An efficient airspace configuration forecast

David Gianazza, Cyril Allignol, Nicolas Saporito

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D. Gianazza, C. Allignol, N. Saporito
DSNA Toulouse, France

***Abstract*— This publication is the continuation of previous research which aims at improving the predictability and the flexibility of the airspace management process by computing realistic forecasts of the airspace configurations in *En-route* ATC centers. In previous papers, we selected relevant complexity metrics to predict the controllers workload, using neural networks trained on historical data. We also introduced new algorithms to build optimally balanced airspace configurations, exploring all possible combinations of elementary sectors. These workload prediction model and airspace partitionning algorithms were tested on real recorded traffic.**

In this paper, airspace configurations are forecast from planned traffic, using the CATS/OPAS simulator to compute trajectories from flight plans. The efficiency of the resulting airspace configurations is assessed by comparing to the actual FMP (Flow Management Position) prediction. Some preliminary developments of an experimental HMI that will be used to test and tune our algorithms are also presented.

***Keywords:* air traffic complexity, airspace configuration, neural networks, forecasting.**

INTRODUCTION

The european upper airspace is currently partitionned into managerial units – air traffic control centers (ATCC) – which are themselves partitionned into *elementary* (or *modular*) *sectors*. These basic airspace modules may be combined together so as to form *control sectors* operated each by a small team of 2-3 controllers. New concepts for the future air traffic management (see [1], [2], and [3]) point out the lack of flexibility of the current system, and plan to re-focus air traffic operations on the aircraft 4D-trajectories, with a more dynamic and flexible allocation of airspace resources.

In many countries however, the real-time airspace configuration is already highly flexible: the partitionning of the ATCC's airspace into control sectors changes across the day, depending on the incoming traffic and controllers workload. Sectors may be split[1] when the workload increases, or merged (or collapsed) when the workload decreases. More complex recombinations may sometimes be decided by the control room manager, when necessary. An additional controller may assist the two controllers operating a sector when the traffic is heavy.

Although the current system might be improved by using more flexible sector boundaries[2] in areas where severe weather conditions cause aircraft reroutings on an everyday basis, it is actually flexible and adaptive when faced to traffic variations. The current mode of operation is mainly limited by two factors: first, the fact that overloads may occur in elementary sectors that cannot be split, and second, the number of controllers on duty may not be sufficient to open as many control sectors as would be necessary.

In our opinion, the most striking limitation of the current air traffic management system is not its lack of flexibility, but its *lack of predictability*. This is most obvious when comparing the prediction made by flow managers (FMPs) to the actual airspace configurations, as we shall see in section I.

The work presented in this paper is the continuation of previous research ([5], [6], [7], [8]) which aims at forecasting airspace configurations with a good degree of realism, using a reliable workload prediction grounded on relevant air traffic complexity metrics. A neural network, trained on historical data, is used to assess this workload and is combined with a *branch & bound* algorithm (or an exhaustive tree search method for small instances) exploring all valid combinations[3] of elementary sectors, so as to build an airspace partition where workload is balanced as best as possible among the control sectors.

In these previous studies, the complexity metrics were computed from recorded radar tracks, and the resulting airspace configurations were compared to actual sector configurations. The aim was to test the algorithms on historical data. Radar tracks cannot be used for prediction, however, as they are not available before the aircraft have actually flown. In the current paper, airspace configurations are predicted only from

[1] Splitting a control sector requires that it is made of at least two elementary sectors.

[2] There is however some concern that unlimited flexibility in the sectors boundaries would lead to a loss of situational awareness by the air traffic controllers (see discussion and litterature review in [4]).

[3] A valid combination of sectors is an airspace partition made only of operationally valid control sectors, taken from the list defined in the air traffic control database.

data that is currently available before the flights take-off. A fast-time simulator is used to compute aircraft trajectories from flight plans. The relevant air traffic complexity metrics are computed from these simulated trajectories, and the forecasted airspace configurations are compared both to the actual prediction made by the flow management positions (FMPs), and to the archived sector configurations.

Section I describes the current situation, and compares the prediction made by the french FMPs to the real sectors openings. A quick overview of research on air traffic complexity and airspace management is given in section II. The algorithms used to predict airspace configurations are shortly described in section III. Section IV presents the CATS/OPAS fast-time simulator used to compute trajectories from flight plans. The resulting airspace configurations are assessed in section V, by comparing to the real number of control sectors. The efficiency of the airspace configuration forecast is assessed by comparing to the FMP prediction, and the displays of an experimental HMI currently under development are also presented in this section. Section VI concludes the paper and gives some perspectives of future work within the SESAR programme, and of potential applications.

I. Today's situation

A. Current FMP airspace configuration forecast

In some european countries, pre-tactical sectors opening schedules are built by the FMP operators one or two days ahead, in order to anticipate potential overloads. In France, the current method to build such schedules is fairly simple. A set of usual airspace configurations is filed in a database. The FMP operator chooses among them the ones he (or she) thinks are the most adequate for each time period of the day (usually 30 or 20 minutes). Candidate configurations are empirically assessed by comparing flight counts in each control sector to pre-defined threshold values (*sector capacities*).

These pre-tactical schedules are highly unrealistic, partly because they rely on an estimated traffic demand, but also for other reasons: first the traffic load is assessed using flight counts in a period of time (incoming flows) and this is not sufficient to model the actual controllers workload, and second only a small subset of pre-defined configurations is considered. The current method is directly issued from former procedures where the traffic load was assessed by counting the number of flights that were planned to enter each sector in a one hour time interval, when this count was made by hand.

As a consequence, the FMP schedules are not actually used to forecast future overloads. FMP and CFMU operators rather rely on their past experience of similar traffic situations to enforce flow regulations on specific airspace boundaries, entry points, or airspace volumes The causal relationship between the slot allocation based on these regulations and the actual workload experienced by the controllers in real time is not clearly established. A more accurate assessment of future workload and a better forecast of future airspace configurations could certainly improve the predictability of the air traffic management system.

B. Comparing FMP predictions to real configurations

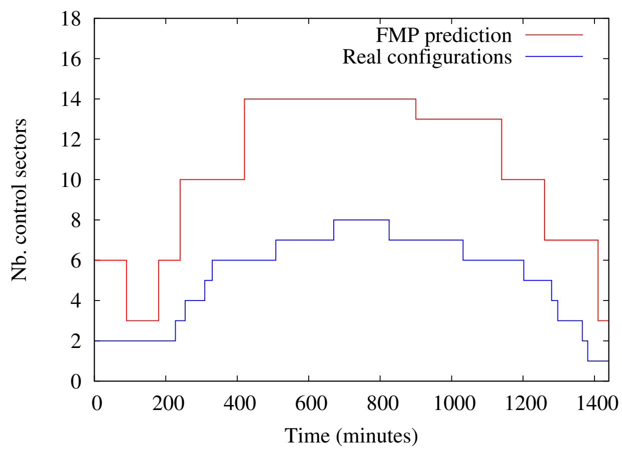

Fig. 1. Number of control sectors (FMP prediction and actual sector configurations) in Brest ACC, june 2003 the 2nd.

The gap between the FMP prediction and the real sectors openings is illustrated on figure 1 (Brest ATCC, 2003, june 2nd). A similar gap is observed in the other french ATCCs for that day.

In order to quantify the quality of the prediction, let us define a *dissimilarity metric* as the surface of the difference between the predicted curve and the real curve, divided by the reference surface (real sector openings). With this quality metric, a perfect forecast would have a coefficient of 0. The dissimilarity between the FMP prediction and the real sectors openings in the example of figure 1 is 1.01.

C. Discussion on the potential benefits of a better prediction

At this point, it must be emphasized that one cannot expect to perfectly adjust the staff variable to the traffic demand on an everyday basis, even with a perfect airspace configuration forecast. The staff variable is adjusted to the peak traffic, estimated well in advance, as it takes several years to train a controller. The total number of controllers in operations cannot be finely tuned over the year: this would require to employ less controllers in the winter than during the summer for example, which is not acceptable and not feasible: air traffic controllers are a highly trained and highly qualified work force.

Note also that the difference between the FMP prediction and the actual sectors openings is somehow a result of the flexibility of the french ATC system. In other countries, some ATCCs are much less flexible in the way to merge or to split sectors, and strictly follow a pre-defined duty roster, thus exhibiting no difference between prediction and reality.

The french system is flexible enough to offer the most adapted configuration to the airspace users in real-time, allowing easy recombinations like AB-C to A-BC for example (where A, B and C are modular sectors). Merging sectors while keeping spare staff available allows air traffic controllers to maintain their level of proficiency by working on normally loaded control sectors at every time of the day, while keeping ready to split sectors and offer more capacity when the traffic increases. This is particularly useful when unexpected peaks of traffic occur.

Although it may be improved by making it more predictable, the current french system is already highly flexible and efficient, and the gap between the duty roster and the real sectors opening brings more capacity and more safety to the airspace users. So, even if this gap could be more finely tuned, the most important benefit that may be expected from a greater accuracy of the workload prediction and airspace configuration forecast lies elsewhere: a more realistic prediction would provide a better anticipation of overloads than today, allowing to take earlier measures of rerouting and flow balancing. We may also expect that coupling dynamic flight reroutings (or other flight plan modifications) with airspace configuration forecast algorithms would provide a better service to the airspace users.

II. Related works

A. Related works on air traffic complexity

Assessing the controllers workload and predicting when this workload exceeds safe limits are difficult problems involving human factors, and have been the subjects of many research (see [9] for a review). Some of them focus on the relationship between air traffic complexity metrics and controllers workload, using various methods to maximize the correlation of candidate metrics with a quantifiable dependant variable assumed to represent the actual controller's workload.

Some background on the various methods and metrics (see [10], [11], [12], [13]) that were proposed in the literature may be found in previous papers ([5], [7], [8]). The reader may also refer to [14] and [15] for a review.

Our main contribution on this subject ([5] and [6]) was to use the sector status (*merged*, *normal*, or *split*) as dependant variable, trying to find the subset of metrics that is most correlated to this sector status. The basic assumption is that the decision to reconfigure control sectors is somewhat related to the actual contoller's workload. The main advantage of this dependant variable, when compared to others like the physical activity ([16], [12]), physiological indicators ([17], [18]), simulation models of the controller's tasks ([19], [20]), or subjective ratings ([10], [13], [11]) , is that a large amount of historical data (past airspace configurations) is available. In addition, it does not require a heavy experimental setup to collect the data, and it is truly representative of the controllers workload in the context of airspace configuration.

B. Related works on airspace design and management

Airspace design and management have also been the subjects of many studies, using several methods: mixed integer programming techniques ([21]), evolutionary algorithms ([22], [23], [24]), seed growth methods inspired from crystal growth ([25]), constraint programming ([26], [27], [28]), computational geometry ([29]), graph partitionning methods or a new metaheuristic inspired from the nuclear fusion and fission ([30], [31]), manual iterations by experts, using transparents and fast-time simulations ([32]). These studies address a variety of operational contexts: strategic airspace design, pre-tactical planning, tactical airspace management, and consequently use various definitions of "workload".

Focusing on dynamic pre-tactical and tactical contexts, let us cite [23], where Delahaye et al. address the dynamic sectorisation problem with genetic algorithms, although only with mock-up convex sectors. In [21], Verlhac and Manchon apply mix integer programming techniques to improve the pre-tactical planning of sector configurations in Europe, using actual sectors. Flight counts are used to assess the traffic load, and only a relatively small set of pre-defined candidate configurations is considered. In [28], tactical reroutings and flight profile modifications allow Flener et al. to balance traffic complexity among several sectors, for tactical multi-sector planning purposes. However, no airspace reconfiguration is proposed.

Our contribution addresses medium-term issues, trying to improve the predictability and the flexibility of today's airspace management in Europe, for pre-tactical or tactical purposes. The aim is to find optimal combinations of elementary (or modular) sectors that will provide the maximum throughput to a given input traffic, and balance the controllers workload as best as possible among the control sectors. In [33], we proposed several algorithms exploring all combinations of elementary sectors, although still using the same variables (flight counts in a period of time) and thresholds (sector capacities), as well as the same constraints (number of controllers on the duty schedule) than the french Flow Management Positions (FMP). Classical tree search methods proved efficient when considering only operationnally valid control sectors, that is those defined in the air traffic control center database. An evolutionnary algorithm was also proposed as an alternative, in case one may consider a wider range of sectors and possibly larger geographic areas. How the optimized schedule could improve the overall efficiency of the slot allocation process was assessed in [34] and [35]. The results, although showing the algorithms efficiency, were far too unrealistic. The conclusion was that a better assessment of the controllers workload was needed.

The next step ([5], [6]) was to select more relevant air traffic complexity metrics in order to assess the actual controllers workload. Neural networks were used to that purpose. Among the initial 28 metrics chosen from [10], [13], [36], [37] and other sources, the 6 most relevant variables were the sector volume V, the number of aircraft within the sector *Nb*, the average vertical speed *avg_vs*, the incoming flows with time horizons of 15 minutes and 60 minutes (F_{15}, F_{60}), and the number of potential trajectory crossings with an angle greater than 20 degrees (*inter_hori*). The iterative algorithm that builds realistic sectors opening schedules was introduced in [7], using a simple exhaustive tree search method for local sector recombinations. In [8], we tried to smooth the input metrics so as to avoid too frequent reconfigurations.

In the current paper, a *branch & bound* algorithm computes optimal combinations of modular sectors taken from the current ATCCs databases. It is hybridized with a neural network that assesses the controllers workload, using as input a subset of relevant air traffic complexity metrics. In order to be as close as possible to a true forecast, the complexity metrics are computed from simulated trajectories, using the CATS/OPAS fast-time simulator, and considering the initial flight plans.

III. Forecasting airspace configurations

The algorithms that were used to produce the results presented in this paper have already been detailed in previous publications ([7], [8]). A few modifications have been introduced since [7]: first, a more simple and straightforward cost function for the airspace configurations have been designed, and second, the tree search logic that combines sectors have been improved. We shall not go into the details of these algorithms in this publication. Let us just describe their main features.

A. A neural network for workload prediction

A feed-forward neural network was used, with a softmax function on the output layer (see [38] and [39] for an extensive presentation of neural networks for pattern recognition, or [40] for a shorter review). This network addresses classification problems.

The input variables are the relevant complexity metrics $\{V, Nb$, *avg_vs*, F_{15}, F_{60}, *inter_hori*$\}$, smoothed over a 30 minutes period of time (see [8]), and normalized by substracting the mean value and dividing by the standard deviation. These metrics are computed from input aircraft trajectories. In previous works, recorded radar tracks were used to that purpose. In this paper, we have simulated these trajectories from flight plans (see section IV).

The neural network's parameters were tuned on historical data, so as to give the best possible workload prediction. The output is a triple of joint probabilities on the sector status: they indicate if the sector should be merged with another sector (low workload), or if it could be normally operated, or if it should be split into smaller sector (high workload) when this is possible.

The neural network is trained on data samples from a wide variety of sectors, taking into account the traffic complexity, so it can generalize to any en-route sector. This is an interesting feature, as the model will also give an indication of when an elementary sector (which cannot be split) will get overloaded, extrapolating from overloads occuring in wider control sectors that can be split.

The model only needs a single set of parameters for all en-route control sectors. Similar results could probably be obtained by using sector-specific variables and thresholds, finely tuned for each control sector. In fact, such metrics and thresholds are already used in the operational tools. However, using them would require a model with much more parameters, which values should be set by the FMP operators, or collected from the FMP tools.

The neural network gives us an indication of workload for any given sector. However, it is unable to make complex recommendations such as to split the sector's volume in several parts and then to merge each of these parts with other sectors. Sector recombinations are made by tree search algorithms that assess candidate configurations using a cost function.

B. Cost of an airspace configuration

The cost of an airspace configuration depends on the number of overloaded, under-loaded and normally loaded control sectors in the configuration, and of the values of the sector status probabilities provided by the neural network for each control sector. The cost function was described in [8].

C. Tree search algorithms for airspace partitionning

A *Branch & bound* algorithm may now be used to reconfigure either a few sectors or the whole airspace, as an alternative to the exhaustive tree search described in [7] that made local sector recombinations only. The detailed description of the *Branch & bound* algorithm will be the subject of a next publication, but the reader may refer to [34], [33], and [35] where a very similar algorithm is detailed.

D. Sectors opening schedule

So far, we have described how to assess the controllers workload for any given control sector, and how to partition the airspace so as to balance this workload as best as possible among all control sectors, at any given time t. Now, let us see how to build an airspace configuration schedule for a whole day of traffic.

Finding an optimal airspace partition of the whole airspace at every moment of the day seems the most straightforward solution, but it would lead to a succession of drastically different configurations in short periods of time. In reality, the airspace is reconfigured around 30 times a day (for french airspace), and usually with relatively minor changes from one configuration to another. The reason is that transferring a sector, or a portion of a sector, from one controller to another must be done safely, ensuring that the receiving controller does not miss any potentially dangerous situation in the new traffic and the new airspace sector he will have to handle.

1) `Initial configuration (t=0):`
   `1 control sector` ⟵ `all elementary sectors`
2) `At each time step (1 minute):`
   - `Decide if airspace must be reconfigured`
     ⟶ `check status of each control sector`
   - `Reconfigure sectors that need to be split or merged:`
     - `build the subset of elementary sectors,`
     - `explore all combinations,`
     - `select configuration with minimum cost.`

Fig. 2. Iterative algorithm for airspace sectors opening schedule.

So it was decided to mimmick the actual behaviour of control room managers as best as possible. Figure 2 describes the main loop of the chosen algorithm. The current airspace configuration is checked at each time step. The default behaviour is to recombine only sectors for which the neural network recommends an action (split or merge). There are some cases, however, when this limited recombination is not sufficient, for example when the neural network issues a "merge" recommendation for two sectors that are not geographically adjacent. So we check the number of connex components of the set of control sectors that need to be reconfigured, and if there are more than two components, then a full airspace reconfiguration (with the *Branch&bound*) is triggered.

In previous works, the above algorithms had only been tested on recorded radar tracks. Let us now see how they could be used to actually *forecast* airspace configurations, using simulated trajectories computed from flight plan data.

IV. Fast-time air traffic simulation

A. Overview of the CATS/OPAS simulator

The CATS/OPAS[4] (see [41]) simulator was developped in CENA[5], starting in the mid 90's. It has a very light and modular structure: its core is less than $3,000$ lines of CaML[6] code, which makes it easy to maintain and fully adaptable. Furthermore, it provides a practical model development for route network and sector design, air traffic assignment, conflict resolution and airborne collision avoidance.

The core of the CATS system is en en-route traffic simulation engine. It is based on a discrete, fixed time slice execution mode: the positions and velocities of aircraft are computed at fixed time steps (in our case, one position every 15 seconds). The simulator uses BADA[7] performance tables, derived from the total energy model of EUROCONTROL. They provide ground speed, vertical speed and fuel burn as a function of altitude, for every aircraft type and flight phase (climb, cruise or descent).

Aircraft trajectories are computed from flight plans that can be either user-defined, or taken from historical data. Aircraft can use different navigation modes:

- standard routes: they follow the sequence of navigation aids described in their flight plan;
- direct routes to their destination.

[4]CATS: Complete Air Traffic Simulator or CaML Air Traffic Simulator

[5]CENA: Centre d'Études de la Navigation Aérienne

[6]CaML is a strongly typed programming language based on λ-calculus, and developped by INRIA, France's national research institute for computer science.

[7]BADA: base of aircraft data

The simulator provides built-in trajectory prediction, and conflict detection and resolution.

B. Capabilities and outputs

The CATS/OPAS simulator integrates two automatic conflict resolution methods, based on heading deviation maneuvers: an on-board resolution and a centralized resolution. At each simulation time step, futur aircraft trajectories are predicted with a chosen time horizon, taking into account the uncertainties on ground speed and vertical speed (see [41] for more information).

The on-board method ([42]) is a reactive short term (3 to 10 minutes) conflict solver. Each 1-to-1 conflict is handled individually. A specific distributed token allocation algorithm was designed to handle the priority among aircraft.

The centralized method, presented in [43], is designed for high density areas and medium term control (10 to 15 minutes ahead). An evolutionary algorithm is used to solve the n-conflicts clusters[8] issued from the conflict detection process.

The system records and computes the following output information:

- aircraft trajectories;
- instantaneous aircraft count per sector;
- aircraft flow rates through sectors;
- conflict statistics (geometry, aircraft maneuvers, duration, etc);
- conflict resolution statistics (number of maneuvres, number of clusters, clusters sizes, maneuvres duration, delays due to maneuvres);
- airborne separation and collision avoidance system statistics;
- statistics from other filters such as ground delays, runway capacity utilization, etc.

For our purpose, only the basic trajectory simulation feature of the CATS/OPAS simulator was used. Air traffic complexity metrics were computed from simulated trajectories, using the initial traffic demand.

In previous works, our algorithms were tested on recorded radar tracks. We are now able to actually forecast airspace configurations from a given traffic demand. The results are given in the next section.

V. Results and airspace configuration display

A. Planned vs. real

Let us first observe the impact of flight plan uncertainties on the airspace configuration forecast. Figure 3 shows the results of our algorithms when computing the complexity metrics from recorded radar tracks. As

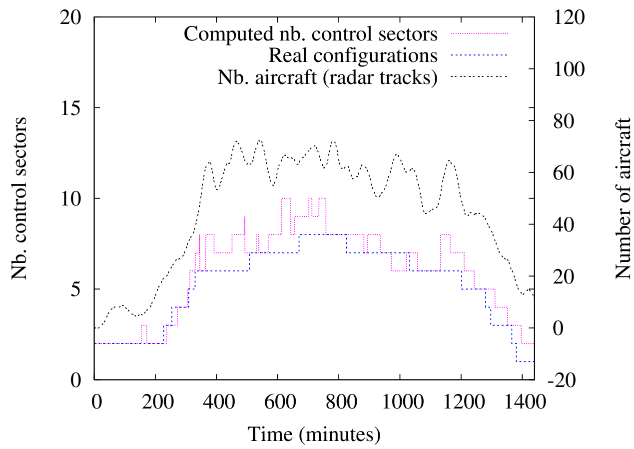

Fig. 3. Computed *vs.* real number of control sectors, using real traffic only (Brest ACC, june 2003 the 2nd).

already stated in previous papers, the computed number of control sectors is fairly close to the real number of control sectors that were operated that day. The figure also shows the number or aircraft[9] (smoothed over 30 minutes) within the airspace boundaries.

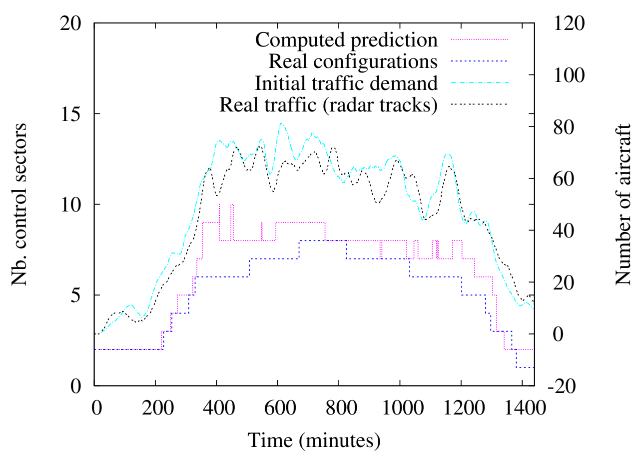

Fig. 4. Simulated traffic (initial flight plans) and predicted number of control sectors *vs.* real traffic and real configurations (Brest ACC, june 2003 the 2nd).

Figure 4 shows both the real traffic and the simulated traffic within Brest ATCC airspace on the 2nd of june 2003 (upper curves), together with the output of our algorithms when computing the complexity metrics from simulated trajectories, and also the real number of sectors. We may observe that the computed number of control sectors is less close to the real number of sectors than when using recorded radar tracks only. This difference can be explained by the fact that the

[8] An interactive example of resolution can be found at http://pom.tls.cena.fr.

[9] Number of aircraft on the right y axis. The curve have been shifted upward so as to separate the traffic curves from the other curves (left axis).

initial traffic demand does not match the real traffic.

One of the great improvements that may be expected from the SESAR programme is a greater accuracy of the planned 4D-trajectories, although maybe with a shorter anticipation than today's flight plans. The work presented here is a part of the contribution proposed by DSNA to the SESAR work package 4 (project 4.7.2: *Complexity management in en-route*).

B. Efficiency of the computed prediction

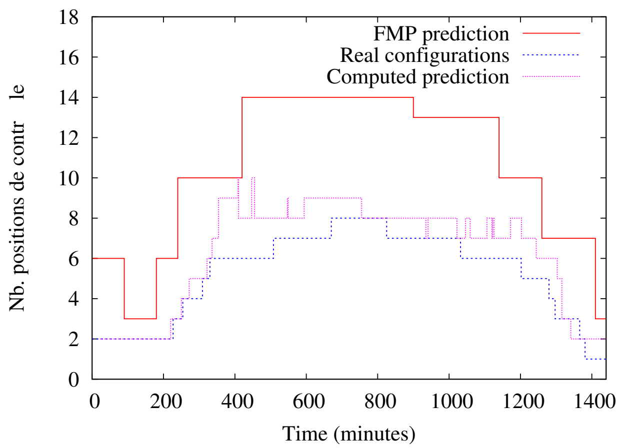

Fig. 5. Number of control sectors (FMP prediction, computed prediction, and actual sector configurations) in Brest ACC, june 2003 the 2nd.

Figure 5 shows the number of control sectors in the FMP prediction, and in our prediction computed with simulated trajectories, as well as the actual number of sectors that were operated that day, in Brest ATCC (2003, june 2nd). The *dissimilarity* measure between the FMP prediction and real sector openings was 1.01 (see section I). The dissimilarity between our prediction and the actual airspace configuration is 0.20, which is much closer to a perfect prediction (that would have a coefficient 0).

As already discussed in section I, one cannot truly expect to finely tune the staff variable to the traffic demand, even with a good prediction. However, provided that accurate enough 4D-trajectory contracts are available in advance, the proposed method would allow to adjust the duty roster so as to adapt as well as possible to the traffic demand. In addition, it would allow to identify which sectors will be overloaded when the ATCC cannot open enough control sectors to cope with the traffic or when an elementary sector is overloaded.

To do that, we need to display airspace configurations with more details than just the number of control sectors. The following subsection describes some preliminary developments of an experimental HMI that will be used to demonstrate, improve, and validate our algorithms.

C. Airspace configuration display and workload prediction

An experimental Graphic User Interface is currently being developped. Its first goal is to test and tune our algorithms, but a prospective reflection on the use of the application in an operational context is also being led. User-Centered Design methods are applied to identify which information should be displayed, and how it should be presented to the operator.

The first observation is that the quantity of information available for display is quite high: successive airspace configurations across the day, transitions between configurations, workload prediction for each control sector at every minute of the day, or other complexity metrics on demand. Consequently, we should present both a global view and a detailed one. The user must be able to switch quickly from one to the other, and moreover, must not lose the focus on the general trend when in detailed "mode". So it has been decided to make a flexible representation of the day (fish-eye like), rather than two distinct modes (general/zoomed).

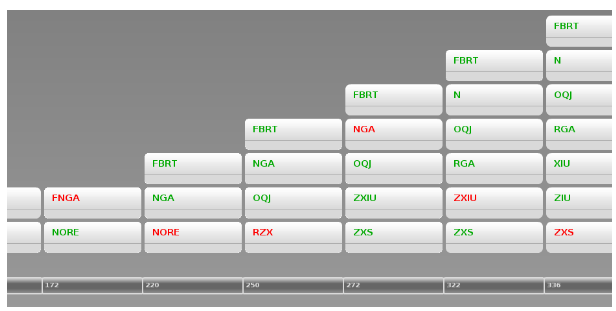

Fig. 6. Folded view of an airspace configuration forecast.

On this flexible view, standard configurations are folded by default (low level of information but a lot of configurations), and may be unfolded when selected by the user (high level of information on a few chosen items). The awareness of connection and evolution is reinforced by animated transitions between folded/unfolded states.

This is illustrated by figures 6, 7 and 8. On the folded view (figure 6), the configurations proposed by the model are displayed as stacks of sectors alongside a time scale (time in minutes from the beginning of the day). The sector names are colored according to the forecast workload just before the next reconfiguration: red for split, blue for merge, green for normal.

On figure 7, the configuration at time $t = 250$ is unfolded. The links between the sectors of three successive configurations (centered on the selected

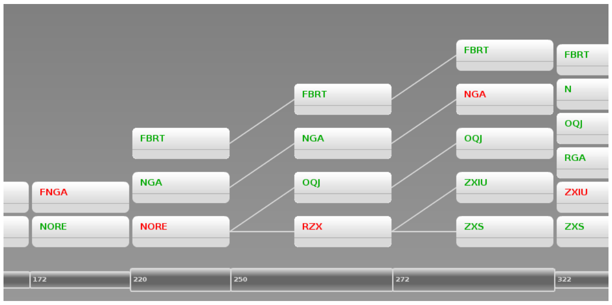

Fig. 7. Unfolded view of an airspace configuration forecast.

configuration) are diplayed in order to have a better idea of a specific reorganisation of sectors. It is also possible to unfold the overall view and make all links visible.

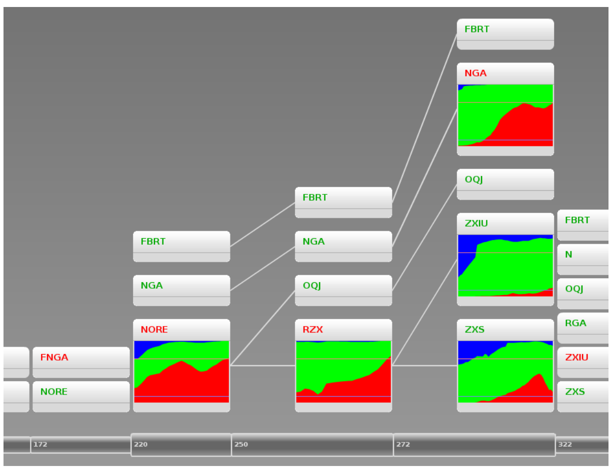

Fig. 8. Unfolded view with workload.

It is also possible to focus on specific control sectors: probability graphics are then displayed for the selected sectors, with a red[10] area for the "split" probability, a green[11] area for the probability of "normal" operation, and a blue[12] area for the "merge" probability. The sum of the three probabilities is always 1, which allows us to stack them on a single graph (the "split" probability is in the lowest area, and the "merge" probabilty is in the upper area).

The threshold values of split and merge probabilities are also displayed (thin lines with same color code as areas) so that it's possible to identify the sector(s) that triggers the configuration changes.

For example, considering the workload graph of sector NORE on figure 8 (leftmost graph), one may see that the "split" probability reaches the decision threshold (probability 0.7) at time $t = 250$, triggering a reconfiguration where this overloaded sector is split into two smaller sectors OQJ and RZX. Later, at time $t = 272$, sector RZX also gets overloaded and a new reconfiguration is triggered.

Before concluding, let us remind that this graphical interface is experimental and still under development. Its features may change in the near future, following remarks from HMI experts, human factors experts, or ATC experts. However, the above figures give a good hint of what kind of forecast may be expected from the proposed algorithms.

VI. Conclusion and perspectives

In conclusion, the workload prediction model that was only tested on recorded traffic in previous works is now applied to simulated trajectories. The CAT/OPAS fast-time simulator uses flight plans from the initial traffic demand to compute these trajectories. The efficiency of the airspace configuration forecast using this model have been demonstrated by comparing to the current FMP forecast. Although the benefits that we may expect from a good prediction are limited by other factors than the prediction's quality (staff recruitment and training, traffic variability accross the year), it is clear that even gaining a small part of the current difference between the FMP prediction and the actual sector openings is worth trying.

The airspace configurations are less realistic when using planned traffic instead of recorded radar tracks. This is due to the discrepancies between the flight plans and actual trajectories. We may expect that more accurate 4D-trajectories, as envisionned in the SESAR programme, would improve the results. The work presented in this paper have been proposed as a contribution to the *Complexity management in en-route* project of the SESAR work package 4. In this project, the experimental HMI that we have presented in this paper will allow to test and tune our algorithms in a context of tactical planning. Beyond this first objective, the new features provided by the proposed algorithms may lead to a new *modus operandi* for airspace and flow managers. So we may have to design an experimental interface for a user that doesn't really exist today. This potentiality is yet to be explored through a user-centered design process.

Future works may also deal with the improvement of the workload prediction in a tactical context. In previous works, we were mainly focused on the pre-tactical sectors opening schedule. A simple feed-forward neural network was used to predict the controllers workload from input complexity metrics. These metrics were smoothed by computing a moving average over 30 minutes, so as to avoid too frequent

[10] medium grey on black & white prints
[11] very light grey on black & white prints
[12] dark grey on black & white prints

reconfigurations (see [8]). This is acceptable for a pre-tactical prediction but maybe not in a tactical context. This smoothing strategy seems too drastic and may lead to miss the exact moments at which reconfigurations should be triggered. We may expect better results by considering the input metrics as time series, and by using recurrent neural networks instead of simple feed-forward networks.

Let us remind a basic fact about the proposed method, which has some consequences on the perspectives of application in an operational context: our model is trained on historical data. It only models an average behaviour of the controllers and control room managers in the past. A first consequence is that one cannot expect that airspace configurations computed with this model will be exactly the same as the actual configurations, although we expect results as realistic as possible. A second consequence is that this model *should definitely not be used for tactical decision support*, when actually deciding when to split or merge sectors. Doing so would infinitely reproduce the same behaviour, and would prevent from taking advantage of new improvements in the technology or the working method.

However, the proposed model and algorithms could be used to forecast future airspace configurations, and to anticipate when control sectors get overloaded. It could also be used to test preventive measures expected to alleviate the controllers workload in such sectors, showing how the workload would shift to other control sectors, or how the airspace may be reconfigured as a consequence of these measures.

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BIOGRAPHIES

David Gianazza is currently researcher in the Planning, Optimization, and Modelling team[13] of the DSNA/DTI R&D center, in Toulouse (France). He received his engineer's degrees (IEEAC in 1986, IAC in 1996) from the french civil aviation academy (ENAC) and his M.Sc. (1996) and Ph.D. (2004) in computer science from the "Institut National Polytechnique de Toulouse" (INPT). A more detailed biography may be found here: http://pom.tls.cena.fr/∼gianazza/

Cyril Allignol is currently a PhD student in the Planning, Optimization, and Modelling team of the DSNA/DTI R&D center, in Toulouse (France). He received his engineer's degree (IEEAC in 2006) from the french civil aviation academy (ENAC) and his M.Sc. (2006) in computer science from the "Institut National Polytechnique de Toulouse" (INPT).

Nicolas Saporito is currently engineer in the Planning, Optimization and Modelling team of the DSNA/DTI R&D center. He received his engineer's degree (IEEAC in 2008) from the french civil aviation academy (ENAC) and his Professional Master (2008) in Computer Human Interaction from ENAC and Paul Sabatier University in Toulouse.

[13]The POM team was formerly part of the Global Optimization Laboratory LOG CENA/ENAC