Results from simulations and analysis of results

Deliverable D5.1

APACHE

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APACHE

ASSESSMENT OF PERFORMANCE IN CURRENT ATM OPERATIONS AND OF NEW CONCEPTS OF OPERATIONS FOR ITS HOLISTIC ENHANCEMENT

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Abstract

This document presents the results from validation exercises of the APACHE Project. Its purpose is to identify, describe and assess the results generated by the different assessments and simulations carried out towards the fulfilment of the objectives of the Project. The APACHE Project proposes a new framework to assess European ATM (air traffic management) performance based on simulation, optimization and performance assessment tools. This framework implements new (or enhanced) performance indicators (PIs) aiming at bridging some of the gaps identified in current state-of-the-art methodologies in ATM performance assessment. Furthermore, this Framework can also be used to better identify interdependencies and trade-offs between different key performance areas (KPA).

In order to validate these new PIs and the proposed methodology, one post-ops and four pre-ops scenarios have been assessed (analysing historical and simulated/synthesised data, respectively). Pre-ops scenarios are designed to perform an initial assessment of certain SESAR 2020 solutions and to test the appropriateness of the APACHE PIs to capture ATM performance in the future concept of operations envisaged by SESAR 2020. Each scenario is composed, in turn, by several Case Studies, mainly to assess the sensibility to different air traffic demand levels and different quality of the input data. Moreover, ad-hoc "a priori" case studies have also been conducted to assess specific trade-offs between KPAs. Finally, some of the PIs currently used by the SES Performance Scheme have been implemented for benchmarking purposes. Results show the appropriateness of the new PIs proposed by APACHE, especially for the Cost-efficiency, Environment and Safety KPAs. PIs for Access and Equity, Capacity and Flexibility represent indeed a contribution beyond current practices, but deserve more research and fine-tuning to raise their maturity level.

[1] The opinions expressed herein reflect the author's view only. Under no circumstances shall the SESAR Joint Undertaking be responsible for any use that may be made of the information contained herein.

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1 Introduction

The APACHE Project covers the topic ER-11-2015 – ATM Performance within the area of ATM (air traffic management) Operations, Architecture, Performance and Validation and proposes a new approach based on simulation, optimization and performance assessment tools, which aim to better capture ATM performance (by means of new or enhanced performance indicators), as well as the complex interdependencies between key performance areas (KPAs). In this context, a new platform (the APACHE Framework) has been developed in the Project, which is the result of the integration (and enhancement) of different existing tools previously developed by some of the APACHE consortium members.

1.1 Purpose, context and scope of the document

This Deliverable *D5.1 – Results from simulations and analysis of results*, as part of the work package (WP) 5: *WP5 – Simulation and Assessment,* aims to identify, describe and assess the results of the different validation exercises and case studies conducted by the Project.

As it is shown in Figure 1-1, this document takes as main inputs the work carried out in WP4 (Development of the APACHE framework), which was reported in Deliverable D4.1 (APACHE Consortium, 2018a); and in WP2 (Scope and definition of the concept of operations), where the high-level requirements for the Project validation were stablished, aligning them with the SESAR 2020 terminology and the SESAR future concept of operations.

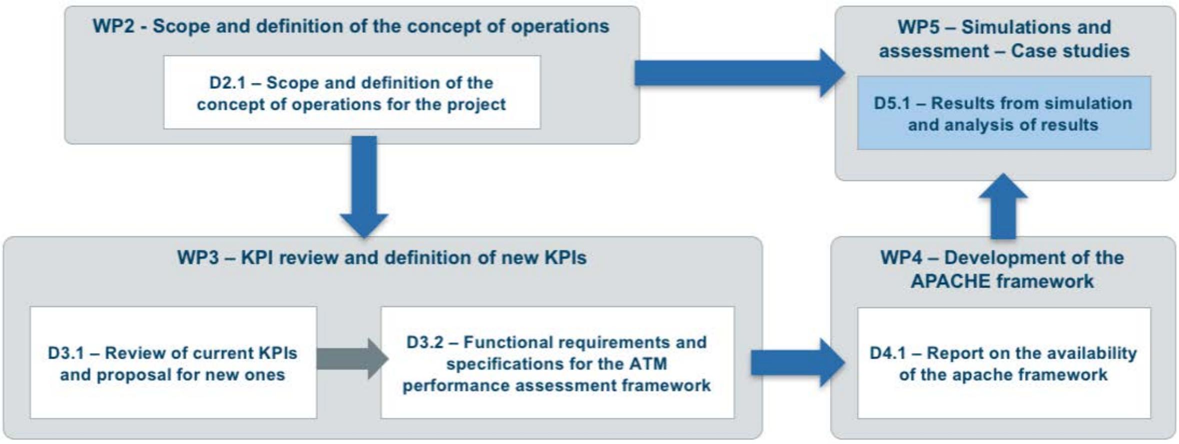


Figure 1-1. Context of deliverable D5.1

1.2 The APACHE Framework

As reported in the APACHE Project Deliverable D3.2 (APACHE Consortium, 2018b), The APACHE project revolves around a novel framework that is expected to generate optimal trajectories, considering 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 enabling System can be configured to reproduce different modes of operation, representative of current ATM, or simulating (with certain limitations) the influence of future operational concepts.

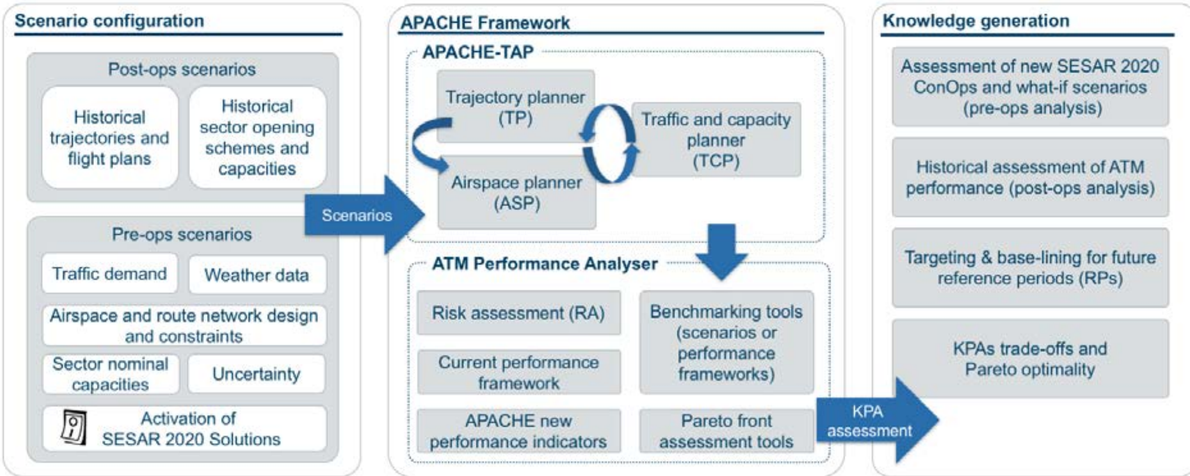


Figure 1-2. Context of the APACHE Framework within the APACHE Project

Figure 1-2 shows the overall concept of the whole APACHE Framework. First, several scenarios to be studied are defined, setting up different options regarding the demand of traffic, airspace capacities and eventual restrictions; SESAR solutions or future operational concepts to be simulated; and the level of uncertainty to be considered.

As detailed in (APACHE Consortium, 2018b) two types of performance assessment are foreseen in this Project: **"Post-ops"** (monitoring) analysis, using scenarios created from historical data; and **"Pre-ops"** (planning) analysis, over synthesised scenarios with the purpose to enable "what-if" studies or the assessment of different ATM performance trade-offs.

As seen in Figure 1-2, the APACHE Framework consists of the integration of different software components. On one hand, the **Performance Analyser (PA)** module, which implements all the performance indicators (PIs) proposed in the APACHE performance framework, including as well some indicators from the current performance scheme for benchmarking purposes. On the other hand, the **APACHE-TAP (trajectory and airspace planner)**, which could be seen as a small prototype of an ATM simulator and having a double functionality in this Project:

- 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.).
- To synthesise 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).

This double functionality of the APACHE-TAP is also shown in the block diagram of Figure 1-3.

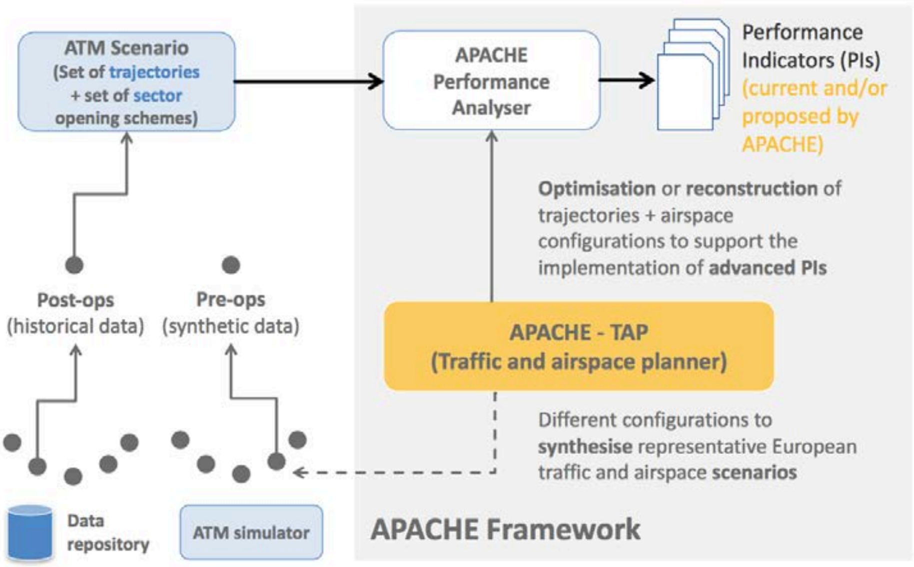


Figure 1-3. Double usage of the APACHE-TAP within the APACHE Framework

1.3 Document structure

The document is structured as follows:

- **Section 1:** Introductory section that outlines the context and purpose of this deliverable, containing also a glossary of terms.
- **Section 2:** Presents the objectives of the simulations performed and describes the different simulation scenarios and case studies, explaining the characteristics of each of them.
- **Section 3:** Presents the results of the post-ops assessment.
- **Section 4:** Presents the results of the pre-ops assessments.
- **Section 5:** Presents the interdependencies and trade-offs in ATM performance based on some tailored pre-ops simulations.

1.4 Glossary

Term	Explanation
ADCB	Advanced Demand and Capacity Balance
AEQ	Access and Equity key performance area
ANS	Air Navigation Services
ANSP	Air Navigation Service Provider
ASP	Airspace Planner (APACHE system component)
ATC	Air Traffic Control
ATCO	Air Traffic Controller
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management

Term	Explanation
ATS	Air Traffic Services
AU	Airspace User
CAP	Capacity key performance area
CASA	Computer Assisted Slot Allocation
CCC	Continuous Cruise Climb
CE	Cost-efficiency key performance area
CI	Cost Index
ConOps	Concept of Operations
CPR	Correlated Position Reports
CRCO	Central Route Charging Office
DAC	Dynamic Airspace Configuration
DCB	Demand and Capacity Balance
DCT	Direct Routes
DDR2	Demand Data Repository 2
ECAC	European Civil Aviation Conference
ENV	Environnement key performance area
ER	Exploratory Research
FABEC	Functional Airspace Block Europe Central
FL	Flight Level
FLEX	Flexibility key performance area
FR	Free route
FRA	Free Route Area
GCD	Great Circle Distance
ICAO	International Civil Aviation Organization
KEA	Key performance Environment indicator based on Actual trajectory
KEP	Key performance Environment indicator based on last filed flight Plan
KPA	Key Performance Area
KPI	Key Performance Indicator
PA	Performance Analyser (APACHE system component)
PF	Pareto Front
PI	Performance Indicator
PRU	Performance Review Unit
RA	Risk Assessment (APACHE system component)
RBT	Reference Business Trajectory
RP	Reference Period
SAF	Safety key performance area
SBT	Shared Business Trajectory
SES	Single European Sky
SJU	SESAR Joint Undertaking
SOC	Sector Configuration
SR	Structured route
STATFOR	Statistics and Forecasts Service
TAP	Trajectory and airspace planner module (main component of the APACHE system)
TCP	Traffic and Capacity Planner (APACHE system component)
TP	Trajectory Planner (APACHE system component)

Table 1-1. Glossary

2 APACHE validation plan

This Chapter describes the objectives of the APACHE validation exercises and details the set of Scenarios and Case Studies proposed to achieve these validation objectives.

2.1 Validation objectives

Two main objectives have been identified within the context of the APACHE Project validation:

- To assess the applicability and usefulness of the **APACHE Framework Performance Indicators** using historic or synthesised/simulated data compared to the current SES PRU / SESAR2020 PF[2], as well as to **capture interdependencies among KPAs** when assessing ATM performance.
- To initially **assess** the impact of specific **SESAR Solutions** on the APACHE Framework Performance Indicators in order to evaluate their applicability to assess ATM performance.

These objectives are in line with the APACHE Project objectives, stated in APACHE Deliverable D2.1 (APACHE Consortium, 2017a). The overall project objectives aim at assessing ATM performance with a novel (or enhanced) set of performance indicators (PIs); at capturing the interdependencies across several ATM key performance areas (KPA); and at performing an initial impact assessment of some SESAR 2020 Solutions, along different KPAs.

Both objectives should be envisaged for various levels of air traffic demand, which have been materialised in the various Case Studies planned for each simulated scenario. The detailed list and description of these scenarios and Case Studies can be found in Section 2.2 below.

Figure 2-1 depicts the connection between the two main simulation objectives described above with the two main blocks of assessments (post-ops and pre-ops). The post-ops assessment is focused on the assessment of the current Performance Framework PIs and new APACHE PIs considering real historic data for two (2) levels of air traffic demand (one day of summer and one day of winter) in the FABEC region. This type of assessment supports the comparison of how the current PF PIs (SES PRU and SESAR2020 Performance Framework) and new APACHE PIs are able to assess ATM performance for the different KPAs. Hence, this post-ops assessment is geared towards the first objective (Applicability of APACHE Framework PIs).

The second type of assessment (pre-ops – synthesised/simulated data) complements the previous assessment in the achievement of the first objective (Applicability of APACHE Framework PIs), as it

[2] Single European Sky Performance Review Unit and SESAR 2020 Performance Framework

assesses the results of an additional level of air traffic demand (future summer day – high demand). Moreover, the pre-ops assessment is key for the achievement of the second objective (Impact of SESAR Solutions on APACHE PIs). This assessment is aimed at assessing the performance of a reduced set of SESAR 2020 Solutions (different SESAR Operational Improvements) not yet implemented, or not fully implemented, in current operations. Each specific Solution or a combination of several Solutions will be used to characterise the different simulation scenarios.

Finally, pre-ops assessments have also been used to assess interdependencies and trade-offs among different KPAs: by comparing results between scenarios, but also generating tailored simulations to capture "a priori" certain interdependencies.

The next section of this deliverable presents details on such scenarios and Case Studies.

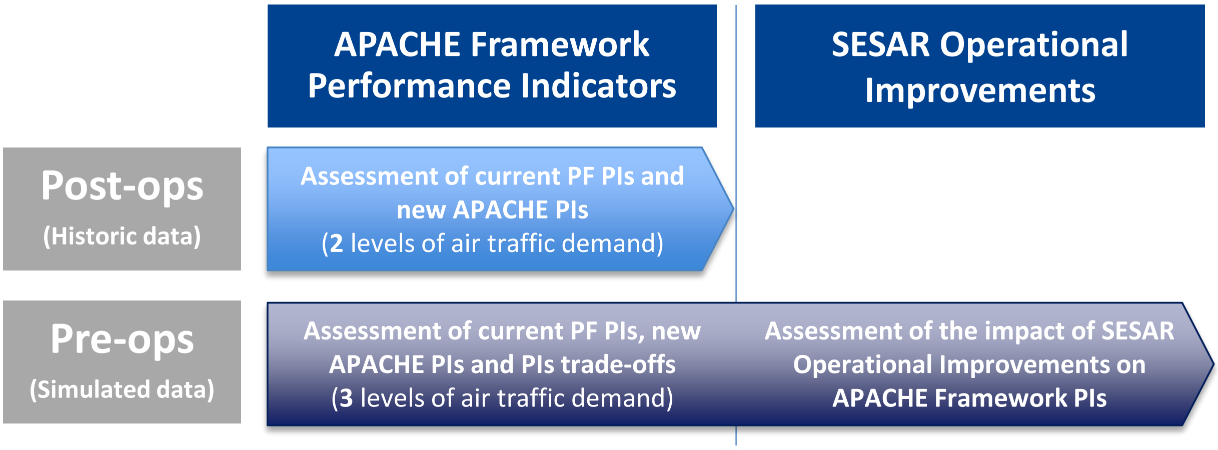


Figure 2-1: Overall APACHE simulation objectives

As detailed in previous APACHE deliverables, the APACHE-TAP is composed by various modules (see also Figure 1-2). These modules have been configured to simulate operations in the current ATM paradigm **(with no SESAR Solution implemented**) and to simulate operations with some SESAR solutions enabled (**with one or more SESAR Solutions implemented**), in line with the available information on the SESAR 2020 Transition ConOps (SESAR Joint Undertaking, 2016).

Consequently, the following APACHE-TAP modules enable or disable some functionalities inspired by these selected SESAR solutions:

- **Trajectory Planner module** is configured to implement SESAR 2020 solutions PJ06 (trajectory based free routing) and PJ07-01 (AU processes for trajectory definition) as well as to allow, Continuous Cruise Climbs (not a SESAR 2020 solution, but used here to explore the theoretical limits in flight efficiency).
- **Airspace planner module** is configured to implement SESAR solution PJ08 (Management of dynamic airspace configurations), as well as to maintain the static sectorisation mode of operations.
- **Traffic and capacity planner module** is configured to implement Advanced DCB (demand and capacity balancing) inspired by SESAR solution PJ09, as well as to maintain the computer assisted slot allocation (CASA) algorithm currently used to balance demand and capacity.

Further details on the parameters and capabilities of all APACHE System modules can be found in APACHE deliverables D4.1 and D3.2 (APACHE Consortium, 2018a; 2018b).

2.2 Scenarios and Case Studies description

The concept «Scenario» has been used to name a particular APACHE-TAP configuration and «Case Study» to name any variation of a particular scenario, involving for instance, different traffic samples, geographic coverage, time coverage, treatment of uncertainty, internal configuration parameters for some APACHE-TAP modules, etc. Therefore, the following types of scenarios have been proposed and assessed within APACHE WP5:

- **Baseline scenario**: Common point of reference to be used by multiple validation exercises in order to perform measurements relative to a common, well-known and consistent origin. This scenario has been named as Scenario S0.
- **Reference scenario**: Scenario including traffic and operational environment and without the SESAR Solutions that are the subject of the validation, matched in time with the solution scenario. This scenario has been named as Scenario S1.
- **Solution scenario**: Scenario including traffic and operational environment and SESAR operational improvements that is the subject of the validation. Different Solution scenarios have been proposed based on the different SESAR Solutions (Scenarios S2-S7).

An additional scenario classification has been developed based on the source of the data. The following two types of analysis have been identified and performed on the scenarios:

- **Post-ops analysis (Scenario S0):** Historic trajectory data from DDR2[3] or PRU[4] (actual, regulated and planned trajectories). Only trajectories crossing FABEC airspace have been considered for the assessment of the results. A full day of operations (24h) has been considered for each Case Study.

- **Pre-ops analysis (Scenarios S1-S7):** Synthesised/simulated trajectories and airspace sectorisations using the APACHE-TAP for specific concepts of operations (current ConOps or implementing one or more SESAR Operational Improvements). The APACHE System will bring synthesised shared business trajectories (SBT), modelling the behaviour of the AUs; and reference business trajectories (RBT), as well as the negotiation process via the Network manager to balance demand and capacity. Only trajectories crossing FABEC airspace have been considered for the assessment of the results. A full day of operations (24h) has been considered for each Case Study.

Please refer to (APACHE Consortium, 2018b) for further details on the types of performance assessment in the APACHE Project and to (APACHE Consortium, 2018a) for the details of the implementation of the APACHE-TAP, as well as the main limitations and assumptions done.

[3] DDR2: Demand data repository 2 from Eurocontrol (http://www.eurocontrol.int/articles/ddr2-web-portal)

[4] Correlated position reports gathered by the PRU (performance review unit) in Eurocontrol (http://www.eurocontrol.int/ansperformance/pru)

Table 2-1 shows the different pre-ops scenarios planned, including the different SESAR Operational Improvements considered for each scenario and stating the different modes for the TP, ASP and TCP.

Scenario	TP mode		ASP mode	TCP mode
S0	Post-ops analysis			
S1	Current route network	FL allocation/orientation	Static sectorisation	Current DCB (CASA)
S2	Enhanced FRA scenario	FL allocation/orientation	Static sectorisation	Current DCB (CASA)
S3	Current route network	Continuous Cruise Climbs	Static sectorisation	Current DCB (CASA)
~~**S4**~~	~~Current route network~~	~~FL allocation/orientation~~	~~Dynamic sectorisation~~	~~Current DCB (CASA)~~
S5	Current route network	FL allocation/orientation	Static sectorisation	Advanced DCB
~~**S6**~~	~~Enhanced FRA scenario~~	~~FL allocation/orientation~~	~~Dynamic sectorisation~~	~~Advanced DCB~~
~~**S7**~~	~~Enhanced FRA scenario~~	~~Continuous Cruise Climbs~~	~~Dynamic sectorisation~~	~~Advanced DCB~~
Strikethrough scenarios were finally not run in WP5 due to the de-scoping of the ASP component in WP4				

Table 2-1: APACHE validation scenarios

As shown, scenarios S2-S5 incorporate different SESAR Solutions (operational improvements), namely:

- **Scenario S2:** Enhanced free-route area (FRA) scenario, pushing at the limits the concepts developed by SESAR 2020 Solutions PJ-06 and PJ-07, assuming completely full free-route operations between origin and destination airports (i.e. assuming that the whole ECAC area is a single FRA).
- **Scenario S3:** Continuous Cruise Climbs (CCC) scenario, pushing vertical flight efficiency to the theoretical limits by removing any constraint in the vertical trajectory (i.e. removing any level-off in climb/descent phases, but also removing current flight level allocation and orientation schemes).
- **Scenario S4:** Dynamic sectorisation scenario, implementing dynamic airspace configuration (DAC) strategies (in line with SESAR 2020 Solution PJ-08), aiming at optimising the usage of airspace capacity at the same time that operational costs are reduced for air navigation service providers (ANSPs).
- **Scenario S5**: Advanced demand and capacity balance (ADCB) scenario, implementing a prototype for future collaborative decision making strategies to deal with imbalances between demand and capacity, in line with SESAR 2020 Solution PJ-09 and allowing the network manager to solve the DCB problem by using delays, re-routings and level cappings into a single global optimisation problem.

Scenario S6 incorporates the SESAR Solutions of S2, S4 and S5 (i.e. all SESAR Solutions “activated” at the same time); while **Scenario S7** adds on top CCC operations, not a SESAR Solution per se, but identified in other research programmes such as AIRE. This scenario S7 will be considered the optimal/utopic theoretical scenario, including all possible Solutions.

During WP4 activities, however, some de-scoping of the APACHE System was done and the ASP module was not finally integrated with the DAC capability. Consequently, no results have been obtained at the end for the three different pre-ops scenarios that include this DAC module: S4, S6 and S7 (strikethrough scenarios in Table 2-1).

The simulation results assessments have been then focused on the post-ops scenario (S0) and on four (4) pre-ops scenarios finally completed (S1, S2, S3 and S5), as shown in Figure 2-2.

Overall, the Enhanced FRA scenario (S2) and ADCB (S5) SESAR Solutions aim at achieving clear benefits regarding Capacity KPA results. The Continuous Cruise Climbs scenario (S3), in turn, has a special focus on enhancing Environment KPA results, pushing flight efficiency to its maxim theoretical limits. Moreover, all three scenarios will be carefully analysed from the Safety point of view, aiming to capture the effects of these SESAR Solutions on this KPA. However, it should be noted that the Enhanced FRA scenario (S2) also focuses on enhancing other KPAs such as Airspace User Cost-efficiency and Environment. These ultimate goals are shown in Figure 2-2.

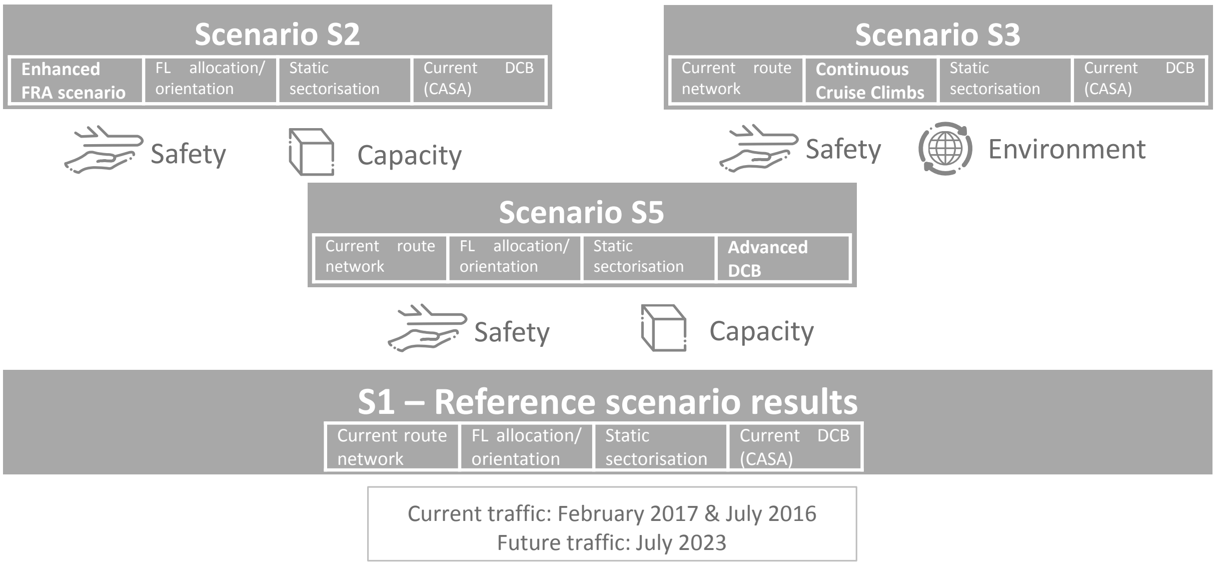


Figure 2-2: Selected scenarios for pre-ops analysis

A **Case Study** is a variant of the scenario were some input parameters may change (such as traffic demand, weather conditions, etc.) or where the scope of the simulation may change (simulated timeframe, simulated geographical area, etc.). For the final APACHE PA simulations planning, different case studies have been proposed for each simulation scenario based on the timeframe and its associated traffic demand, as well as on the origin of the trajectory data. Different case studies have been considered for the two main types of assessment (post-ops and pre-ops):

For the post-ops assessment scenario (Scenario 0 - Baseline), three case studies have been considered based on two levels of air traffic demand and two different sources for historical trajectory data:

- S001: **Medium** demand (24h of operations in July 28th 2016) using **DDR2** trajectory data.
- S003: **Low** demand (24h of operations in February 20th 2017) using **DDR2** trajectory data.
- S005: **Medium** demand (24h of operations in July 28th 2016) using **PRU** trajectory data.

Regarding the pre-ops assessment, three case studies have been used for the simulations for each Scenario X, based only on three levels of air traffic demand taken from Eurocontrol's DDR2:

- SX01: **Medium** demand (24h of operations in July 28th 2016).
- SX03: **High** demand (24h of operations in July 21st 2023 generated by Eurocontrol's STATFOR tool configured to give the maximum amount of demand for that representative day).
- SX05: **Low** demand (24h of operations in February 20th 2017).

2.3 Data sources

As stated in previous sections, for the **post-ops scenarios** trajectory data is taken from Eurocontrol DDR2 data base. In DDR2, three types of So6 files are found (Eurocontrol, 2016), and all three will be used in the APACHE post-ops assessments:

- a trajectory recreation based on the **last filed** flight plan by the airspace user (M1 file);
- a trajectory recreation based on the **regulated** flight plan (M2 file)[5]; and
- a trajectory recreation obtained from the position correlation from different surveillance systems (M3 file).

Only for S005 Case Study, actual trajectories will be taken from PRU correlated position reports (CPR), which show a higher degree of accuracy in the position (Spinelli et al., 2017).

Realised sectorisations are also taken from DDR2.

Regarding **pre-ops scenarios**, trajectory and sectorisations are generated by the same APACHE-TAP. Yet, some DDR2 inputs are still used to define the traffic demand (flight ID, aircraft type, origin/destination airport and date/time of departure) and the sector definitions and nominal capacities. For the future traffic demand the **STAFOR service** from Eurocontrol has been used.

This defines the input data for the APACHE Performance Analyser (recall Figure 1-3). Yet, the APACHE-TAP still requires some additional data sources in order to compute certain PIs. In the validation exercises presented in this document, the following sources have been used:

- Route structure, direct routes (DCT) and free route areas (from Eurocontrol DDR2)
- Weather data (from NOAA)
- Aircraft performance data (from Eurocontrol BADA)
- Cost Index and Payload values (educated guesses and literature review)
- Airspace blocks, elementary sectors, configs. (from DDR2, AIS Database and CAUTRA for French airspace)
- Nominal capacities (from DDR2 and CAUTRA for French airspace)
- Feasible configuration transitions (educated guesses from historical data or internal ACC documentations when available)
- Geometrical description of the elementary and collapsed sectors (from DDR2)

[5] M1 and M2 trajectories are identical and might only differ in flight delay.

3 Results of the post-ops assessment

The baseline scenario of the APACHE PA simulations includes the evaluation of the post-operations analysis. This scenario, which is named Scenario 0, is based on historic trajectory data from DDR or PRU repositories. Trajectories crossing ECAC airspace have been considered for the assessment of the simulation results. However, specific sectorisation and Demand Capacity Balance (DCB) assessments were performed only at FABEC level.

The overall objective of this post-ops assessment is to evaluate the performance of the APACHE Framework indicators against real historic data. Several case studies (S00X) have been proposed for this scenario considering both medium levels of air traffic demand (S001 – one day in Summer 2016) and low levels of air traffic demand (S003 – one day in Winter 2017). For both case studies (S001 and S003), the data has been gathered from DDR2 database and a full day of operations (24h) has been assessed.

Moreover, an additional Case Study (S005) has been conducted for the medium levels of air traffic demand (one day in Summer 2016) but using PRU CPR data instead of DDR2 data. PRU CPR data provides higher accuracy in the actual flown trajectories and it has only been used for the Safety KPA indicators, which are very sensitive to the quality of the input data (in terms of aircraft 4D position accuracy). The other KPAs were not assessed in S005 as the difference with S001 was inexistent or negligible.

3.1 Access and Equity KPA

As stated in ICAO Doc 9854, Access and Equity ensures that all airspace users have equal right of access to the ATM resources. All types of airspace user missions and all types of vehicles and associated characteristics must be accommodated, while minimising restriction of access to airspace. The KPI defined at ICAO level is “unsatisfied demand versus overall demand”.

Given the scope of SESAR 2020 performance framework regarding this KPA and based on the indicators proposed in APACHE Deliverable D3.1 (APACHE Consortium, 2017b), indicators concerning strategic access to the network are not investigated in APACHE. Moreover, in terms of Equity, SESAR 2020 Solutions must not result in inequitable impacts between individual or groups of airspace users; and they must ensure that there is no significant overall detrimental impact on the ATM system as a whole, even if some individual or groups of airspace users are benefitting.

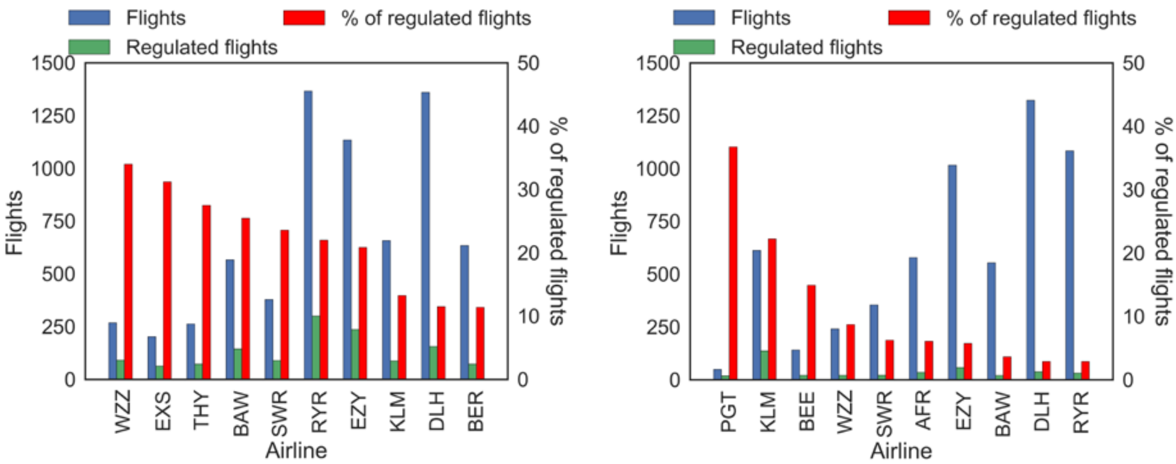
From the five PIs proposed in Deliverable D3.1, the two of them developed by APACHE project have been selected for the simulations conducted (APACHE Consortium, 2017b):

- **AEQ-1:** Percentage of RBTs which are equal to the first submitted SBTs per AU[6]
- **AEQ-2:** Worst penalty cost[7]

Both AEQ PIs can be quantified in the "post-ops" assessment and in the "pre-ops" mode of performance assessment, as they address the tactical phase of operations.

AEQ-1 tries to capture the fairness of the ATM system when regulating flights in situations that the demand exceeds the capacity. Figure 3-1 shows the equity assessment of the two post-ops Case Studies using this indicator, showing only the 10 most affected airlines (in terms of number of regulated flights) for each of the two days under study.

As it is shown in Figure 3-1a, in S001 two airlines suffered from regulations to more than the 30% of their flights (WZZ, EXS), closely followed by THY, BAW, SWR, RYR and EZY, who experienced regulations between 20% and 30% of their respective flights. The other day of study (S003 in Figure 3-1b) in turn, had much less regulations in general and PGT is the AU with the highest percentage of regulated flights (36.7%), although they only scheduled 49 flights in total. KLM, with 612 scheduled flights experienced 136 regulations (22%), followed by BEE (15%) and WZZ, SWR, AFR and EZY experiencing between 5% to 10% of their flights regulated.



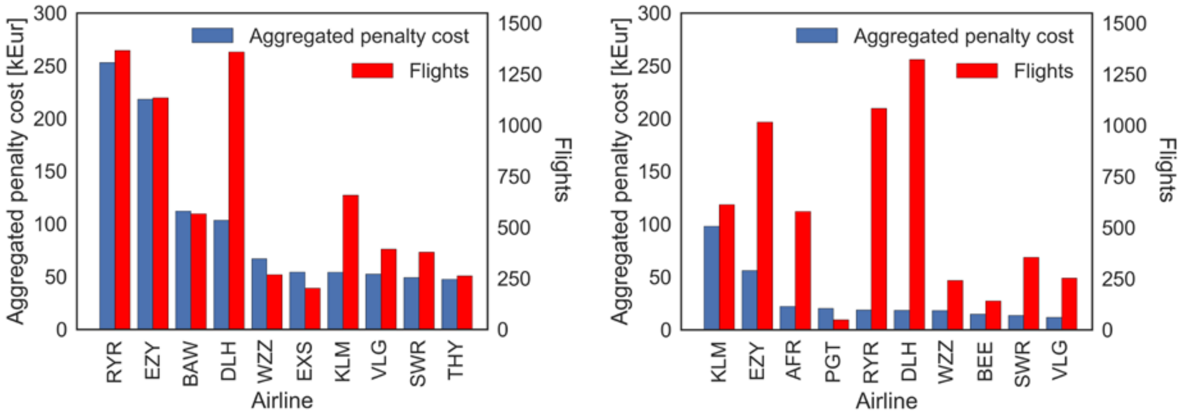
a) S001 (24h FABEC Jul 28th 2016) **b) S003 (24h FABEC Feb 20th 2017)**

Figure 3-1: Post-ops results for AEQ-1 (RBTs which are equal to SBTs per AU)

Figure 3-2 shows, for the two Case Studies, the 10 most affected airlines in terms of penalty cost, computed by comparing the last filed flight plan with the regulated trajectory. AEQ-2 represents the difference between maximum penalty cost among all AUs and average penalty costs for all AUs. Since current regulations are only in form of ATFM delay, all the cost observed here is the cost associated to the aggregation of these delays per AU. With the SESAR 2020 ConOps in place, it is expected that this indicator will capture all costs resulting from differences between the first SBT and the RBT, thus

[6] Defined as: Maximum (Total number of RBTs equal to the first submitted SBT) / (Total number of first submitted SBTs)) – average (Total number of RBTs equal to first submitted SBT) / (Total number of the first submitted SBT))). Calculated per AU.
[7] Defined as: Maximum (Penalty cost among all AUs) – Average (Penalty cost for all AUs) in Euros.

accounting for ATFM delays, but also re-routings or level cappings. As observed in the Figure 3-2, costs for S001 are much higher than for S003, since much more regulations were issued.



a) S001 (24h FABEC Jul 28th 2016) b) S003 (24h FABEC Feb 20th 2017)

Figure 3-2: Post-ops results for AEQ-2 (maximum penalty cost per AU)

However, it should be noted that these two PIs show partial information of the ATM system equity, since regulations are strongly related to the geographic location of the possible hotspots or demand imbalances. Thus, if airline A has planned more flights through an area that is likely to experience congestion than another airline B, which is mostly flying in less dense routes, airline A will consequently experience more regulations than airline B. Thus, an interesting variant of this PI would be to segregate the results per areas or even per origin/destination pair. This in-depth analysis is one possible direction for future research.

Finally, Table 3-1 shows the results for the AEQ PIs for both post-ops Case Studies, along with the total number of flights considered and the total number of regulated flights. If instead of the 10 most affected AUs, all flights are considered it is quite likely to find an AU with few flights (even one single flight) regulated. Thus, for that AU the percentage of regulated flights would be 100% and this is what is captured in AEQ-1, which then subtracts the average of regulated flights (see the PI definition above). This leads to the paradoxical results of Table 3-1: since S001 has more regulated flights the average of regulated flights per AU will be higher and therefore AEQ-1 will be lower. For this reason, this PI is not suitable to be used for the whole set of data, but for a subset as done before or even for origin-destination pairs.

AEQ-2, in turn, is a good indicator for aggregated results, since it captures at aggregate level the worst penalty cost for the AU. Since S003 has less regulations, it is expected to observe lower delays and therefore lower penalty costs for the AUs.

Performance Indicator	S001	S003
AEQ-1	88.96%	97.27%
AEQ-2	249 kEur	97 kEur
Total flights	17,146	13,971
Regulated flights	2,703	698

Table 3-1: Post-ops resulst for access and equity KPA

3.2 Capacity KPA

In APACHE two new Capacity indicators (based on ATFM delay as proxy) were implemented, together with current SES PRU ATFM delay indicator (APACHE Consortium, 2017b). These three indicators are summarised as follows:

- **C-CAP-1:** Average en-route ATFM delay per flight (accounting for **departure** delay).
- **CAP-1:** Robust maximum en-route delay
- **CAP-2:** Average flow management **arrival** delay.

Table 3-2 summarises the Capacity PI values for post-operation evaluation of the two Case Studies: medium (S001) and low (S003) traffic demand. Measurement of the ATM system capacity using the proposed macroscopic indicators is difficult based on the single-day traffic Case Study, due to high sensitivity to individual ATC sector demand (themselves dependent on origin/destination pairs and on route distribution). Since medium and low traffic scenarios are represented by the different days of operation (summer/winter season), they are characterised by different traffic demand patterns. Therefore, differences in the values of the indicators are rather the result of this difference, than reflecting a capacity change of the system.

Performance Indicator	S001	S003
C-CAP-1	2.60 min	0.70 min
CAP-1	22.02 min	15.19 min
CAP-2	2.60 min	0.70 min

Table 3-2: Post-ops results for capacity KPA

Nevertheless, it could be seen that the reduction of average en-route ATFM delay (existing indicator C-CAP-1) between S001 and S003 Case Study is not followed by a proportional reduction in the indicator CAP-1[8]. This confirms[9] the hypothesis that system capacity increase must be followed by a significant reduction of both existing C-CAP-1 and complementary indicator CAP-1. The reduction of the average delay, not followed by the reduction of the robust maximum delay is linked to the way how the indicator is calculated (normalised by the total number of flights) and not to the capacity increase, and could be caused by two situations: decrease in the total delay due to lower traffic, as in this experiment (see Figure 3-3) or decrease in average delay due to increase of the traffic in the areas of the low traffic demand.

Table 3-3 shows that almost 20% of traffic decrease between Case Studies S001 and S003 is followed by the 15% (non-equal) reduction of the active ATCOs on duty (hours), that finally led to the decrease of the total number of regulated flight by 75% and reduction of the average delay indicator as

[8] Computed as the average of: the en-route ATFM departure delay greater than average value + Standard deviation of en-route ATFM departure delay.

[9] Disclaimer: Authors once again recall that the word “confirm” should be taken with precaution since results of the indicators could be only valid if counted for the larger period of time (year as it is calculated nowadays).

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previously shown. Hence, these figures confirm demand reduction being the main reason for the C-CAP-1 and CAP-1 decrease.

	S001	S003	Decrease
ATCOs hour	6,990	5,960	0.15
Flights	17,146	13,977	0.19
Regulated flights	2,703	689	0.75

Table 3-3: ATCO hours on duty, flight and regulated flight number for post-ops

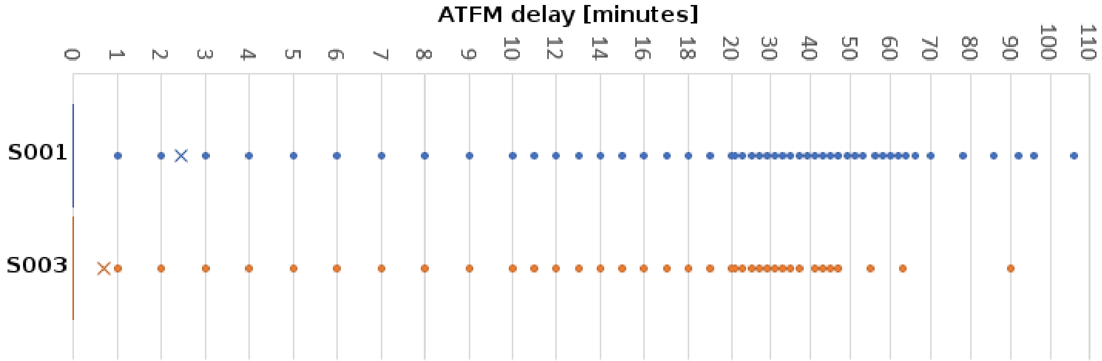


Figure 3-3: Flight delay distribution for the post-ops capacity assessment

Similar to previous conclusion, the macroscopic indicator CAP-2 delay is not suitable as well in expressing capacity performance of the short duration Case Study since it is influenced by local specifics of the traffic demand. Additionally, in the current ATM system, rerouting decisions due to lack of the ATM system capacity, are not captured by the regulated trajectories (M2 files in DDR2 used in this assessment), but they result in change of the initial flight plan (M1 DDR2 files). Therefore, using existing traffic databases (DDR mainly) only departure delay could be recovered, which is why CAP-2 indicator shows no difference if compared to C-CAP-1.

To summarise, based on the carried experiments for the post-ops study, it could be seen that ATM system capacity is more adapted to the traffic demand (in the size and distribution) represented by the Case Study S003. On the other hand, the analysis of the CAP-1 indicator values suggests that there was no particular change in the system capacity. **The proposed indicator CAP-1 shows promising results in complementing information loss of C-CAP-1 due to delay averaging**. To confirm statistical significance of the hypothesis, however, larger sets of data (several years) should be tested, which was of the scope in the APACHE Project.

3.3 Cost-efficiency KPA

Cost-Efficiency KPA, as defined by ICAO, addresses the cost-efficiency of all the stakeholders of the ATM community, including the Airspace User Cost-Efficiency and ANS Cost Efficiency. All the Cost-Efficiency PIs that have been proposed by the APACHE project team and the ones already used by the SESAR2020 Performance Framework have been used for the conducted simulations, except the CE-1.3 (En-route ATM charges cost for the AU) PI, as route charges are always computed taking the planned trajectory, regardless of the actual track, under the current system the values always being zero. This indicator was proposed in D3.1 in case the charging system is changed in the near future, taking into account the actual en-route trajectory instead of the planned one (APACHE Consortium, 2017b).

Cost-efficiency PIs are divided in two big families: those measuring cost-efficiency for the AUs and those focused in the air navigation services (ANS).

3.3.1 Airspace User Cost-efficiency

Two groups of airspace user cost-efficiency indicators are proposed in APACHE: cost-based indicators (CE-1.x) and time-based indicators (CE-4.x). Each family has additional indicators aiming to decouple inefficiencies due to different layers of the ATM (strategic, tactical or both). Each of these indicators, in turn, can be computed by using different optimal trajectories as baseline «optimal» reference. Moreover, current SES PRU indicator representing the share of the regulated flights as a macroscopic measure of the system efficiency is also implemented (C-EFF-1).

Overall, the following Airspace User Cost-efficiency (CE(AU)) indicators have been considered (APACHE Consortium, 2017b):

- C-EFF-1: **Share of regulated flights.**
- CE-1: **AU cost** inefficiency due to **all** ATM layers.
- CE-1.1: **AU cost** inefficiency due to **strategic** ATM.
- CE-1.2: **AU cost** inefficiency due to **tactic** ATM.
- CE-4: **Flight time** inefficiency due to **all** ATM layers.
- CE-4.1: **Flight time** inefficiency due to **strategic** ATM.
- CE-4.2: **Flight time** inefficiency due to **tactic** ATM.

Table 3-4 shows the results of C-EFF-1 indicator. The number of regulated flights is result of the demand and capacity imbalance, and therefore this PI measuring on-time performance is influenced mainly by the capacity of the ATC sectors and traffic demand distribution. It is a macroscopic indicator that does not capture the magnitude of the regulations, neither route efficiency (how much actual/regulated route is far from the user preferred route), neither the actual cost for the AUs.

Performance Indicator	S001	S003
C-EFF-1	15.76%	4.93%
Total flights	17,146	13,971
Regulated flights	2,703	698

Table 3-4: Post-ops results for C-EFF-1

It could be seen that Case Study S003, represented with lower traffic demand, show higher efficiency in the terms of number of regulated traffic that is three times less than for medium traffic demand Case Study (S001). The increase of the regulated traffic between S003 and S001 is not proportional to the increase of the number of flights; 23% of the traffic increase has caused increase of the number of regulated flight by almost 300%. These results are mainly linked to the distribution of the traffic demand in the space and time.

New **cost-based indicators** proposed in APACHE try to estimate the cost inefficiencies in terms of extra fuel burnt, extra flight time and ATFM delay (if any). This estimation requires complex fuel estimation algorithms (fuel is estimated only from observed radar tracks as for the Environment indicators); the cost of extra flight time is computed taking into account the estimated Cost Index for that flight, while the simple model proposed by (Eurocontrol, 2015) is taken to estimate the cost of ATFM delay. More details are given in (APACHE Consortium, 2018a; 2018b). In D3.1 (APACHE Consortium, 2017b) CE-1.x indicators were proposed, to account for the total cost inefficiencies. In this deliverable CE-4.x indicators are introduced, to isolate only flight time inefficiencies, since flight time reduction is one of the aspiration levels given in the ATM Master Plan (SESAR Joint Undertaking, 2015)[10].

Table 3-5 and Figure 3-4 show the assessment of the two post-ops Case Studies using the AU cost-based indicators enumerated above (CE-1.x).

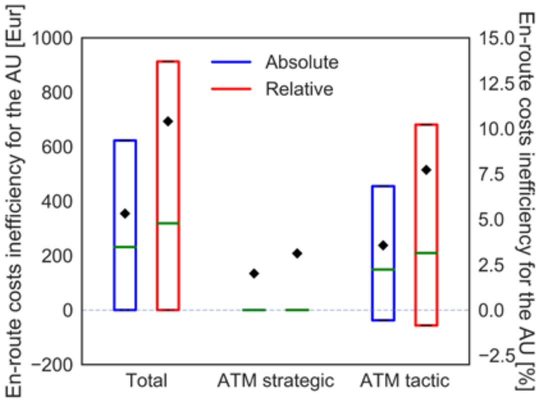
The results presented in Figures 3-4a and 3-4b used the last filed flight plan by the AU (the first SBT according to the SESAR 2020 ConOps) as baseline trajectory (i.e. the trajectory that is used to compare with the actual trajectory and compute the cost inefficiency). This is an important hypothesis, 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. 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 (APACHE Consortium, 2017b).

Results shown in Figures 3-4c and 3-4d, in turn, assume that 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).

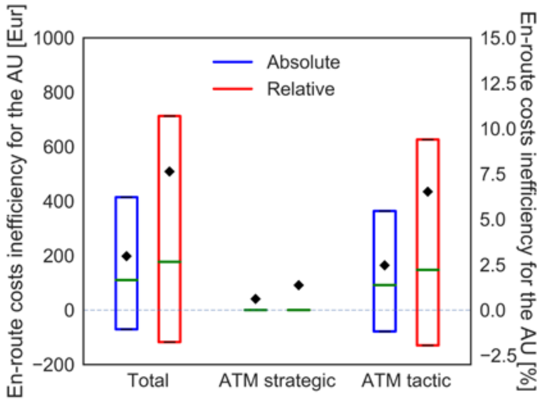
Performance Indicator	S001				S003			
	average		median		average		median	
CE-1 (Eur/flight) [Total *]	354	10.4%	232	4.8%	198	7.6%	110	2.7%
CE-1.1 (Eur/flight) [ATM strategic*]	134	3.1%	0	0.0%	41	1.4%	0	0.0%
CE-1.2 (Eur/flight) [ATM tactic*]	237	7.7%	149	3.1%	164	6.5%	92	2.2%
CE-1 (Eur/flight) [Total **]	934	22.6%	720	16.0%	795	21.1%	560	15.1%
CE-1.1 (Eur/flight) [ATM strategic]**	704	14.6%	439	10.9%	631	14.2%	372	11.0%
CE-1.2 (Eur/flight) [ATM tactic]**	237	7.7%	149	3.1%	164	6.5%	92	2.2%
[*] Last filed flight plan (or SBT) taken as baseline trajectory – [**] AU Cost-optimal trajectory taken as baseline								

Table 3-5: Post-ops results with cost-based AU cost-efficiency indicators (CE-1 family)

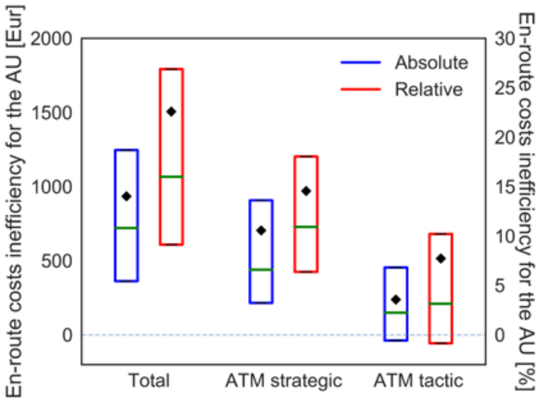
[10] Operational Efficiency SESAR ambition target – 4-8 minutes of flight time reduction per flight (3-6% relative saving (https://www.atmmasterplan.eu/)



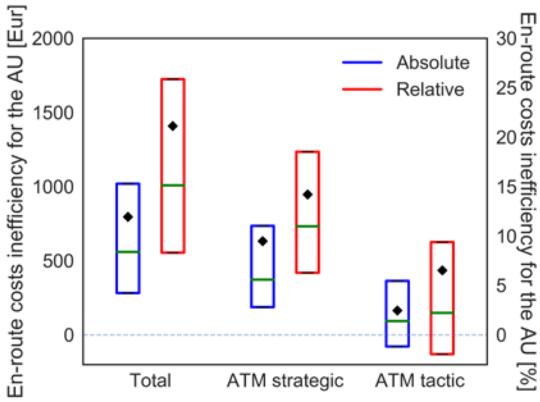
a) S001 (24h FABEC Jul 28th 2016) with last filed flight plan as baseline trajectory



b) S003 (24h FABEC Feb 20th 2017) with last filed flight plan as baseline trajectory



c) S001 (24h FABEC Jul 28th 2016) with optimal full free-route trajectory as baseline



d) S003 (24h FABEC Feb 20th 2017) with optimal full free-route trajectory as baseline

Figure 3-4: Post-ops results with cost-based AU cost-efficiency indicators (CE-1 family)

When **comparing with the last filed flight plan (or first SBT)**, see Figures 3-4a and 3-4b, the total trajectory cost inefficiency has a median (green horizontal bar) of 230 EUR (4.8% of the total flight cost) for S001 and 110 EUR (2.6%) for S003. As it was already observed in Figure 3-1, in S001 more ATFM delays (regulations) were issued, if compared with S003, leading in this case to higher cost inefficiencies for the AUs.

The cost of ATFM delays is isolated in CE-1.2 indicators (labelled as ATM strategic in the Figures). The median of this cost is zero, meaning that more than the 50% of the flights were not delayed (so the SBT equals to the RBT and therefore the strategic cost inefficiency is zero). Yet, the average value is not zero, but 134 EUR (3.1%) for S001 and 41 EUR (1.4%) for S003 (see also Table 3-5). These strategic inefficiencies account for the differences in cost between the regulated trajectory (or RBT) and the last filed flight plan (or first SBT). Since, at present, regulated trajectories are the same as planned trajectories plus an ATFM delay, the strategic inefficiencies shown in these figures are directly the cost for the AU of these ATFM delays.

The tactical layer (CE-1.3 indicator) however, introduces much more variability in the indicator penalising the majority of flights with extra costs (due to extra fuel consumption and/or extra flight time). Yet, as observed in Figures 3-4a and 3-4b we can also observe for some flights some “cost savings" (i.e. negative inefficiencies) in the ATM tactical layer, which might be due to route shortcuts issued by air traffic controllers during the execution of the flight leading to shorter flight times with respect to the last filed flight plan (or first SBT) flight time.

Finally, it is also interesting to note that average values (black diamonds in the plots) differ significantly from median values (horizontal green bars), meaning that for some few flights in the data set the cost inefficiency was relatively high. Further work could focus to study these highly inefficient flights.

If instead of using the last filed flight plan (or first SBT) the baseline for CE-1.x indicators is the **optimal trajectory assuming a full free-route airspace and flown at the AU's desired Cost Index**, then the cost inefficiency increases with respect to previous case (see Figures 3-4c and 3-4d). This behaviour is mainly caused by the fuel inefficiencies appearing as the consequence of using a static en-route network (instead of flying free routes), which is consistent with the significant increase on the ATM strategic cost inefficiencies observed in these Figures.

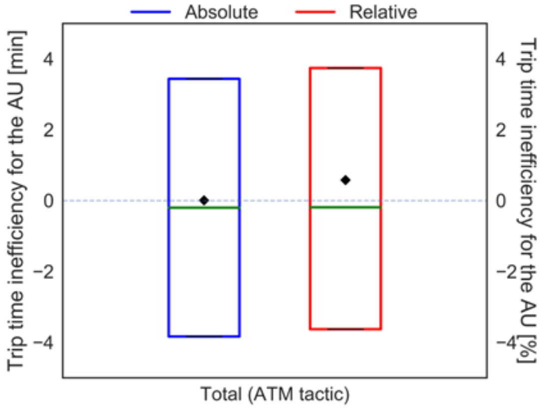
Table 3-6 and Figure 3-5 show the assessment of the two post-ops Case Studies using the AU time-based indicators enumerated above (CE-4.x). Like in Figure 3-4, the results presented in Figures 3-5a and 3-5b use the last filed flight plan by the AU (or the first SBT) as baseline trajectory, while results shown in Figures 3-5c and 3-5d assume that the baseline trajectory is an ideal full free-route trajectory (from origin to destination) flown at the AU's desired Cost Index.

When the **last filed flight plan is used as baseline trajectory**, flight time inefficiencies can only be observed in the **tactical** layer (ATFM delay is not considered in this indicator, which purely captures flight time inefficiency). This is why in Table 3-6 only CE-4.2 is shown. Results show a median of -0.2 minutes (-0.2%) for S001 and -0.3 minutes (-0.3%) for S003, meaning that approximately half of the flights were delayed tactically few minutes (notice that the 3rd quartile is around 3 minutes), while the other half benefited from flight time reductions while airborne, also for only few minutes.

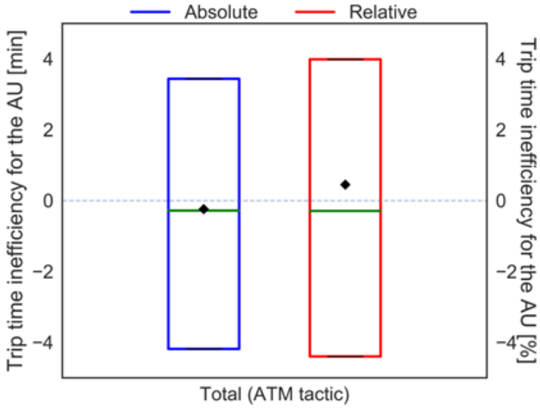
When the **optimal trajectory assuming a full free-route airspace and flown at the AU's desired Cost Index** is used as baseline trajectory, we can observe, on one hand, the **flight time** inefficiencies due to the ATM strategic layer (i.e. due to the fact that aircraft are constrained to follow published airways) and, as observed before, positive/negative time inefficiencies due to ATC intervention at tactical level (see Figures 3-4c and 3-4d). The median of the strategic flight time inefficiencies are around 10 minutes (11% in relative terms with respect to the total flight time) for both Case Studies. See Table 3-6 for the precise figures.

Performance Indicator	S001				S003			
	average		median		average		median	
CE-4.2 (min) [ATM tactic*]	0.01	0.58%	-0.20	-0.19%	-0.24	0.45%	-0.28	-0.29%
CE-4 (min) [Total]**	10.22	12.81%	9.27	10.33%	10.12	14.24%	9.37	11.33%
CE-4.1 (min) [ATM strategic]**	10.04	12.19%	9.35	10.20%	10.25	14.01%	9.53	11.50%
CE-4.2 (min) [ATM tactic]**	0.01	0.58%	-0.20	-0.19%	-0.24	0.45%	-0.28	-0.29%
[*] Last filed flight plan (or SBT) taken as baseline trajectory – [**] AU Cost-optimal trajectory taken as baseline								

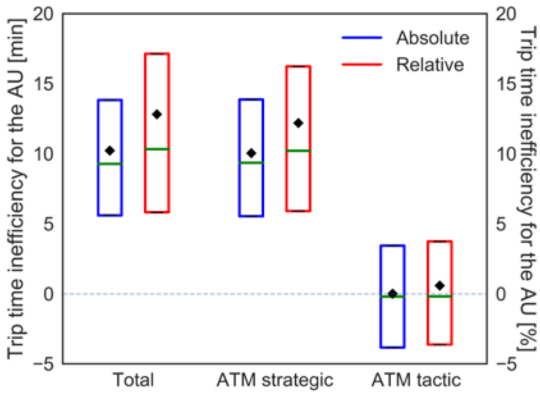
Table 3-6: Post-ops results with time-based AU cost-efficiency indicators (CE-4 family)



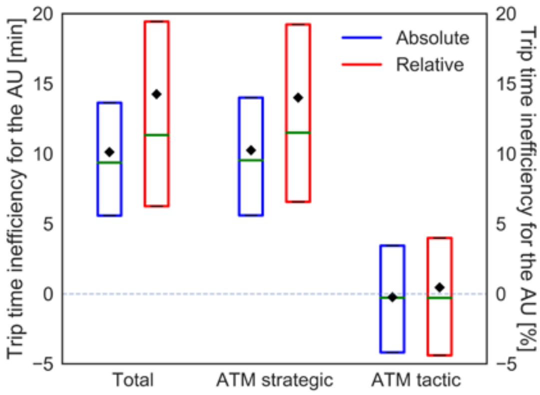
a) S001 (24h FABEC Jul 28th 2016) with last filed flight plan as baseline trajectory



b) S003 (24h FABEC Feb 20th 2017) with last filed flight plan as baseline trajectory



c) S001 (24h FABEC Jul 28th 2016) with optimal full free-route trajectory as baseline



d) S003 (24h FABEC Feb 20th 2017) with optimal full free-route trajectory as baseline

Figure 3-5: Post-ops results with time-based AU cost-efficiency indicators (CE-4 family)

3.3.2 ANS cost-efficiency

Apart from the airspace user cost-efficiency indicators, two (2) ANS cost-efficiency (CE) indicators have been proposed by the APACHE Framework and have been assessed as part of the post-ops assessment with historic data (APACHE Consortium, 2017b):

- CE-2: **Sectorisation costs** (%)[11]
- CE-3: **Flights per ATCO hour** on duty.

These indicators address the cost-efficiency of the ANS operations, whether airspace is sectorised in the optimal way (CE-2: Sectorization cost) and the ATCO productivity (CE-3: Flights per ATCO hour on duty). CE-2 compares the number and time of operations of en-route active sectors with the number

[11] Calculated as: [(Number of active en-route sectors)·(Time sectors were active)] / [(Number of optimal en-route sectors)·(Time sectors would be active)]*100

and time of optimal en-route sectors. CE-3, in turn, evaluates the overall amount of flights handled versus the total number of ATCO hours of ATCOs on duty. Table 3-7 presents the post-ops results for these two ANS cost-efficiency indicators for S001 and S003.

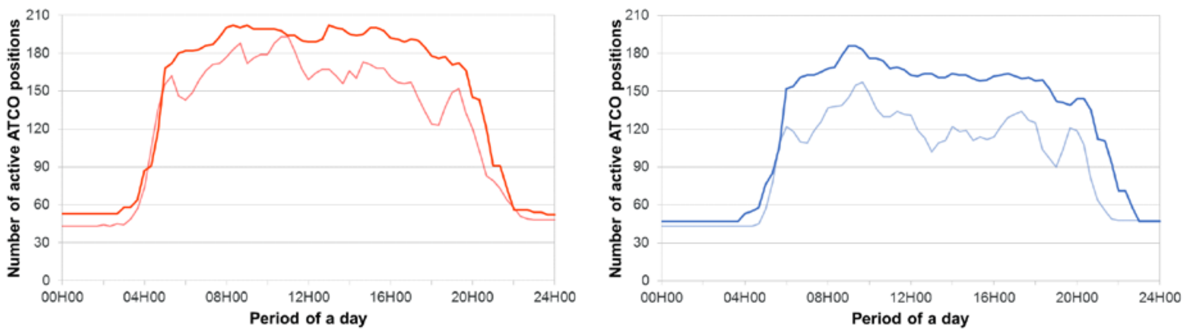
Performance Indicator	S001	S003
CE-2	116.67%	131.07%
CE-3	2.03 flights/h	1.88 flights/h
Total flights	17,146	13,971
Regulated flights	2,703	698

Table 3-7: Post-ops results for ANS cost-efficiency focus area

When assessing the two presented Case Studies, the cost-efficiency in terms of sectorisation costs is higher for the medium air traffic demand Case Study (S001) than for the low air traffic demand one (S003) represented by lower CE-2 indicator. For the low air traffic demand Case Study, much lower sectorisation costs could be achieved using the optimal airspace sectorisation. However, this cost reduction is not visible in reality (see Figure 3-6) . With the increase of the traffic demand the sectorisation cost of the optimal sectorisation scheme are increased as well (Figure 3-6), driven by the main ATM objective to accommodate demand without imposing significant penalties to the traffic demand. Therefore, the medium air traffic demand Case Study requires higher optimal sectorisation costs than the low demand. However, the increase in the optimal sectorisation cost is not followed by proportionally increase in actual sectorisation cost (Figure 3-7), which is why medium traffic demand Case Study shows higher cost-efficiency.

It can also be noticed that the increase in actual sectorisation costs with the increase of the demand is limited by the operational resources, which once reached result in the traffic regulations (see Table 3-7 for the number of regulated flights). It may be concluded that main reason for low cost-efficiency at the lower traffic demand (winter season) is the result of system capacity dimensioning based on the high traffic demand (summer season), hence system capacity is being underutilised during periods of the low traffic demand.

Similar figures are shown in terms of flights per ATCO on duty indicator (CE-3), where number of flights handeled per ATCO hour is higher for the medium air traffic demand Case Study than for the low air traffic demand Case Study. This again confirms higher ANS cost-efficiency with the increasing air traffic demand under the current operations.



a) S001 (24h FABEC Jul 28th 2016) **b) S003 (24h FABEC Feb 20th 2017)**

Figure 3-6: Comparison of the realised and optimal sectorisations for the two post-ops Case Studies.

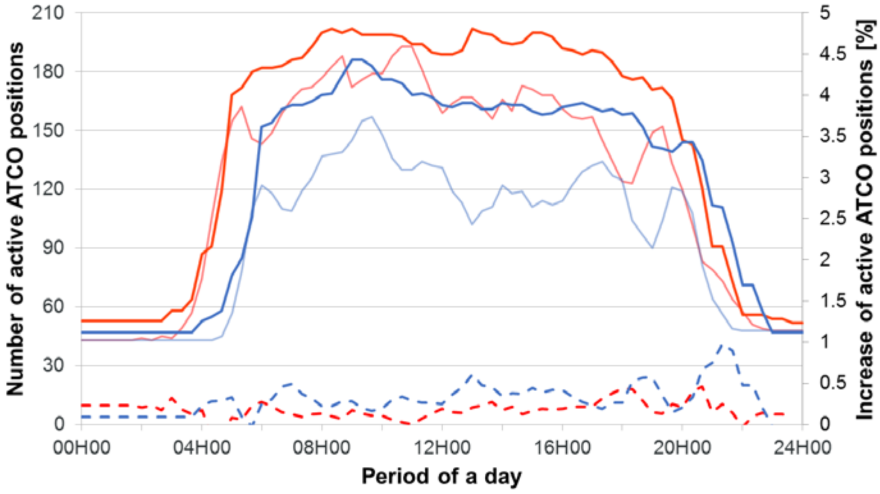


Figure 3-7: Actual, optimal and increase of the ATCO number for the different Case Studies (demand).

3.4 Environment KPA

APACHE Environment PIs are divided in two big families: distance-based indicators (ENV-1.x) and fuel-based indicators (ENV-2.x). Each family has several indicators aiming to capture different types 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). Each of these indicators, in turn, can be computed by using different optimal trajectories as baseline «optimal» reference, leading at the end to a wide set of different possible indicators for the Environment KPA.

This section presents the post-ops results using these APACHE indicators. Distance-based indicators, in turn, are compared with indicators that use the great circle distance between origin/destination airports (similar to current SES PRU indicators).

In should be noted that the indicators shown in this Section can be computed for each individual flight. For each indicator and Case Study, the analysis below shows the average, the median and the first and third quartiles (which quantify dispersion) of the data set. Among these statistical indicators, the median, which lies at the midpoint of the frequency distribution of the observed values such that there is an equal probability of falling above or below, will be taken for analysis and comparison. The reason is because the median is more robust to both skewness and outliers (e.g. few flights with very high or low values of a particular indicator can easily increase or decrease the average value).

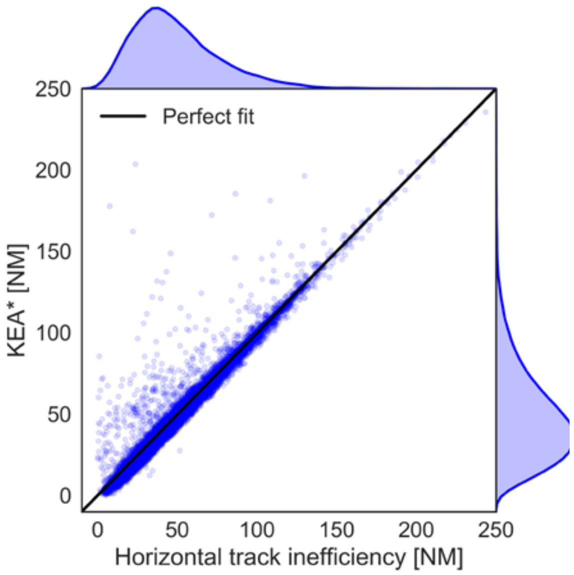
3.4.1 ENV-1: Distance-based indicators

Distance-based indicators have the advantage that they are easier to compute if compared with fuel-based indicators. Yet, they cannot capture inefficiencies in the vertical domain. The indicators proposed in APACHE, however, represent already a step beyond current state-of-the-art indicators that compare the actual flown distance with the great circle distance (geodesic distance) between origin and destination airports[12], since the actual flown distance is compared with the optimal flight distance taking into account weather conditions (which could differ from the geodesic distance).

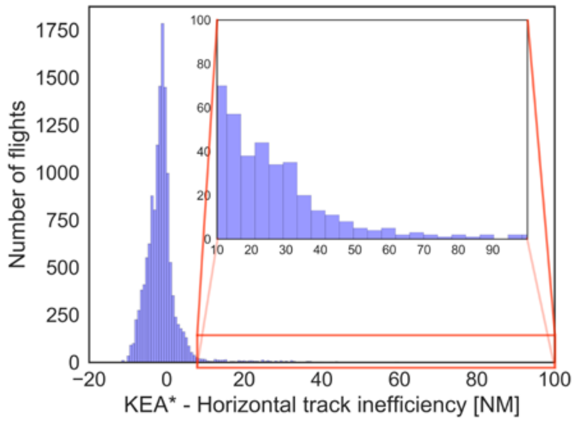
In APACHE two of these “current” indicators are computed (APACHE Consortium, 2017b):

- **C-ENV-1**: Average horizontal en-route flight efficiency for the filed flight plan trajectory. Similar to SES PRU’s key performance environment indicator based on the planned trajectory (KEP), but computing the inefficiency for each individual flight (no averaging or aggregation) and accounting these inefficiencies from origin to destination airports[12]. Thus, this particular implementation is referred as **KEP*** in this document.
- C**-ENV-2:** Average horizontal en-route flight efficiency of the actual trajectory. Similar to previous indicator but focusing in the actual trajectory instead. This indicator is referred as **KEA*** in this document, to differentiate from current SES PRU’s KEA[12].

Figure 3-8 shows the correlation and histogram of the differences between C-ENV-2 (actual route distance minus the geodesic distance) and ENV-1 (actual route distance minus the weather optimal route distance) for all S001 flights. This optimal trajectory has been computed assuming a full free-route airspace with a flat route-charges scheme and assuming maximum range operations (i.e. trying to minimise as much as possible the fuel consumption of the whole trajectory).



a) Scatter plot



b) Histogram

Figure 3-8: ENV-1 vs. C-ENV-2 (KEA*) for S001 (24h FABEC Jul 28th 2016).

As it can be seen in the Figure, there exist a significant correlation between the two indicators, meaning that most of the time C-ENV-2 (KEA*) captures environmental inefficiencies in a similar way ENV-1 does (i.e. the weather optimal trajectory is very similar to the geodesic trajectory). In fact, for this

[12] More precisely, current SES PRU indicators KEP and KEA, exclude the segments of trajectory within a 40NM radius around the origin and destination airports and they also show results in percentages of flight efficiency, taking into account the route length when aggregating results at ANSP/network level.

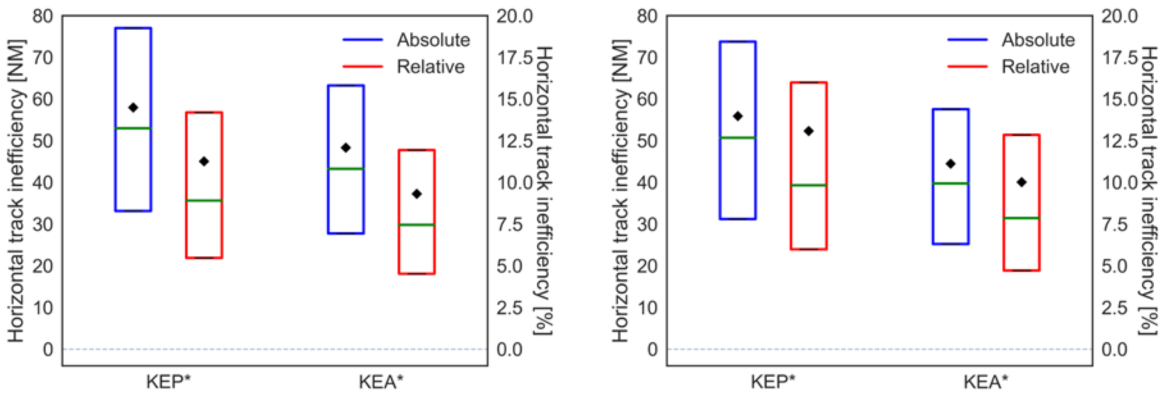
particular example we observed 13,236 flights with differences between the two indicators below +/- 10 NM. In only 24 flights the KEA* underestimated the inefficiency below -10NM, while for 335 flights KEA* overestimated the inefficiency above 10NM (Figure 3-8b shows the distribution). Underestimating (points below the 45º line in the Figure) means that the actual trajectory was flown close to the geodesic trajectory, albeit the optimal route (the one minimising fuel and therefore, the environmental impact) was longer due to weather conditions. When overestimating (points above the 45º line in the Figure), the optimal route was also longer than the geodesic trajectory and the actual trajectory was close to this optimal route and not to the geodesic route. It is worth noting that these discrepancies can reach up to 100 NM or more, as seen in Figure 3-8, but only for very few flights.

For S003, a similar correlation is found, with 10,291 flights with differences under +/-10 NM, 38 flights with KEA* underestimating the environmental inefficiency below -10 NM and with 465 flights with KEA* overestimating the environmental inefficiency above 10 NM.

Figure 3-9 shows the environmental impact assessment of the two post-ops Case Studies using KEA* and KEP*, while Figure 3-10 shows the same assessment when using the three distance-based indicators proposed in APACHE (APACHE Consortium, 2017b):

- ENV-1: Total ATM inefficiency in the horizontal track
- ENV-1.1: Strategic ATM inefficiency in the horizontal track
- ENV-1.2: Tactic ATM inefficiency in the horizontal track

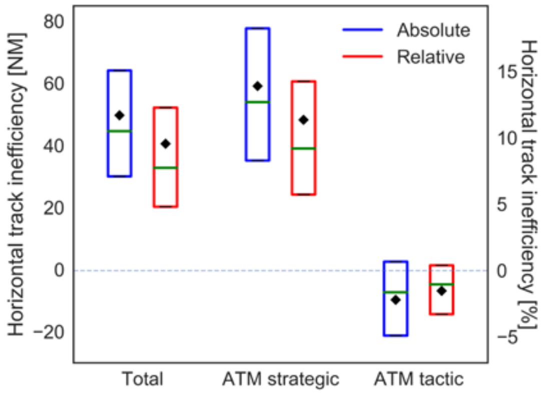
As observed in the Figure 3-9 the inefficiency of the actual (flown) trajectory if compared with the great circle distance has a median (green horizontal bar) around 43NM (7.5% in relative terms, if compared with the total route extension), while the inefficiency of the planned trajectory has a median of 53NM (9% in relative terms). As it is well known, in current operations KEA figures are typically lower than KEP figures, due to the fact that the executed trajectories benefit most of the time from short-cuts given at tactical level by the ATC.



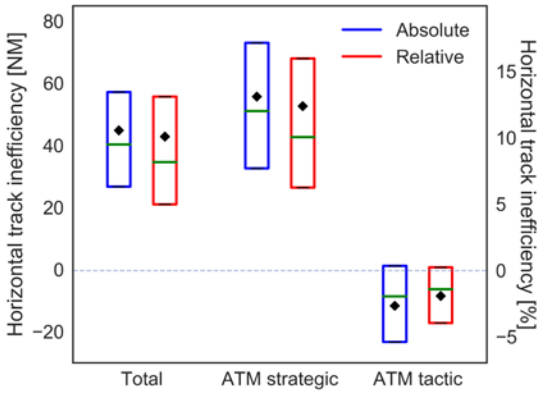
a) S001 (24h FABEC Jul 28th 2016) a) S003 (24h FABEC Feb 20th 2017)

Figure 3-9: Post-ops results with distance-based environmental indicators similar to SES PRU indicators (KEP* and KEA*)

Using the APACHE distance-based indicators (Figure 3-10) 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). The average values (black diamonds) are higher (almost 50 NM for S001 representing the 10% in relative terms) due to the fact that few flights experience high route inefficiencies. In the same Figure, we observe how the tactical layer (i.e. mainly the action of the air traffic controllers) introduces, for most of the flights, a “negative inefficiency”, meaning that ATC contribute to reduce route extension by short-cutting the planned trajectory. For this tactical layer, the inefficiency has a median around -8 NM (around -1.2% in relative terms).



a) S001 (24h FABEC Jul 28th 2016)



a) S003 (24h FABEC Feb 20th 2017)

Figure 3-10: Post-ops results with distance-based environmental indicators (ENV-1 family)

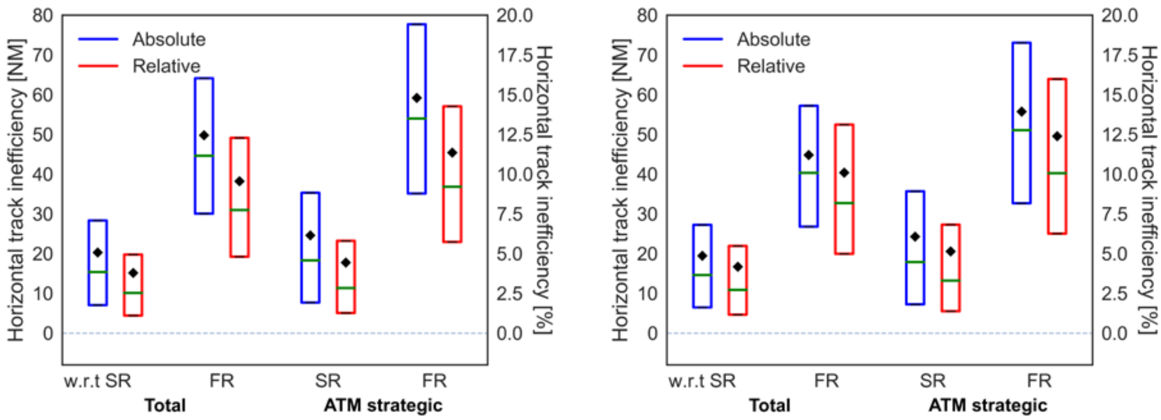
Table 3-8 shows the average and median results for the (distance-based) environment PIs used above to assess both post-ops Case studies.

Performance Indicator	S001				S003			
	average		median		average		median	
ENV-1 [Total]	50 NM	9.6 %	45 NM	7.7%	45 NM	10.1%	40 NM	8.2%
ENV-1.1 [ATM strategic]	59 NM	11.4%	54 NM	9.2%	56 NM	12.4%	51 NM	10.0%
ENV-1.2 [ATM tactic]	-10 NM	-1.5%	-7 NM	-1.1%	-12 NM	-1.9%	-9 NM	-1.4%

Table 3-8: Post-ops results with distance-based environmental indicators (ENV-1 family)

The optimal trajectory used as baseline for the previous three indicators has been computed assuming a full free-route airspace with a flat route-charges scheme and maximum range operations. Figure 3-11 shows ENV-1 (Total inefficiency) and ENV-1.1 (ATM strategic inefficiency) indicators using two different trajectory baselines: one assuming a full free-route (FR) airspace (as used above) and the other constraining the optimal trajectory to choose among the segments (i.e. waypoints and airways) of the current structured routes (SR) network.

The results for both days of study are very similar. It is interesting to observe how the ATM strategic environmental inefficiency goes from a median of around 52 NM (10%) if a full free-route case is considered as baseline optimal trajectory to a median of only 18 NM (3%). In other words, this environmental inefficiency is due to the fact that for some reasons the AU did not plan its trajectory using the best route in the network. The total inefficiency values show even smaller figures due to the ATC tactical layer, which helps in general to reduce these inefficiencies as discussed above.



a) S001 (24h FABEC Jul 28th 2016) a) S003 (24h FABEC Feb 20th 2017)

Figure 3-11: Post-ops results with distance-based environmental indicators (ENV-1 family) using different trajectory baselines

3.4.2 ENV-2: Fuel-based indicators

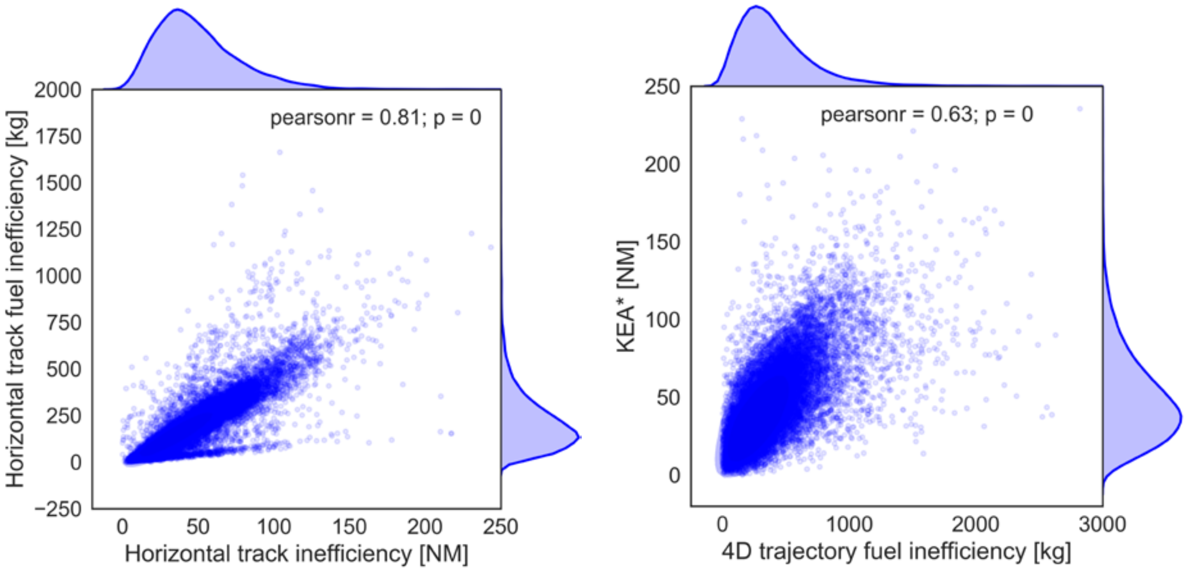
Fuel-based indicators try to estimate the flight inefficiencies in terms of extra fuel burnt, which is directly proportional to the CO_2 emissions. The have the advantage to be a more direct estimate on the environmental impact but their computation is more difficult since they require complex fuel estimation algorithms: fuel is estimated only from observed radar tracks, so the difficulty is to estimate the fuel of the observed trajectory without requiring confidential or sensitive data from the AUs (such as the take-off mass of the aircraft).

In APACHE, a wide family of fuel-based indicators was proposed (APACHE Consortium, 2017b):

- ENV-2: **Total** ATM inefficiency on trip fuel
- ENV-2.1: **Total** ATM **vertical** trajectory inefficiency on trip fuel
- ENV-2.2: **Total** ATM **horizontal** trajectory inefficiency on trip fuel
- ENV-2.3: **Strategic** ATM inefficiency on trip fuel
- ENV-2.4: **Strategic** ATM **vertical** trajectory inefficiency on trip fuel
- ENV-2.5: **Strategic** ATM **horizontal** trajectory inefficiency on trip fuel
- ENV-2.6: **Tactic** ATM inefficiency on trip fuel
- ENV-2.7: **Tactic** ATM **vertical** trajectory inefficiency on trip fuel
- ENV-2.8: **Tactic** ATM **horizontal** trajectory inefficiency on trip fuel

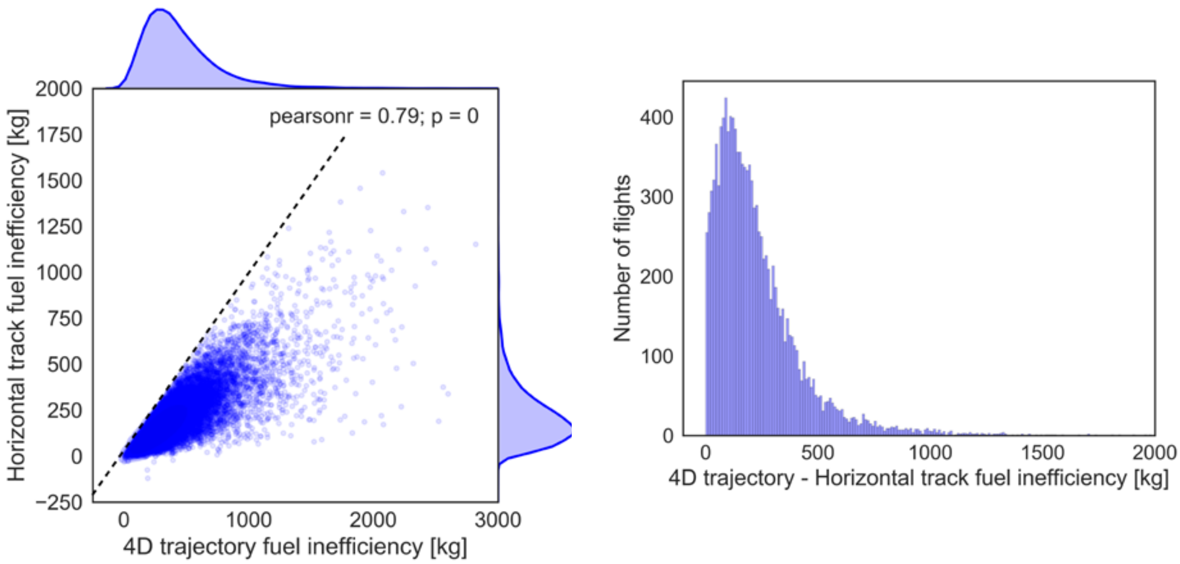
As explained before, APACHE indicator ENV-1 quantifies total ATM inefficiency in the horizontal track in terms of distance, and this already an enhancement with respect to current indicators (KEA) that use geodesic baselines. ENV-2.2 also quantifies the total ATM inefficiency in the horizontal track, but in terms of fuel. Figure 3-12a shows the correlation between these two indicators for all S001 flights. The baseline trajectory used as “optimal reference” has been computed assuming a full free-route airspace with a flat route-charges scheme and assuming maximum range operations (i.e. trying to minimise as much as possible the fuel consumption of the whole trajectory).

For most of the flights we observe a clear correlation of 4.7 kg of fuel inefficiency per NM of horizontal track inefficiency. A very similar value is also observed in S003. Yet, it is interesting to observe that for some flights the fuel inefficiency is much larger (for the same horizontal track inefficiency) and sometimes smaller. This behaviour probably shows the importance and influence of the weather conditions: the same route extension could lead to different fuel inefficiencies depending on how much head or tail wind the aircraft is experiencing, for instance.



a) ENV-2.2 vs. ENV-1 **b) ENV-2 vs. C-ENV-2 (KEA*)**

Figure 3-12: Correlation between distance-based and fuel-based environmental indicators for S001 (24h FABEC Jul 28th 2016).



a) Scatter plot **b) Histogram (vertical fuel inefficiency)**

Figure 3-13: ENV-2 vs. ENV-2.2 for S001 (24h FABEC Jul 28th 2016).

Figure 3-12b, in turn compares the total ATM inefficiency in terms of trip fuel (ENV-2) with the KEA* indicator. Although a direct correlation between these two indictors is still observed (as expected), the dispersion of the data set is larger, since vertical inefficiencies are captured by ENV-2 but not by KEA*.

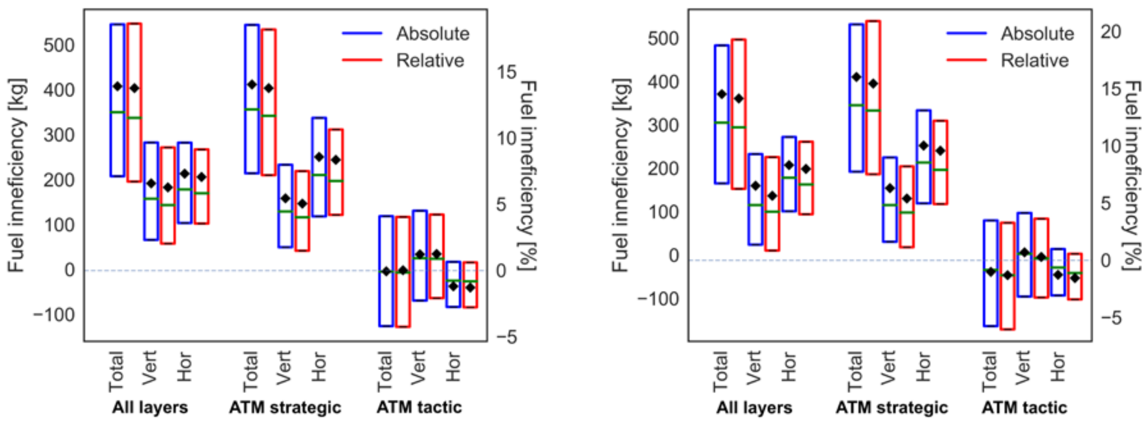
As it will be shown latter on in this same section, non-optimal vertical profiles could have a significant impact in the total fuel inefficiency of the 4D trajectory.

Finally, Figure 3-13a shows the correlation between ENV-2 and ENV-2.2 and the corresponding histogram with the differences, which are in fact the vertical fuel inefficiencies. As expected, the total 4D trajectory fuel inefficiency is, at least, the same as the fuel inefficiency due to route extensions (45º line in the scatter plot). Yet, the majority of flights observe fuel inefficiencies due to non-optimal vertical profiles (besides eventual inefficiencies due to non-optimal routes). The histogram of Figure 3-13b, quantifies these vertical inefficiencies, which mainly lie between 0 and 500 kg of fuel. Very similar results are obtained for S003 Case Study.

Figure 3-14 shows the environmental impact assessment of the two post-ops Case Studies using the nine fuel-based indicators enumerated above. The optimal trajectory used as baseline has also been computed assuming a full free-route airspace with a flat route-charges schemes and assuming maximum range operations.

As observed in the Figure, the total inefficiency has a median (green horizontal bar) around 350 kg for S001 and 300 kg for S003 (around 11% in relative terms if compared with the total fuel burnt) mostly due to the strategic part of the ATM, as we already observed with the distance-based indicators (recall Figure 3-10). The average values (black diamonds) are higher (around 400 kg, representing the 14% in relative terms), due to the fact that few flights experience high route inefficiencies. Here, the effects of ATC tactical interventions, which can lead to “negative inefficiencies”, are also observed: for S001 the median is -7.5 kg (0.2%) and for S003 the median is -35 kg (1.3%).

An advantage of the fuel-based indicators proposed in APACHE is the possibility to decouple the vertical and horizontal sources of fuel inefficiency. According to Figure 3-14, 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.



a) S001 (24h FABEC Jul 28th 2016)

a) S003 (24h FABEC Feb 20th 2017)

Figure 3-14: Post-ops results with fuel-based environmental indicators (ENV-2 family)

Table 3-9 shows the average and median results for the (fuel-based) environment PIs used above to assess both post-ops Case studies.

Performance Indicator	S001				S003			
	average		median		average		median	
ENV-2 [Total]	408 kg	13.8%	350 kg	11.5%	371 kg	14.1%	305 kg	11.6%
ENV-2.1 [Total - vertical]	192 kg	6.3%	157 kg	4.9%	160 kg	5.6%	115 kg	4.2%
ENV-2.2 [Total - horizontal]	213 kg	7.1%	178 kg	5.8%	207 kg	8.0%	178 kg	6.6%
ENV-2.3 [Strategic]	412 kg	13.8%	356 kg	11.7%	411 kg	15.4%	345 kg	13.1%
ENV-2.4 [Strategic - vertical]	158 kg	5.0%	129 kg	4.0%	155 kg	5.4%	115 kg	4.2%
ENV-2.5 [Strategic - horizontal]	251 kg	8.4%	210 kg	6.8%	252 kg	9.6%	213 kg	7.9%
ENV-2.6 [Tactic]	-6 kg	0.1%	-7 kg	-0.2%	-40 kg	-1.0%	-36 kg	-1.3%
ENV-2.7 [Tactic - vertical]	34 kg	9.1%	25 kg	17.2%	6.4 kg	16.4%	2.7 kg	20.6%
ENV-2.8 [Tactic - horizontal]	-37 kg	-1.1%	-25 kg	-0.8%	-45 kg	-1.3%	-29 kg	-1.0%

Table 3-9: Post-ops results with fuel-based environmental indicators (ENV-2 family)

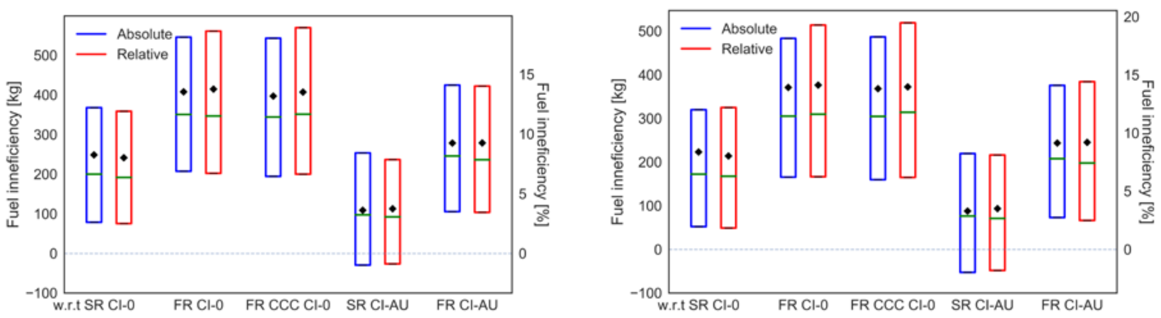
The optimal trajectory used as baseline for all previous indicators has been computed assuming a full free-route airspace with a flat route-charges scheme and maximum range operations (Cost Index set to zero). Figure 3-15 shows the same ENV-2 indicator computed with five different optimal trajectory baselines:

- assuming a full free routes and Cost Index (CI) zero (FR CI-0), as in previous figures;
- assuming full free routes, CI=0 and also continuous cruise climbs (FR CCC CI-0);
- constraining the optimal trajectory to the current en-route network and with CI=0 (SR CI-0);
- constraining the optimal trajectory to the current en-route network and with the CI estimated from the actual trajectory (SR CI-AU); and
- assuming full free routes but using the CI estimated from the actual trajectory (FR CI-AU).

As expected (and already noticed in Figure 3-11) inefficiencies for the SR cases are lower, since the optimal trajectory baseline is also constrained to follow segments of the current route network. If CI=0 the median of the total inefficiency goes from 350 kg (11%) to around 200 kg (6.3%) for S001 (a similar trend is observed for S003). Interestingly, allowing for continuous cruise climbs does not practically change the inefficiency values, meaning that for these Case Studies the benefits of flying continuous cruise climbs are negligible, providing the aircraft can fly at their optimal (constant) cruise altitudes, which is not always the case as observed before.

The SR CI-0, FR CI-0 and FR CCC CI-0 baselines all three consider that the optimal trajectory is flown at maximum range operations (CI=0), since this is the operational conditions that minimises fuel consumption. Yet, the decision to fly slower or faster mainly resides on the AU, who selects the best cruising speeds (i.e. the CI) according to their cost-break down structure and business models. For this reason, it would be unfair to attribute to the ATM system all the environmental inefficiencies commented so far, since some of these inefficiencies are a consequence of the AU flying faster than the minimum fuel consumption speed. This is what SR CI-AU and FR CI-AU baselines try to capture.

As observed in Figure 3-15, the inefficiencies that could be attributable to ATM go down to approximately 250 kg (7.8%) if a full free-route scenario is considered for the baseline trajectories (instead of 350 kg – 11%), or 97 kg (3.0%) if the structured route network is considered (instead of 200 kg – 6.3%). In other words, AU's induced fuel inefficiencies (due to flying faster than the maximum range speed) have a average around 100 kg (3% in relative terms approximately).



a) S001 (24h FABEC Jul 28th 2016)

a) S003 (24h FABEC Feb 20th 2017)

Figure 3-15: Post-ops results with distance-based environmental indicators (ENV-2 family) using different trajectory baselines

3.5 Flexibility KPA

In APACHE three flexibility indicators were proposed and implemented for post-ops analysis (APACHE Consortium, 2017b):

- **FLEX-1:** Percentage of RBTs which are equal to SBTs.
- **FLEX-2:** Spare capacity.
- **FLEX-3:** Sector changes per hour.

Table 3-10 summarises the results for the two Case Studies. The difference between medium (S001) and low (S003) traffic demand case is clearly notable and indicates less restrictions imposed by the ATM system in the case of less challengeable traffic demand. As expected, the percentage of non-regulated flights (FLEX-1) is higher in S003, as well as spare capacity in the network (FLEX-2). The low demand case (S003) also leads to less sector changes per hour in average, which can be explained by the fewer number of active sectors needed to accommodate the traffic demand.

Performance Indicator	S001	S003
FLEX-1	84.24%	95.07%
FLEX-2	36.92	45.17
FLEX-3	5.45	5.30

Table 3-10: Post-ops results for the flexibility KPA

3.6 Safety KPA

In APACHE seven safety indicators were proposed and implemented for post-ops analysis (APACHE Consortium, 2017b):

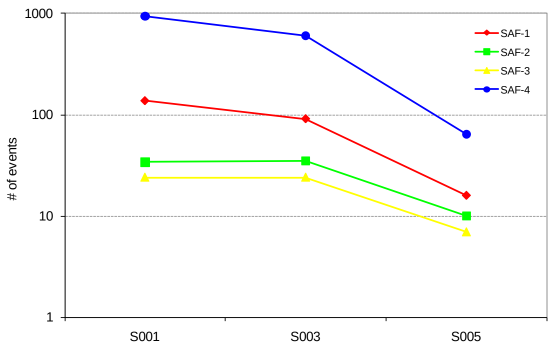
- **SAF-1:** Number of Traffic Alerts warnings
- **SAF-2:** Number of Resolution Advisors issued
- **SAF-3:** Number of Near Mid Air Collisions
- **SAF-4:** Number of separation violations
- **SAF-5:** Severity of separation violations
- **SAF-6:** Duration of separation violations
- **SAF-7:** Risk of conflicts

Recall that in (APACHE Consortium, 2017b; 2018b) for post-ops analysis a C-SAF-1 indicator is proposed, but it fully corresponds to SAF-4 indicator, so it is not further analysed separately.

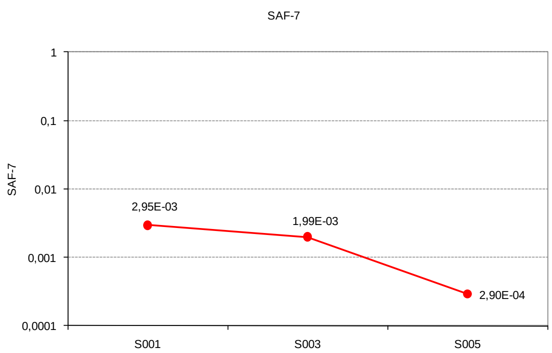
The values for Safety KPA are shown in Table 3-11. Comparison between S001 (summer – medium traffic demand) and S003 (winter – low traffic demand) shows that SAF values behave in a logical manner, meaning that in case of higher traffic SAF values are generally equal or higher. Reduction of values is evident for SAF-1 and SAF-4. SAF-2 and SAF-3 are (almost) the same (see Figure 3-16a). SAF-5 and SAF-6 (Figure 3-17) are higher in case of low traffic demand which is explained by lower number of conflicts (SAF-4, smaller sample) and specific conflict geometry influencing its severity (SAF-5) and duration (SAF-6). Finally, SAF-7 (Figure 3-16b) has higher value in case of higher traffic demand which could be explained by the higher number of conflict situations (SAF-4) for which severity (SAF-5) and duration (SAF-6) are computed.

Performance Indicator	S001	S003	S005
SAF-1	137	91	16
SAF-2	34	35	10
SAF-3	24	24	7
SAF-4	938	602	64
SAF-5	0.407 ± 0.299	0.428 ± 0.307	0.587 ± 0.351
SAF-6	89.89 ± 265.01 s	140.60 ± 461.12 s	392.03 ± 647.32 s
SAF-7	2.95 · 10-3	1.99 · 10-3	2.9 · 10-4

Table 3-11: Post-ops results for the safety KPA

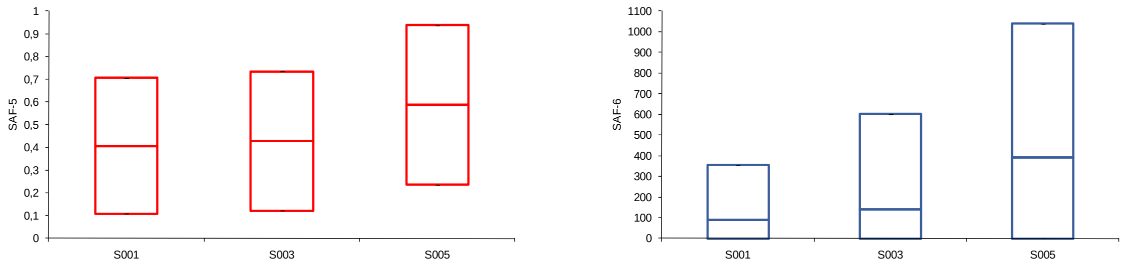


a) SAF-1, SAF-2, SAF-3 and SAF-4



b) SAF-7

Figure 3-16: Comparison of the different safety PIs for the three post-ops Case Studies considered



a) SAF-5 b) SAF-6

Figure 3-17: Comparison of SAF-5 and SAF-6, for the three post-ops Case Studies considered, showing average +/- the standard deviation

Comparison between S001 (summer – medium traffic demand) and S005 (summer – medium traffic demand, obtained from PRU) shows significant differences. Namely, in case of S005 values for SAF-1 to SAF-4 indicators are very much lower. Unlike that, SAF-5 and SAF-6 values are higher (Figure 3-17). This could be explained by lower number of conflicts (small sample, "only" 64 conflicts) for which the values are computed. However, value for SAF-7 is lower for one order of magnitude, as seen in Figure 3-16b ($2.95 \cdot 10^{-3}$ vs. $2.9 \cdot 10^{-4}$).

The main conclusion of this comparison is that difference between PRU data and data from DDR2 exists, as well as that SAF indicators are sensitive to "accuracy" of input data in the context of aircraft position. PRU data comes from correlated position reports obtained from the different ANSPs (radar tracks). 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 (Eurocontrol, 2016; Spinelli et al., 2017). 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.

Sensitivity of SAF indicators to input data quality is illustrated with the spatial distribution of SAF-1 to SAF-4 indicators in Figures 3-18 to 3-21 (showing 24 hour of aggregated data in a single figure). S001 are based on inputs from DDR, so points shown on maps are "potential" points in which certain safety events may occur, while for S005 they should be "real" points, even though evidences for them were not available. In Figures 3-18 to 3-21 only points in European airspace are shown, although certain safety events occur outside this airspace (among flights which are passing through FABEC airspace).

a) S001 (DDR2 data) b) S005 (PRU CPR data)

Figure 3-18: Spatial distribution of SAF-1

a) S001 (DDR2 data) b) S005 (PRU CPR data)

Figure 3-19: Spatial distribution of SAF-2

a) S001 (DDR2 data) b) S005 (PRU CPR data)

Figure 3-20: Spatial distribution of SAF-3

a) S001 (DDR2 data) b) S005 (PRU CPR data)

Figure 3-21: Spatial distribution of SAF-4

4 Results of the pre-ops assessment

After the assessment of the historic data (post-ops results), this chapter presents the results of the APACHE simulations (pre-ops – simulated data). The objective of the pre-ops assessment is to compare the results of the different Solution scenarios (S2, S3 and S5) with the reference scenario (S1), assessing the performance and applicability of the APACHE Framework indicators to evaluate various SESAR Solutions.

As previously stated, the reference scenario includes the traffic and environment and **without** the SESAR Solution that are the subject of the validation, matched in time with the solution scenario. On the other side, the Solution scenarios are the scenarios including traffic and environment and **also including** SESAR operational improvements that are the subject of the validation (see Chapter 3).

As for the post-ops assessment, several Case Studies have been proposed considering the levels of air traffic demand, as gathered from Eurocontrol's DDR2:

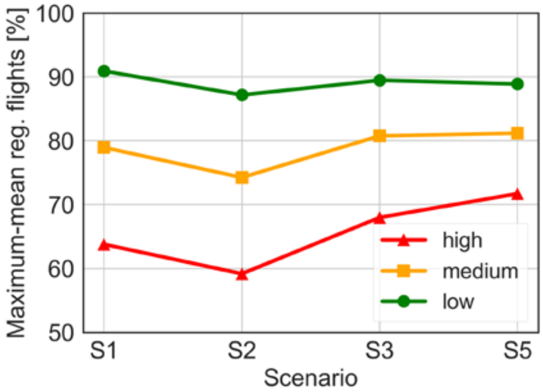
- SX01: **Medium** demand (24h of operations in July 28th 2016).
- SX03: **High** demand (24h of operations in July 21st 2023 generated by Eurocontrol's STATFOR tool configured to give the maximum amount of demand for that representative day).
- SX05: **Low** demand (24h of operations in February 20th 2017).

Overall, three Solution scenarios have been used for the assessment of the simulations results. Each of the scenarios implies the use of a specific SESAR Solution (S2: Enhanced FRA, S3: Continuous Cruise Climbs and S5: Advanced DCB).

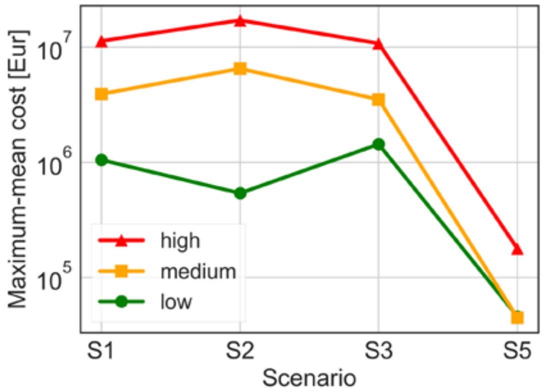
All the APACHE PA simulation results have FABEC region as scope (i.e. only trajectories crossing FABEC and only ATC sectors within FABEC have been considered) and the same KPAs as for the post-ops assessment have been used for the analysis of the results. Some APACHE Framework indicators, however, have not been considered for the pre-ops assessment, as they are only applicable for the post-ops assessment due to the limitations of the current implementation of the APACHE-TAP (not simulating tactical operations). Please refer to (APACHE Consortium, 2018b) for further details on the applicability of the APACHE Framework indicators.

4.1 Access and Equity

The simulations conducted evaluate the previously described PIs (AEQ-1 and AEQ-2) for the four different scenarios and for the three different levels of air traffic demand (low, medium and high). The results are presented in Figure 4-1. For the Access and equity (AEQ) KPA the same PIs can be used for post-ops and pre-ops analysis.



a) AEQ-1



b) AEQ-2

Figure 4-1: Pre-ops results for the access and equity KPA

For AEQ-1, the comparison among the different scenarios shows that the enhanced FRA scenario (S2) is the only one leading to an overall lower difference between the maximum percentage of regulated flights and the average percentage of regulated flights for all demand levels compared to the reference scenario (S1). This could be done, however, by the fact that in S2 more regulations are issued and therefore this average of regulated flights (per AU) is higher (see remarks already provided in section 4.1). The other two scenarios: continuous cruise climbs (S3) and advanced DCB (S5) lead to similar or slightly larger differences between AUs than the reference scenario.

Regarding AEQ-2, the worst penalty costs would be obtained in the S2 scenario, except for the low demand level, which leads to similar results for all scenarios. The enhanced FRA scenario (S2) entails higher differences between the first SBT submitted and the RBT, because for this scenario more regulations are needed since ATC sectorisation is not conceived for the traffic patterns arising from full free-route operations. Overall, the best results are obtained in the S5 scenario as the ADCB leads to the highest level of equity minimizing this indicator for all demand levels.

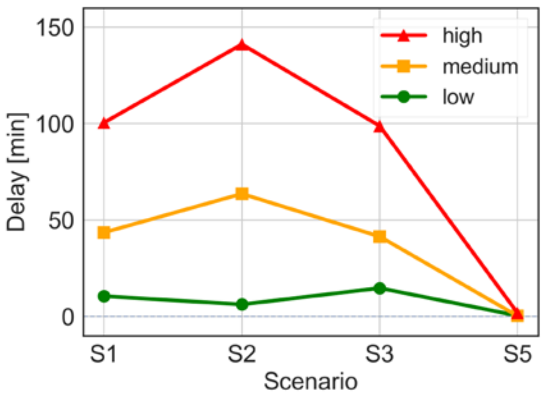
In terms of sensitivity to demand, the benefits or drawbacks derived from the specific solutions are magnified with the increase of traffic demand. For instance, S3 and S5 lead to (similar but) lower results for AEQ-1 for low traffic demand; but they present better results than S1 for the medium and especially high demand levels. This is due to the fact that the AEQ-1 PI is the subtraction of the maximum number of regulations per AU and the average number of regulations. In all Case Studies, there are always few AUs with a very small number of regulated flights (i.e. 1 or 2). Thus, this maximum value is 100%. Then, with more demand, more regulations are observed and the average value increases which leads to a lower value of the PI. The definition of AEQ-1 should be reviewed in the future taking into account, for instance, the top 10 regulated AUs, as proposed in section 3.1, or filtering somehow these outliers.

Penalty costs are also magnified with demand, as it can be derived from the increased costs of S2 compared to S1 for the medium and high demand levels. However, this does not apply to all scenarios, as the S5 is completely unaffected by the demand levels and always lead to the minimised AEQ-2 results.

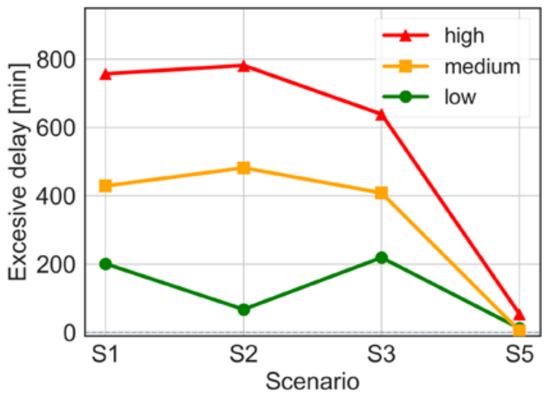
4.2 Capacity

Nowadays system capacity is being measured by how well it suits current needs i.e. whether current demand may be served without imposing traffic regulations. Existing PI, C-CAP-1 – Average en-route ATFM delay, represents indirect metric of the capacity that measures negative impact of the capacity shortfalls. CAP-1 - Robust maximum en-route ATFM delay is also indirect measure aiming to replace information loss due to ATFM delay averaging.

Figure 4-2 shows evolution of C-CAP-1 and CAP-1 indicators for different scenarios and three traffic demand levels. Comparing S1, S2 and S3 (reference, enhanced FRA and CCC scenarios, respectively), the first thing to be notice is that both average and maximum robust ATFM delay are increased with the increase of the traffic demand. Similar to the post-ops analysis, these results suggest that current ATM system capacity is better adapted to the Case Studies represented by the lower traffic demand.



a) C-CAP-1



b) CAP-1

Figure 4-2: Pre-ops results for the ATFM departure delay (C-CAP-1) and Robust maximum en-route ATFM delay (CAP-1)

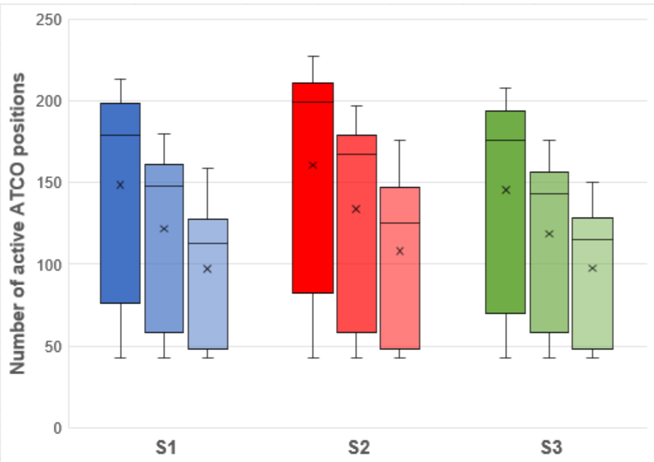


Figure 4-3: ATCO distribution for the pre-ops scenarios and the three traffic demand Case Studies.

Similarly, Figure 4-3, showing the distribution of the ATCO positions for the reference scenarios S1 (blue), enhanced FRA scenario S2 (red) and CCC scenario S3 (green) for three Case Studies (high, medium, low demand) with different color shades (lighter representing lower demand), reveals that for all operational scenarios distribution of the ATCO position is increased with the increase of the traffic demand.

Compared with reference scenario (S1), the enhanced FRA scenario (S2) shows an increase of the average delay, the increase being more pronounced with an increase of traffic demand. A naive and wrong interpretation of the increase in the ATFM delay would be that FRA has less capacity compare to the conventional airspace organization. Since existing ATC sectors were used in the study, **the increase of the delay is result of the traffic concentration in the certain ATC sector due to more flexible route choice.** This is in line with results of section 4.1, where we already observed that S2 had more ATFM regulations. Therefore, results should be interpreted as current airspace sectorisation not being adapted to the FRA. This conclusion is confirmed with CAP-1 indicator values that are not significantly changed compared to values of the reference scenarios.

Although Figure 4-3 shows an increase in the number of active ATCO positions in S2 compared to the referenced scenario, this increase (below 10% in ATCO hours on duty for all demands) is not proportional to the increase of the flight restrictions (40% of average delay increase for the high demand). This significant flight restriction could not be resolved by the simple increase of the ATCOs on duty due to mentioned concentration of the traffic (460 active sectors experienced traffic higher than the double-capacity compared to less than 300 in the reference scenario).

Continuous cruise climb operations (S3) do not show to significantly affect system capacity in terms of traffic regulations with values of both indicators being comparable. This may be confirmed with Figure 4-4 showing distribution of the ATCO positions for the reference scenarios S1 (blue) and CCC scenario S3 (green) for different Case Studies. This Figure does not show significant changes in the airspace sectorisation with introduction of the CCC operations.

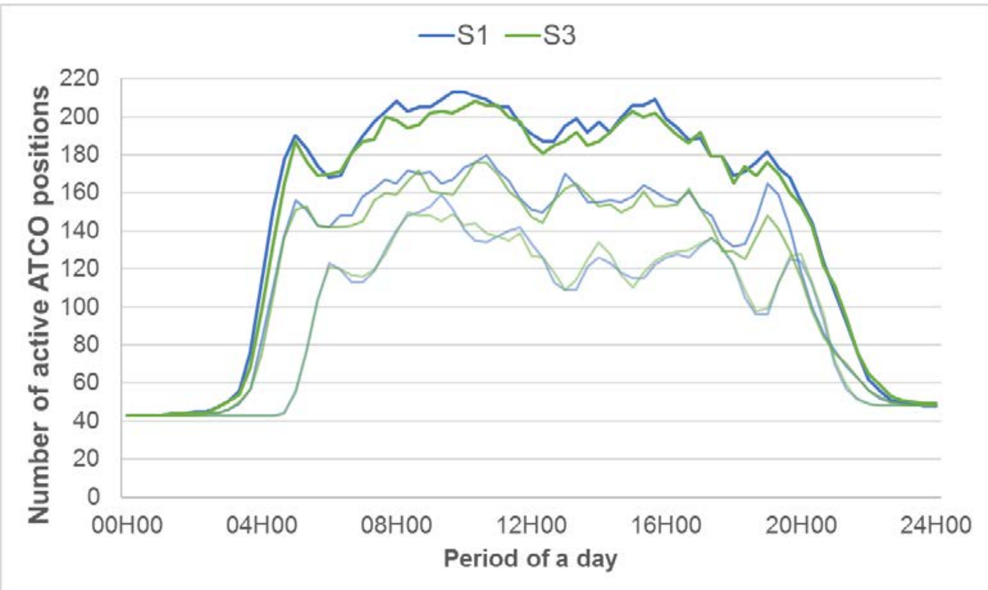


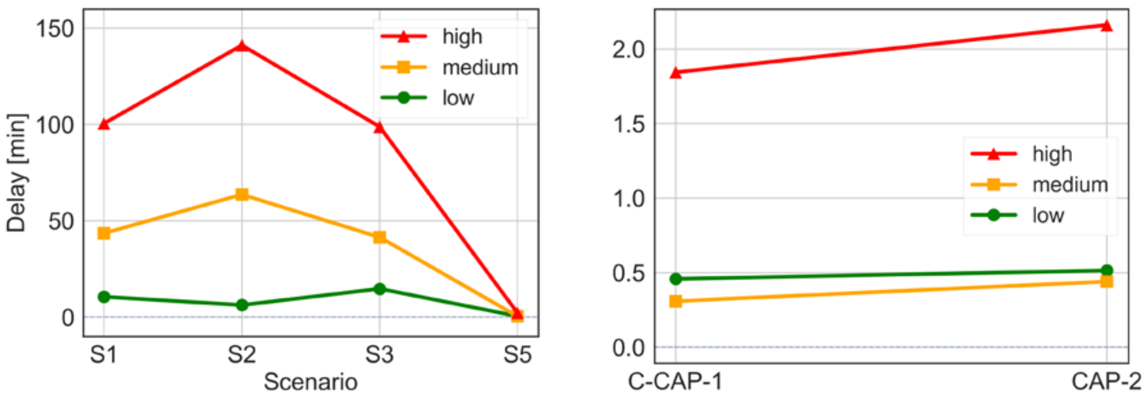
Figure 4-4: ATCO distribution for the pre-ops scenarios S1 and S3 and the tree Case Studies (demand)

Finally, scenario S5 (with ADCB implemented), shows a huge reduction in both average and robust maximum ATFM delay compared to the reference (and all other) scenario. This is due to the fact that traffic demand in the ADCB is regulated by the traffic rerouting in addition to the traffic delay. Therefore, part of the traffic regulations is not caught by any of the two indicators shown in Figure 4-

3. This is why in the APACHE framework, another metric CAP-2 – Average flow management arrival delay is proposed aiming to capture all changes in the user preferred route including: departure delay, longer route, suboptimal cruising altitude, etc.

Figure 4-5 ashows CAP-2 indicator for the same scenarios and Case Studies. The value of the indicator CAP-2 is not changing if compared to indicator C-CAP-1 for the scenarios S1, S2, and S3, since the only demand regulation used is traffic delay. Figure 4-5b focuses on the comparison of the C-CAP-1 and CAP-2 for S5, since the differences are not easily visible in previous figures due to scaling. An increase in the arrival delay (CAP-2), due to traffic rerouting is illustrated in Figure 4-5, if compared with departure delay (C-CAP-1) in the S5. This increase, however, is negligible compared to the level of decrease of the average delay between reference scenario S1 and scenario S5.

Therefore, it can be concluded conclude that rerouting causes less demand restrictions in terms of delay and airspace capacity could be more efficiently used with rerouting regulation applied instead of the delays solely. The gain of rerouting is more pronounced with higher traffic demand, since higher excess of the ATC sector capacity is expensive to solve by delaying flights.



a) CAP-2 b) C-CAP-1 vs. CAP-2 in S5

Figure 4-5: Average flow management arrival delay (CAP-2) and its comparison with ATFM departure delay (C-CAP-1) for the pre-ops scenarios

4.3 Cost-Efficiency

Since in the current implementation of the APACHE-TAP tactical operations are not synthesised for pre-ops analysis, only the AU cost-efficiency PIs that capture strategic inefficiencies are displayed in this section. For the same reason, only CE-3 (Flight per ATCO hour on duty) is shown for the ANS cost-efficiency focus area.

4.3.1 Airspace User cost-efficiency

Figure 4-6 shows value of the existing PRU indicator labeled C-EFF-1 representing the share of the regulated flights for four different scenarios and three traffic demand levels. Since the flight regulations are result of the demand and capacity imbalance, PI value increase with the traffic demand, as shown at the figure for all scenarios, was expected.

The enhanced FRA scenario (S2) shows higher number of regulated flights if compared to the reference scenario (S1), for all traffic demand levels. Furthermore, the difference between S1 and S2 is higher with the increase in demand. As already acknowledged, this is linked with the concentration of the traffic due to more flexible route choice in the FRA. The continuous cruise climb scenario (S3) does not show significant differences if compared to the reference scenario in terms of flight efficiency measured solely by the number of regulated flights.

Finally, S5 scenario with ADCB shows the most interesting results. For the low demand Case Study, the number of regulated flights is increased in scenario S5 compared to reference scenario, giving the straightforward conclusion that S5 is “less efficient” than the reference scenario. However, looking at Figures 4-2 and 4-5, showing capacity KPA indicators, it could be noted that average delay in the S5 is reduced compared to the reference scenario. This means that reduction of the delay magnitude in S5 is achieved by a more collaborative way to solve demand and capacity imbalances using a higher number of flights, instead of penalizing a smaller number of flights as in S1.

For the medium demand, the effectiveness of the re-routings and level cappings is already visible and the number of regulated flights (along with traffic delay) of S5 becomes lower than the reference scenario. This difference is further increased for the high demand Case Study. The results shown clearly confirm that S5 scenario is more efficient in the terms of capacity utilization i.e. demand and capacity balancing. Since it is a macroscopic indicator, which does not capture the magnitude of the regulations, whether this efficiency is reflected in the terms of route efficiency it is not certain, and in the APACHE different indicators are proposed for this purpose, as shown below.

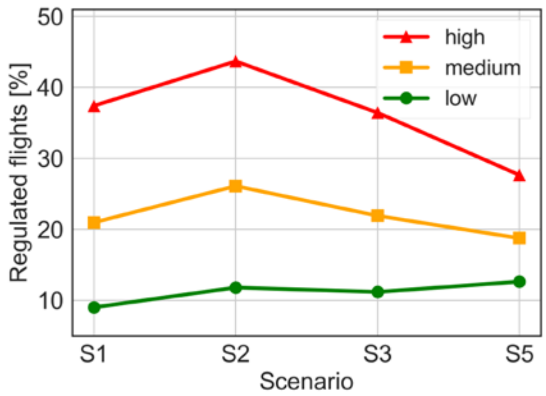


Figure 4-6: Pre-ops results using current SES PRU indicator for AU cost-efficiency (C-EFF-1)

Table 4-1 shows the median and average values for the new AU cost-efficiency indicators proposed in APACHE.

When the cost-based indicator (CE-1.1) is computed using **the last filed flight plan (or first SBT) as baseline trajectory** the median values are zero for all scenarios, meaning that more than the 50% of the flights were not regulated (so the SBT equals to the RBT and therefore the strategic cost inefficiency is zero). Yet, the average value is not zero as seen in Table 4-1. The trip time based indicator (CE-4.1), in turn, shows zero values for S1, S2 and S3 since ATFM delay is not considered in the computation of the indicator. **Interestingly, for S5 this indicator properly captures the extra trip time (not delay) as consequence of ATFM re-routings or level cappings.**

PI	Low demand				Medium demand				High demand			
	average		median		average		median		average		median	
Scenario S1												
CE-1.1 (Eur/flight) [*]	595	26.6%	0	0.0%	2,365	92.0%	0	0.0%	5,519	205.9%	0	0.0%
CE-1.1 (Eur/flight) [**]	813	34.3%	190	5.5%	2,609	103.5%	257	6.2%	5,783	225.9%	406	9.1%
CE-4.1 (min) [*]	0	0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%
CE-4.1 (min) [**]	4.7	6.5%	4.0	5.2%	5.0	6.1%	4.3	5.0%	5.1	6.1%	4.5	5.0%
Scenario S2												
CE-1.1 (Eur/flight) [*]	358	16.3%	0	0.0%	3,495	131.9%	0	0.0%	7,695	282.6%	0	0.0%
CE-1.1 (Eur/flight) [**]	361	16.4%	0	0.0%	3,498	132.0%	0	0.0%	7,698	282.7%	0	0.0%
CE-4.1 (min) [*]	0.0	0.0%	0	0.0%	0.0	0.0%	0	0.0%	0.0	0.0%	0	0.0%
CE-4.1 (min) [**]	0.1	0.0%	0	0.0%	0.1	0.1%	0	0.0%	0.1	0.1%	0	0.0%
Scenario S3												
CE-1.1 (Eur/flight) [*]	485	17.5%	0	0.0%	2,246	83.7%	0	0.0%	5,383	186.7%	0	0.0%
CE-1.1 (Eur/flight) [**]	805	34.0%	182	5.4%	2,599	102.1%	248	6.1%	5,770	224.4%	397	9.1%
CE-4.1 (min) [*]	0.0	0.0%	0	0.0%	0.0	0.0%	0	0.0%	0.0	0.0%	0	0.0%
CE-4.1 (min) [**]	4.5	6.3%	3.9	5.2%	4.9	6.0%	4.1	5.0%	4.8	5.9%	4.3	5.0%
Scenario S5												
CE-1.1 (Eur/flight) [*]	28	1.0%	0	0.0%	22	0.7%	0	0.0%	66	2.1%	0	0.0%
CE-1.1 (Eur/flight) [**]	248	7.2%	180	5.3%	263	6.5%	210	5.1%	314	8.1%	231	5.4%
CE-4.1 (min) [*]	0.1	0.1%	0	0.0%	0.1	0.2%	0	0.0%	0.3	0.4%	0	0.0%
CE-4.1 (min) [**]	4.8	6.6%	4.2	5.3%	5.1	6.3%	4.5	5.1%	5.4	6.5%	4.7	5.3%

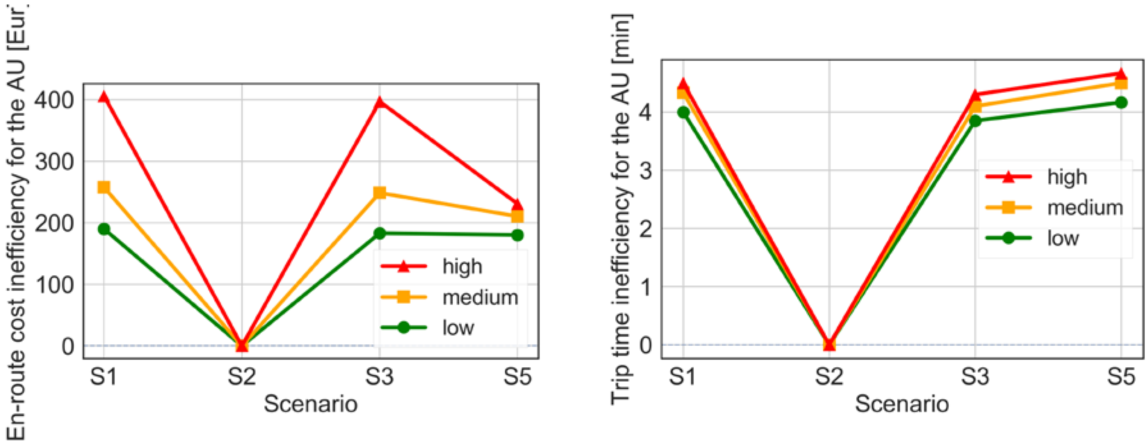
[*] Last filed flight plan (or SBT) taken as baseline trajectory – [**] AU Cost-optimal trajectory taken as baseline

Table 4-1: Pre-ops results for the AU cost-efficiency focus area

If instead of using the last filed flight plan (or first SBT) the baseline for these indicators is the **optimal trajectory assuming a full free-route airspace and flown at the AU's desired Cost Index**, then the cost inefficiency increases with respect to previous case, as it was also observed in the post-ops assessment (see section 3.3.1). This behaviour is mainly caused by the fuel inefficiencies appearing as the consequence of using a static en-route network (instead of flying free routes). Figure 4-7 shows the median values for CE-1.1 and CE-4.1 when these baseline trajectories are used and Table 4-1 also shows their average values.

As expected, S2 shows the lowest values of AU inefficiencies, being the enhanced FRA scenario. S3 performs approximately as the reference scenario (S1), meaning that continuous cruise climbs do not introduce significant benefits, as the AU economic costs would not be significantly affected for the en-route phase. Regarding S5 (where an ADCB algorithm is used to regulate demand), it is interesting to observe how the AU cost-inefficiencies decrease with respect to S1 (notably for the high and medium demand Case Studies). This ADCB algorithm minimises the AU cost by optimally allocating delays, re-routings, level cappings or a combination of these, in order to regulate the demand. Thus, the eventual extra cost of a re-routing or level-capping is compensated by the greater gains of having less delay.

Recall that CE-4.1 (Figure 4-7b), does not take into account ATFM delays but purely extra trip time. Thus, the time inefficiencies observed for S1 and S3 are the consequence of flying longer routes (if compared with the enhanced FRA scenario). For S5, besides these longer routes of the first SBT we also observe the increase of flight time for those flights that were assigned with a re-routing or a level capping in order to avoid a congested area.



a) AU cost-based indicator (CE-1.1)

b) Trip time indicator (CE-4.1)

Figure 4-7: Pre-ops results for the AU cost-efficiency indicators with optimal full free-route trajectory as baseline

4.3.2 ANS cost-efficiency

Regarding the ANS cost-efficiency as captured by CE-3, the S2 scenario shows much lower results than the reference scenario S1 (see Figure 4-8). Figure 4-9, in turn, represents the increase of the active ATCO positions with respect to reference scenario S1. As shown in this last Figure, a higher number of ATCO positions is needed to serve the same traffic demand in the enhanced FRA environment (S2) compared to the reference scenario using the conventional ATS route network (S1) and assuming current airspace sectorisation operations.

This increase in the number of active ATCO positions, for the same traffic demand, reduce ATCO productivity and finally leads in the reduction of the ANS cost-efficiency PI. In this regard, S2 is the scenario that leads to the lowest amount of flights per ATCO hour (lowest ANS cost-efficiency), contrary to the smallest trip time difference for all demand levels (highest ANS cost-efficiency).

The differences of S3 (CCC operations) compared to the reference S1 are minor, as seen in Figure 4-9, while S5 is equivalent to S1 with respect to the ANS cost-efficiency, since ADCB does not affect airspace sectorisations.

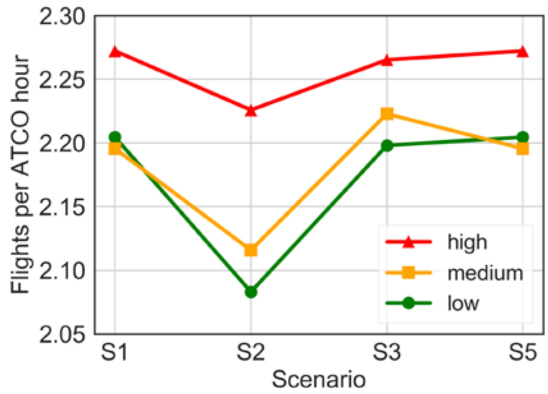


Figure 4-8: Pre-ops results for the ANS cost-efficiency indicator (CE-3)

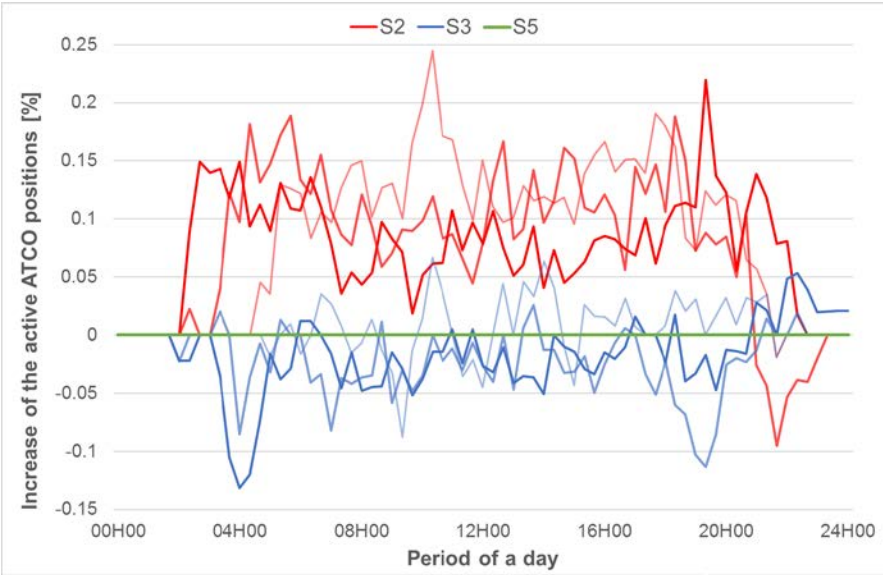


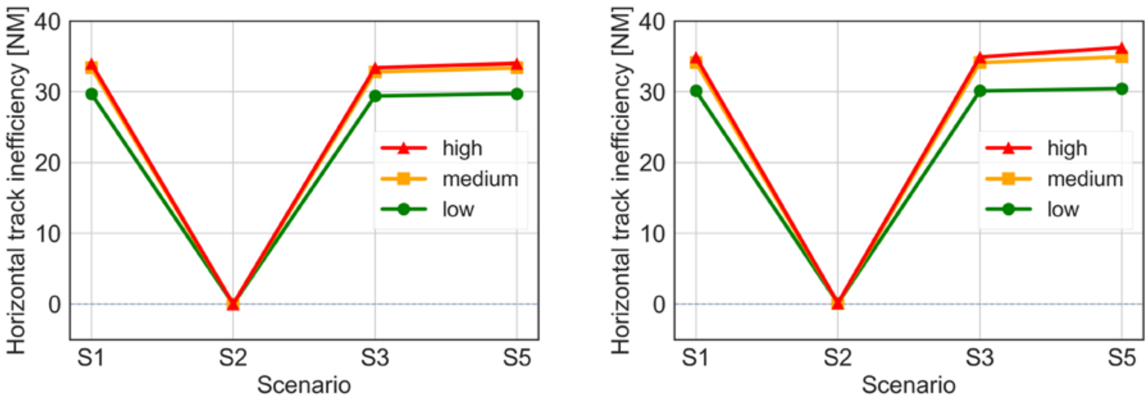
Figure 4-9: Percentage of increase of active ATCO positions of pre-ops scenarios compared to S1

4.4 Environment

Since in the current implementation of the APACHE-TAP tactical operations are not synthesised for pre-ops analysis, only the environment PIs that capture strategic inefficiencies are displayed here.

Figure 4-10 shows, for each pre-ops scenario and demand level assessed, the median for the distance-based environment PIs: C-ENV-1 (or KEP*), which compares the regulated trajectory with the geodesic trajectory; and ENV-1.1, which an optimal baseline trajectory is used for comparison instead of the geodesic trajectory. This baseline trajectory has been chosen as the utopic or ideal trajectory that minimises the environmental impact, which is assuming a full free-route scenario, continuous cruise climbs, no route charges and maximum range operations (i.e. Cost Index zero). Table 4-2, in turn, displays the median and average values for these assessments.

In light of these results, it is worth noting the very small differences between the assessment using C-ENV-1 or using ENV-1.1 PIs. This means that for this particular data set (including the traffic patterns but also the weather conditions simulated) the optimal trajectories (used in ENV-1.1) were very close to the geodesic trajectories (used in C-ENV-1).



a) C-ENV-1 (KEP*) b) ENV-1.1

Figure 4-10: Pre-ops results for the environment KPA (distance-based PIs)

Comparing the scenarios and as expected, a significant difference is found between the scenarios with full enhanced FRA (S2) and those with structured routes (S1, S3 and S5). The median for S2 is almost zero for both metrics, meaning that more than the half of the trajectories under assessment had no strategic environmental inefficiencies in the horizontal track (resulting from already environmentally optimal planned/regulated trajectories). Yet, the average is not zero, as seen in Table 4-2. Recall that the baseline trajectory for this indicator assumes cost index zero (i.e. maximum range operations), since this minimises fuel burnt. Thus, the small inefficiencies observed in Table 4-2 for S2 are due to small differences in the horizontal track due to different cost indexes (being the synthesised trajectory for S2 flown at a cost index different from zero).

PI	Low demand				Medium demand				High demand			
	average		median		average		median		average		median	
Scenario S1												
ENV-1.1 (NM)	35.3	7.7%	30.1	5.8%	38.4	7.3%	34.1	5.8%	39.1	7.3%	34.9	6.3%
Scenario S2												
ENV-1.1 (NM)	1.4	0.1%	0.1	0.02%	1.2	0.1%	0.1	0.02%	1.2	0.1%	0.1	0.02%
Scenario S3												
ENV-1.1 (NM)	35.2	7.6%	30.2	5.9%	38.5	7.3%	34.0	5.8%	39.0	7.3%	34.9	6.3%
Scenario S5												
ENV-1.1 (NM)	35.6	7.7%	30.5	6.3%	39.5	7.5%	34.9	6.0%	41.3	7.7%	36.3	6.1%

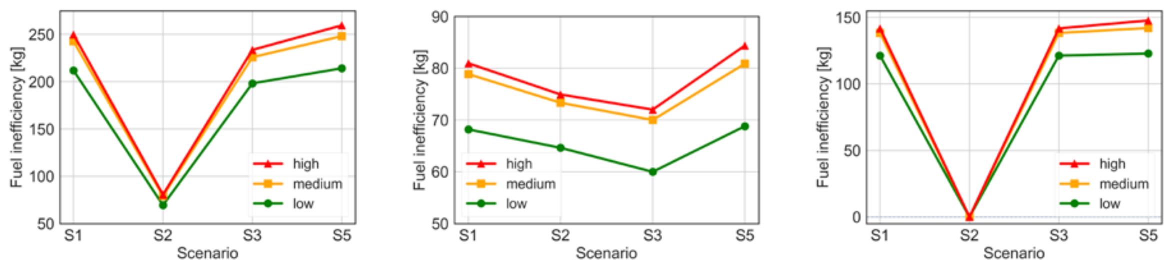
Table 4-2: Pre-ops results for the environment KPA (distance-based PIs)

Results for S5 shows more route inefficiencies due to the application of the ADCB algorithm, which is re-routing some aircraft to balance capacity and demand. Recall that for S1, S2 and S3 traffic is regulated only with delay. These differences are slightly higher for the medium and high demand Case Studies, which contains more regulations than the low demand Case Studies.

Figure 4-11 shows, for each pre-ops scenario and demand level assessed, the median for the fuel-based environment PIs: ENV-2.3 (total inefficiency); ENV-2.4 (vertical inefficiency); and ENV-2.5 (horizontal inefficiency). Table 4-3 displays the average and average values for these assessments.

PI	Low demand				Medium demand				High demand			
	average		median		average		median		average		median	
Scenario S1												
ENV-2.3 [Strategic - Total] (kg)	250	8.8%	212	7.7%	278	8.5%	243	7.5%	282	8.5%	250	7.5%
ENV-2.4 [Strategic - Vertical] (kg)	93	2.7%	68	2.3%	107	2.6%	79	2.3%	107	2.6%	81	2.4%
ENV-2.5 [Strategic - Horizontal] (kg)	149	5.7%	121	4.6%	163	5.5%	138	4.5%	167	5.5%	142	4.5%
Scenario S2												
ENV-2.3 [Strategic - Total] (kg)	96	2.9%	70	2.5%	106	2.8%	79	2.5%	108	2.8%	81	2.5%
ENV-2.4 [Strategic - Vertical] (kg)	88	2.6%	65	2.3%	98	2.5%	73	2.3%	100	2.5%	75	2.3%
ENV-2.5 [Strategic - Horizontal] (kg)	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%
Scenario S3												
ENV-2.3 [Strategic - Total] (kg)	234	8.6%	198	7.4%	257	8.3%	226	7.2%	263	8.3%	234	7.2%
ENV-2.4 [Strategic - Vertical] (kg)	84	2.5%	60	2.2%	94	2.4%	70	2.2%	95	2.4%	72	2.2%
ENV-2.5 [Strategic - Horizontal] (kg)	149	5.7%	121	4.6%	163	5.5%	138	4.5%	167	5.5%	142	4.5%
Scenario S5												
ENV-2.3 [Strategic - Total] (kg)	252	8.9%	214	7.8%	283	8.7%	284	7.7%	294	8.9%	260	7.9%
ENV-2.4 [Strategic - Vertical] (kg)	93	2.7%	69	2.4%	109	2.7%	81	2.4%	110	2.7%	84	2.5%
ENV-2.5 [Strategic - Horizontal] (kg)	150	5.8%	123	4.7%	167	5.6%	142	4.6%	176	5.8%	148	4.7%

Table 4-3: Pre-ops results for the environment KPA (fuel-based PIs)



a) ENV-2.3 (Total) b) ENV-2.4 (Vertical) c) ENV-2.5 (Horizontal)

Figure 4-11: Pre-ops results for the environment KPA (fuel-based PIs)

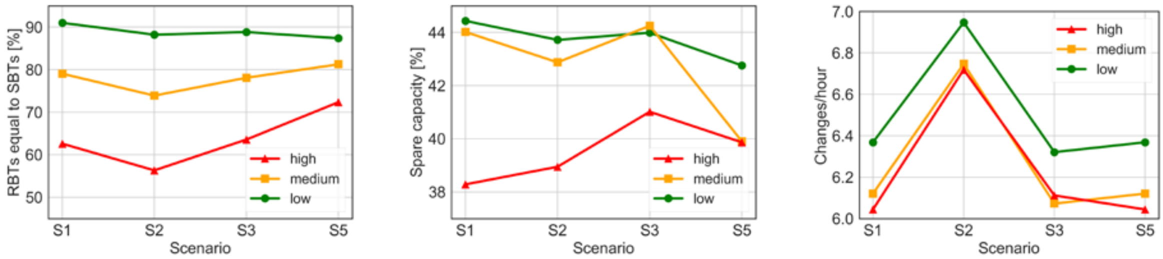
The results are in line with the conclusions drawn with the distance-based PIs, being S2 the most efficient scenario. Although in S2 we are assuming a full free-route airspace, the observed fuel inefficiencies are due to the fact that the baseline optimal trajectory is assuming maximum range operations (i.e. Cost Index zero), while the SBT (and RBT) is an optimised trajectory taking into account route charges and the AU's desired Cost Index. The same rationale applies for vertical inefficiencies for S3: although this scenario is assuming continuous cruise climbs the synthesised trajectories (SBT/RBT) as computed taking into account route charges and non-zero Cost Index for the different AUs. Notice the higher vertical inefficiencies for S5, due to the level cappings used by the ADCB algorithm.

Regarding the sensitivity to demand no conclusions can be drawn, since at this level, fuel/distance inefficiencies basically depend on the exact composition of the origin-destination demand. Yet, comparing S1 and S5 we can indeed observe that for the high demand Case Study more flight inefficiency is produced since more ATFM regulations are applied and consequently more re-routings or level cappings are implemented in the RBT.

4.5 Flexibility

Flexibility KPA, as defined by ICAO, addresses the ability of the airspace users to modify their flight trajectories in order to exploit occurring operational opportunities. Therefore, this KPA is very difficult to quantify in the “pre-ops” mode of performance assessment, as it mainly addresses the tactical phase of operations.

However, it can also be considered as the ability of the airspace users to fly their preferred trajectories, without restrictions imposed by the ATM system. Therefore, being highly dependent on the supply side of the ATM system, Flexibility KPA should also take into account the flexibility of the ANSPs to successfully accommodate additional/modified traffic, minimizing the negative effects on the AUs’ operations (delay, re-routing, level-capping, etc.). This explains why some of the proposed indicators deal with the flexibility of the ANSPs, facilitating the quantification of the KPA.



a) FLEX-1 b) FLEX-2 c) FLEX-3

Figure 4-12: Pre-ops results for the flexibility KPA

As seen in Figure 4-12, the share of non-regulated flights (FLEX-1) is the lowest in the enhanced FRA scenario (S2), since the traffic pattern is more challenging and requires more regulations to be applied by the ANSPs. Also, it is notable that S5, which implements ADCB techniques, better deals with more demanding traffic (medium and high demand case), with slightly lower share of non-regulated flights in low demand Case Study.

As for the spare capacity in the network (FLEX-2), obtained results do not suggest any clear conclusion regarding the cross-scenario comparison, except for the fact that spare capacity expectedly decreases with the increase of traffic demand.

Average sector changes per hour (FLEX-3) are in the range between 6 and 6.4 in all scenarios and case studies, except in the enhanced FRA scenario (S2) which requires more sectors to be open in order to accommodate this challenging traffic, thus increasing the number of sector changes and, consequently, ATCO coordination workload.

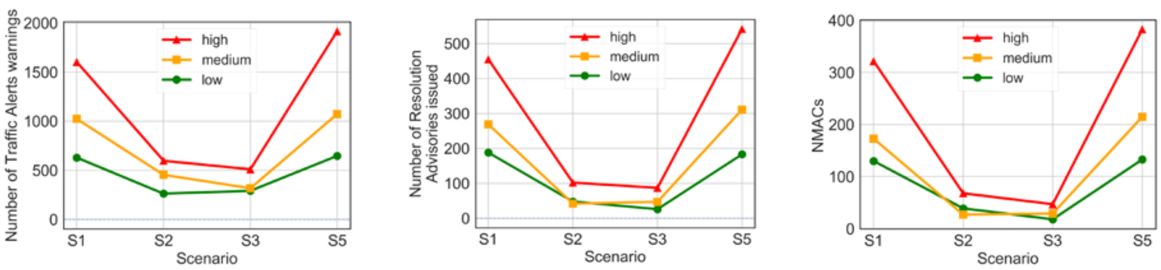
An additional PI was proposed in APACHE for pre-ops studies, FLEX-4, which accounts for the total number of DCB solutions, normalised by the total number of regulated trajectories, as a proxy for the flexibility of the demand and capacity balancing processes. Table 4-4 shows the results for this PI. Since in S1, S2 and S3 delay is the only option to regulate demand, the PI gives 1. For S5, however, more options are available for the network manager such as delay, re-routing, level capping and a combination of these. As expected, the higher the traffic demand, the higher the number of regulations and therefore the higher number of different options that can be submitted to the affected flights.

Total number of DCB solutions /Number of regulated trajectories	**Traffic Demand**		
	Low	Medium	High
Scenario S1	1.00	1.00	1.00
Scenario S2	1.00	1.00	1.00
Scenario S4	1.00	1.00	1.00
Scenario S5	2.86	3.69	4.23

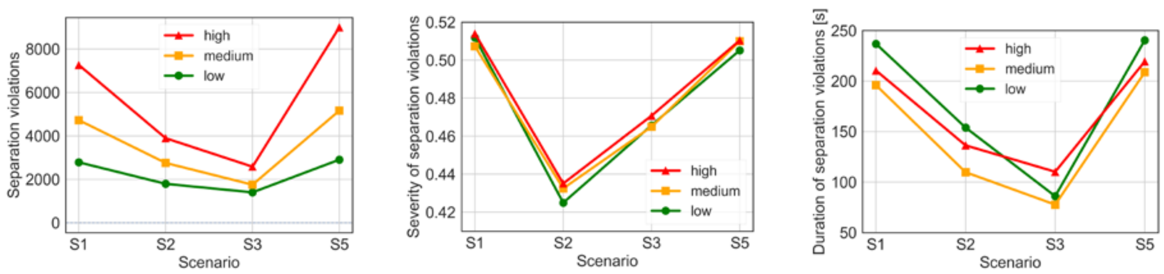
Table 4-4 Pre-ops results for FLEX-4

4.6 Safety

Safety KPA as KPA with the highest priority in aviation, is represented with seven PIs already mentioned in Section 3. Figures 4-13 and 4-14 show the results for these Safety PIs for all the pre-ops Scenarios and Case Studies.



a) SAF-1 b) SAF-2 c) SAF-3



d) SAF-4 e) SAF-5 f) SAF-6

Figure 4-13: Pre-ops results for the safety PIs: SAF-1 to SAF-6

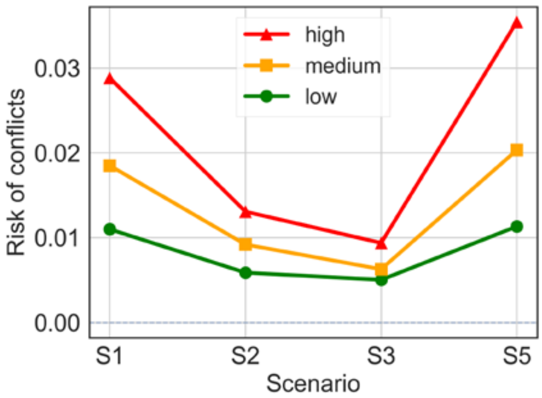


Figure 4-14: Pre-ops results for SAF-7 (Risk of conflicts)

From the figures above it is evident that increase in traffic demand leads (mostly) to an increase of Safety PI values in all observed scenarios, which seems to be logical. However, it can be noticed that this increase is not linear.

Comparing S2 with S1, it can be seen that all PIs are significantly reduced (more than half of the value in S1). Without consideration of other factors and the tactical ATC actions, it could be concluded that the application of enhanced FRA concept has a positive influence on safety. This can be explained by a smaller amount of conflict situations, which are widely distributed in the airspace, and by the fact that conflict points are less concentrated on the crossing points observed in the case of S1 when flights are using existing airways.

A similar trend can be observed in the case of comparison between S3 and S1. Values of all PIs are significantly reduced (even more then in the case of S2), leading to conclusion that the introduction of continuous cruise climbs has a positive influence on safety too. Results can be explained by the fact that flights do not enter into conflict situations in vertical plane due to constant climb, i.e. they are "avoiding" each other more often than in the case of S1.

Finally, in the case of S5 vs. S1 comparison, it is evident that the values of all PIs are equal or higher in S5 compared to S1 (difference increases with the increase of traffic demand). These results lead to the conclusion that the application of ADCB, although positive from the air traffic flow point of view, does not show a positive effect on safety. Therefore, it is possible that the resolution of certain congestion problems could lead to some safety-related issues.

At the end, we can conclude that S2 and S3 have shown positive effects on Safety KPA, while S5 caused deterioration of the safety PIs.

5 Interdependencies and trade-offs in ATM performance

After the assessment of the results per KPA, including post-ops and pre-ops analysis, this Chapter is focused to the assessment of interdependencies and trade-offs in ATM performance that go beyond to those interdependencies directly observed by comparing the different pre-ops scenarios in Chapter 5. Hence, in this chapter a series of trade-offs are investigated through tailored Case Studies varying a specific parameter or group of parameters in order to assess "a priori" interdependencies (i.e. interdependencies that are considered interesting to explore by a priori expert judgement). This assessment will look at interdependencies between two PIs from different KPAs (or focus areas).

In general terms, the overall objective of these assessments is to **illustrate the capabilities of the APACHE Framework to capture interdependencies among KPAs**, quantify them and assess Pareto optimality. By no means the results and discussions presented below are intended to analyse in detail these interdependencies, neither to seek for the reasons or causality of the observed behaviour, to perform a sensitivity analysis, nor to derive conclusions for decision or policy making. Thus, the 7 representative examples shown in this chapter are indeed simple examples (Case Studies) aiming to capture interdependencies and theoretical performance limits for some KPA.

ID	Trade-offs under investigation	Applicable scenarios	Simulation variation
PF-1	ENV vs. CE(ANS) ENV vs. CE(AU)	S1, S2	Change **unit costs** for route charges
PF-2	CE(ANS) vs. CAP CE(ANS) vs. CE(AU) CE(ANS) vs. FLEX CE(AU) vs. CAP	S1, S5	Restrict the list of **available sector configurations** in order to progressively reduce the number of sectors (improving in this way CE for ANS).
PF-3	CE(AU) vs. FLEX ENV vs. CAP	S1	Change the percentage of **capacity reduction** for certain regulations.
PF-4	ENV vs. SAF CAP vs. CE(AU) CAP vs. CE(ANS)	S1	Change the availability of **direct routes (DCT)**
PF-5	ENV vs. SAF CAP vs. CE(AU) CAP vs. CE(ANS)	S3	Change the percentage (or amount) of flights performing **continuous cruise climbs (CCC).**

Table 5-1: Tailored simulations to capture Pareto-Front interdependencies

The starting **hypothesis** (i.e. "a priori" trade-off) is to find a Pareto optimal solution, in such a way that it is impossible to make any improvement in one particular KPA without making at least one other KPA worse. This is why the different tailored simulations have been identified with the label PF (Pareto Front), as shown in Table 5-1. Yet, it should be noted that some results lead indeed to potential trade-offs (i.e. Pareto optimality), but some of them just showed some correlation between PIs, but not Pareto optimality.

Five different Pareto-Front groups (PF-X) have been considered based on the variable parameter(s) in the simulation. Table 5-1 presents the overall planning of these tailored simulations, including the "a priori" trade-offs under investigation and applicable simulation scenarios for each specific Pareto-Front. The following sub-sections present the results for these 7 individual trade-off assessments ordered by Scenario. As seen in Table 5-1, there are four analyses for Scenario 1 (Reference scenario), one for Scenario 2 (Enhanced FRA), one for Scenario 3 (Continuous Cruise Climbs) and one for Scenario 5 (ADCB).

5.1 S1-PF1: Changing the unit costs for route charges

This first analysis investigates the existing trade-offs between the Environment KPA and the Cost-efficiency KPA (both for Airspace User and ANS). It applies to the Reference Scenario (S1 – Current ConOps) and the variable parameter is the **unit costs for route charges**. Four possibilities have been considered for these unit costs: same route charges unit rate for all countries (low, medium and high price) and a flat rate scheme. In addition, the current CRCO charging scheme has also been considered as baseline Case (see Table 5-2).

Scenario	Pareto Front ID	Trade-offs under investigation	Variable parameter with respect to origin scenario	Parameter Scan
S1	**PF1**	ENV vs. CE(ANSP) ENV vs. CE(AU)	Change unit costs for route charges.	a- Same route charges unit rate for all countries (low price) b- Same route charges unit rate for all countries (medium price) c- Same route charges unit rate for all countries (high price) d- Flat rate scheme (route independent).

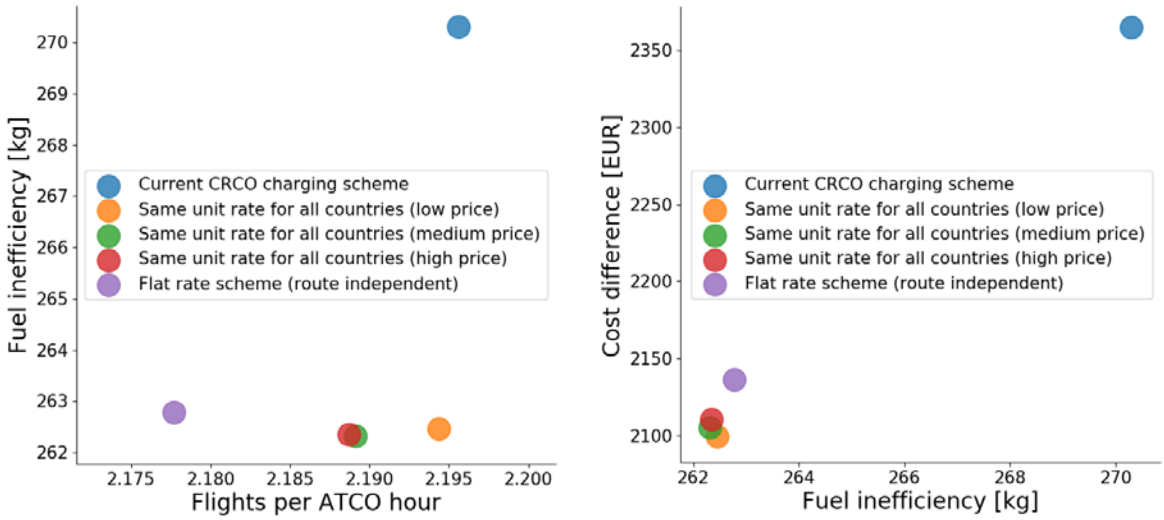
Table 5-2: S1-PF1 simulation details

The outputs of the assessment have been represented in the Pareto-Front graphs shown in Figure 5-1. Figure 5-1a evaluates the trade-off between the environment KPA (using ENV-2.3: Strategic ATM inefficiency on trip fuel) and the ANS cost-efficiency focus area (using CE-3: Flights per ATCO hour on duty). Figure 5-1b, in turn, assesses the trade-off between the same environment PI and the AU cost-efficiency focus area (using CE-1.1: En-route unit economic costs for the Airspace User – Strategic).

The changes in the unit costs for route charges do not lead to a clear trade-off, as some of the parameter alternatives lead to similar results (coincident points in the graphs in Figure 5-1b).

In general terms, based on Figure 5-1 it could be stated that the adoption of the flat rate scheme or of a same unit rate for all countries would lead to lower fuel inefficiencies and to lower cost differences for the airspace users compared to the current CRCO charging system. In terms of flights per ATCO hour, the flat rate scheme would imply the optimal situation.

One of the difficulties for the reader would be to identify the conceptual difference between a charging system with the same unit rate for all countries (low, medium or high price) and a flat rate scheme (route independent). If considering the same unit rate for all countries, the airspace users still have route charges to pay. It is true that they are the same price for all countries, so they will not try to avoid certain countries as in the nominal case. However, the APACHE TP will still take into account the route-charges costs along with the fuel and time costs.



a) ENV vs. CE(ANS)

b) ENV vs. CE(AU)

Figure 5-1: Interdependencies for S1-PF1

Nevertheless, there are external conditions that are not considered in the APACHE TP. For instance, if there is an area with beneficial “tail winds” that requires to fly a longer (ground) distance, it may be worth it considering fuel consumption and trip time reduction. If this distance increment involves much more route charges to pay, perhaps what the airspace user gains from tailwind it is converted into paying taxes. Hence, there is still a trade-off in case route charges completely disappear from the equation. The APACHE TP, however, will only look for the optimal trajectory minimizing fuel and time (multiplied by the Cost Index), reproducing the behaviour of what would do the AU when planning their trajectories.

The fact that some of the Pareto-Front graphs points are nearly coincident may be derived from two possible reasons:

1. The scope of the simulation results only covers flights crossing the FABEC region, which entails rather homogeneous unit costs for each country. The most usual trajectories avoiding expensive airspace are found when two countries with very different unit rates are next to each other (i.e. Spain-Portugal, East Europe with Germany/Italy, etc.). Therefore, FABEC may not be the best scenario to explore this Pareto-Front.
2. Weather data has only been considered for two days (one summer day and one winter day). Hence, the wind conditions may have not been suitable to observe significant differences between a, b, c and d.

In conclusion, a further analysis of this Pareto-Front would require future explorations of this trade-off with other scenarios (i.e. ECAC region), more weather variability, etc. As stated in the introductory part of this Chapter 6 the purpose here was to show the capability of the APACHE Framework to eventually capture these trade-offs when assessing ATM performance.

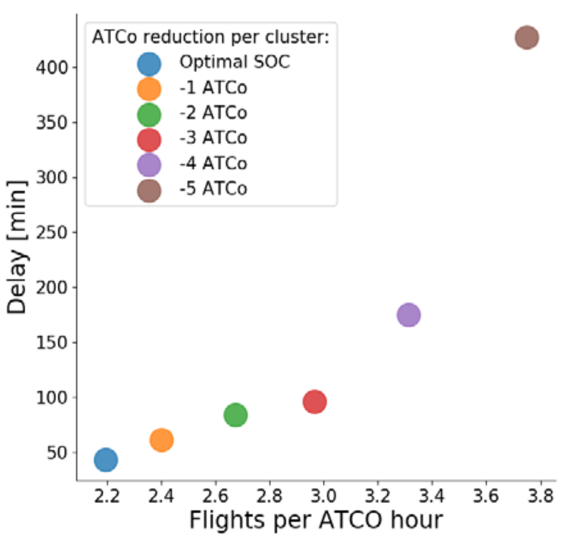
5.2 S1-PF2: Reducing the number of ATCOs

The second trade-off analysis for the Reference scenario (S1) investigates the existing trade-offs between the cost-efficiency KPA (considering both ANS and AU focus areas) and capacity or flexibility KPAs. This time the variable parameter is the **availability of sector configurations**. Five configuration sets have been considered for the parameter scan: reducing the ATCO number per cluster (from -1 to -5). In addition, the optimal sector configuration (SOC) has also been considered as baseline Case (see Table 5-3).

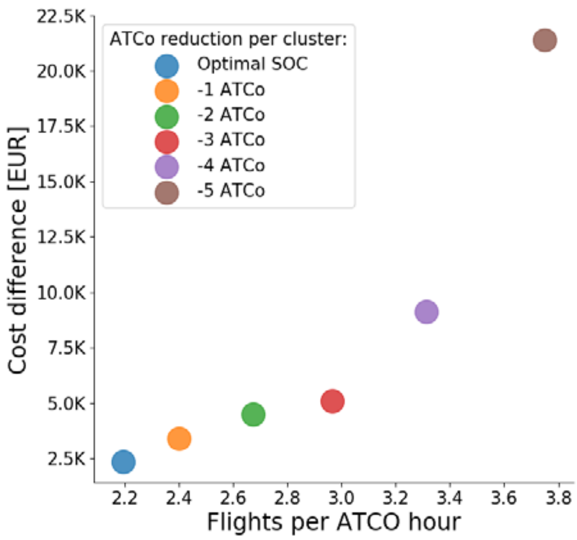
Scenario	Pareto Front ID	Trade-offs under investigation	Variable parameter with respect to origin scenario	Parameter Scan
S1	**PF2**	CE(ANSP) vs. CAP CE(ANSP) vs. CE(AU) CE(ANSP) vs. FLEX CE(AU) vs. CAP	Restrict the list of available sector configurations in order to progressively reduce the number of sectors (improving in this way CE for ANSP).	a- Configuration set 1 (-1 ATCo per cluster) b- Configuration set 2 (-2 ATCo per cluster) c- Configuration set 3 (-3 ATCo per cluster) d- Configuration set 4 (-4 ATCo per cluster) e- Configuration set 5 (-5 ATCo per cluster)

Table 5-3: S1-PF2 simulation details

Multiple outputs are derived from this assessment. All trade-offs have been represented as Pareto-Front graphs. Figure 5-2a evaluates the trade-off between the ANS cost-efficiency focus area (using CE-3: Flights per ATCO hour on duty) and the capacity KPA (using C-CAP-1: Average en-route ATFM delay per flight). Figure 5-2b, in turn, assesses the trade-off between the same ANS cost-efficiency PI and the AU cost-efficiency focus area (using CE-1.1: En-route unit economic costs for the Airspace User – Strategic).



a) CE(ANS) vs. CAP

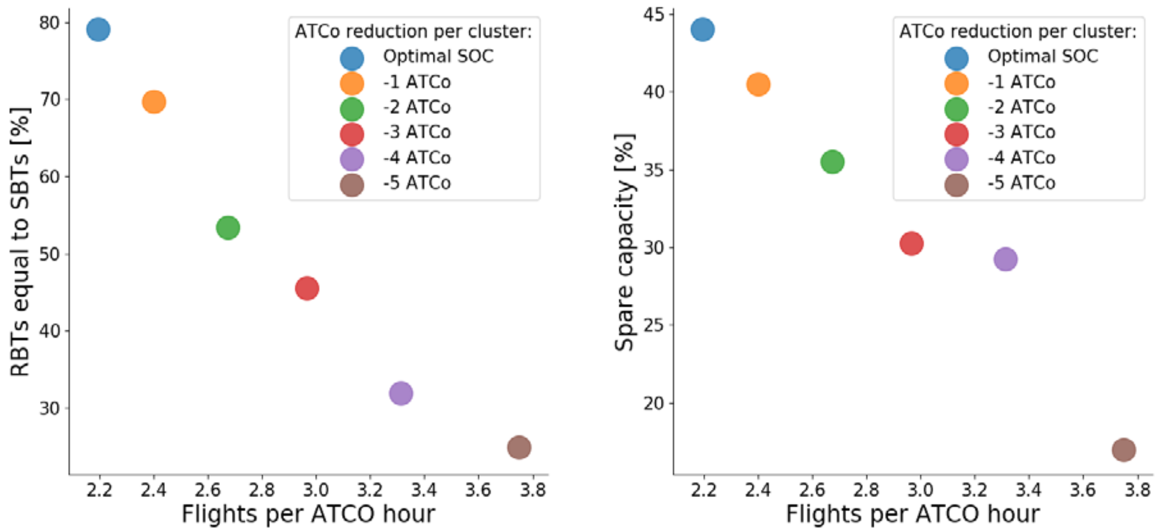


b) CE(ANS) vs. CE(AU)

Figure 5-2: Interdependencies for S1-PF2: CE(ANS) vs. CAP vs. CE(AU)

The reduction in the number of ATCOs per cluster, which improves the ANS cost-efficiency by increasing the number of flights per ATCO hour, entails an increase in en-route ATFM delay (C-CAP-1) and in the cost due to strategic ANS actions for the airspace user (CE-1.1). This increase becomes especially significant when the reduction is larger than 3 ATCOs fewer per cluster (the increase seems to be non-linear). In terms of capacity, removing the fourth ATCO per cluster entails an increase of more than 50% in en-route ATFM delay. The removal of the fifth ATCO per cluster leads an extremely high increase (more than 150%) in delay (increase seems to be non-linear).

On the other hand, the improvements in ANS cost-efficiency are much less significant when removing one ATCO per cluster. Each ATCO removal entails an increase of flights per ATCO hour lower than 20%. Therefore, it could be said that the optimal Pareto-Front solution for this assessment would be a reduction of 3 ATCOs per cluster. A similar analysis with the same conclusions could be performed for the assessment between ANS vs. AU cost-efficiency as shown in Figure 5-2b.



a) CE(ANS) vs. FLEX-1 b) CE(ANS) vs. FLEX-2

Figure 5-3: Interdependencies for S1-PF2: CE(ANS) vs. FLEX

Figure 5-3 assesses the trade-off between the same ANS cost-efficiency PI and two different PIs for the flexibility KPA (FLEX-1: Percentage of RBTs which are equal to the first submitted SBTs and FLEX-2: Spare capacity). In terms of flexibility, the first Pareto-Front graph (Figure 5-3a) does not yield to clear conclusions, as the percentage of RBTs equal to SBTs decreases in a (mostly) linear way when reducing the number of ATCOs per cluster. The number of flights per ATCO hour presents an increasing similar (almost linearly) pattern.

The second Pareto-Front graph, however (Figure 5-3b), shows that there is one point for which removing an additional ATCO per cluster entails a (significant) increase in ANS cost-efficiency with a limited reduction of spare capacity. This would probably be an acceptable Pareto optimal solution: a reduction of 4 ATCOs per cluster. In this regard, the hypothetical removal of a fifth ATCO per cluster would have a very high impact on the percentage of spare capacity for this particular example.

Finally, a trade-off analysis has been performed between the AU cost-efficiency focus area (using CE-1.1: En-route unit economic costs for the Airspace User – Strategic) and capacity (using C-CAP-1:

Average en-route ATFM delay per flight). Results can be seen in the Figure 5-4. The Pareto-Front graph above shows that the en-route ATFM delay and the cost different for the airspace users between their RBTs and first submitted SBTs are directly related. However, as it can be seen there is a point for which removing an additional ATCO per cluster leads to much higher delays and AU costs. This point would be the removal of a fourth ATCO per cluster. Hence, we find a similar situation as we found in the previous case (see Figure 5-3): a reduction of 3 or 4 ATCOs per cluster would be considered probably the best trade-off.

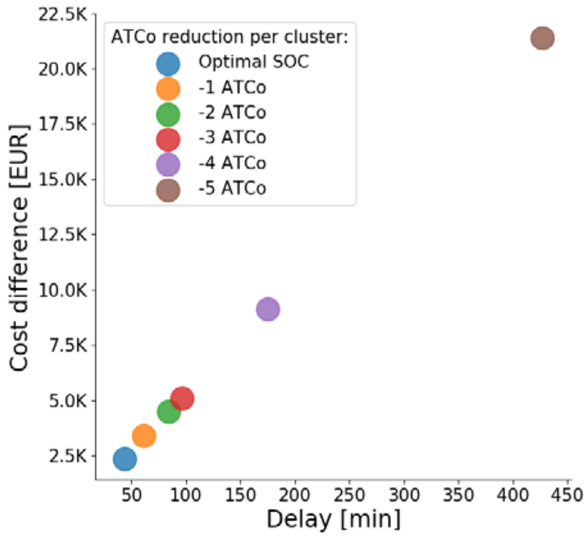


Figure 5-4: Interdependencies for S1-PF2: CE(AU) vs. CAP

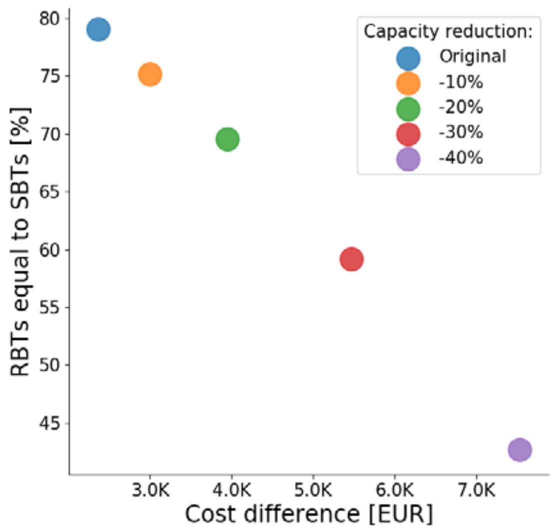
5.3 S1-PF3: Reducing nominal capacity

This third Pareto-Front analysis evaluates the impact of **nominal capacity reduction** (aiming at increasing ATFM flexibility) on multiple KPAs. Specifically, two trade-offs have been investigated for the Reference scenario (S1): AU cost-efficiency vs. flexibility and environment vs. capacity. Four parameter values have been considered for the parameter scan: reducing the available nominal capacity for all sectors by 10%, 20%, 30% and 40%. In addition, the original capacity availability has also been considered as the reference value (see Table 5-4).

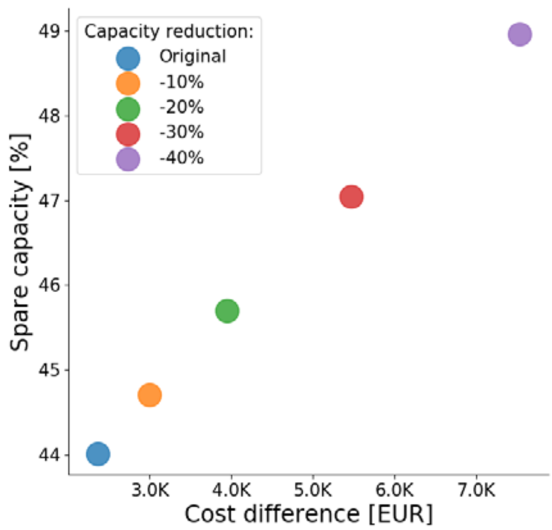
Scenario	Pareto Front ID	Trade-offs under investigation	Variable parameter with respect to origin scenario	Parameter Scan
S1	**PF3**	CE(AU) vs. FLEX ENV vs. CAP	Change the percentage of capacity reduction for certain regulations.	a- 10% reduction b- 20% reduction c- 30% reduction d- 40% reduction

Table 5-4: S1-PF3 simulation details

Two Pareto-Front graphs have been produced to evaluate the trade-off between the AU cost-efficiency focus area (using CE-1.1: En-route unit economic costs for the Airspace User – Strategic) and the two different PIs for flexibility (FLEX-1: Percentage of RBTs which are equal to the first submitted SBTs and FLEX-2: Spare capacity). Results are shown in Figure 5-5.



a) CE(AU) vs. FLEX-1



b) CE(AU) vs. FLEX-2

Figure 5-5: Interdependencies for S1-PF3

Nominal capacity reductions lead to increases in AU costs and to reductions in the percentage of RBTs equal to SBTs. However, these effects become especially significant from a capacity reduction of 30% on. This conclusion can be clearly seen in Figure 5-5a.

The derived conclusions would be similar for the second Pareto-Front graph (Figure 5-5b). Nevertheless, the capacity reductions lead to slightly higher increases in the percentage of spare capacity (FLEX-2). The possible reason might be that the ASP opens more sectors to accommodate demand, which are subsequently less utilised. In other words, more sectors with less declared capacity are opened. Considering the AU cost-efficiency as the main affected focus area by the capacity reductions, the same conclusions can be obtained as for the previous Pareto-Front graph.

Regarding the second trade-off to be investigated (ENV vs. CAP); the results show that capacity reductions do not produce an impact on the interdependencies between the environment and capacity KPAs. Therefore, no Pareto-Front graph has been produced for this trade-off.

5.4 S1-PF4: Changing the availability of direct routes (DCT)

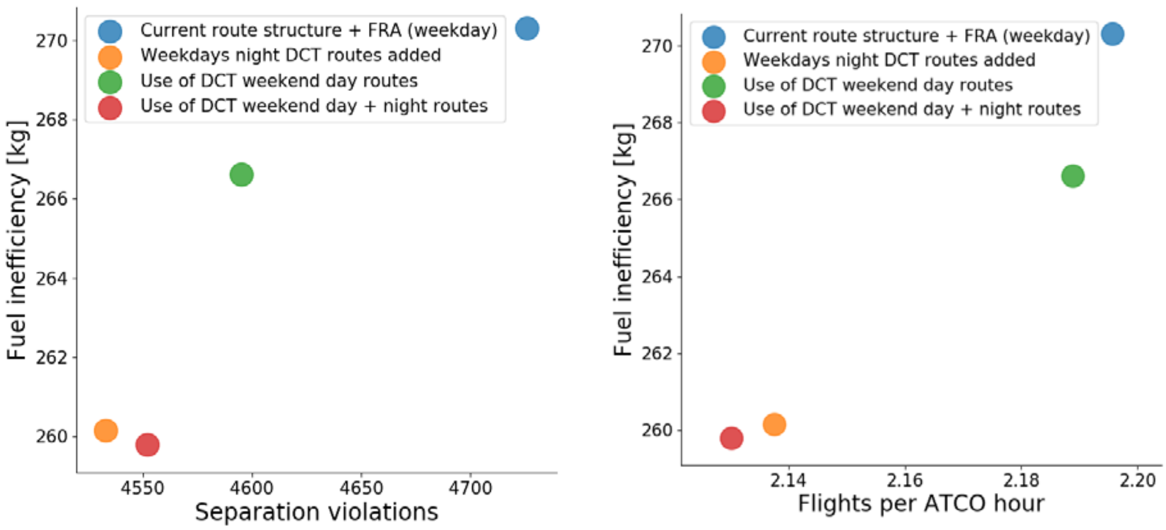
The final trade-off analysis for the Reference scenario (S1) investigates the existing interdependencies between different KPAs when varying the **availability of direct routes (DCT)** for trajectory planning. Four individual trade-offs have been considered assessing the environment KPA with respect to safety and ANS cost-efficiency, as well as capacity vs. cost-efficiency.

Three possibilities have been configured for the variable parameter: 24h availability of current Night DCT, inclusion of current weekend-only DCT (only during the day); and 24h availability of current weekend-only DCT. In addition, the current route structure (including current FRA during weekdays) has also been considered as baseline Case (see Table 5-5).

The first two Pareto-Front graphs (Figure 5-6) evaluate the trade-off between an environment PI (ENV-2.3: Strategic ATM inefficiency on trip fuel) and two other KPA performance indicators: one from the safety KPA (SAF-4: Number of Separation Violation and one from the ANS cost-efficiency focus area (using CE-3: Flights per ATCO hour on duty).

Scenario	Pareto Front ID	Trade-offs under investigation	Variable parameter with respect to origin scenario	Parameter Scan
S1	**PF4**	ENV vs. SAF ENV vs. CE(ANSP) CAP vs. CE(AU) CAP vs. CE(ANSP)	Change the availability of direct routes (DCT)	a- Add Night DCT (available all day) b- Use DCT weekend c- Use DCT weekend + DCT weekend night

Table 5-5: S1-PF4 simulation details



a) ENV vs. SAF **b) ENV vs. CE(ANS)**

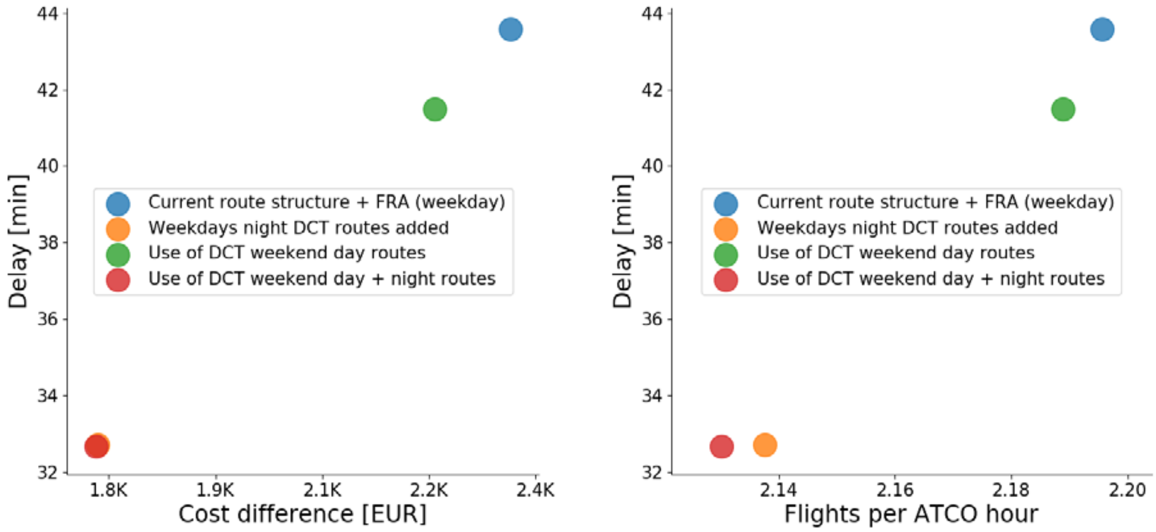
Figure 5-6: Interdependencies for S1-PF4: ENV vs. SAF vs. CE(ANS)

When considering DCT for additional time periods, the separation violations decrease significantly, together with the fuel inefficiency. These reductions become especially remarkable for the use of DCT during the night period (blue and grey points in the graph). Specifically, the use of DCT during the weekday nights leads to fewer separation violations for a similar fuel inefficiency compared to using DCT on the weekends (day and night).

On the other side, ANS cost-efficiency becomes lower when using DCT routes, especially during the nights. Thus, no evident solution can be derived from this Pareto-Front; however, it should be noted that the use of DCT routes during the weekend days (no nights) entails substantial fuel efficiency gains in exchange of a small reduction of ANS cost-efficiency.

The second sub-set of Pareto-Front graphs (Figure 5-7) evaluates the trade-off between capacity (using C-CAP-1: Average en-route ATFM delay per flight) and two different cost-efficiency PIs: one related to AU (CE-1.1: En-route unit economic costs for the Airspace User – Strategic) and the other one related to ANS (CE-3: Flights per ATCO hour on duty).

In terms of en-route ATFM delay, the use of DCT routes leads to delay reductions. As for the previous analyses, this effect becomes more significant when DCT routes are used during night periods.



a) CAP vs. CE (AU) b) CAP vs. CE (ANS)

Figure 5-7: Interdependencies for S1-PF4: CAP vs. CE

Regarding airspace users cost-efficiency, the cost difference for the airspace users would highly decrease when using DCT routes during the nights. Moreover, the delay performance indicator would also decrease, leading to an optimal solution for the airspace users. In terms of ANS cost-efficiency, the same conclusions derived in Figure 5-6b apply.

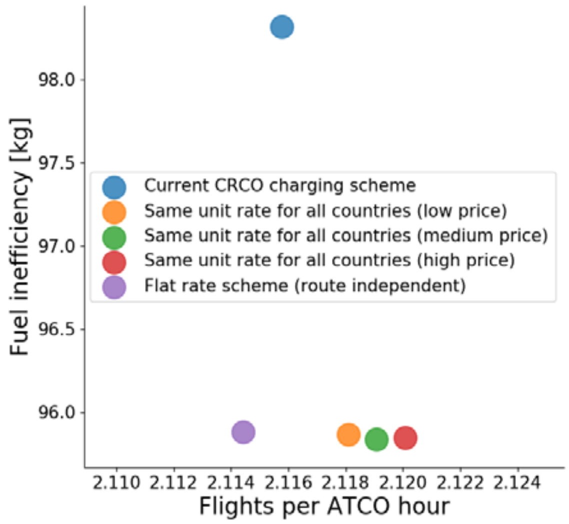
5.5 S2-PF1: Changing the unit costs for route charges in a full free-route scenario

The KPA interdependencies associated to Scenario 2 (Enhanced FRA) have been assessed by investigating the trade-offs between the environment cost-efficiency KPAs. The variable parameter for this assessment has been the unit costs for route charges, as done for S1-PF1, consequently allowing the comparison between S1 and S2 regarding the same interdependencies. The same four possibilities have been considered for the unit costs change as for S1-PF1, as well as the current CRCO charging scheme (see Table 5-6).

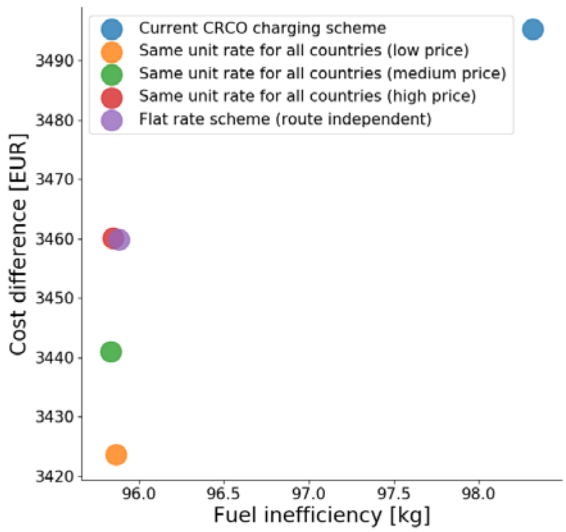
Scenario	Pareto Front ID	Trade-offs under investigation	Variable parameter with respect to origin scenario	Parameter Scan
S2	**PF1**	ENV vs. CE(ANSP) ENV vs. CE(AU)	Change unit costs for route charges.	a- Same route charges unit rate for all countries (low price) b- Same route charges unit rate for all countries (medium price) c- Same route charges unit rate for all countries (high price) d- Flat rate scheme (route independent).

Table 5-6: S2-PF1 simulation details

The same Pareto-Front graphs as used in S1-PF1 PIs have also been generated (see Figure 5-8): ENV-2.3: Strategic ATM inefficiency on trip fuel; CE-3: Flights per ATCO hour on duty; CE-1.1: En-route unit economic costs for the Airspace User – Strategic.



a) ENV vs. CE(ANS)



b) ENV vs. CE(AU)

Figure 5-8: Interdependencies for S2-PF1

Considering the Enhanced FRA scenario (S2), changing the unit costs for en-route charges would lead to a worsening of the fuel efficiency, as it can be seen in Figure 5-8a.

The flat rate scheme would imply the highest fuel inefficiency, as the airspace users would not have any financial incentive to use the shortest trip as the en-route costs would not change. Nevertheless, this scheme leads to the highest ANS cost-efficiency (highest number of flights per ATCO hour). This could be explained by the fact that the airspace users are not incentivised to take the shorter routes, leading to a higher number of flights per sector. As explained in S1-PF1, it must be considered that there are some external elements that the APACHE TP does not take into account, such as wind conditions, given the fact that only two days of data were simulated.

Regarding Figure 5-8b, the additional output is that AU cost-efficiency is improved with all possible changes in the unit costs for en-route charges. The most beneficial situation for the airspace user would be (according to this very preliminary assessment) to have the same unit rate for all countries (low price). This way, the airspace user is incentivised to perform shorter routes (even shorter than the reference scenario considering the Enhance FRA scenario) as there is no flat rate, but paying for a low homogeneous unit rate.

5.6 S3-PF5: Changing the percentage of flights performing CCC

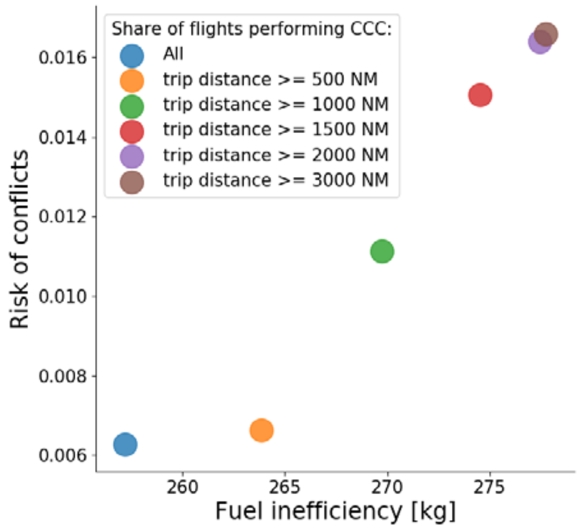
Regarding the Continuous Cruise Climbs Scenario (S3), four trade-off analyses have been developed to evaluate the interdependencies between different KPAs when varying **the percentage of actual flights performing CCCs**. Overall, six Case Studies have been considered for the assessment depending on the share of flights performing CCCs, as a function of the trip distance (see Table 5-7).

The first sub-set of Pareto-Front graphs (see Figure 5-9) evaluates the trade-off between one environment performance indicator on fuel inefficiency (ENV-2.3) and PIs from two different KPAs:

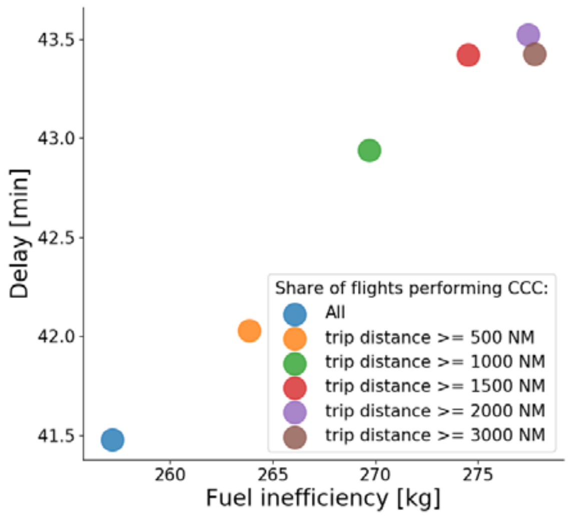
safety (SAF-7: Risk of conflicts/accidents) and Capacity (C-CAP-1: Average en-route ATFM delay per flight).

Scenario	Pareto Front ID	Trade-offs under investigation	Variable parameter with respect to origin scenario	Parameter Scan
S3	**PF5**	ENV vs. SAF CAP vs. ENV CAP vs. CE(AU) CAP vs. CE(ANSP)	Change the percentage (or amount) of flights performing continuous cruise climbs.	a- CCC if trip distance >= 500 NM b- CCC if trip distance >= 1000 NM c- CCC if trip distance >= 1500 NM d- CCC if trip distance >= 2000 NM e- CCC if trip distance >= 3000 NM

Table 5-7: S3-PF5 simulation details



a) ENV vs. SAF



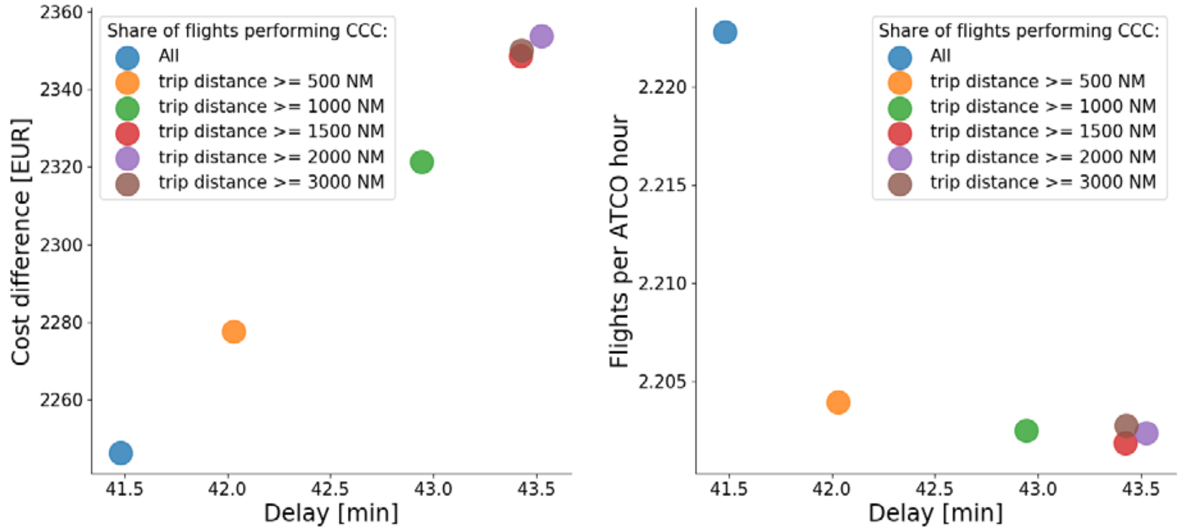
b) CAP vs. ENV

Figure 5-9: Interdependencies for S3-PF5: ENV vs. SAF vs. CAP

The Continuous Cruise Climb operations imply clear fuel efficiency benefits (i.e. the lowest flight inefficiency in the graphs), especially when all flights perform such type of operations. Regarding safety, an interesting paradox is observed: the risk of conflicts increase as the number of CCC flights decrease (see Figure 5-9a). This is because CCC flights are no longer following flight levels at constant altitude and therefore increase the dispersion of flights in the sky, lowering the probability of conflicts. A similar situation was observed in Chapter 4 when comparing the full free-route scenario (more dispersion) with the structured route scenario (less dispersion). This result, however, does not directly imply that CCC or free-route operations are “safer” than current operations. What is observed is a lower probability of having conflicts, but perhaps the remaining conflicts are harder to detect and/or to resolve. This is, indeed, an interesting topic for future research.

In terms of en-route ATFM delay, the same reasoning applies, as the delay increases if only part of the flights performs CCCs. Nevertheless, when the limit is set to 1500, 2000 or 3000NM, the resulting delays are largely similar. In fact, if only flights with trip distances over 3000NM perform CCCs, the delay would be lower than if the limit was set to 2000NM trip distance. This could be explained by the fact that the share of flights with a trip distance over 3000NM is insignificant in the geographical scope of the simulations (FABEC).

The second sub-set of Pareto-Front graphs (Figure 5-10) evaluates the trade-off between the same Capacity performance indicator (C-CAP-1) and two different cost-efficiency performance indicators: one for AU (CE-1.1) and the other for the ANS (CE-3).



a) CAP vs. CE(AU) b) CAP vs. CE(ANS)

Figure 5-10: Interdependencies for S3-PF5: CAP vs. CE

As previously mentioned, the delay can be reduced if all flights perform CCCs. In addition, the cost difference for the airspace users is also reduced when performing CCCs. The main improvement would be seen if all flights with a trip distance over 500NM performed CCCs, as the gains in AU cost difference and in delay would be remarkable.

It is interesting to notice the fact that if the CCCs performing limit is set to 3000NM, the resulting AU costs would be lower than if the limit was set to 2000NM. This could sound anti-intuitive. However, differences are actually very small (0,1 min and 1 flight). Thus, points for 1500NM, 2000NM and 3000NM are almost the same.

Regarding ANS cost-efficiency, the number of flights per ATCO hour could be increased if all flights perform CCCs as fewer ATCO-flight interactions would be required. The same thresholds as in the previous assessments apply to ANS cost-efficiency: the larger benefits are seen when the limit is set in flights with a trip distance over 500NM and the apparent incoherencies appear when the limit is set to 1500, 2000 or 3000NM.

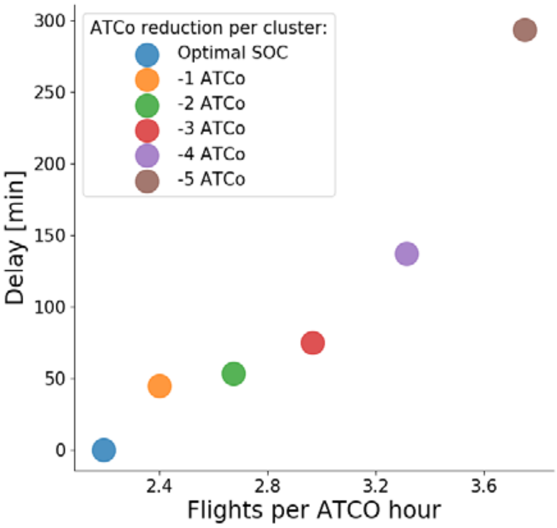
5.7 S5-PF2: Reducing the number of ATCOs when using ADCB

Finally, an "a-priori" trade-off analysis has been performed for the ADCB scenario (S5), assessing the interdependencies of the cost-efficiency performance KPA with other KPAs. As for S1PF2, the variable parameter is the **availability of different sector configurations**, which ranges from the optimal SOC to a reduction of 1, 2, 3, 4 or 5 ATCOs per cluster (see Table 5-8).

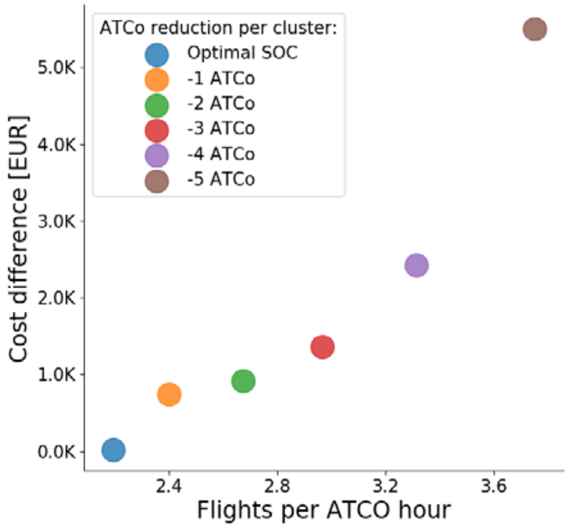
Scenario	Pareto Front ID	Trade-offs under investigation	Variable parameter with respect to origin scenario	Parameter Scan
S5	**PF2**	CE(ANSP) vs. CAP CE(ANSP) vs. CE(AU) CE(ANSP) vs. FLEX CE(AU) vs. CAP	Restrict the list of available sector configurations in order to progressively reduce the number of sectors (improving in this way CE for ANSP).	a- Configuration set 1 (-1 ATCo per cluster) b- Configuration set 2 (-2 ATCo per cluster) c- Configuration set 3 (-3 ATCo per cluster) d- Configuration set 4 (-4 ATCo per cluster) e- Configuration set 5 (-5 ATCo per cluster)

Table 5-8: S5-PF2 simulation details

The Pareto-Front graphs in Figure 5-11 assess the trade-offs between the ANS cost-efficiency (using CE-3: Flights per ATCO hour) and the capacity KPA (using delay as captured by C-CAP-1); or comparing this ANS cost-efficiency with AU cost-efficiency (using CE-1.1).



a) CE(ANS) vs. CAP



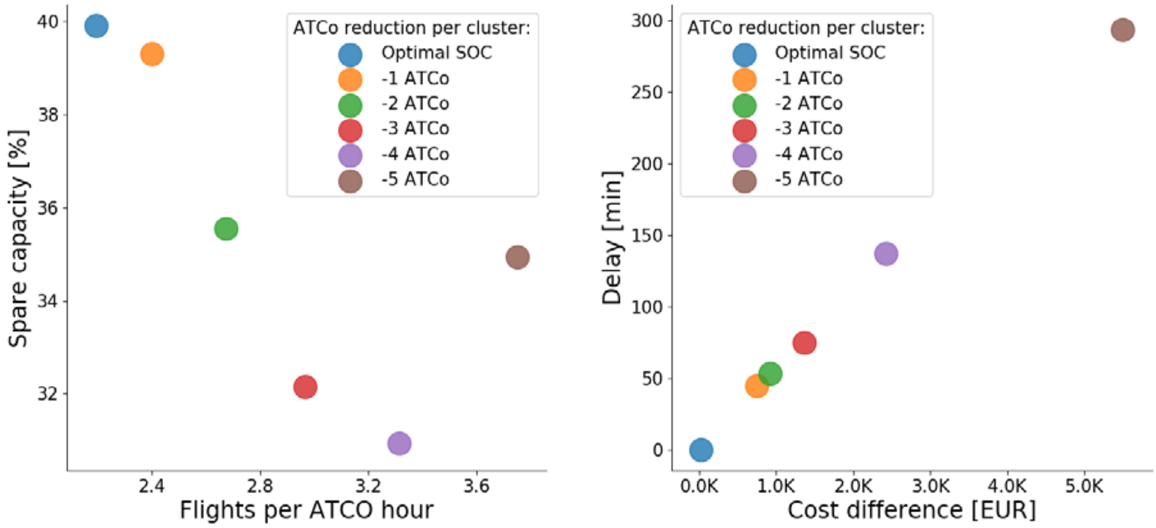
b) CE(ANS) vs. CE(AU)

Figure 5-11: Interdependencies for S5-PF2: CE(ANS) vs. CAP vs. CE(AU)

Similarly, as for S1-PF2, the reduction of sector availability (number of available ATCOs positions per cluster) affects the ANSP cost-efficiency by increasing flights per ATCO hour. However, this reduction is followed by the increase in the flights regulations represented by the increase of the average en-route ATFM delay (see Figure 5-11a). Scenarios S1 and S5 experience equivalent increase of the ANS cost-efficiency, but S5 shows lower increase of the C-CAP-1 delay if compared to S1, placing **ADCB as enabler for the better capacity utilisation**. Even though, increase of delay shows exponential properties, being significant with decrease of the available ATCOs (fourth and fifth ATCO position removed per cluster result in delay of more than 100 minutes per flight).

Comparing the two Pareto-Front graphs above, it can be inferred that the same impact applies to the delay and to the AU cost difference (Figure 5-11b). The comparison with S1-PF2 shows significant reductions in the AU cost with the introduction of the ADCB, cost being reduced from 22.5kEur to 5KEur for the highest pareto Case Study.

Figure 5-12a shows the outputs of the trade-off analysis for the ANS cost-efficiency performance indicator (CE-3) and the FLEX-2 PI; while Figure 5-12b depicts the interdependencies between the AU cost-efficiency (using CE-1.1) and capacity (delay as captured by C-CAP-1).



a) CE(ANS) vs. FLEX   b) CE(AU) vs. CAP

Figure 5-12: Interdependencies for S5-PF2: CE vs. FLEX vs. CAP

Flexibility, shown by FLEX-2 indicator is reduced with the reduction of the available ATCO positions. Since ANS cost-efficiency is increased, as previously explained, Figure 5-12a shows natural inverse trade-off relation between flexibility and ANS cost-efficiency focus area. The Case Study, in which available ATCO positions are removed by five per cluster, show exception to this conclusion that could not be explained by the tests performed. Thus, further analysis is required to derive proper conclusions on this particular trade-off.

Finally, Figure 5-12b shows almost a linear relation between AU costs and ATFM delay, both being increased with the reduction of the available ATCO positions. Linear relation shown in the S1-PF2 is slightly braked with the flight re-routing, offered by the ADCB implementation, that does not affect departure delay.

As previously stated in other S5-PF2 assessments, the most significant impacts on the en-route ATFM delay and on airspace user cost-efficiency can be seen when removing a fourth and specially a fifth ATCO per cluster. Removing three available ATCOs positions per cluster do not lead to high increases in delay and AU cost differences, and offers an improvement in the ANS cost-efficiency. This represents, in certain way, a limit of the current ATM system – capacity, since any additional reduction of the available active positions after three per cluster, results in significant decrease in system performance.

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