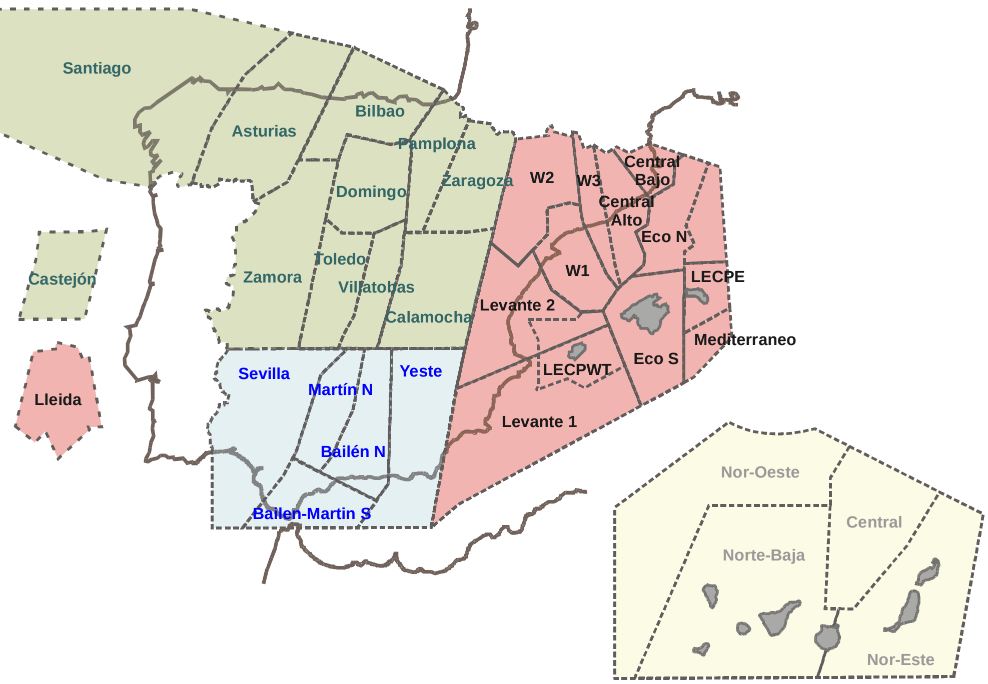


Figure 2. Route ATC Sectors in Spain

Network effect: The risk of taking the sector capacity as focal point of the analysis is to obtain a vision with little network perspective. Due to this, the vision of the ATC as a system should be systemic and developed to take into account the network effect that results from the distribution of the demand organized by traffic flows (Stein 1995, Alipio 2003,MIT 2008).

- **Tactical focus:** Methodology is focused onto the current ATC sector structure, thus limits the validity of the analysis results, in its current state, to the short and medium term. This diagnostic methodology would need re-engineering for its adaptation to longer term because it is generally accepted through the aeronautical international community that the modus operandi based on the classic ATC sector concept will not be compatible with the expected air traffic demand for that time frame. On future concepts, dynamically changing sectors are expected to balance demand and capacity and eventually reduce controller workload. New techniques will be required for restructuring sectors to accommodate fluctuating demand, such as those envisaged on (Kicinger 1998, Pawlak 1998, Min Xue 2008, Mitchell 2008, Brinton 2009). Once these techniques have been consolidated revision of the proposed methodology would be possible.

- **Relative character:** The lack of a consolidated capacity reference model has led to the need of performing the analysis in relative terms, that is, based on the comparison of the behavior of the different ATC sectors analyzed (Majumdar 2009). This deliberate relativity is a conceptual need if the results are to have effective value and not be so vulnerable to ‘double nature’ criticism.

- **Objectivity:** To avoid controversy, the previous relativity is complemented by a balanced view of the different topics used to qualify the sectors performance. That is, once the initial hypotheses are formulated, the application of the analysis methodology will obtain the results without incorporating any particular judgment. In this way, the results can only be argued as far as the initial hypotheses or the method can be adequate, moving the argument from the specific casuistic to the theoretical plane of the definitions.
- **Exclusion**: This criterion is used to fix the conditions of the analysis. The objective is to attain the asepsis of the method, in this sense two major assumptions are made: a “standard” CNS component for high density traffic ATC system is available, and the human component is qualified to perform the control of this CNS scenario. In other words, the methodology does not need to take into account the human or the CNS components.

2.2. Methodology steps.

The methodology presented in this paper is based on the characterization of the ATC system following the criteria established above. The method proposed is based on a top-down deductive process, which ends with the diagnostic of the system and the proposal of possible specific solutions to the detected problems.

The steps to be followed are briefly described below, although they are explained in further detail in the upcoming sections.

- Definition of system performance indicators: Definition of the **metrics** that would allow modeling the behavior of the system and, in this way, to measure and evaluate the features decided to be representative of its status.
- Scenario characterization: The process to obtain all the necessary **data** corresponding to the scenario, which can be measured as a function of the indicators defined earlier.
- Network effects analysis: Identification and quantification of the **relations** among the system elements.
- Diagnostic: Preparation of the **System status diagram** and evaluation of the ATM system development limit without modifying the current operational concept.
- Conclusions: Formulation of **conclusions**, simplified CBA and proposal of solutions.

3. DEFINITION OF PERFORMANCE INDICATORS.

Two different levels are taken into account to develop a definition of the system performance indicators. The lower level, System Status, deals with the system simplest components, the sectors, while the higher level, deals with relations among those elements.

3.1. System Status

The indicators based on the System Status are established as a function between the actual performance of the ATM system (Capacity) and the demanded services (Air traffic). They are expressed in quantitative terms related to the number of movements. It was decided not to use standard performance indicators, as defined in (Eurocontrol 2000b), due to practical difficulties in application from available air traffic and sector characterization data and due to its lack of capacity to reflect, with simple formulation, the fundamental aspects of the ATC system in this study.

Two different aspects that characterize the System Status are considered: the criticality and the efficiency, which would define the demand versus capacity and the operating ‘complexity’ of the different sectors. To evaluate the nominal criticality and efficiency, which are the actual quantitative factors to be used in the diagnostics, they are subdivided into measurable magnitudes.

3.1.2. Criticality

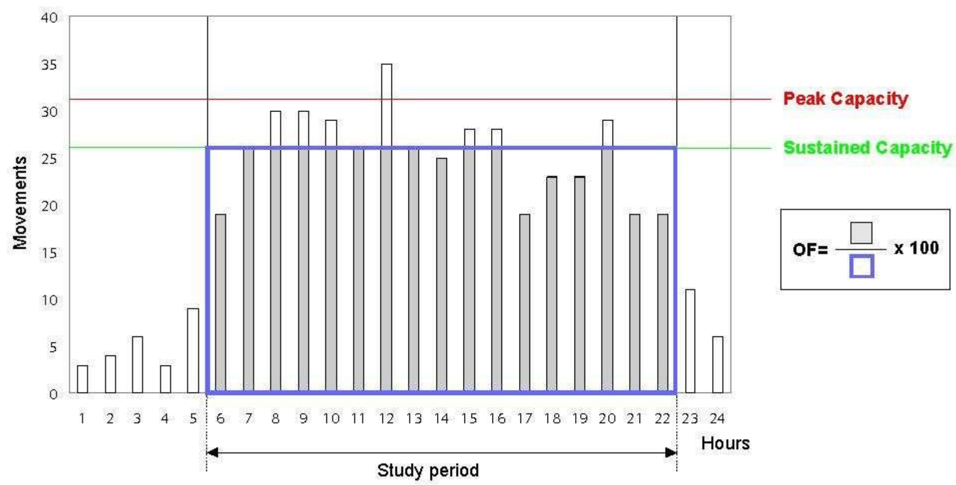
The Criticality, in a qualitative formulation, provides the idea of the relationship between the air traffic demand and the ATC capacity of a given sector (Scott 1998) .

To express the Criticality in quantitative terms, the following “Capacities” are defined:

- Declared Sustained Capacity: Maximum number of movements per time unit (hour) that a sector is capable to manage in normal operational conditions.
- Declared Peak Capacity: Maximum number of movements per time unit (hour) that a sector is capable to manage (occasionally) without compromising the safety levels.
- Residual Capacity: Difference between the peak and the sustained capacity, multiplied by the number of hours of the time period.

Then, three factors are defined to characterize the relation between the traffic demand and the sector capacity.

- Occupation Factor: Percentage relation between the number of movements that do not exceed the declared sustained capacity of the sector and the total capacity of the sector (related to a period of time). See figure 3.



-Figure 3. Occupation Factor

- Overflow Factor: Percentage relation between the number of movements that exceeding the declared sustained capacity of a sector and do not exceed its declared peak capacity, over the residual capacity of the sector (related to a period of time). See figure 4.

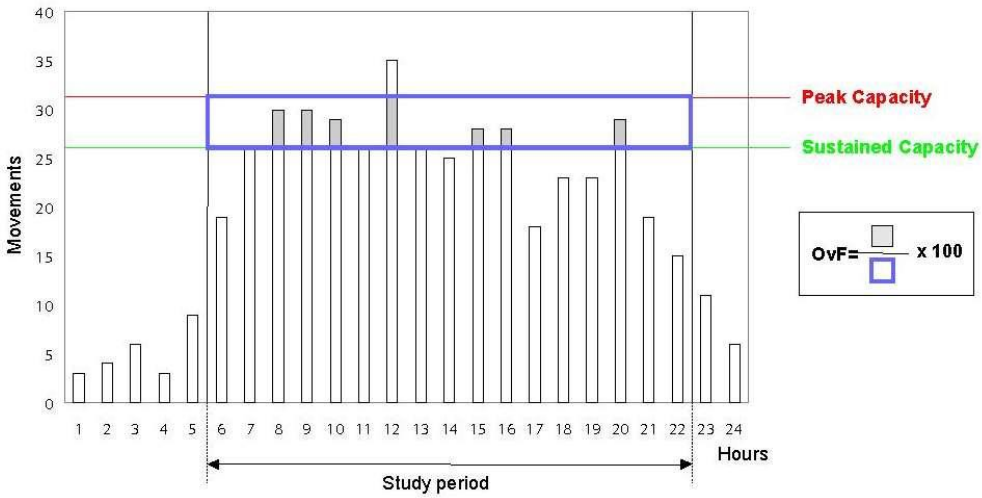


Figure 4. Overflow Factor

- Saturation Factor: Number of movements that exceed the sector's peak capacity in a time period, multiplied by the relative saturation frequency (relation between the number of hours in which saturation exists and the total number of hours of the period). See figure 5.

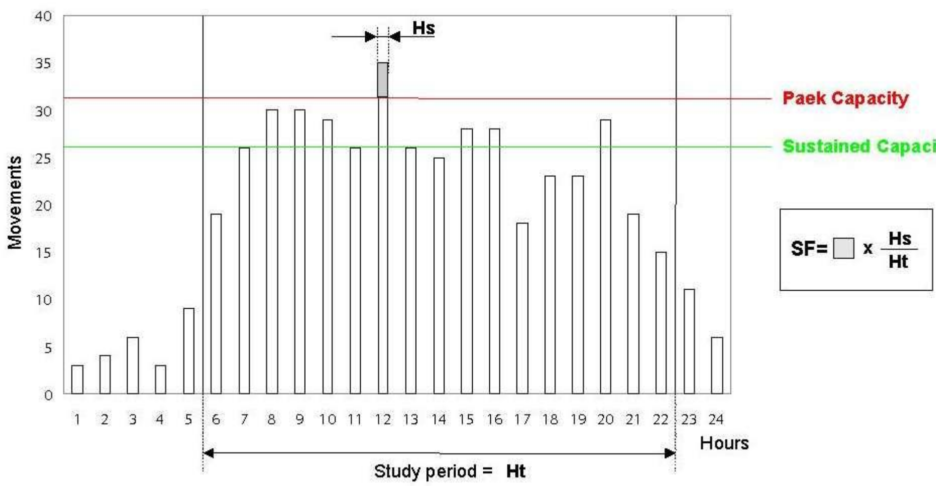


Figure 5. Saturation Factor

A sector is considered to be in **critical status** when, for a specific time interval (of several hours), it presents a traffic demand grater that its declared peak capacity; that is, a sector with **Saturation Factor** greater than zero. A priori, those sectors with **Occupation Factor** equal to 100% are also considered critical.

To establish a prioritization order, it is considered that for two sectors with equal Saturation Factor, the one with higher Occupation Factor shall be considered more critical. Furthermore, in the case that both factors are equal, the sector with greater Overflow Factor shall be considered more critical.

The actual quantitative indicator that shall be employed in the analysis is the so called **Nominal Criticality**, which is computed for every ATC sector**.** In order to have a quantitative value for Nominal Criticality, it is defined as the sum of the **Saturation Factor** and the **Occupation Factor**, weighed by 1.2 and 0.8 respectively (having into account the previously established prioritization order).

$$C = 1.2SF + 0.8OF$$

where:

C: Criticality

SF: Saturation factor

OF: Occupation factor

Table 1 shows the values of the previously defined indicators for the route ATC sector subject to study, considering a representative medium traffic day.

SECTOR	Criticality	Occupation Factor	Saturation Factor
Central Barcelona	**19.88**	9.8	10.0
Oeste Barcelona	**19.20**	10.0	9.4
Mediterráneo	**10.07**	9.5	2.6
Santiago	**9.16**	9.0	2.2
Zamora	**8.84**	8.4	2.3
Levante	**8.82**	8.7	2.1
Maella	**8.01**	8.8	1.4
Eco	**7.57**	7.8	1.6
Bilbao	**7.32**	8.0	1.3
Toledo	**6.87**	7.6	1.2
Pamplona	**6.77**	7.5	1.2
Domingo	**6.70**	7.4	1.2
Bailén	**6.65**	7.4	1.1
Villatobas	**4.52**	4.6	1.0
Castejón	**4.23**	4.2	1.0
Lleida	**4.19**	4.1	1.0
Zaragoza	**4.14**	4.1	1.0
Sevilla	**3.81**	3.6	1.0
Nor-Este Canarias	**3.79**	3.5	1.0
Martín	**3.55**	3.2	1.0
Yeste	**2.85**	2.2	1.0
Nor-Oeste Canarias	**2.80**	2.1	1.0
Central Canarias	**2.31**	1.4	1.0
Calamocha	**2.00**	1.0	1.0

Table 1. Critial sectors (medium traffic day).

3.1.3. Efficiency

The Efficiency, in qualitative formulation, allows performing a **preliminary evaluation of the declared capacities** of the sectors, comparing the declared capacity with the capacity that could be expected taking into account several intrinsic (structural) features that can represent, in principle, the complexity of the sector.

These structural features are defined as follows:

- Co laterality: Number of sectors adjacent to a given sector that have interrelation by principal air traffic flow.
- Traffic Mix: Proportion between traffic in evolution and established traffic.

- Mean Flight Time: Statistic value that gives the mean time that a flight remains inside the sector.

Based on the previous definitions an efficiency indicator is defined, called **Declared Nominal Efficiency**, which is the sum of the **Declared Sustained Capacity** (scaled to a certain value of reference: i.e. 20 "points") plus the sum of the **Co laterality**, **Traffic Mix** and **Mean Flight Time** (also scaled to "20"), weighed by factors 0.2, 0.5 and 0.3 respectively (consensus figures, after project internal Air Traffic Controllers discussions).

$$DNE = DSCap + (0.2Col + 0.5TM + 0.3MFT)$$

where:

DSCap: Declared Sustained Capacity (scaled)

Col: Co laterality

TM: Traffic Mix

MFT: Mean Flight Time

Table 2 presents the values of the previous indicators considering the route ATC sectors subject to study.

SECTOR	END	DSCap	0.5 Ma + 0.2Col + 0.3 MFT	Col	TM	MFT
Castejón	**15.08**	8.1	7.0	6.6	10.0	2.3
Toledo	**14.36**	8.1	6.3	8.9	7.8	2.0
Domingo	**14.31**	8.7	5.6	6.6	6.3	3.8
Villatobas	**12.75**	10.0	2.8	4.4	2.5	2.1
Nor-Este Canarias	**12.36**	4.2	8.1	2.1	9.4	10.0
Eco	**12.15**	6.8	5.4	5.5	6.6	3.2
Levante	**12.05**	4.9	7.2	10.0	8.1	3.8
Central Barcelona	**11.35**	4.9	6.5	8.9	7.9	2.5
Nor-Oeste Canarias	**11.29**	4.2	7.1	2.1	9.0	7.2
Calamocha	**10.93**	8.1	2.9	4.4	1.8	3.5
Bailén	**10.37**	4.2	6.2	3.3	8.1	4.8
Zaragoza	**9.97**	8.1	1.9	1.0	1.7	2.9
Pamplona	**9.94**	8.1	1.9	2.1	1.0	3.1
Oeste Barcelona	**9.13**	4.2	4.9	5.5	6.4	2.0
Mediterráneo	**8.99**	4.9	4.1	5.5	4.6	2.5
Martín	**8.92**	4.2	4.7	2.1	6.7	3.1
Sevilla	**8.86**	4.2	4.6	1.0	6.0	4.9
Bilbao	**8.34**	4.9	3.5	5.5	2.7	3.5
Zamora	**8.25**	4.9	3.4	3.3	2.9	4.3
Lleida	**8.01**	2.3	5.7	2.1	10.0	1.0
Yeste	**7.70**	2.9	4.8	1.0	5.7	5.8
Maella	**7.18**	2.3	4.9	2.1	7.2	2.9
Central Canarias	**7.05**	1.0	6.1	1.0	8.9	4.7
Santiago	**6.80**	2.3	4.5	3.3	2.5	8.7

Table 2. Declared Nominal Efficiency.

3.2. Relationship between sectors

ATM is a complex system composed of (depending on the selected approach) a large number of elements (in this case, ATC sectors) strongly related to each other (Sridhar 1998). With the goal of evaluating **network effects**, that is, the impact that the status and actions on a sector may have on the rest of the system, an indicator is defined to identify the relations among the different elements of the system and their “intensity”.

The related effects among the ATC sectors are based on the nature of air traffic demand, through the ‘main traffic flows’ of the system. They are defined as the aggregation of the main flows of each sector, which in turn are those flows that represent, at least, say 80% of the number of movements/day in the sector. Figure 6 presents the main traffic flows passing trough the on route sectors.

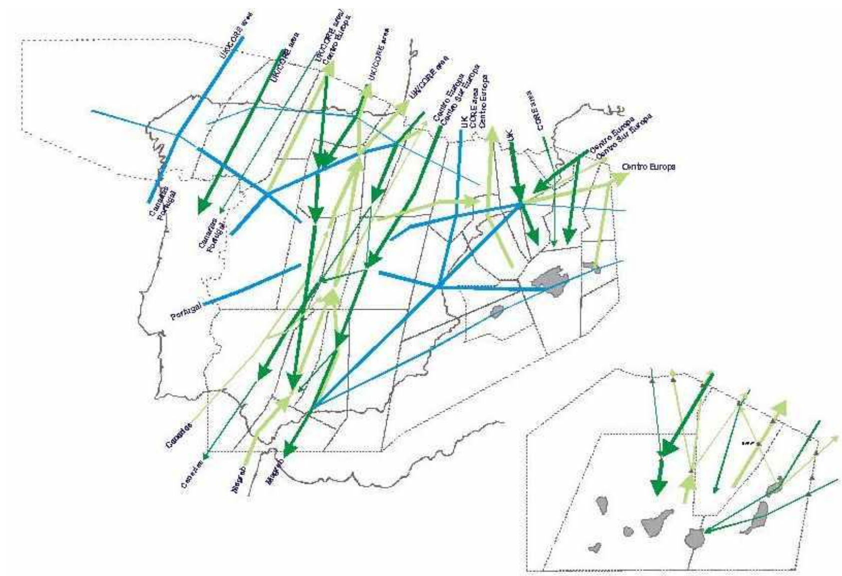


Figure 6. Identification of main traffic flows

The quantitative indicator, **Traffic Shared Between Sectors**, is defined as the number of aircraft per day that cross any pair of ATC sectors (all the combinations), independently of the fact that the sectors were or not collateral.

Figure 7 illustrates the high of low interaction between sectors, depending on the number of traffic shared according to the following color code:

White: 0-60 movementes/day

Grey : 60-120 movements/day

Blue: 120-180 movements/day

Red: 180-240 movements/day

Violet: >240 movements/day

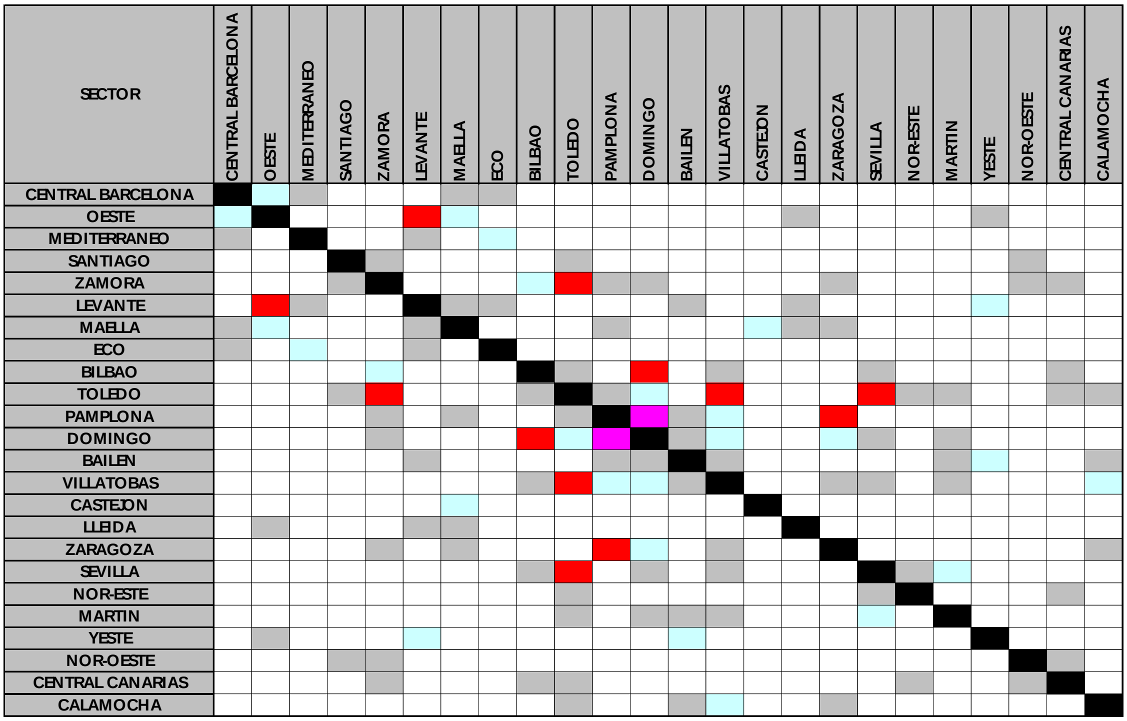


Figure 7. Interaction between sectors.

4. ANALYSIS OF NETWORK EFFECTS.

With the purpose of obtaining an overall vision of the degree of interdependence among sectors, the proposed tool is to represent the sectors in a two-entry table ordering them by their nominal criticality (see Figure 8). The result is a matrix symmetrical with respect to the main diagonal (top left corner, bottom right corner).

The criterion to group the sectors is that between them there is an exchange of movements greater than the value corresponding to the percentile 50 of the distribution.

In this way, several types of sector groupings can be found:

- Critical Sectors Grouping: Set of related sectors that are not able to cope adequately with the air traffic demand in their airspace. Due to this, they need “urgent” actions related with the improvement/optimization of their capacity, either individually or in-group.
- Non Critical Sectors Grouping: Set of related sectors that have enough capacity to efficiently cope with the air traffic demand in their airspace.
- Critical and ‘Support’ Sectors Grouping: Set of related sectors where sectors that are not able to cope adequately with the air traffic demand (critical sectors) coexist with other sectors that, in general terms, are still able to provide ATC service to a greater number of aircraft in their airspace (support sectors).

Figure 8 shows an example of Network Effect Analysis performed onto ATC sectors in Spain.

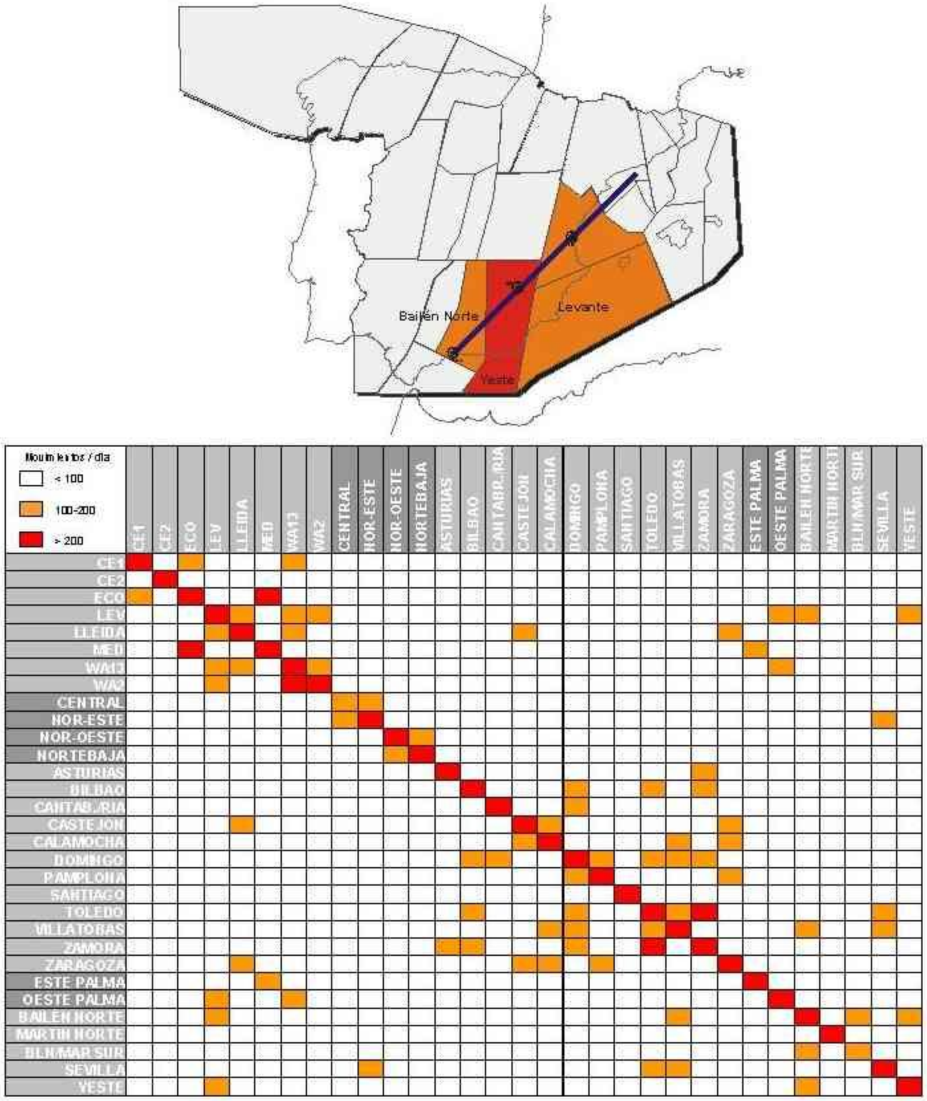


Figure 8. Analysis of Network Effects

5. DIAGNOSIS: STATUS DIAGRAM.

The Relative Status Diagram represents the situation of each sector respect from the collectivity as a function of a combined analysis of their physical characteristics, the traffic nature and demand and their declared capacities.

The Y-coordinate locates the sector according to its nominal criticality (as it is defined above and scaled to a certain value of reference) which informs of the degree of agreement between the traffic and the declared capacity of the sector.

On the other hand, X-coordinate reflects its declared nominal efficiency (as defined above), providing information about the relation between the declared capacity and the 'complexity' of the sector.

Therefore, the position of a sector in the diagram and related to the position of the other sectors, indicates the degree of relative equilibrium (comparative analysis) between its "demand/capacity" and its "performance/stress".

As this is a relative diagram, once the different sectors are represented, we would use the sector "*best in its class*" as a reference for comparison. This sector would be the one with highest efficiency and "good level of criticality". Assuming the technical means and the qualification of the personnel in all the sectors are the same, it is possible to conclude that all of them could operate as well as the best one. In this way, we define another parameter, **elasticity**, which gives the idea of the possibility for improving the performance of the sector.

Figure 9 shows a status diagram and its graphical interpretation.

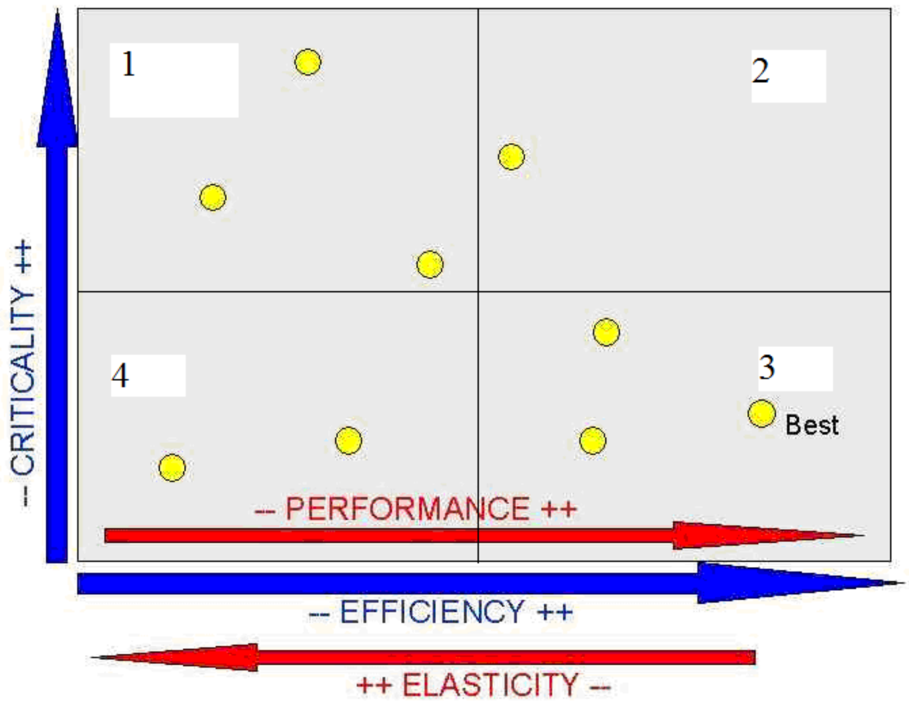


Figure 9. Status diagram. Interpretation

If the diagram includes two lines representing the medians (X and Y) for the values, the diagram is divided into four quadrants that can be interpreted as follows:

1. The top-left quadrant contains sectors with high criticality, low efficiency and high elasticity. These sectors have problems shown in the high criticality. To solve them, they require, comparatively, modifications with greater emphasis in the revision of their declared capacity than on redesign.
2. The top-right quadrant contains sectors with high criticality, high efficiency and low elasticity. These sectors also have problems, but have low margin to increase declared capacity as shown in their low elasticity. To solve them, they require, comparatively, modifications with greater emphasis on redesign than in the revision of their declared capacity.
3. The bottom-left quadrant contains sectors with low criticality, low efficiency and high elasticity. These sectors are underused, comparatively, and their resources are being wasted.
4. The bottom-right quadrant contains sectors with low criticality, high efficiency and low elasticity. These sectors, comparatively, are operating adequately.

This first level analysis allows diagnosing at a glance the ATC sectors and their improvement needs/possibilities. Figure 10 shows graphically these quadrants.

To move the analysis a step further and entering into the realm of future improvements and "what-if", taking into account the statement mentioned above that all the sectors are "similar", we would modify the declared capacity of all the sectors to obtain for each of them the declared nominal efficiency of the "*best in the class*". In this way, the values for criticality are thus modified, so a new ordering in terms of criticality revised by efficiency considerations is obtained. This ordering is shown in a blue line in Figure 10.

Figure 10 shows an example Status Diagram developed for the actual study of the Spanish ATC system mentioned above. A projection taking into account the expected traffic increase for the year of analysis is also included as a red bar in the right hand side.

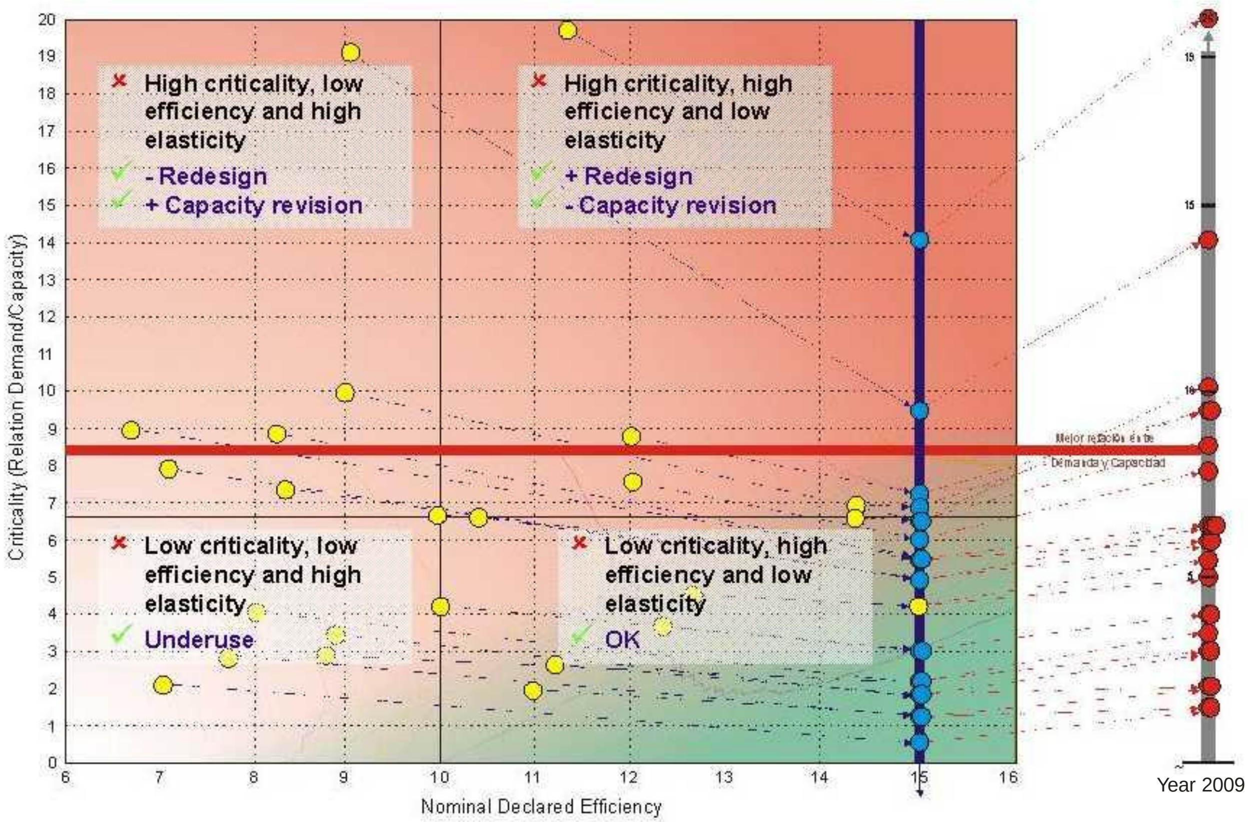


Figure 10. System Status Diagram

6. ATC SYSTEM DEVELOPMENT LIMIT.

The diagnose methodology presented above is applicable for the current status evaluation and for short to medium term measures, but if we want to consider longer term analyses, it is important to take into account the widely accepted fact (Erzberger 2002) that the classical ATC sector concept could not cope with the expected air traffic demand for that time frame.

An analytical method to evaluate the ATC system development proposed methodology time limit is defined. This methodology establishes the number of ATC sectors needed to cope with the traffic growth, assuming the same operational scenario. The following magnitudes are defined for this purpose:

- Number of Aircraft Simultaneously in a sector (NAS): It is defined as the mean flight time (MFT) in the sector (expressed in hours) multiplied by the average Hourly Demand (HD) in the sector (in the considered time period) expressed in movements/hour.

$$NAS = MFT \times HD \qquad (1)$$

- Number of Aircraft Simultaneously in ACC (NAS ACC): It is obtained as the sum of the NAS of the different sectors of the ACC (NASi).

$$NAS\ ACC = \sum NASi$$

The initial hypothesis is based on statistical studies developed by EUROCONTROL (FAP) (Eurocontrol 1999a) corresponding to the ECAC area that show that in ACC's with more than 600 movements per day, a correlation of 92% exists between the Volume of the sector (Vs) and the mean flight time (MFT) in it. (The 5 ACC's corresponding to the Spanish airspace fulfills, in average, this over 600 daily movement condition).

The relation between these two parameters is as follows:

$$MFT = K \times Vs^{0.31} \quad where\, K = 0.26 \qquad (2)$$

From expression (1) and (2) we can conclude:

$$NAS = HD \times K \times Vs^{0.31}$$

If we assume that the average hourly demand in a sector (HD) is constant, then:

$$NAS = K' \times Vs^{0.31} \quad where\, K' = constant$$

Moreover, if we assume that the order of magnitude of the volume of the sectors of the same ACC is similar, that is, Vs=constant, and if we define Ns as the number of sectors of an ACC, then:

$$NAS\ ACC = K' \times Vs^{0.31} \times Ns$$

This last expression provides a direct relation between the number of sectors of an ACC with the number of aircraft simultaneously in it, for a fixed time instant. The relation between NAS ACC and Ns in two different time instants 1 and 2 is:

$$\frac{NAS\ ACC2}{NAS\ ACC1} = \frac{K' \times {Vs_2}^{0.31} \times Ns2}{K' \times {Vs_1}^{0.31} \times Ns1} \qquad (3)$$

As the volume of the ACC is constant, we find that the relation between the number of sectors of an ACC and their respective volume are in inverse ratio:

$$\frac{Ns2}{Ns1} = \frac{Vs1}{Vs2} \qquad (4)$$

Finally, the combination of expressions (3) and (4) provide the analytic expression that allows calculating the increment in number of sectors of an ACC between two time instants if the air traffic demand (NAS) in those times is known:

$$Ns2 = Ns1 \times \left(\frac{NAS\ ACC2}{NAS\ ACC1} \right)^{\frac{1}{0.69}}$$

The figure 11 shows an example of this analytical calculation for the 5 Spanish ACC that cope with upper airspace:

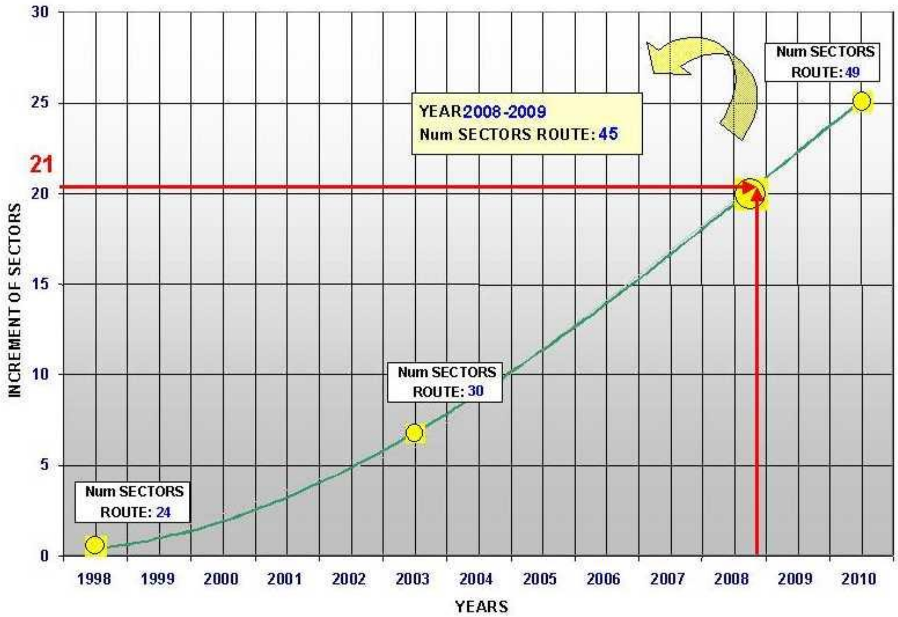


Figure 11. Increment of sectors. Example

The theoretical result concludes that for the planned traffic growth, made in 1998, the obtained time evolution of the number of ATC route sectors is close to the actual figures for the 1998-2006 time frame.

Partial results for this study were presented in (Negrete 2003, Gomez 2006).

7. CONCLUSIONS

The analysis and subsequent diagnostic methodology, developed for the en route ATC sectors, described above allow to perform the following assessments :

- Identification of weaknesses and strengths of the ATC system elements in the short and medium term (using the so called Nominal Criticality).
- Evaluation and quantification the nature of the weaknesses, leading to the identification of possible solutions in terms of redesign or revision of capacity (using proposed Status Diagram).
- Identification of the relations among the system elements (sector grouping) and evaluation of common action possibilities (using proposed Network Effects Analysis).
- Identification of the current ATM system development limit without changing the operational concept (by mean of proposed formulation of the ATC system development limit).

In further steps the author will research on the possibilities to extent the current method to future operational conepts where dynamically changing sectors are expected to balance demand and capacity and eventually reduce controller workload and new techniques will be required for restructuring sectors to accommodate fluctuating demand.

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