# Enhanced Indicators to Monitor ATM Performance in Europe

## Main findings of the APACHE SESAR Exploratory Research project


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***Abstract*—This paper highlights the principal contributions and outcomes of the APACHE Project (a SESAR 2020 exploratory research project) in air traffic management performance assessment for monitoring purposes (post-ops analysis). Novel distance- and fuel-based indicators are proposed to assess environmental impact inefficiencies, taking as input only surveillance data sets. Similarly, novel cost- and trip-time-based indicators are proposed to assess airspace user cost-efficiency. In both cases, optimal trajectories are generated as baselines for these indicators, which are compared with actual (historical) trajectories. Regarding air navigation services cost-efficiency, a similar strategy is presented, where optimal sectorisations are compared with historical sectorisations. The paper also presents new indicators to assess safety from surveillance data in an automated fashion. A couple of indicators to better estimate system capacity are also given, which look at air traffic management delay as proxy. Finally, some illustrative examples are given to show the applicability of all these indicators.**



***Keywords-ATM performance monitoring; post-ops analysis; environmental impact; cost-efficiency; safety; capacity.***


### I. Introduction

The International Civil Aviation Organization (ICAO) launched in 2003 a worldwide initiative to ensure that the future global ATM system is performance driven [1,2]. Consequently, the ongoing ATM modernisation programmes, such as SESAR in Europe and NextGEN in North-America, build on top of this ICAO concept, which has also worldwide support by the Civil Air Navigation Services Organisation [3]. A performance-based approach, as defined by ICAO [2], shall be based on strong focus on desired/required results, informed decision making driven by these desired/required results, and reliance on facts and data for appropriate decision making. This consequently entails the need for new methodologies and tools for performance measurement, performance evaluation and decision support.

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].

The SESAR Programme, in turn, includes research and innovation projects ranging in maturity from exploratory research through to very large scale demonstrations. Within SESAR 2020 Industrial Research activities, Project 19 (PJ-19) is devoted to the Content Integration, with work package 4 (noted PJ-19.04) being responsible for performance management within the Program [5]. The first call of Exploratory Research in SESAR 2020 was released in 2015, including ATM Performance (ER-11-2015), among other topics. One of the awarded projects was APACHE [6], along with INTUIT [7] and AURORA [8] projects.

The INTUIT project was focused in using data science for discovering and modelling unexpected patterns in some key performance areas (KPAs). The project made an initial exploration of the potential of visual analytics and machine learning for understanding performance trade-offs. In addition, some cause-effect relationships were identified between indicators and new support tools for ATM performance monitoring and management were developed. The AURORA project, in turn, explored new performance indicators assessing the operational efficiency of the ATM from the airspace user's point of view. The core for these new indicators were automatic dependent surveillance-broadcast (ADS-B) data and a set of basic user-preferred trajectories.

The APACHE Project proposed a new framework to assess ATM performance, making use of simulation, optimisation and performance assessment tools. A wide set of new (or enhanced) ATM performance indicators (PIs) were proposed in several KPAs. The aim was to bridge some gaps with current state-of-the-art methodologies, which have shown important limitations to proper capture performance. These limitations are mainly due to the lack of availability or quality of the input data required; or because the implementation of too simple models in the computation of these indicators. In fact, ATM performance often is assessed by using proxy indicators, which in some cases is difficult to draw clear conclusions [9]. APACHE not only focused to improve current ATM performance assessment, but a significant effort was devoted to propose new indicators (or enhance existing ones) aiming at better capturing performance in a future ATM paradigm, with several new SESAR solutions implemented.

In [10], the APACHE project objectives and main methodology was presented. This current paper, in turn, summarises the principal contributions of the APACHE Project in ATM performance assessment for monitoring purposes (post-ops analysis) in the KPAs of environmental impact, cost-efficiency, capacity and safety.

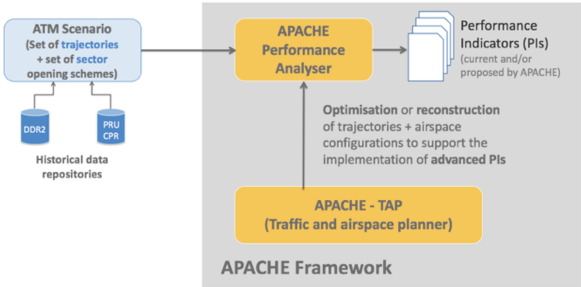



Figure 1. APACHE methodology for post-ops assessment

## II. APACHE Methodology for Post-ops Analysis

Two types of performance assessment were foreseen in APACHE: **"Post-ops"** (monitoring) analysis, where the scenarios under study were gathered from historical data; and **"Pre-ops"** (planning) analysis, over synthesised scenarios with the purpose to enable "what-if" studies, the (initial) assessment of the impact of some SESAR 2020 solutions, or the assessment of different ATM performance trade-offs. This paper focuses in the "post-ops" assessments.

Fig. 1 shows a block diagram summarising the methodology used. The performance analyser is the core module of the Framework, which receives the set of historical trajectories and airspace sectorisations subject to study (post-ops scenario) and implements all the performance indicators (PIs) of the APACHE Framework; including, as well, some indicators from the current Performance Scheme for benchmarking purposes.

Some PIs computed by the APACHE performance analyser require complex computations, such as optimized trajectories or optimized airspace sectorisations. This advanced functionality is provided by the APACHE-TAP (trajectory and airspace planner). Details on this methodology can be found in APACHE project deliverables D3.1 [9], D3.2 [11] and D4.1 [12]. Next, the two principal functionalities of the APACHE-TAP, when used for post-ops assessments, are summarised.

### A. *Trajectory optimisation.*

The APACHE-TAP is able to optimise large amounts of trajectories for ATM performance assessments. The computed trajectories can be optimised according to different optimisation objectives and/or constraints, which are then used to build PIs designed to capture different performance factors.

For example, the APACHE-TAP is able to compute the most preferred trajectory for the AU in a structured route environment (i.e. considering airways), using real weather forecasts and taking into account airspace route charges (needed to compute certain AU cost-efficiency PIs). Furthermore, it is also capable to compute the most environmentally friendly trajectory, regardless of current ATM constraints, assuming for instance a full free route environment and/or continuous cruise climb operations (needed to compute certain environment PIs).

This 4D trajectory optimisation functionality [14] has been developed by UPC and embeds a model of aircraft performance based on Eurocontrol's BADA 4.1 [13] and a module to process realistic weather data, taken from the global forecast system (GFS) models provided by NOAA (National Oceanic and Atmospheric Administration).

### B. *Sector optimisation*

The APACHE-TAP is able to optimise airspace sectorisations, also for ATM performance assessments. The sectorisation problem considering current practices, which consist of finding optimal opening schemes where for each period of time one airspace configuration is selected among a finite list of options, is modelled as a Shortest Path problem and solved using a Dynamic Programming method [15]. Moreover, the sectorisation problem implementing 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 and finding the optimal grouping of the sector building blocks for each period of time, is modelled as multi-period geometric graph partitioning problem and efficiently solved using heuristic method as reported in [16].

This sector optimisation functionality has been developed by ENAC and more details can be found in [11].

## III. Proposed Indicators and Main Contributions

The APACHE Project initially tried to cover all key performance areas (KPAs) defined in the SESAR 2020 Performance Framework [17]. A total of 89 new, or enhanced, performance indicators (PIs) were proposed in the Project (see [9] for details). Among them, 16 PIs were not finally implemented in the APACHE Framework, due to its low level of maturity and/or to the lack of data required to implement or validate them. Nevertheless, they are candidates for implementation in future evolutions of the APACHE Framework. Thus, in the context of the Project, a total of 73 new (or enhanced) PIs were finally implemented in the following KPAs: 45 PIs for Environment; 12 PIs for Cost-efficiency[1]; 7 PIs for Safety; 3 PIs for Capacity; 2 PIs for Equity and 4 PIs for Flexibility.

[1] Within the Cost-efficiency KPA, the SESAR 2020 Performance Framework defines two focus areas: one for the Airspace User (AU) cost-efficiency and another for the air navigation services (ANS) cost-efficiency. APACHE proposed 10 PIs in the former and 2 PIs in the latter.

PIs for Equity and Flexibility were initially designed to capture performance in their respective areas once the SESAR 2020 concept of operations would be in place, in particular under the trajectory based operations paradigm. Since they were validated using only historical data, their full potential in post-ops could not be shown. For similar reasons, some PIs in other areas proved not suitable for current operations or did not show a remarkable advance with respect to the state-of-the-art indicators when analysing historical data.

This section summarise the most relevant contributions done for the first four KPAs enumerated above. Section IV shows the results of some illustrative assessments.

*A. Environment KPA*

The main contribution in the environment KPA was to propose indicators that take into account optimal trajectories as baselines to capture environmental flight inefficiencies measured in terms of extra distance flown or extra fuel burnt.

Thus, distance (or fuel consumption) was firstly estimated from historical trajectories. Then, these figures were compared with the distance (or fuel consumption) obtained from optimal trajectories generated with the APACHE-TAP (see Fig. 1), which takes into account the historical weather conditions.

Current state-of-the-art indicators used in the SES PRU (Single European Sky Performance Review Unit) compute these inefficiencies by comparing the actual or planned trajectory with the geodesic distance (i.e. the minimum ground between origin and destination airports) . The SESAR 2020 PF, in turn, already proposes fuel-based indicators, but for pre-ops assessment only (i.e. when both reference and solution trajectories are synthesised and therefore, the fuel consumption can be easily computed). The main contribution in APACHE was to extend these concepts for post-ops analysis, where fuel is estimated only from observed surveillance data from the AUs, such as the mass of the aircraft or the cost index.

The new environment PIs proposed in APACHE are divided in two big families: distance-based indicators and fuel-based indicators. Each family has several indicators aiming to capture different sources of environmental inefficiencies, such as inefficiencies in the vertical or lateral domain of the trajectory (only for ENV-2.x) or inefficiencies due to different layers of the ATM (strategic, tactical or both). Moreover, each of these indicators, in turn, can be computed by using different baseline reference trajectories, allowing to better isolate the different sources of environmental inefficiencies, leading at the end to 45 different indicators for the Environment KPA.

*1) Distance-based indicators*: which are easier to compute if compared with fuel-based indicators. Yet, they cannot capture inefficiencies in the vertical domain, so they could not either capture benefits of certain SESAR 2020 solutions that aim to improve vertical flight efficiency. These indicators, however, represent already a step beyond current state-of-the-art indicators used by the SES PRU for monitoring purposes, which use geodesic distances as baselines for the indicators (the geodesic route is not always the optimal route if realistic weather conditions are taken into account).

*2) Fuel-based indicators*: trying to estimate the flight inefficiencies in terms of extra fuel burnt, which is directly proportional to the $CO_2$ emissions. They have the advantage to be a more direct estimate on the environmental impact but their computation is more difficult since they require complex fuel estimation algorithms, since fuel is estimated only from observed surveillance data. In APACHE, the algorithm proposed in [18], enhanced with a Savitzky-Golay filter and using Eurocontrol's Base for Aircraft Data (BADA) version 4.1, was implemented to estimate fuel from surveillance data.

*B. Airspace User (AU) Cost-Efficiency Focus Area*

The main contribution of APACHE in the AU cost-efficiency focus area was to propose indicators that take into account flight time inefficiencies and direct operating costs inefficiencies, using, as done in Environment KPA, optimal trajectories as baselines for these PIs.

Current state-of-the-art indicators used in the SES PRU compute the share of regulated flights as a macroscopic measure of the system efficiency. The SESAR 2020 PF, in turn, proposes similar AU cost-based indicators, but for pre-ops assessment only (i.e. when both reference and solution trajectories are synthesised and therefore the AU related cost can be easily computed). Like in the Environment KPA, the main contribution in APACHE was to extend these concepts for post-ops analysis, where AU cost is estimated only from surveillance data. This means that estimation of flight costs might not be accurate for certain AUs or flights, but these indicators are still very useful for relative comparison between two or more scenarios or case studies. A similar initiative is presented in [19], where user-centric cost-based efficiency indicators are also presented.

The new AU cost-efficiency PIs proposed in APACHE are divided in two big families: cost-based indicators (CE-1 family) and trip-time-based indicators (CE-4 family). Each family has several indicators aiming to capture AU cost-inefficiencies due to different layers of the ATM (strategic, tactical or both) or can be computed by using different optimal trajectories as baseline "optimal" references to compute the PI. This variability leads, at the end, to 10 different indicators for this focus area.

*1) Cost-based indicators*: which try to estimate the inefficiencies in terms of direct operationg costs for the AUs. Like fuel-based indicators presented in section III.A.2, they represent a more direct estimate on the impact for the AU, but require complex cost estimation algorithms to be computed. In APACHE, this cost is estimated in terms of estimated fuel consumption (using the estimation algorithms described above); cost associated with extra flight time (tactical cost of time computed by a given cost index); and cost of air traffic flow management (ATFM) delay, taking the simple linear model proposed in [20].

*2) Trip-time-based indicators:* which are much easier to compute, if compared with cost-based indicators, and directly capture performance in one of the aspiration levels set in the ATM Master Plan [21]: trip-time. Although trip-time is one of the key aspects in the AU cost-breakdown structure it is not the only one and therefore, this PIs may show partial information of the ATM System performance.

### *C. Air Navigation Services (ANS) Cost-Efficiency Focus Area*

The main contribution of APACHE in this focus area was to propose new approaches to estimate the cost of providing ANS. In this context, 2 PIs were proposed:

- Sectorisation costs: trying to capture if the airspace is sectorised in the optimal way, by comparing the actual/planned opening scheme with the optimal opening scheme generated by the APACHE-TAP (see Section II.B).
- Flights per air traffic control officer (ATCO) hour on duty, which evaluates the overall amount of flights handled versus the total number of hours of ATCOs on duty.

### *D. Safety KPA*

In the Safety KPA, APACHE proposed some new indicators compliant with the Performance Objective One stated in [22]: Reduction of loss of separation incidents both horizontally and vertically by focusing on system risk, which can be estimated in pre-tactical phase in order to identify hotspots on the network and take measures to increase safety.

The SES PRU is currently assessing a range of PIs in the field of safety, e.g. number of accidents and serious incidents, number of reported unauthorised penetrations of airspace, number of reported separation minima infringements, etc., among which two are used as KPIs: *total commercial air transport accidents*; and *the number of accidents with air navigation service contribution*. All PIs are based on the reports of accident/incident investigations (reactive safety approach) and are aggregated at annual level. Conversely, APACHE proposed 7 PIs which are measurable either in pre-ops simulations or automatically analysing post-ops traffic.

These post-ops PIs could be measured in a real system on a daily or hourly level, and are not dependent on accident/incident reporting (i.e. proactive safety approach). They are given as counts of specific occurrences: Traffic Alert (TA) warnings (SAF-1), Resolution Advisories (RA) issued (SAF-2), Near Mid Air Collisions (NMAC) (SAF-3). TAs/RAs, NMACs occur very often. So, count of those occurrences could be a good proxy of what could happen in the airspace. Of course, TAs/RAs, NMACs are based on anticipation of distance at closest point of approach (CPA) between two aircraft when this anticipation is time-based. Similarly, the number of potential separation violations (SV) i.e. conflicts, is used to indicate safety (SAF-4). Its determination is based on actual distance between two aircraft and depends on separation minima applied.

All these indicators (SAF-1 to SAF-4) could be also given as rates of specific occurrences, i.e. as counts normalized by the number of flights or total flight hours through the given airspace showing in such a way demand and complexity level in a given airspace. More details are given in [23].

Regarding SAF-1, SAF-2, SAF-3 and SAF-4 indicators, they may rely on reporting by the airlines and ANSPs, but it is more likely to expect that they might be reluctant to disclose information on alerts triggered. In order to avoid getting unreliable results from the incomplete reports, the APACHE System aims at performing post-ops analysis by simulating realised (executed) traffic. In such a way, indicators are derived based on the TAs, RAs, NMACs and SVs that should have been occurred under the given conditions, regardless of whether they have been or not reported.

### *E. Capacity KPA*

The main contribution of APACHE in the capacity KPA is twofold: first, proposing a new indicator to be considered jointly with the existing SES PRU indicator (*Average en-route ATFM delay per flight),* that complements information lost due to delay averaging; and secondly, proposing a new indicator as a replacement of the existing one, in line with SESAR trajectory based operations paradigm.

The current indicator used by the SES PRU computes yearly average en-route delay per flight caused by the ATFM. Considering current ATFM measure of slot allocation explains use of ATFM delays as a proxy for the capacity, since any imbalance between ATC capacity and demand directly materializes in ATFM delays. This approach, however, presents several drawbacks that were discussed in [9]. The new indicator, CAP-1 (*Robust maximum en-route delay*), proposed in APACHE aims at complementing information loss of SES PRU indicator due to delay averaging. Naturally, the indicators are considered as post-operational. Yet, considering the APACHE framework capabilities to synthesize scenarios, these concepts could be extended for pre-ops analysis too.

In line with SESAR trajectory based operations paradigm, initial shared business trajectory may be changed spatially and/or temporally in the search for the system acceptable solution (agreed RBT), through the collaborative decision-making process. The use of the existing SES PRU indicator might be insufficient since not all operational penalties are captured. In APACHE, the concept of the average (departure) en-route ATFM delay is extended to the average arrival delay (CAP-2), aiming to capture total delay compared to the user preferred route caused by slot allocation, rerouting, speed/level change, etc. According to the SESAR 2020 concept of operations, trajectory information will be available for the pre- and post-ops analysis. Conversely, in current operations the only means to identify the agreed (regulated) trajectory for the pre-ops analysis is by simulation, which is the main contribution of the APACHE framework. This is even more true for the "real" initial user demand that is usually unknown but could be regenerated using APACHE-TAP capabilities and knowing to some extent the AU business models.

# IV. ILLUSTRATIVE RESULTS

This section presents some illustrative results assessing post-ops ATM performance with the indicators proposed in the previous section. Two scenarios are analysed, each one with 24h of historical flown trajectories and realised airspace sectorisations. A first scenario corresponds to July 28th 2016 (high demand), while the second to February 20th 2017 (low demand). Data were extracted from Eurocontrol's DDR2 database [24], except for safety indicators, where the data analysed were taken as well from the (much more accurate) correlated position reports from Eurocontrol's PRU [25]. All assessments shown in this paper only considered FABEC airspace and the trajectories crossing it during the day of study.

## *A. Environment KPA*

As explained in Section III.A, APACHE environment indicators capture flight inefficiencies by comparing the actual trajectory with an optimal trajectory baseline. In this study, this baseline has been computed assuming a full free-route airspace, with a flat-rate for en-route charges, imposing maximum range operations (i.e. cost index zero) and using the historical weather conditions for the day of study[2].

Fig. 2 shows the environmental inefficiencies computed with the APACHE distance-based PIs for the summer day under study. Different PIs are proposed to capture different sources of inefficiency, decoupling those inefficiencies originated from the tactical and strategic layers of ATM. Respectively, these are inefficiencies due to ATC interventions or to the fact that AUs are still limited to plan the majority of their flights in a structured en-route networks (airways).

For the day of study, the total inefficiency has a median (green horizontal bar) around 42 NM (around 8% in relative terms if compared with the total route extension), mostly due to the strategic part of the ATM (the fact that AUs are still forced to use a structured en- route network). In fact, it is worth noting how the tactical layer introduces, for most of the flights, a "negative inefficiency", meaning that ATC contribute to reduce route extension by short-cutting the planned trajectory. The average values (black diamonds) are higher (almost 50 NM for the total mean inefficiency) due to the fact that few flights experience high route inefficiencies.

Fig. 3 shows the same assessment using fuel-based PIs. An advantage of the fuel-based indicators proposed in APACHE is the possibility to decouple the vertical and horizontal sources of fuel inefficiency, besides differentiating, as well, inefficiencies originating in the tactical layer or the strategic layer of the ATM. This leads to 9 different indicators, as observed in Fig. 3.

[2] It is worth noting that since different airlines may have different cost index preferences, their optimum trajectory might still present some flight inefficiencies from the environment point of view, as a consequence of flying faster than the maximum range operations. This portion of the flight inefficiency cannot be attributed to ATM, but is included in the aggregated results presented in this section. Further work is underway to de-couple these sources of environmental impact flight inefficiency.

As observed in Fig. 3, the total inefficiency has a median around 350 kg (around 11% in relative terms), mostly due to the strategic part of the ATM, as we already observed with the distance-based indicators. Here we also observe higher average values (around 400 kg or 14%) due to the fact that few flights experience high route inefficiencies.

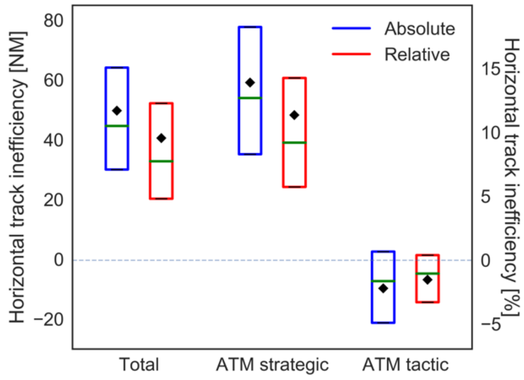



Figure 2. Distance-based flight inefficiency (Jul 28th 2016, FABEC)

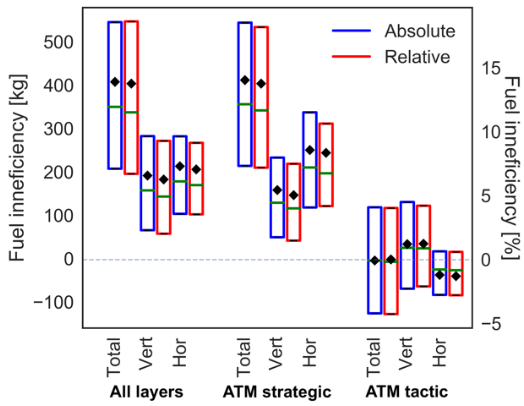



Figure 3. Fuel-based flight inefficiency (Jul 28th 2016, FABEC)

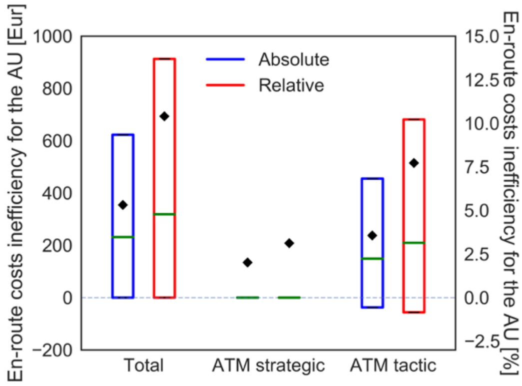
Strategic inefficiencies on the route (i.e. the effects of route restrictions and structured route networks) are clearly above strategic inefficiencies on the vertical profile (i.e. the impossibility to fly at the optimal planned altitudes). At tactical level, however, we see that route inefficiencies are most of the time negative, meaning the ATC is actually shortcutting most of the flights, while we still have some positive (on average) vertical flight inefficiency due to ATC intervention.

In [26] more results are given using different trajectory baselines to compute the performance indicators, which allows to capture even more sources of inefficiency, such as those inefficiencies attributable to the AUs by flying faster than maximum range operations; or those due to the fact that cruise is constrained at constant altitude(s), instead of performing a continuous climb; among others. Similar results are found for the second case study (historical data from 20th Feb 2017).

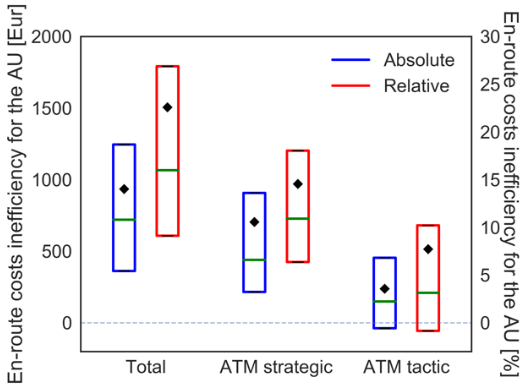
## *B. Airspace User Cost-Efficiency Focus Area*

APACHE AU cost-efficiency indicators also compare the actual trajectory with an optimal trajectory baseline.

Fig 4. a) shows the inefficiencies when this baseline is set to the last filed flight plan by the AU (the first SBT according to the SESAR 2020 ConOps). This is an important hypothesis, since we are assuming that the last filed flight plan is what really the AU would like to fly and therefore, any deviation from this flight plan is considered a cost-inefficiency of the ATM system. This assumption will hold true perhaps in the future if we are able to effectively capture the first SBT submitted by the AU. In present operations, however, it is not always the case that the last filed flight plan by the AU truly represents its real intentions, since, for example, they might intentionally submit a flight plan avoiding a certain airspace likely to experience congestion




a) Optimal baseline set to the last filed flight plan




b) Optimal baseline computed assuming a full free-route airspace

Figure 4. Cost-based flight inefficiency (Jul 28th 2016, FABEC)

As observed in Fig. 4 a), the total trajectory cost inefficiency has a of 230 EUR (4.8% of the total flight cost). The figure also shows the cost-inefficiency due to the ATM strategic layer. Since, at present, regulated trajectories are the same as planned trajectories plus an ATFM delay (if any), these strategic inefficiencies are directly the cost, for the AU, of the ATFM delay. As seen in the figure, the median is zero (meaning that more than the 50% of the flights were not delayed) and the average value is 134 EUR (3.1%). In this context, it is worth noting that although some equity indicators were initially proposed in APACHE, they maturity level is still too low and are out of the scope of this paper. Fig. 4 a) also shows cost-inefficiencies due to the tactical layer, which introduces much more variability in the indicator penalising the majority of flights with extra costs (due to extra trip fuel and/or time) and rewarding few of them due to ATC short-cuts.

Fig. 4 b) shows the same assessment, but when the baseline trajectory is an ideal full-free route trajectory (from origin to destination) flown at the AU desired cost index (which is estimated from the actual trajectory). As observed in the Figure, the cost inefficiencies increase, since the extra cost due to flying with a static en-route network (instead of flying free routes) is accounted in the indicators.

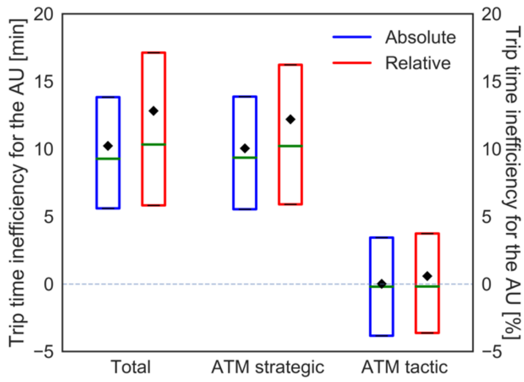



Figure 5. Trip-time-based flight inefficiency (Jul 28th 2016, FABEC)

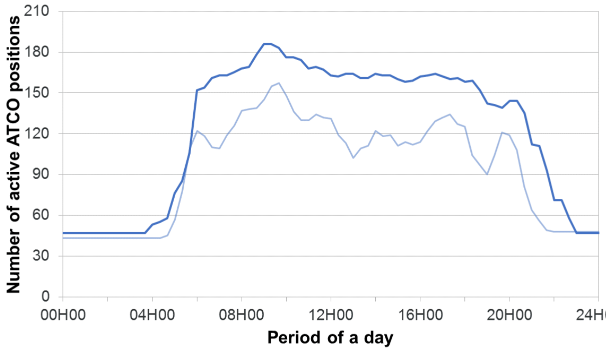
Fig. 5 shows the assessment of the day under study when using the AU time-based cost indicators, when the baseline trajectory is an ideal full-free route trajectory (from origin to destination) flown at the AU's desired cost index. We can observe, on one hand, the flight time inefficiencies due to the ATM strategic layer (i.e. due to the fact that aircraft are constrained to follow published airways) and, as observed before, positive/negative time inefficiencies due to ATC intervention at tactical level. The median of the strategic flight time inefficiencies are around 10 minutes (11% in relative terms with respect to the total flight time).

Similar results are found for the second case study (historical trajectories from 20th Feb 2017).

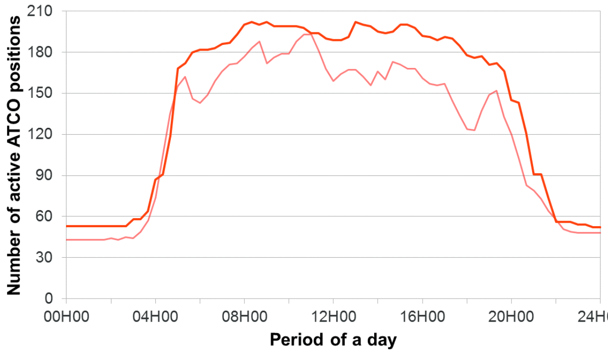
### *C. Air Navigation Services Cost-Efficiency Focus Area*

The proposed indicators were able to capture the effects of seasonal demand (analysing one full day of operations in summer and another in winter), showing that the cost-efficiency in terms of sectorisation costs is higher for the summer day assessed rather than for the winter day.

Fig. 6 shows the number or active ATCO positions compared with the optimal number of these positions, as computed by the APACHE-TAP (see Section II.B). In winter (Fig.6 a)), much lower sectorisation costs could be achieved using the optimal airspace sectorisation. However, this cost reduction is not visible in reality. With the increase of the traffic demand (summer day) the cost of the optimal sectorisation scheme is increased as well (see Fig. 6 b)), driven by the main ATM objective to accommodate demand without imposing significant penalties to the traffic. Therefore, the summer case study requires higher optimal sectorisation costs than the low demand. However, the increase in the optimal sectorisation cost is not followed by a proportional increase in actual sectorisation cost, which is why the summer case study shows higher cost-efficiency.



a) Winter day (Feb 20th 2017)



b) Summer day (Jul 28th 2016)

Figure 6. Sectorisation cost (FABEC)

## D. Safety KPA

An example comparison of some post-ops safety PIs (SAF-1 to SAF4) is given in Fig. 7. PIs are compared for different traffic demands: summer day (S001) and winter day (S003) using Eurocontrol DDR2 data as input; and the same summer day using Eurocontrol PRU CPR data as input.

PRU data comes from correlated position reports obtained from the different ANSPs (radar tracks) [25]. Conversely, DDR2 trajectories are based on reconstructed flight plans and if the actual trajectory deviated more than 20NM in lateral or 700ft in vertical, these differences are shown in the DDR2 trajectory, otherwise, the flight plan reconstructed trajectory is recorded [24]. In other words, potential ATC intervention at tactical level (i.e. in the executed trajectory) is not seen in DDR2 data if these interventions lead to trajectory changes below the thresholds (typically the case to solve a conflict). For this reason, SAF indicators show greater number of apparent conflicts and other safety events with DDR2 data. Many of them, however, did not happen.

Figure Fig. 8 shows the geographical distribution of SAF-4 (number of separation violations) for the summer day of historical PRU CPR operations, showing 24 hour of aggregated data in a single figure. The main conclusion from our analysis based on comparison between DDR and PRU data is that difference between them exists – PRU data are more accurate, as well as that SAF indicators are sensitive to "accuracy" of input data in the context of aircraft position.

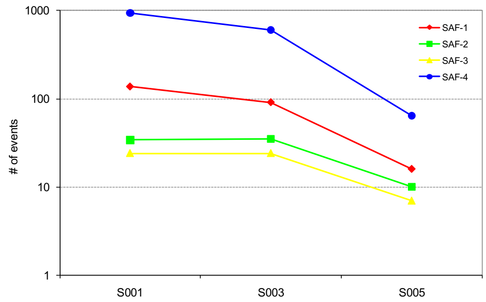


Figure 7. Comparison of the different safety PIs

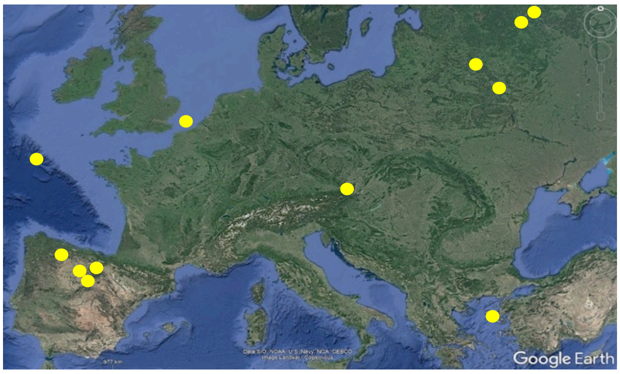


Figure 8. Spatial distribution of SAF-4 (PRU CPR data)

## E. Capacity KPA

Comparative post-ops analysis of the system performance in the capacity area is performed for two chosen traffic demand scenarios. Fig. 9 shows the distribution of the ATFM delays and the value of the existing PI (in blue) and the indicator proposed in APACHE (in red).

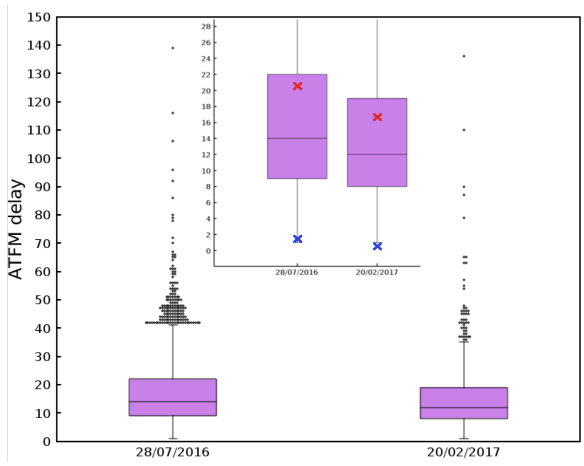


Figure 9. Distribution of the ATFM delay and capacity PIs

As discussed in [26], measuring the ATM system capacity using the proposed macroscopic indicators based on a single-day case study is difficult, due to the high sensitivity to individual ATC sector demand (themselves dependent on origin/destination pairs and on route distribution). In this analysis it is appreciated that the reduction of the current indicator is not followed by a proportional reduction of the APACHE indicator, which does not signify an increase in system capacity, but it is linked to the way how the current indicator is measured. This could be caused by: a decrease in the total delay due to lower traffic (as in this experiment), or a decrease in average delay due to an increase of the traffic in the areas of the low traffic demand. This confirms the hypothesis that system capacity increase must be followed by a significant reduction of both indicators at the same time.

The main conclusion from the analysis is that ATM system capacity is more adapted to the traffic demand (in the size and distribution) represented by the low traffic-demand case study.

## V. Conclusion

APACHE is a SESAR 2020 Exploratory Research project that has explored the potential of advanced simulation and optimization tools to improve air traffic management (ATM) performance assessment across a wide range of key performance areas (KPAs).

Several new (or enhanced) performance indicators have been proposed, showing they applicability to better capture ATM performance under either current or future concepts of operation, with the aim to enable a progressive performance-driven introduction of new operational and technical concepts in ATM, in line with the SESAR 2020 goals.

Moreover, the APACHE methodology can be used to better estimate the theoretical optimal limits for certain KPAs, under different optimality assumptions, supporting in this way a better target setting (or aspiration levels) in ATM performance. The APACHE framework enables proactive and predictive analysis of the current and future ATM system, as a first step towards Performance Based Operations.

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