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MODELLING, GENERATING AND EVALUATING SECTOR CONFIGURATION PLANS - METHODOLOGY REPORT OF THE SESAR VP-755 EXERCISE

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Abstract

One of the objectives of the European SESAR program, which aims at generalizing and harmonizing ATM solutions at the European level, is to improve the current process of building airspace configurations, with more dynamicity, notably through a higher granularity of the elementary airspace building blocks used to form control sectors. We present here the methodologies and tools of the SESAR 07.05.04 VP-755 exercise, which consisted in a performance assessment of sector configuration plans based on this new paradigm. Optimization and simulation techniques supporting the generation and the evaluation of these sector configuration plans are presented, together with decision support tools developed to facilitate Flow Management Position's tasks.

1 General Introduction

The European airspace is currently controlled by Air Traffic Management units called Area Control Centers (ACC), in charge of providing air traffic control services to controlled flights within their area of jurisdiction.
European Area Control Centers (ACCs) are subdivided into volumes of airspace called elementary sectors that can be combined to form air traffic *control sectors*. This subdivision of the ACC into control sectors varies throughout the day, depending on the incoming traffic and the number of available controllers. At any moment, we call *configuration* the set of control sectors deployed to ensure the ACC's role. For instance, Fig. 1 shows one of the possible configurations with five control sectors deployed in the French ACC of Reims.

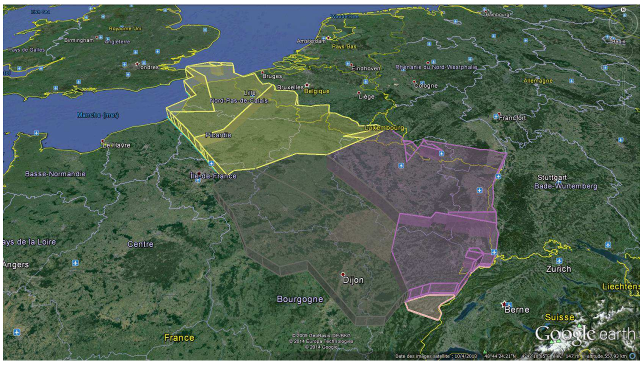

Fig. 1. Reims airspace configuration in 5 control sectors.

The Flow Management Position (FMP), in charge of building these airspace configurations, compares predicted flight counts with sector capacities to assess the different airspace configurations available in its database and manually choose the best configuration for each time period of the day. We call *sector configuration plan* (or opening scheme), of a given ACC for a given day, the description of these different configurations throughout the day.
In order to adapt the airspace configurations to the traffic situation, sectors are typically split when controllers' workload increases and merged when it decreases. In case of hotspot (overloaded area), the sector is split in two control sectors, to share the ATC workload and resolve the demand and capacity imbalance, as illustrated by Fig. 2.

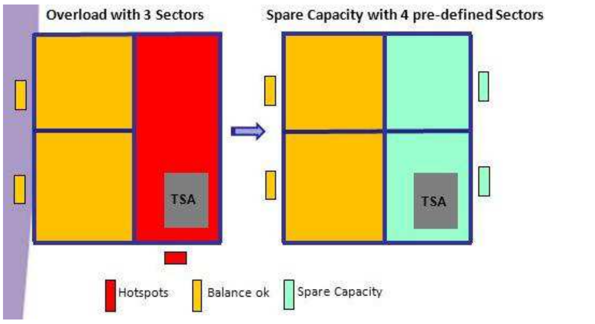

Fig. 2. Hotspot resolution by splitting one overloaded control sector (one additional sector).

If this process allows to build and modify dynamically sector configuration plans, some limitations remain:

- Hotspot resolution systematically requires to increase the number of control positions;
- Some hotspots remain at the level of elementary sectors that cannot be split;
- Only a small subset of predefined configurations is considered instead of exploring all the possible combinations of elementary sectors [1];
- Some metrics currently used to assess the controller's workload often prove insufficient, if not irrelevant [2], which makes difficult for the FMP to assess and balance airspace configurations.

2 SESAR context and problem statement

To face these limitations, the European SESAR program [3] implements modular and flexible dynamic airspace configurations [4]. Large airspace blocks, such as ACCs, are hence decomposed into airspace building blocks, smaller than current elementary sectors, and delineating typical demand forecast patterns, e.g. traffic flows. These building blocks, which are not necessarily controllable, are grouped into control sectors named Controlled Airspace Blocks. In this way, control sectors are more adapted to traffic specificities, which enables to solve hotspots by reorganizing the frontiers of control sectors, with the same total number of control sectors, in order to balance the ATC workload, instead of splitting one of the existing control sector, as illustrated by Fig. 3.

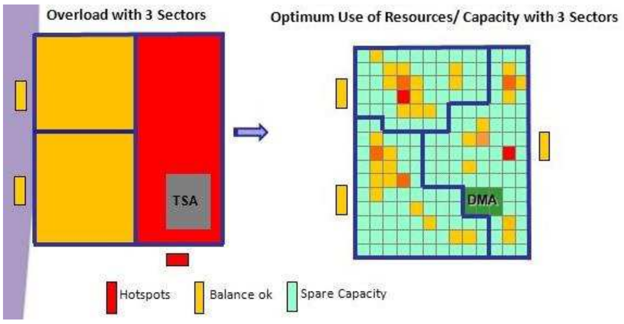

Fig. 3. Hotspot resolution by reorganizing control sectors (same number of sectors).

We present in this paper methodologies and tools developed within the SESAR VP-755 exercise of the SESAR 07.05.04 project (led by EUROCONTROL), which consists in a performance assessment of sectorization algorithms based on this new paradigm. Main objectives of this exercise are to assess the benefits that could emerge from this higher granularity and this dynamicity – in terms of time, but also in terms of flexibility in shape – and to introduce automated algorithms and tools that could support this evolution.

3 Modelling of building blocks

The focus of the VP-755 exercise was made on sector configuration processes. Nevertheless the sector design phase is a crucial step to ensure the relevance of elementary building blocks.

The first data set used was realized from the Reims operational data of the 21 elementary sectors. The objective was to validate optimization algorithms described in §4.2 and to verify if such techniques could give relevant airspace configurations out of the classic FMP catalog.

Then a manual sector design was made to assess the benefits that could emerge from a higher granularity. 42 building blocks were created by the FMP from the current 21 elementary sectors, as shown by Fig. 4 hereafter.

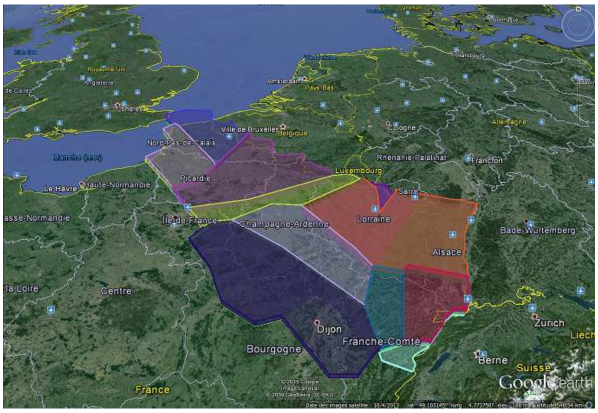

Fig. 4. Manual sector design of Reims ACC in 42 building blocks

Basically, elementary sectors were divided according to the FMP expertise on specific traffic flows and complexity issues.
If the VP-755 relied on manual sector design, it has to be noted that the overall architecture has been realized to be compatible with any sector design. A next step could be to work with building blocks automatically generated, for instance by the EUROCONTROL ASTAAC algorithms [5].
Once the building blocks have been defined and modelled with the data model presented in previous paragraph, interrelations between these building blocks were automatically given by an in-house algorithm based on the MATLAB program described in [6]. The result of this algorithm is an adjacency table between all building blocks, summarizing which building block is adjacent (a common surface in horizontal or vertical face) to another, as illustrated by Fig. 5.

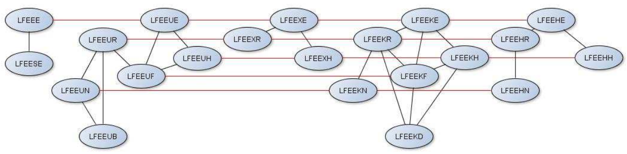

Fig. 5. Adjacencies of the 21 Reims ACC building blocks

4 Generation of sector configuration plans

4.1 Generation process

Each run of the VP-755 exercise consisted in the realization of a sector configuration plan on the day considered, then an evaluation of this sector configuration plan through a set of metrics as presented in §5.4, and finally the comparison with a reference sector configuration plan. This reference was realized by modelling the operational sector configuration plan recorded by the FMP, as illustrated by Fig. 6 hereafter.

00h00	1	LFEECTA															
04h02	2	LFEEURMN	LFEEKDFE														
04h43	5	LFEEURMN	LFEE4E	LFEE4H	LFEEKD2F	LFEEESE											
05h41	8	LFEE4N	LFEEUXR	LFEEKHR	LFEE4H	LFEEKHE	LFEEUXE	LFEEKD2F	LFEEESE								
07h08	6	LFEE4N	LFEE4R	LFEE4E	LFEE4H	LFEEKD2F	LFEEESE										
09h05	12	LFEEESE	LFEE2F	LFEEXKHH	LFEEUH	LFEEUXE	LFEEKHE	LFEEKD	LFEEUXR	LFEEKR	LFEEHR	LFEEKHN	LFEEUBN				
09h26	10	LFEEESE	LFEE2F	LFEE4H	LFEEUXE	LFEEKHE	LFEEKD	LFEEUXR	LFEEKHR	LFEEKHN	LFEEUBN						
10h10	13	LFEEESE	LFEEKF	LFEEUF	LFEEHH	LFEEUXH	LFEEKH	LFEEUXE	LFEEKHE	LFEEKD	LFEEUXR	LFEEKHR	LFEEKHN	LFEEUBN			
10h24	14	LFEEESE	LFEEKF	LFEEUF	LFEEHH	LFEEUXH	LFEEKH	LFEEUXKE	LFEEHE	LFEEKD	LFEEUXR	LFEEKR	LFEEHR	LFEEKHN	LFEEUBN		
10h27	16	LFEEESE	LFEEKF	LFEEUF	LFEEHH	LFEEUXH	LFEEKH	LFEEUXKE	LFEEHE	LFEEKD	LFEEUR	LFEEXR	LFEEKR	LFEEHR	LFEEHN	LFEEKN	LFEEUBN
11h29	14	LFEEESE	LFEEUF	LFEEHH	LFEEUXKH	LFEEKF	LFEEUXE	LFEEKHE	LFEEKD	LFEEUR	LFEEXR	LFEEKHR	LFEEHN	LFEEKN	LFEEUBN		
12h40	13	LFEEESE	LFEE2F	LFEEKHH	LFEEUXH	LFEEKHE	LFEEUXE	LFEEKD	LFEEUXR	LFEEKR	LFEEHR	LFEEHN	LFEEKN	LFEEUBN			
13h02	11	LFEEESE	LFEE2F	LFEEKHH	LFEEUXH	LFEE4E	LFEEKD	LFEEUXR	LFEEKR	LFEEHR	LFEEKHN	LFEEUBN					
14h42	9	LFEEESE	LFEEKD2F	LFEEUXH	LFEEKHH	LFEE4E	LFEEUXR	LFEEKHR	LFEEKHN	LFEEUBN							
15h41	11	LFEEESE	LFEE2F	LFEEUXH	LFEEKHH	LFEEHE	LFEEUXKE	LFEEKD	LFEEUXR	LFEEKHR	LFEEKHN	LFEEUBN					
15h55	13	LFEEE	LFEESE	LFEE2F	LFEEUXH	LFEEKHH	LFEEHE	LFEEUXKE	LFEEKD	LFEEUXR	LFEEKR	LFEEHR	LFEEKHN	LFEEUBN			
16h14	12	LFEEE	LFEESE	LFEE2F	LFEE4H	LFEEKE	LFEEHE	LFEEUXE	LFEEKD	LFEEUXR	LFEEKHR	LFEEKHN	LFEEUBN				
16h39	10	LFEEESE	LFEEXKHH	LFEEUH	LFEEKHE	LFEEUXE	LFEEKD2F	LFEEUXR	LFEEKHR	LFEEKHN	LFEEUBN						
18h06	7	LFEEESE	LFEE4H	LFEE4E	LFEEKD2F	LFEEUXKR	LFEEHR	LFEE4N									
19h35	9	LFEEESE	LFEEKHH	LFEEUXH	LFEEUXE	LFEEKHE	LFEEKD2F	LFEEUXKR	LFEEHR	LFEE4N							
20h18	7	LFEEESE	LFEE4H	LFEE4E	LFEEKD2F	LFEEKHR	LFEEUXR	LFEE4N									
20h35	5	LFEE5EH	LFEEKD2F	LFEEKHR	LFEEUXR	LFEE4N											
21h11	3	LFEEKDFE	LFEE4R	LFEE4N													
21h50	2	LFEEURMN	LFEEKDFE														
22h26	1	LFEECTA															
23h59	1	LFEECTA															

Fig. 6. Reference operational sector configuration plan

This sector configuration plan is composed of 24 airspace configurations associated to 24 variable time periods, and based on the deployment of 1 to 16 control positions.
The sector configuration plans realized during the VP-755 exercise are based on these data. The division in time periods is the same as the reference one, and for each time period, the number of sectors is the same as the real ATC roster of the day considered, even if an optimization of this parameter would make sense in another context.
For each run, the sector configuration plan is generated by the following process:

- Optimization algorithms provide the FMP with a set of good airspace configurations for each time period, and a default sector configuration plan, realized by selecting the best combination of these solutions to minimize the changes between time periods.
- Then the FMP analyzes these airspace configurations, through a decision support tool presented in §4.3, and selects one airspace configuration for each time period, to build the final sector configuration plan.

4.2 Optimization principles

As described in our previous work [7], our optimization algorithms are based on the resolution of a combinatorial problem of graph partitioning, as illustrated by Fig. 7.

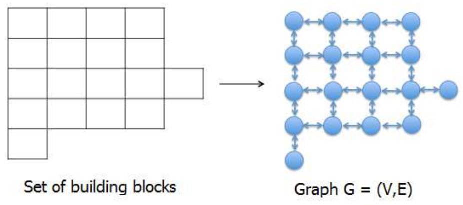

Fig. 7. Graph partition modelling

The graph G = (V, E) denotes the representation of the airspace, where V (the set of vertices) is the set of airspace building blocks and E (the set of edges), is such that (u, v) belongs to E only if there can be a direct trajectory from u to v.
The graph is valuated both on its vertices and edges as follows:

• $D_v(\Delta t)$: density workload that occurs at vertex v during a given time period Δt. Density is notably proportional to the time spent by aircraft in the sector and can integrate a complexity metric based on the number of potential conflicts;

• $CC_e(\Delta t)$: coordination workload assigned to the edge e during a given period Δt. It depends on the number of aircraft from a sector to another.

For a given time period Δt, we call $P_k(\Delta t)$ a partition of this graph G in k parts such as $P_k(\Delta t) = \{S_1,...,S_k\}$. Each subset S_i of the partition must be disjoint from the empty set and from the other subsets and the union of all the subsets must entirely cover the graph G and satisfies the connectivity constraint: the different elements of a subset, the aforementioned vertices, must be connected.
To build the optimal partition of airspace into k sectors, we may consider different objectives to minimize:

- The workload imbalanced distribution measured by the sum of distances to the average of the density of each sector within each sector configuration period;
- The total number of transfers measured by the sum of flights transiting from one sector to another within each sector configuration period;
- The total number of overloads defined by the number of overloads of traffic (over a given threshold) in a sector during a given period of time;
- The total number of reentries : a reentry corresponds to a flight that enters at least twice in the same sector;
- The total number of short transits: a short transit corresponds to a flight that spends less than four minutes in a sector.

The complexity of such an optimization problem is considered as NP-complete [7]. If we don't consider the connectivity constraint, the number of possible solutions is given by the second Stirling number

$$S(n,k) = \frac{1}{k!}\sum_{j=0}^{k}(-1)^{k-j}\binom{k}{j}j^n$$

where

n is the number of building blocks

k is the number of wanted partitions

$\binom{k}{j}$ is the binomial coefficient $\frac{k!}{j!(k-j)!}$.

For instance, if we want to open 8 positions the Reims Airspace, we have 132 511 015 347 084 possible solutions with 21 blocks and 2 048 320 078 742 103 108 851 269 258 081 470 with 42 blocks. It is clearly impossible to assess such a number of sector configurations in a reasonable time. Those high values are due to the large number of possible sectors and the considerable possibilities to combine them.
In reality, the controllers do not exploit much more than 80 sectors. In that case, the number of possible solutions is given by the binomial coefficient $\binom{80}{k}$. The number of possible solutions is still huge but if we consider the connectivity constraint, we have a limited set of

possible sector configurations, as shown in Fig. 8.

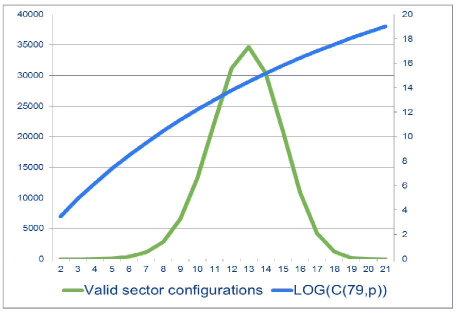

Fig. 8. Logarithm of the theoretical number of possible configurations in blue (right scale) and number of valid sector configurations in green (left scale).

Those solutions are obtained by cutting in a sector tree the branches that definitively conduct to a configuration sector that does not satisfy the constraints. If the FMP catalog of sectors should be increased, it would be possible to reduce the exploration by eliminating configuration sectors that clearly conducts to an imbalance, independently of the traffic, e.g. a large sector with a small sector.

For each time period, we are then able to assess a limited number of sector configurations in respect of the previous minimization objectives and build successive Pareto fronts. A Pareto front contains all the solutions that cannot be dominated by any other solution of the same front. In other words, each front shows the optimal solution and compromises between the different objectives.

So, we have different good solutions for each time period through these Pareto fronts. The second step is then to combine them to form the sector configuration plan of the day, as illustrated by Fig. 9.

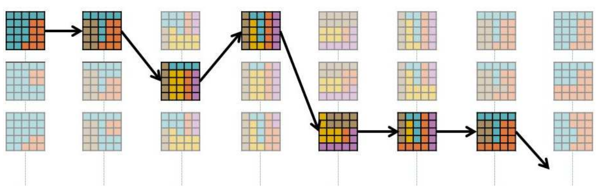

Fig. 9. Smoothest combination of airspace configurations to form the sector configuration plan.

Between two time periods, we must minimize the distance between each sector configuration. It is a classic of the Bellman's Principle of Optimality [9]. Given two partitions P and P' of the same graph G, we define the distance $D(P,P')$ between these two partitions as the smallest sum of weights of any nodes of G whose removal causes the two induced partitions to be identical [10]. From an ATM stance, this is the total density workload of the building blocks which differ when switching from the first partition to the second one. To be more operational, the partition-distance has been revised to favor what we called the collapsing/de-collapsing operations. A collapsing operation corresponds to two sectors that are merged together to form a unique sector. A de-collapsing option corresponds to the inverse one.

At the end of this deterministic phase, we have at our disposal:

- For each time period, a set of very good airspace configurations;
- A sector configuration plan built upon these solutions to be as smooth as possible.

Nevertheless, as these airspace configurations rely on the current FMP catalog, we complement this process with a stochastic approach to explore unknown solutions.

Our stochastic algorithms rely on the Simulated Annealing metaheuristic, as described in [7]. The objective is to explore new airspace configurations by exchanging building blocks, in order to check if criteria mentioned previously, e.g. the workload imbalanced distribution, could be improved without degrading the flow of airspace configurations throughout the day, and consequently their acceptance by ATCOs.

Two main approaches have been considered. In the first one, the algorithm is initialized with one of the good solutions provided by the determinist algorithm described previously. For instance, the time period with largest number of control sectors is selected. Then we build the neighbor solutions (previous and next time period), by exploring solutions around this good solution, modified to match the requested number of control positions. The advantage of this technique is to introduce from the optimization phase a consideration on the stability of successive configurations. Nevertheless one of the main issues is that depending on the selected solutions, the distance to the selected reference can rapidly be irrelevant. In a second approach, we therefore take for each time period a reference configuration given by the determinist algorithm, i.e. the smoothest sector configuration plan found. We then explore through the same Simulated Annealing method if small exchanges around this "backbone" can improve significantly one or several objectives, while being close to operational situational awareness of ATCOs, and smooth by construction.

4.3 Decision support tool

Once optimization algorithms have provided a set of airspace configurations for each time period, the run consists in the human-in-the-loop process of analyzing these configurations and selecting the most suitable one to form the final sector configuration plan. The FMP has at his disposal a set of tools to facilitate this process, as pictured in Fig. 10 hereafter.

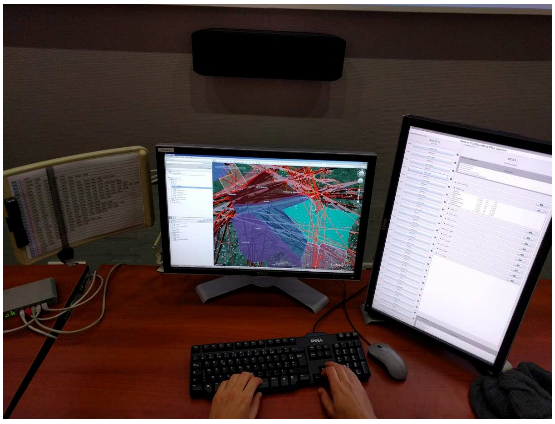

Fig. 10. VP-755 FMP working position

The working position is composed of a 3D visualization tool, enabling the visualization of traffic and airspace data of each time period considered, and of an *ad hoc* HMI called Sector Configuration Plan creator, as pictured in Fig. 11 hereafter, synthesizing all airspace configurations obtained through optimization algorithms, and providing the FMP with a set of information to help him choose the best association of configurations.

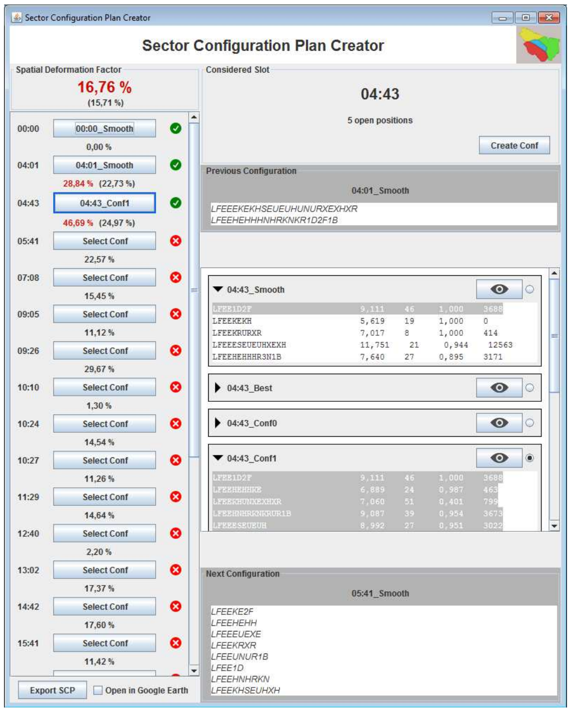

Fig. 11. VP-755 Sector Configuration Plan creator

The interface displays dynamically the following information:

- For each airspace configuration, the differences with the previous and next configurations, and the associated distance computed between these configurations, as described in previous paragraph;
- For each control sector of the airspace configuration, the density of flights, the number of transfers during the time period, the vertical compactness of the airspace volume, the number of overloads, the occupancy…

Once the FMP has selected, created or validated an airspace configuration for each time period, the final sector configuration plan of the run is recorded according to the data model described in §5.1.

5 Evaluation of sector configuration plans

The final step of our exercise is the evaluation of the sector configuration plan obtained through optimization algorithms and FMP expertise, as described previously.

5.1 Data model

The data model used in the VP-755 platform is based on the Aeronautical Information Exchange Model (AIXM) [11] and extended with new objects such as the building blocks.
The consistency of data used by different modules is ensured by the use of GAMME, an in-house meta-modelling tool, which enables to generate the different pieces of code that will be used to develop the simulation software and exchange data between the different components [12].

5.2 Overall simulation architecture

Fig. 12 hereafter gives an overview of the VP-755 platform architecture. We describe in §3 and §4 the processes of sector design and airspace configuration generation through optimization algorithms. We will focus in this paragraph on the processes required to evaluate the sector configuration plan generated.

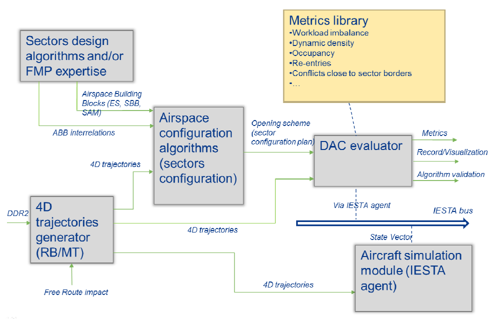

Fig. 12. Architecture of the SESAR VP-755 platform

The VP-755 platform is based on the data model previously described and the ONERA IESTA platform [13]. Fast-time simulation capabilities allow for instance to simulate the traffic with different levels of fidelity. One can choose:

- to use the IESTA Aircraft Simulation Module, based on EUROCONTROL BADA [14], in order to consider these 4D trajectories as new flight plans and to simulate the deviations to these flight plans;
- to exactly follow them, only interpolating between these 4D positions.

5.3 Traffic generation

The day of traffic sample has been chosen according to local Reims ACC observation of recent highly loaded days. We used the EUROCONTROL Demand Data Repository (DDR2) [15] to build the trajectories on one specific day (26/06/15). More specifically, we used the M1 data (from Flight Plan) during the optimization process, and the M3 (Flight Plan updated with Radar Data from CFMU) during the evaluation phase. These DDR2 trajectories were then filtered, in order to keep only the flights with at least one point in the studied area. We then extrapolated these traffic data to build a Free Route traffic, as pictured by Fig. 13 hereafter.

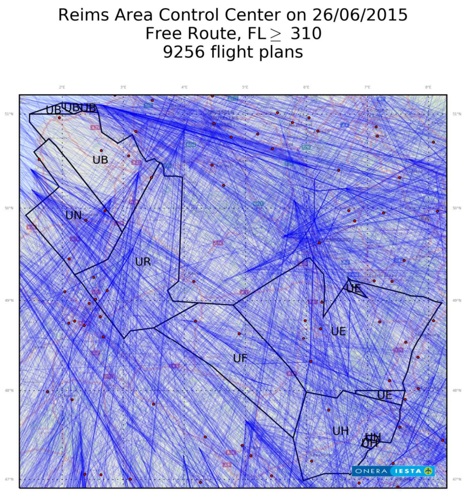

Fig. 13. VP-755 Free Route trajectories

Algorithms were developed to shift in time and space the different points of the trajectory, based on the great circle navigation from FL310. Fig. 14 shows for instance the modifications of the CES569 flight.

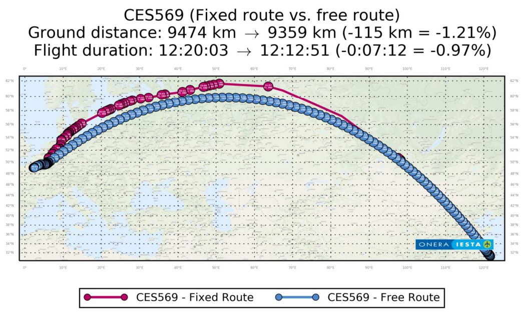

Fig. 14. Free Route trajectory extrapolation

5.4 Metrics

The Reims airspace is described as a set of building blocks composed of volumes. We computed the intersections between these volumes and the trajectories. Both are projected following a gnomonic projection centered on Reims. The advantage of this projection is to transform all great circles into straight lines. The trajectories are transformed into a set of 4D segments while the faces of the volumes are transformed into a set of oriented polygons. Then, we determine which oriented polygons are crossed by the different 4D trajectories in order to determine when and where a flight leaves a building block and enters another one. We can hence determine very quickly the different entries/exits inside the Reims airspace for a full day of operations, which is one of the basis of the different metrics described in next paragraph.

5.4.1 Topological metrics and constraints

The evaluation phase requires to define and implement relevant metrics, in order to evaluate at any moment the resulting configurations of control sectors obtained by aggregating airspace building blocks.

The first metrics to be considered are geometrical ones, used in the airspace design phase to build the airspace building blocks [16] and [17] identified the following constraints in the construction of sectors:

- Convexity constraint: an aircraft cannot enter the same sector twice;
- Minimum distance constraint: the distance between a sector border and a network node must not be less than a given distance;
- Minimum sector crossing time constraint: the aircraft must stay in each crossed sector at least a given amount of time, as illustrated by Fig. 15;
- Connectivity constraint: the sector cannot be fragmented.

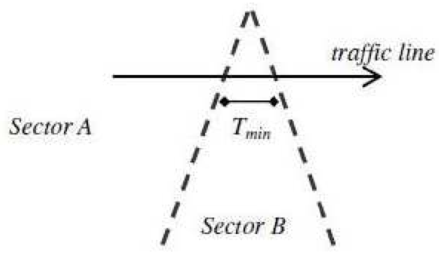

Fig. 15. Minimum sector crossing time objective

As we focused in VP-755 on the airspace configuration phase, we consider that the airspace building blocks that we use have been defined according to such criteria. Nevertheless we still need to verify that the controlled airspace blocks formed by the gathering of these Airspace Building Blocks will not degrade any of these properties.

For instance, when exchanging one building block from one sector to another, we always check that the resulting sectors are not fragmented (connectivity). Besides, as we consider both fixed route and free route operations, some measures such as the minimum distance constraint can be strongly different when analyzing historical traffic flows and real traffic flows on the day of operations, depending notably on weather conditions.

Our evaluation module implements therefore the following metrics:

- Total number of short transits: number of flights transiting in a sector less than n seconds;
- Total number of traffic nodes too close to sector borders: number of routes' intersections located at less than a given distance to the sector's frontiers;
- Total number of re-entries: number of flights re-entering in the same sector within each sector configuration period.

5.4.2 Operational metrics

One of the objectives of the VP-755 evaluation was to enrich common operational metrics, such as the hourly entry count or the occupancy count [18], that prove to be insufficient to assess controllers' workload. We therefore introduced complexity metrics, such as the dynamic density [19], to assess in each timeframe the traffic density and the inherent complexity of tasks allocated to air traffic controllers. The use of this metric nevertheless requires allocating adequate weights to the different sub-parameters, as listed hereafter in Fig. 16.

N	Traffic Density
NH	Number of aircraft with Heading Change greater than 15°
NS	Number of aircraft with Speed Change greater than 10 knots or 0.02 Mach
NA	Number of aircraft with Altitude Change greater than 750 feet
S5	Number of aircraft with 3-D Euclidean distance between 0-5 nautical miles excluding violations
S10	Number of aircraft with 3-D Euclidean distance between 5-10 nautical miles excluding violations
S25	Number of aircraft with lateral distance between 0-25 nautical miles and vertical separation less than 2000/1000 feet above/below 29000 ft
S40	Number of aircraft with lateral distance between 25-40 nautical miles and vertical separation less than 2000/1000 feet above/below 29000 ft
S70	Number of aircraft with lateral distance between 40-70 nautical miles and vertical separation less than 2000/1000 feet above/below 29000 ft

Fig. 16. Parameters of the NASA Dynamic Density metric

More generally, the evaluation module provides many metrics linked to the number of flights, such as those presented in §4.2: density, workload imbalanced distribution, total number of overloads, total number of transfers…

Finally we implemented a metric linked to the stability of successive configurations in terms of geometrical shape. This metric is based on the Hausdorff distance described in [20].

6 Conclusions

First results, based on both quantitative and qualitative analysis, seem promising, in terms of methodology and tools. The generation of sector configuration plans, through optimization algorithms and FMP expertise, gives for instance interesting results in terms of workload distribution, as illustrated by Fig. 17 hereafter.

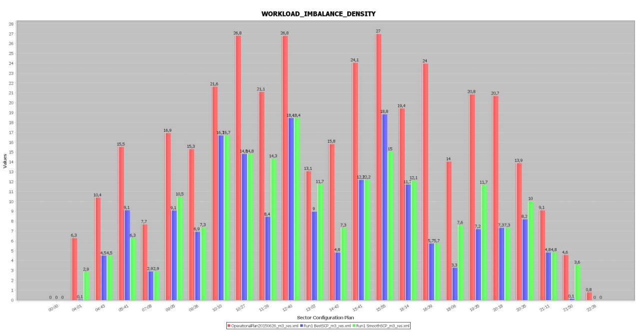

Fig. 17. Significant gain in workload distribution with new sector configuration.

Besides, human factor analysis shows that decision support tools, such as those presented in VP-755 exercise, could facilitate the FMP tasks. Further studies should analyze how such tools could be integrated to the current FMP working tooling.

Within the framework of the SESAR ATM system, such tools and methodology seem necessary to deal with the dynamicity required by unconstrained free route operations. Further studies should also assess the possibility to rapidly generate such opening schemes, with an important number of metrics and with building blocks becoming much smaller, as the pixel view illustrated in Fig. 18 hereafter.

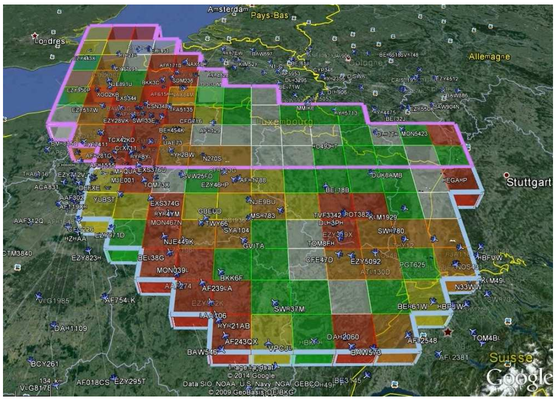

Fig. 18: Reims ACC airspace subdivided in 400 20x20NM cuboids

In any case, such techniques can only be seen as a way to enrich ATC centers' catalogs and as a decision support tool to operational experts. The FMP expertise will always be required to assess the overall relevance of the airspace configurations generated and their potential acceptation by air traffic controllers. Besides such a local optimization should be integrated within a bigger optimization loop, at a Functional Airspace Block (FAB) or European level, to consider side and network effects.

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