Assessing ATM Performance with Simulation and Optimisation Tools The APACHE Project

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The APACHE Project

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***Abstract*—This paper describes the objectives and methodology of the APACHE project, a SESAR Exploratory Research project proposing a new framework to assess European air traffic management (ATM) performance. This framework integrates an ATM simulator prototype used to synthesise scenarios for pre-ops performance assessment, but also needed to compute some novel performance indicators, which require from optimisation or simulation capabilities. This simulator embeds a trajectory planner; an airspace planner; a traffic and capacity planner; and finally, a performance analyser module. An illustrative example is given, showing the successful integration of all these modules, where an initial performance assessment is done for a realistic data set of 24h of traffic over the FABEC airspace.**

***Keywords*—ATM performance, simulation, trajectory and airspace optimisation, risk assessment, environmental impact**

I. Introduction

At present, the European air traffic management (ATM) is evolving in a coordinated manner aiming to improve the overall efficiency of air navigation services across several key performance areas (KPAs). The International Civil Aviation Organization (ICAO) launched in 2003 a worldwide initiative to ensure that the future global ATM system is performance based [1], [2]. Worldwide support to the ICAO initiative is also given by CANSO (Civil Air Navigation Services Organisation) [3]. In line with these initiatives, current ATM performance assessment is addressed in Europe through the Single European Sky (SES) Performance Scheme, which establishes an agreed methodological framework for performance targeting, measuring, baselining and benchmarking in ATM [4].

In [5] a comprehensive review is given, comparing the performance frameworks proposed by ICAO, CANSO, the SES performance review unit (PRU) and SESAR 2020; identifying over 150 PIs for performance management/monitoring in 11 different KPAs. Similarly, in NextGen (the North American ATM modernization programme counterpart to SESAR) numerous PIs have also been proposed to measure the performance of the programme deployment[6], [7].

Despite the evident lack of harmonisation, some of the PIs currently in place show some important limitations, mainly due to the lack of availability or quality of the input data required; or because the implementation of too simple models in the PI computations. In many occasions performance is assessed by using proxy indicators, which in some cases difficult drawing clear conclusions.

Moreover, the SESAR target concept of operations [8] introduces new paradigms, such as TBO and PBO (trajectory based operations and performance based operations); where a more dynamic optimisation and allocation of ATM resources is foreseen, in order to enable the airspace users (AUs) to fly with the minimum amount of constraints. It is expected these new concepts will bring a significant positive impact in ATM performance. Current performance frameworks and PIs, however, might not be able to properly capture ATM performance in this future operational paradigm [5].

It is also worth noting that a very important aspect in ATM performance management is balancing between various KPAs by including their interdependencies into the analysis. So far, all relevant organizations observe KPAs independently. To the best of our knowledge, there is no performance scorecard to track achievements versus goals, such that also captures the effects of promoting one PI versus other PIs belonging to different KPAs, or even to the same KPA.

Aiming to assess these open questions, the APACHE project aims at providing advanced simulation, optimisation and performance assessment tools with the objective to better capture ATM performance and assess the complex interdependencies among KPAs. New (or enhanced) PIs were already proposed [5], which not only aim to improve current ATM performance assessment, but also are expected to better capture performance in a future ATM paradigm.

A key element in APACHE is the development of a novel ATM simulation system, which is used with two different purposes. On one hand, to synthesize traffic and airspace sce-

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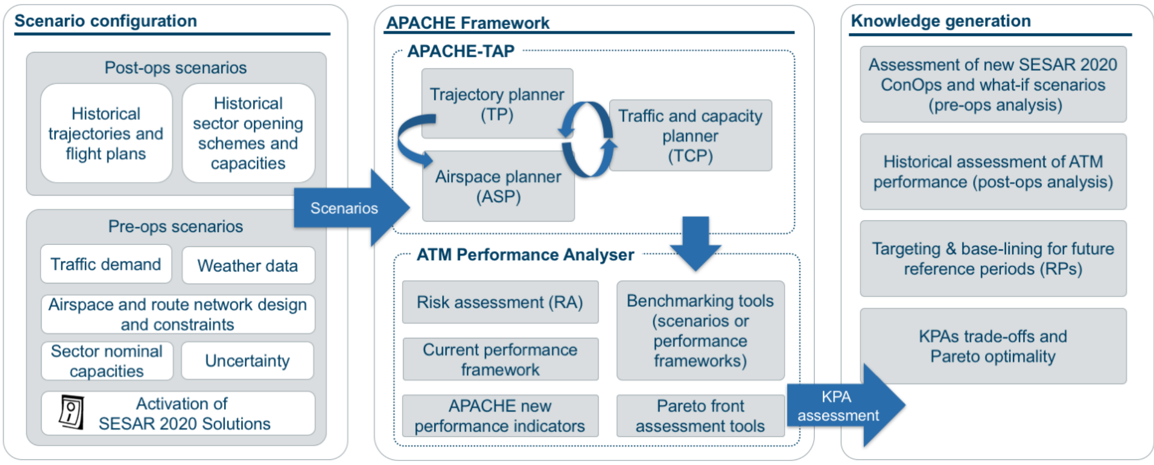


Figure 1. The APACHE framework

narios, simulating different operational contexts and enabling in this way, the possibility to perform *what-if* assessments ("Pre-ops" ATM performance assessment). On the other hand, to provide advanced models and optimisation tools that can support the implementation of novel and more accurate PIs, which can be used for "Pre-ops" but also for "Post-ops" (monitoring) purposes. This paper presents this simulation System and shows some illustrative examples obtained after different software integration and validation tests.

II. The APACHE Project

APACHE (assessment of performance in current ATM operations and of new concepts of operations for its holistic enhancement) is a project funded by the first wave of SESAR 2020 Exploratory Research. The APACHE consortium is formed by UPC (Coordinator), ALG, ENAC and UB-FTTE. The project covers the activity SESAR-11-2015 (ATM performance), started in May 2016 and will run for 2 years.

In this Project a new framework to assess ATM performance based on simulation, optimization and performance assessment tools is proposed. Thus, it is expected to fill some gaps of current state of the art methodologies in ATM performance assessment, aiming to capture the performance impact of ATM operations on different stakeholders taking into account a wide range of KPAs in a holistic approach. The specific objectives of the Project are:

1) to propose new metrics and indicators capable of effectively capturing European ATM performance under either current or future concepts of operation, fostering a progressive performance-driven introduction of new operational and technical concepts in ATM in line with the SESAR 2020 goals;
2) to make an (initial) impact assessment of some SESAR 2020 solutions (PJ06 PJ07-01, PJ08 and PJ09) using the new APACHE Performance Scheme along different KPAs; and
3) to analyse the interdependencies between the different KPAs by capturing the Pareto-front of ATM performance, finding the theoretical optimal limits for each KPA and assessing how the promotion of one KPA may actually reduce (and in which proportion) the performance of other KPAs.

Validation and example case studies are expected to be performed at EU-wide and/or functional airspace block level.

A. Research Approach

APACHE revolves around a novel system that is expected to generate optimal trajectories, considering of the business models of the airspace users; optimal airspace configurations, considering ANSP needs and constraints; and integrate both of them into an advanced air traffic flow management (ATFM) scheme. The same system can be configured to reproduce different modes of operation, representative of current ATM, or simulating some future SESAR 2020 Solutions.

Fig. 1 shows the overall concept of the APACHE framework. First, several scenarios to be studied are defined, setting up different options regarding the demand of traffic, airspace capacities and eventual restrictions; the SESAR solution(s) to be enabled; and the level of uncertainty to be considered. The APACHE-TAP (trajectory and airspace planner), which could be seen as a small prototype of an ATM simulator, has a double functionality in this Project:

- To synthesize traffic and airspace scenarios representative enough of current operations; or emulating future operational concepts in line with the SESAR 2020 ConOps (i.e. one or more SESAR solutions enabled).
- To support the implementation of novel ATM PIs, which require from some advanced functionalities (such as optimal fuel trajectories considering real weather conditions, optimal airspace opening schemes, large-scale conflict detection, etc.)

Then, the performance analyser (PA) module implements all the PIs of the APACHE performance framework, including as well some indicators from the current performance scheme for benchmarking purposes.

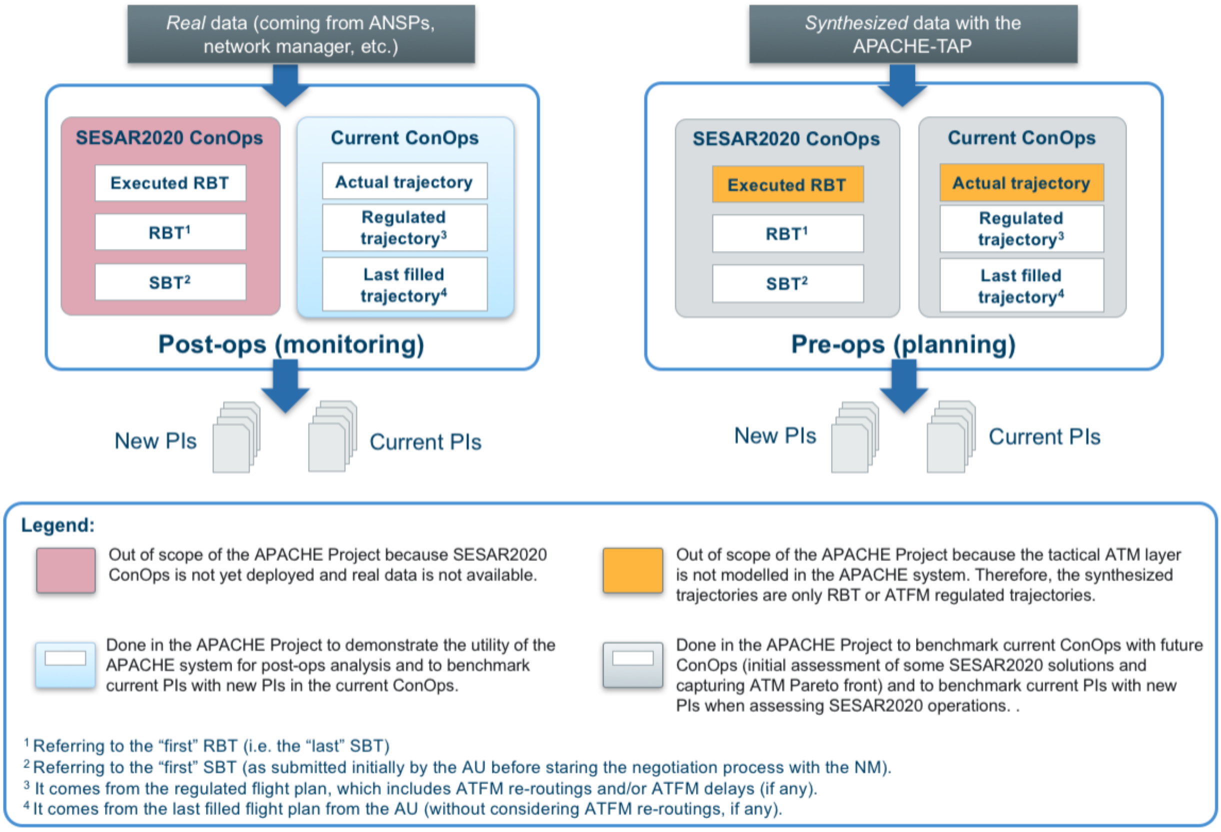


Figure 2. Scope of the ATM performance assessment planned in the APACHE project

B. Scope of the Research

Taking into account the exploratory nature of Project and its short duration, ATM performance at "pre-ops" (planning) level will be only performed for a reduced set of SESAR 2020 Solutions. For benchmarking purposes, some scenarios will enable only certain SESAR solutions (but not all of them at the same time) [9]. Moreover, several assumptions and limitations are present in the implementation of the APACHE-TAP. The most relevant ones are summarised below:

- Only the en-route airspace structure is considered: only the airspace above FL195 (and flights cruising above it).
- The APACHE-TAP does not simulate tactical operations: only AUs trajectory planning, strategic airspace management and ATFM processes (pre-tactical layer) are considered. Moreover, interactions with airports are not taken into account (neglecting delays due to tactical airport operations). Moreover, all delay attributable to AUs (such as maintenance issues) is also neglected.
- Only IFR (instrumental flight rules) traffic is considered.
- Flexible use of airspace (FUA) or advanced FUA concepts are not modelled.
- Remotely piloted aircraft systems (RPAS) and unmanned aircraft systems (UAS) operations are not considered.

Fig. 2 wraps up the scope of the research done in the APACHE project, in terms of ATM performance assessment:

- **"Post-ops" analysis (monitoring)**: the APACHE framework is able to compute a set of PIs for historical data. Ideally, these data should come from the Network manager and/or the different ANSPs. In the context of the APACHE project, this data is taken from Eurocontrol's demand data repository 2 (DDR2) [10]. It contains trajectories according to the last filed flight plan by the AUs (M1 files); regulated trajectories (M2 files); and trajectories as captured in the enhanced tactical flow management system (ETFMS) after the flight has been operated (M3 files). It is expected that this data will be accurate enough to demonstrate the usefulness of the APACHE System.
- **'Pre-ops' analysis (planning)**: Besides being used to support the computation of some PIs (as in the "Post-ops" analysis), the APACHE-TAP is used here to generate (synthesise) the scenarios to be studied. This allows for benchmarking current operations with future concepts and also to capture the Pareto front of ATM performance. Since simulating the tactical layer of ATM is out of the scope of the Project, the APACHE-TAP simulates shared business trajectories (SBT), by modelling the airspace user's behaviour; and reference business trajectories (RBT), by modelling the DCB negotiation process via the Network Manager.

III. The APACHE Framework

As shown in Fig. 1, the APACHE framework consists of the integration of several software modules: those included in the APACHE-TAP and those in the performance analyser (PA).

A. *The APACHE-TAP: traffic and airspace planner*

This module is in charge of simulating trajectories and airspace configurations, either for synthesising hypothetical scenarios, recreating historical data or supporting the PA with essential information to compute certain PIs. All modules composing the APACHE-TAP can be configured either to simulate operations in the current ATM paradigm, or to simulate future operations in line with some SESAR 2020 Solutions.

1) Trajectory Planner (TP): The TP component generates and simulates traffic scenario (4D trajectories) based on real or future traffic demand and weather data. The computed trajectories can be optimised according to different optimisation objectives and constraints, configured in the definition of the scenario. To give a couple of examples, the TP is able to compute the most preferred trajectory for the airspace user in a structured route environment, considering real weather and airspace route charges; or to generate the most environmentally friendly trajectory, needed by the PA to compute certain PIs.

This module, developed by UPC, decouples the optimisation of the lateral and vertical profile, implements a module to model aircraft performance (such as fuel flow and aerodynamic drag magnitudes) and a module to process and model weather data [9], [11]. The principal modes of operation of the TP are:

- **Current operations**: the module is configured to use currently published airways (structured routes) and free route areas (FRA). Data from Eurocontrol's DDR2 is taken. In the vertical domain, current flight level allocation and orientation schemes are used.
- **Full free route**: taking SESAR 2020 solutions PJ06 (trajectory based free routing) and PJ07-01 (AU processes for trajectory definition) [8] to their theoretical limit, this mode of operation will assume that airspace users can freely optimise their trajectories from the origin airport to the destination airport.
- **Continuous Cruise Climbs**: the TP can, eventually, simulate hypothetical future operations where flight level allocation and orientation schemes are removed, allowing continuous cruise climb operations en-route (not a SESAR solution *per se*, but useful as baseline for maximum fuel efficiency flights).

2) Airspace planner (ASP): The main objective of this component is to simulate the airspace management service of the current and future ATM environments. Airspace management services aim to improve airspace design and utilisation in order to ensure delivery of the performance targets for the ATM system. For a given traffic sample and airspace structure with operational limitations, the ASP component finds an optimal sector opening scheme, i.e. an optimal list of airspace configurations or optimal grouping of the Sector Building Blocks (SBB) for each period of time, depending on ATM environment.

This module, developed by ENAC, has two principal modes of operation, as summarised below:

- **Static sectors**: mode according to the current ATM concept of operations, where for each period and for each Air Traffic Control Centre (ACC) one airspace configuration is selected, from the list of predefined set of configurations, consisting of one or more elementary/collapsed sectors. Sector grouping/ungrouping principles are respected by constraints on the airspace configurations that are selected in two consecutive periods. Since, nowadays, each ACC works independently the problem is separable and it's modelled as shortest path problem and solved using dynamical programming method.
- **Dynamic sectors**: simulation of SESAR solution PJ08 (Management of dynamic airspace configurations) allowing airspace to be managed as a continuum in order to make optimum use of available airspace resource. In this mode of the ASP, existing elementary sectors are taken as SBB and grouped into controlled sectors not previously defined and not taking into account ACC borders. To keep stability of airspace configuration to an acceptable level, distance between SBB groupings for two consecutive periods is measured. This problem is modelled as a multi-period graph partitioning problem and solved using evolutionary algorithms ([12]).

More details of the implementation of this component can be found in [9], [11].

3) Traffic and Capacity Planner (TCP): This module, developed by UPC, is in charge of network optimisation by balancing demand and capacity. It has also two main modes of operation:

- **Computer Assisted Slot Allocation (CASA)**: configuration of the module according to current ATM concept of operations, where DCB problems are solved by delaying aircraft on ground following a ration-by-schedule principle [13].
- **Advanced DCB (ADCB)**: simulation of advanced DCB measures enabling some degree of collaborative trajectory planning close to the execution phase aiming at simulating SESAR solution PJ09 (Advanced demand and capacity balancing). In this mode, the TCP will also consider alternative routes, previously proposed by the AUs (ATFM re-routing), and/or flight level capping, and/or linear holding strategies [14]; as alternatives to ground holding for DCB purposes.

B. *Performance Analyser (PA)*

The Performance Analyser (PA) module receives, on one hand, the outputs from the APACHE-TAP in order to compute several PIs for different KPAs; and, on the other hand, might provide some feedback regarding the intrinsic risk of the simulated scenario (traffic patterns and proposed sector opening schemes).

1) Computation of PIs: The PA implements the computation of a wide set of PIs, providing also some visualisation mechanisms to improve the user experience when assessing the results of the different case studies. The PIs implemented in the PA component can be used for 'Pre-ops' assessment, 'Post-ops' assessment, or both.

In [5] a total of 40 new (or enhanced) Performance Indicators (PIs) were proposed, along with 18 possible variants for some PIs, covering a total of 11 KPAs. Taking into account the scope, resources and time-frame of the APACHE Project some of these PIs are not finally implemented in the PA, either because some of them require very complex and mature models, and/or due to the lack of data required to implement them. Nevertheless, they are candidates for inclusion in future evolutions of the APACHE framework. Taking this into account, the APACHE framework finally implements a total of 25 new (or enhanced) PIs and 17 PI variants. Moreover, and for benchmarking purposes, 5 performance indicators of current Performance Framework used by the SES/PRU, and reported regularly in their annual Performance Review Reports (PRRs), will be also computed by the APACHE framework. For further details, the reader is referred to [11].

Note that the APACHE framework could also be set up to monitor and target performance in real-time, or at different time-frames regarding the different traffic and airspace planning phases. These real-time capabilities could contribute to the effective implementation of Performance Based Operations (PBO) in a future ATM in which air traffic and airspace will be planned collaboratively and dynamically in order to adapt the KPA performances of the operations to the uncertain changing conditions of the ATM and weather.

2) Risk Assessment (RA): The RA component, developed by UB-FTTE, has two main objectives: to provide safety feedback on traffic pattern and sectorization provided by APACHE-TAP; and to compute safety PIs. The module is composed by 1) a separation violation detection module; 2) a TCAS activation module; and 3) a risk of conflict/accident assessment module.

The first module compares the separation between two aircraft with a given separation minima (both in horizontal and vertical). Once a conflict is detected, this module calculates its duration and severity. If the situation worsens, the TCAS model is activated, which counts Traffic Alerts, Resolution Advisories, as well as Clear of Conflict warnings.

The risk of conflict assessment module is based on the calculation of 'elementary risk', which is defined as the area between the surface limited by the minimum separation line and the function representing the change of aircraft separation. The risk of conflict is then defined as the ratio between the 'elementary risk' and the observed period of time. Apart from the risk between specific aircraft pairs, an assessment of the total risk in a given sector is also considered.

The conflict/accident risk between aircraft pairs and the total conflict/accident risk depends on airspace geometry, traffic demand, aircraft velocities, spatial and temporal distribution of air traffic in the airspace as well as the applied separation minima. As such, the risk value taken as a safety feedback could suggest changes in flight trajectories and/or changes in sector boundaries, i.e. sector geometry.

More details of the implementation of this component can be found in [15], [16].

IV. Illustrative Examples

Aiming at showing the capabilities of the APACHE System and the successful integration of all components, this section presents some intermediate simulations and preliminary results. It is worth noting that at the moment of finishing this paper the APACHE System was in its last stage of development and testing. According to the APACHE Project schedule, scenario and case studies assessment will take place in the last quarter of 2017.

The test case shown here corresponds to a "pre-ops" analysis done with the traffic demand taken from February 20th 2017, during 24h, and only considering those flights crossing the FABEC airspace. Demand data has been obtained from Eurocontrol's DDR2, including the aircraft type, departure time and origin/destination airports. Since the APACHE Project focuses in the en-route phase, all flights with a requested flight level below FL195 were discarded for the simulations. Moreover helicopter and piston engine aircraft were also discarded, leading to a total of $14,034$ scheduled flights analysed in this test case.

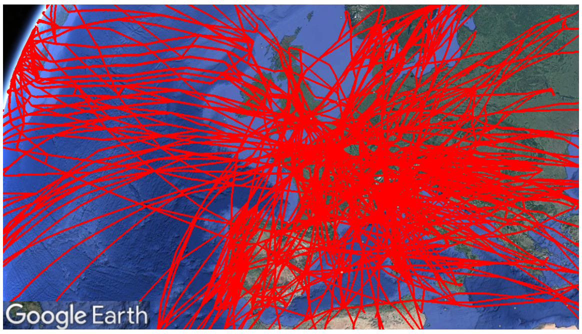
Airspace data, consisting of elementary/collapsed sector and airspace configurations definition, as well as, capacities of the sectors; were also taken from the AIRAC data from the DDR2 supplemented by French national data repository.

A. TP results

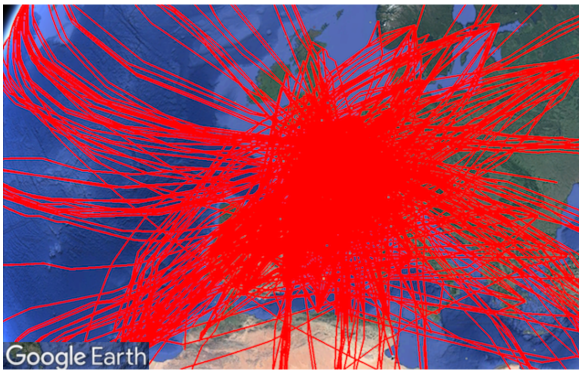
In order to run the TP, weather data for the same day of and region of study was gathered from the Global Forecast System (GFS), a weather forecast model produced by the National Centers for Environmental Prediction (NCEP) and provided in GRIB formatted files. Aircraft performance data, for each aircraft type, was obtained from Eurocontol's BADA v4.2.

As explained before, for "pre-ops" analysis the TP is also used to synthesise the trajectories needed to recreate the scenario to study. For this purpose, each flight has been simulated with a random cost index (CI) and landing mass, following a normal distribution. Depending on the aircraft model, the distribution of the CI has been set assuming that the majority of flights operate at long range cruise (LRC) setting. The normal distribution for the payload mass is centred to 90% of the maximum landing mass, with a standard deviation of 10%.

In order to illustrate the TP capabilities two sets of traffic were synthesised (see Fig. 3): current operations, with structured routes and some FRA; and full free route operations from origin to destination airports. As expected, the spatial distribution for the full free route scenario (Fig. 3(b)) is larger than for the structured route case (Fig. 3(a)), showing also more direct and efficient trajectories (see performance assessment in Sect. IV-D1 below).



(a) Current route structure and free route areas



(b) Full free-route from origin to destination airports

Figure 3. Synthesised trajectories crossing FABEC airspace

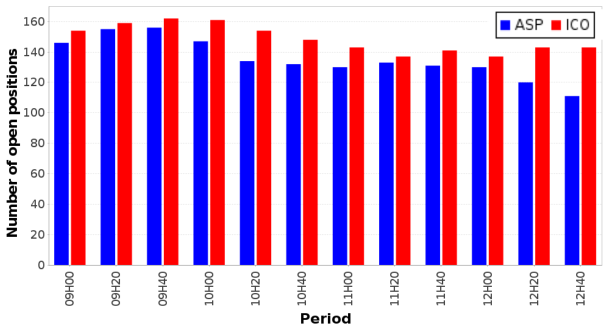
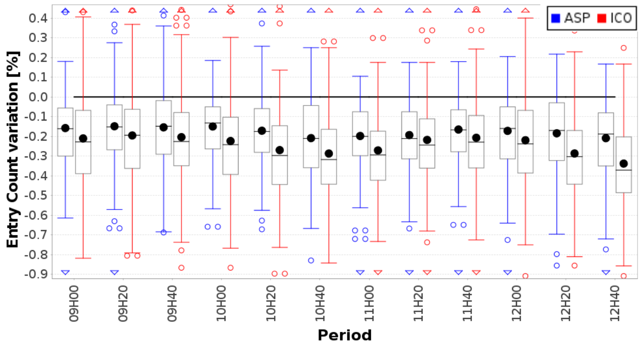
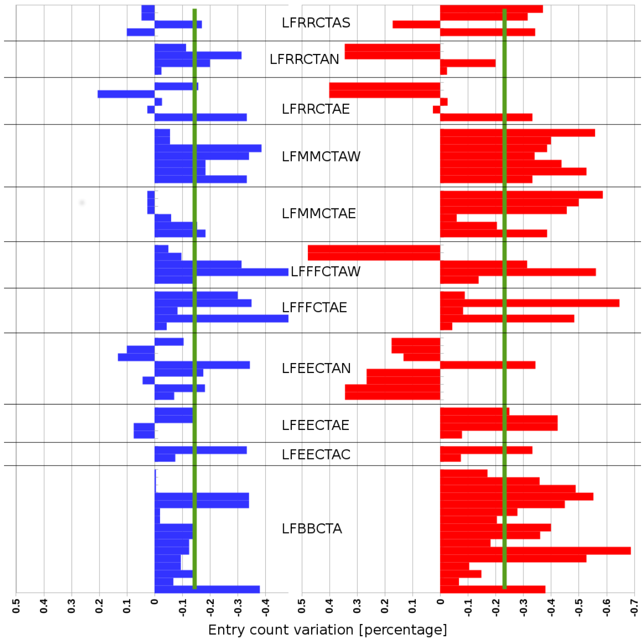


Figure 4. Number of open positions for FABEC airspace



(a) Load distribution per opening period (FABEC)



(b) Detailed sector load comparison for 12h to 13h

Figure 5. Sector load distribution

B. ASP results

Fig. 4 shows the distribution of the number of opened positions in the FABEC airspace during the morning peak of the day of study. The ASP results (blue) are compared with those obtained from NEST ICO tool (red)[1] for validation.

As seen in the figure, there is a high matching between ASP and ICO results. However, due to the higher flexibility of the ASP algorithm airspace configuration is better adapted to the traffic resulting in the lower number of the open positions.

Fig. 5 shows the distribution of the load (overload or underload) of the active sectors, expressed as variation percentage of entry count from capacity value. Fig. 5(a) shows, for each period, a five-number summary of the load distribution, including the Interquartile range - IQR (grey bars), for opening schemes provided by the ASP (blue) and ICO (red). Lower IQR in the opening scheme proposed by ASP signifies smaller dispersion, i.e. more even distribution of the load among active sectors. As shown, load median (black circle in 5(a)) in the ASP opening scheme is always closer to optimal (zero) value that implies higher capacity utilisation and explains lower number of open positions compared to ICO results.

A more detailed analysis is given in Fig. 5(b), showing the distribution of the sector load for a single period of the same example. For the sake of compactness, only sectors from the French airspace are shown, organized in 5 ACC having 11 clusters in total. Blue bars represent ASP results, while red bars represent ICO results. Green lines in the figure represent the mean value of the load. Fig. 5(b) confirms, once more, that ASP opening scheme shows more even distribution of the workload among controllers, represented by smaller deviation

[1]NEST, the Network Strategic Tool from Eurocontrol, is a stand-alone desktop application for airspace structure design and development, capacity planning and post-operations analysis, the organisation of traffic flows, the preparation of scenarios for fast time simulations and *ad-hoc* studies at local and network level.

TABLE I
ADVANCED DCB ALGORITHM RESULTS (FRENCH AIRSPACE)

	Original trajectory	Re-routing	Level capping	Total
Total flights	$6,057$	284	419	$6,760$
Delayed flights	227	20	54	301
Non Delayed flights	$5,830$	264	365	$6,459$

of sector loads from the mean value.

C. TCP results

Once the ASP has generated an optimum sectorisation, trying to better allocate airspace capacity, the TCP is responsible to regulate the demand, avoiding to exceed the maximum capacity in any sector. The illustrative results shown here correspond to the 24h test benchmark described above, but focusing only in the French airspace. Both TCP modes of operation have been tested (current CASA algorithm and advanced DCB).

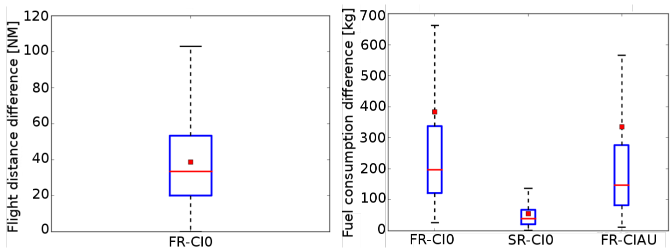
With the CASA algorithm, $2,510$ aircraft were subject to delay with a total system delay of $406,042$ min, leading to 55 min of average delay. The authors acknowledge that these delays are higher than what is commonly seen in the ECAC. The results shown here assume that a sector is regulated when the demand exceeds the published nominal capacity plus a 10% of sector overload allowance. In real operations, however, each hotspot is carefully analysed by the corresponding flight management position (FMP), having different strategies and criteria to finally decide whether a regulation should be applied or not (and which is the sector overload allowance, if any). This detailed behaviour will not be modelled in the APACHE simulator. Nevertheless, results from this *simplified* CASA algorithm could still be valid for benchmarking purposes.

Besides delay, the advanced DCB functionality allows for pre-tactical re-routings or flight level capping as a possible solution to solve the demand-capacity imbalance problem. The extra set of trajectories (avoiding hotspots laterally or vertically) are provided by the TP, emulating a DCB negotiation process with the network manager. Then, the DCB algorithm finds the system-wide optimal solution that minimises the total cost for the airspace users (considering the cost of fuel and an estimated cost of delay).

Table I shows the results, detailing the number of trajectories and delay for each of the three cases. With the advanced DCB algorithm the total departure delay has been significantly reduced (821 min with 301 flights performing delay), but at the expense of allowing less efficient trajectories (re-routings or level capping). This is one of the trade-offs that are subject of study in the APACHE project.

D. Performance Assessment

As illustrative example of the Performance Analyser module, some PIs of the environmental impact and safety KPAs were computed using as input data the set of trajectories following current published structured routes and FRA synthesised by the TP, but filtering for those flights crossing only the French airspace.



(a) Horizontal track inefficiency (b) Fuel inefficiency

Figure 6. Strategic ATM inefficiency (24h traffic over French airspace)

1) Environmental indicators: Fig. 6 shows the PIs *ENV-1.1: Strategic ATM inefficiency on the horizontal track* and *ENV-2.3: Strategic ATM inefficiency on the trip fuel* (see [5] for details).

Essentially, ENV-1.1 compares the horizontal flight distance of the trajectory under assessment (in this case those from Fig. 3(a)) with a *environmentally optimal* baseline trajectory, which in this case was a full-free route trajectory with the Cost Index set to zero and optimized taking into account weather conditions (and therefore, different from the orthodromic trajectory between origin and destination airports). As seen in Fig. 6(a), the average horizontal route inefficiency is approximately 40 NM with particular flights that can reach up to 100 NM of horizontal inefficiency.

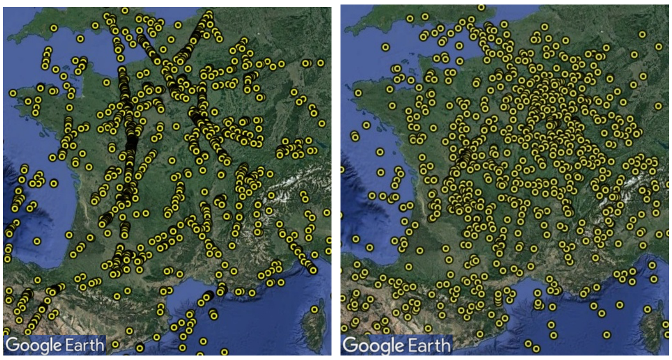
ENV-2.3, in turn, compares the fuel consumption of the trajectories under assessment with the baseline trajectory. As seen in Fig. 6(b), three different baseline trajectories are used (all of them taking into account weather conditions and the corresponding optimal vertical profile):

1) FR-CI0: An optimal full free route trajectory with the Cost Index set to zero.
2) SR-CI0: An optimal trajectory, constrained with current published structured routes and FRA, and with the Cost Index set to zero.
3) FR-CIAU: An optimal full free route trajectory with the same Cost Index as simulated in the assessed trajectory.

If the SR-CI0 trajectory is used as baseline, this PI captures the impact of flying at not optimal altitudes (from an environmental impact point of view), due to the fact that the AU has planned the trajectory at a Cost Index higher than zero (as explained above, following a normal random distribution in our simulations). As seen in the figure, fuel inefficiencies are relatively low (below 100 kg in the majority of flights).

The FR-CI0 variant captures the impact on the environment of flying on structured routes, but also due to the fact that the AU has planned a Cost Index higher than zero. Conversely, the FR-CIAU variant isolates the inefficiency in fuel only attributable to ATM (due to the structured route network). In this case, an average of 350 kg of fuel could be saved if aircraft were allowed to fly full free optimal routes.

2) Safety indicators: A risk assessment was done for the selected day of study and for both sets of trajectories generated



(a) Current route structure (b) Futuristic full free-route

Figure 7. Location of conflicts in French airspace (CPA below 5NM)

TABLE II
SAFETY PIS COMPUTED BY THE RA MODULE FOR FRENCH AIRSPACE

PI	Description	Current network	Full free route
SAF-1	Number of Traffic Alerts	300	131
SAF-2	Number of Resolution Advisories	73	1
SAF-3	Number of Near Mid Air Collisions (NMACs)	50	1
SAF-4	Number of Separation Violations	1376	939
SAF-7	Risk of conflicts/accidents	$5.5 \cdot 10^{-3}$	$3.0 \cdot 10^{-3}$

by the TP but filtering for those flights crossing only the French airspace. Table II shows the results of some safety PIs, as computed by the RA module. The minimum separation values (for SAF-4) were set to 5NM in the horizontal plan and 1000 ft in vertical. Moreover, the simulation time increment was set to 10s. As expected, those indicators are lower for the full free route scenario since potential trajectory crossings are more geographically spread.

Fig. 7 shows the geographical location of the closest points of approach (CPA) that were below 5NM for the example of study. One should keep in mind that CPAs shown are aggregated for 24h, which means that each dot represent a conflict point between different pair of aircraft, at different altitudes and in different time during the day. Also note that even if the test flight set corresponded to flights crossing the French airspace during 24h, CPAs could be located outside this airspace, since the full trajectory was taken into account.

This RA assessment could also be used to easily identify these geographical locations with higher frequency of potential conflicts, which could eventually be used as a safety feedback to amend sector boundaries in the ASP component or to be taken into account for advanced DCB purposes.

V. CONCLUSION

Air traffic management is progressively transitioning to a performance based system, with many key performance areas (KPAs), which show, in the majority of cases, complex and still not well understood interdependences. Properly assessing ATM performance, and conveniently capturing these trade-offs among KPAs, is still a research challenge for the ATM community and a need for correctly deploying novel operational and technical concepts, such those proposed by SESAR.

By combining simulation, optimisation and performance assessment tools, the APACHE framework aims at generating knowledge on the theoretical optimum for each KPA and to assess their Pareto optimality. This will allow a better understanding of the ATM performance drivers and, besides ”post-ops” and ”pre-ops” analysis, it might be useful for targeting and base-lining in future performance reference periods (RPs).

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