Final Project Results Report

Deliverable D1.2

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 report summarises all the research activities performed by the APACHE project and highlights the main project outcomes and contributions. The APACHE Project 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).

Besides performing a thorough review on the SESAR 2020 Concept of Operations and different Performance Frameworks, the main contributions of the Project are the integration of several background tools into a single platform, enabling the "APACHE Framework"; the proposal and validation of 73 new (or enhanced) performance indicators; and the assessment of ATM interdependencies by using this Framework. This report briefly describes these contributions, highlighting the progress done beyond state-of-the-art methodologies in ATM performance assessment.

This report also describes the links with the SESAR programme, identifying the potential uptake of results to Industrial Research and outlines potential future research and innovation activities.

[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 *D1.2 – Final Project Results Report,* is the publishable Final Project Results Report covering all the research activities performed by the APACHE Project. This report also aims to provide enough evidences to discuss the transition of the exploratory research carried out in the Project to subsequent development stages (i.e. SESAR Industrial Research or Very Large Scale Demonstrations), including a self-assessment of the TRL (Technology Readiness Level) achieved at the end of the Project.

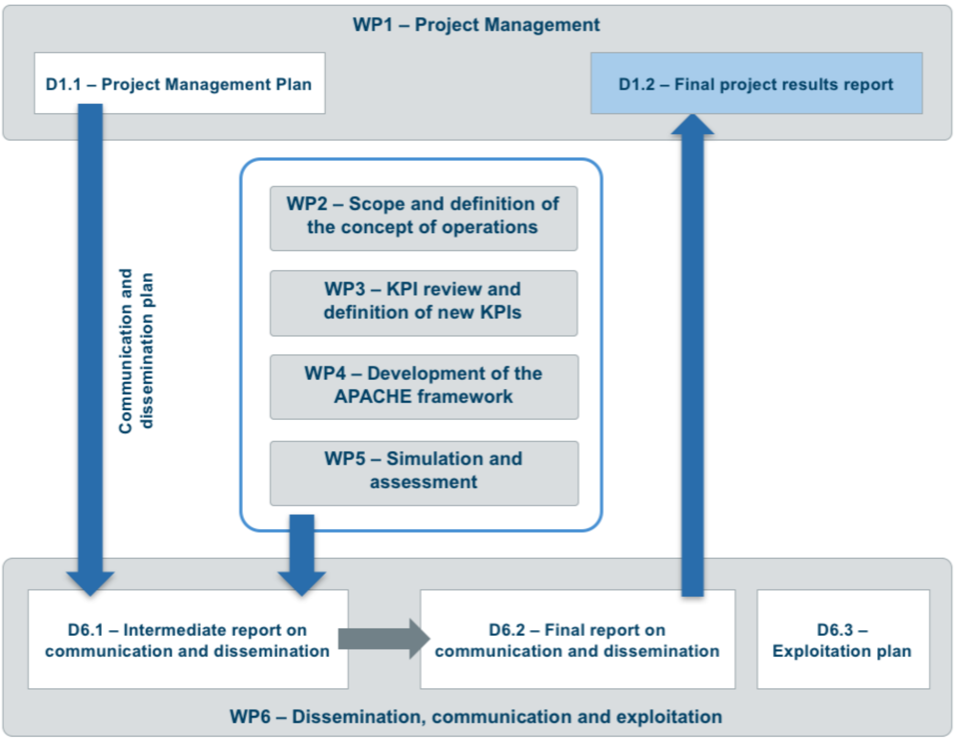


Figure 1-1. Context of deliverable D1.2

As it is shown in Figure 1-1, this document gathers and summarises all the work carried out in the Project. Thus, the purpose of this document is to highlight the principal contributions of the APACHE project beyond the state of the art, show some of the most representative most promising or meaningful results, emphasise the links with the SESAR programme and derive the principal conclusions of this research, lessons learnt and outline potential future research activities.

For specific details on the objectives, methodology or results of the Project the reader may consult the applicable Project Deliverable:

- **Deliverable D2.1:** Scope and definition of the Concept of operations for the project (APACHE, Consortium, 2017a).
- **Deliverable D3.1**: Review of current KPIs and proposal for new ones (APACHE, Consortium, 2017b).
- **Deliverable D3.2:** Functional requirements and specifications for the ATM performance assessment framework (APACHE Consortium, 2018d).
- **Deliverable D4.1:** Report on the availability of the APACHE framework (APACHE Consortium, 2018a).
- **Deliverable D5.1:** Results from simulation and analysis of results (APACHE Consortium, 2018e).

Moreover, regarding communication, dissemination and exploitation, the following two Deliverables are also public:

- **Deliverable D6.2:** Final report on communication and dissemination (APACHE, Consortium, 2017b).
- **Deliverable D6.3**: Exploitation plan (APACHE, Consortium, 2017c).

Appendix A of this document lists and summarises all the public deliverables of the APACHE Project.

1.2 Document structure

The document is structured as follows:

- **Chapter 1:** Introductory section that outlines the context and purpose of this deliverable, containing also a glossary of terms.
- **Chapter 2:** Executive summary of the document (and by extension) to the whole APACHE Project research activities, outlining the main contributions of the Project.
- **Chapter 3:** Overview of the project, recalling its objectives and methodology. Summary of the work performed towards fulfilling these objectives.
- **Chapter 4:** Summary of the principal contributions of the project going beyond the state of the art. Here the APACHE Framework is briefly described, as the successful integration of existing background software components, and all the new Performance indicators proposed by APACHE are outlined, highlighting their appropriateness to capture ATM performance and trade-offs between different KPAs.
- **Chapter 5:** Describes the links with the SESAR programme, identifying the potential uptake of results to Industrial Research and outlines potential future research and innovation activities.
- **Chapter 6:** Summarises the principal conclusions and lessons learnt.

1.3 Glossary

Term	Explanation
ACC	Area Control Center
ADCB	Advanced Demand and Capacity Balance
AEQ	Access and Equity (performance indicators)
AIP	Aeronautical Information Publication
ALG	Advanced Logistics Group
ANS	Air Navigation Service
ANSP	Air Navigation Service Provider
APACHE	Assessment of performance in current ATM operations and of new concepts of operations for its holistic enhancement
ASP	Airspace Planner (APACHE system component)
ATC	Air Traffic Control
ATCO	Air Traffic Controller
ATFM	Air Traffic flow management
ATM	Air Traffic management
ATS	Air Traffic Services
AU	Airspace User
BADA	Base of Aircraft Data
CANSO	Civil Air Navigation Services Organisation
CAP	Capacity (performance indicators)
CASA	Computer Assisted Slot Allocation
CAUTRA	French National Aeronautical Data Repository
CCC	Continuous Cruise Climb
CE	Cost-efficiency (performance indicators)
CI	Cost Index
CO_2	Carbon Dioxide
ConOps	Concept of operations
CPA	Closest Point of Approach
CPR	Correlated Position Reports
CTOP	Collaborative Trajectory Options Program
DCB	Demand and Capacity Balance
DCT	Direct Routes
DDR2	Demand Data Repository
DYNAMO	DYNAMic Optimiser
EAD	European AIS Database
ECAC	European Civil Aviation Conference
ECMWF	European Centre of Medium-Range Weather Forecasts
ENAC	Ecole Nationale de l'Aviation Civile
ENV	Environment (performance indicators)
ER	Exploratory research
E-OCVM	European Operational Concept Validation Methodology
FAA	Federal Aviation Administration
FAB	Functional Airspace Block
FABEC	Functional Airspace Block Europe Central
FL	Flight Level
FLEX	Flexibility (performance indicators)

Term	Explanation
FMP	Flow Management Position
FR	Free Route
FRA	Free Route Areas
HPC	High Performance Computing
ICAO	International Civil Aviation Organisation
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 Indicators
NEST	EUROCONTROL's Network Strategic Tool
NextGen	Next Generation Transportation System
NM	Network Manager
NMAC	Near Mid Air Collisions
OE	Operational Environmnet
OPS	Operations
PA	Performance Analyser (APACHE system module)
PBO	Performance Based Operations
PEP	Airbus Performance Engineering Programs
PF	Performance Framework
PI	Performance Indicator
PRB	Performance Review Body
PRU	Performance Review Unit
RA	Risk Assessment (APACHE system component)
RBT	Reference Business Trajectory
RP	Reference Periods
R&D	Research & Development
R&I	Research & Innovation
SAF	Safety (performance indicators)
SBT	Shared Business Trajectory
SES	Single European Sky
SESAR	Single European Sky ATM Research
SJU	SESAR Joint Undertaking
SR	Structured Route
STATFOR	Statistics and Forecasts Service
SV	Separation Violations
TA	Traffic Alert
TAP	Trajectory and airspace planner module (main component of the APACHE system)
TBO	Trajectory Based Operations
TCAS	Traffic Collision Avoidance System
TCP	Traffic and Capacity Planner (APACHE system component)
TP	Trajectory Planner (APACHE system component)
TRL	Technology Readiness Level
UB-FTTE	University of Belgrade-Faculty of Transport and Traffic Engineering
UPC	Technical University of Catalonia (Universitat Politècnica de Catalunya)
WP	Work Package

Table 1-1. Glossary

2 Executive Summary

APACHE is a SESAR 2020 Exploratory Research project that has explored the potential of advanced **simulation and optimisation tools** to improve ATM performance assessment across a wide range of KPAs. In this context, APACHE has:

- proposed **new (or enhanced) metrics and performance indicators** capable of effectively capture ATM performance, under either current or future concepts of operation, with the aim to enable a progressive performance-driven introduction of new operational and technical concepts in ATM in line with the SESAR 2020 goals;
- analysed **interdependencies between KPAs**, capturing the Pareto-front for different trade-offs; and
- estimated the theoretical **optimal limits** for certain performance indicators, under different optimality assumptions.

A key element in APACHE is the development of a novel **ATM simulation framework, a service-oriented software** that has been used in the project for two different purposes:

- to synthesise traffic and airspace scenarios, simulating different operational contexts and enabling the possibility to perform what-if assessments (**"Pre-ops"** ATM performance assessment); and
- to provide advanced models and optimisation tools that can support the implementation of novel and/or more accurate metrics and performance indicators, which can be used for "Pre-ops" but also for **"Post-ops"** (monitoring) purposes

APACHE has proven the usefulness of such approach to improve the state of the art in ATM performance monitoring and assessment, opening the door to use this framework for performance management, monitoring, target-setting and eventually supporting SESAR 2020 validation exercises.

APACHE has performed a comprehensive **review on performance indicators**, comparing the performance frameworks proposed by ICAO, CANSO, the SES PRU and SESAR 2020 Performance Framework, and has identified over 150 indicators for performance monitoring and management in 11 different KPAs. New (or enhanced) performance indicators have also been proposed aiming at filling some of the gaps identified in state-of-the-art.

The project has tried to cover all KPAs of the SESAR 2020 Performance Framework and **a total of 73 new (or enhanced) performance indicators (PIs)** have been implemented for the following KPAs or focus areas:

- **Environment KPA (45 PIs)**: proposing new distance- and **fuel-based indicators** suitable for pre-ops analysis (in line with current state-of-the-art indicators), but also for post-ops analysis and only requiring surveillance and realised weather data (a clear progress beyond the state of the art). A wide set of indicators have been proposed in this KPA, trying to capture the overall environmental impact of ATM operations, but also **trying to isolate particular contributions** for refined assessments, such as inefficiencies only in the vertical profile of the trajectory, inefficiencies only in the route, inefficiencies due to the strategic layer of the ATM, due to the tactical layer, etc.

- **AU Cost-efficiency focus area (10 PIs):** proposing new indicators considering inefficiencies in **flight time** and **flight cost** and, in line with the previous point, using only surveillance and weather input data and trying to isolate some components of the overall inefficiency figures.
- **ANS Cost-efficiency focus area (2 PIs)**: proposing new approaches to estimate the cost of providing Air Traffic Services based on some characteristics defining airspace sectorisation.
- **Safety KPA (7 PIs)**: proposing new indicators based on the intensive simulation of aircraft trajectories, coupled with advanced collision risk models.
- **Capacity KPA (3 PIs)**: enhancing classical delay indicators, in line with SESAR trajectory-based operations paradigm, and taking into account arrival delay.
- **Access and Equity KPA (2 PIs)**: proposing new indicators to capture cost penalties per Airspace User.
- **Flexibility KPA (4 PIs)**: proposing new indicators in line with SESAR trajectory-based operations paradigm.

Five different scenarios, with different case studies each, were considered as validation exercises of the proposed APACHE Framework:

- One **"Post-ops" scenario** (*baseline scenario*), where historical data, from two different days of study (realised trajectories and airspace sectorisations), were analysed.
- Four **"Pre-ops" scenarios,** where realistic trajectories and sectorisations analysed were synthesised with the APACHE simulator, and for three different days of study (low/medium/high traffic demand):
  - *Reference scenario* synthesising current operations.
  - *Solution scenario* synthesising a hypothetical case with a full free-route environment from origin to destination airports.
  - *Solution scenario* synthesising continuous cruise climb operations.
  - *Solution scenario* synthesising a hypothetical case with an advanced demand and capacity balance (ADCB) mechanism, allowing collaborative trajectory options from airspace users.

Besides the comparison and benchmarking among the previous scenarios, specific and tailored "a priori" case-studies have also been simulated for some pre-ops scenarios in order to assess performance trade-offs (Pareto-front) and interdependencies between KPAs. All case studies have been analysed with the performance indicators proposed in the APACHE Framework and also using some indicators currently employed by the PRU.

The APACHE framework enables proactive and predictive analysis of the current and future ATM system, as a first step towards Performance Based Operations. The project has proven the **usefulness of advanced simulation and optimisation tools to improve or define new performance indicators** overcoming some of the current limitations in performance assessment and **allowing the assessment of interdependencies between different KPA and/or SESAR solutions.**

Some performance indicators proposed by APACHE are mature enough for **a potential uptake to industrial research** with little effort (develop specific web services, front-ends, interfaces, integration into wider platforms, etc.). Examples are some safety indicators; some environment or AU cost-efficiency indicators for pre-ops analysis; or some equity and capacity indicators.

Other indicators still require **further research** to refine certain models, to gather the appropriate input data or to envisage alternatives to avoid requiring confidential or proprietary data. Examples of this category of indicators are some flexibility indicators; ANSP cost-efficiency indicators; and certain environment and AU cost-efficiency indicators for post-ops assessment.

Finally, the APACHE project has also identified some indicators that would require **long term research** and were just mentioned, but not implemented in the APACHE Framework prototype. These include indicators requiring complex or very specific models (global warming models, for instance) and indicators requiring a deeper understanding of certain stakeholders' behaviour or a complex set of input data (to derive, for instance passenger-centric metrics).

The project has opened the door to **a more integrated and holistic methodology to assess ATM performance**, enabling the following potential application use cases:

- support the **validation exercises** of certain **SESAR solutions**, providing
  - a **unified and homogeneous Framework** to compute certain performance indicators on demand (via web services, for instance);
  - assessment of **interdependencies** between SESAR solutions;
  - intensive **model-based simulations,** allowing performance assessment, sensitivity and robustness analysis in several KPAs;
  - the computation of **optimal** (under different constraints to assess different KPAs, focus areas or specific stakeholder needs) **trajectories** and/or **sector opening schemes** on demand (via web services, for instance);
- support the definition of the **high-level performance ambitions** for the European ATM master plan, or even contribute to SESAR validation target setting;
- recreate **tailored simulations** to test and validate the appropriateness of certain performance indicators or refine some of them; and
- **benchmarking/complementation** of different Performance Frameworks.

3 Project overview

The International Civil Aviation Organization (ICAO) launched in 2003 a worldwide initiative to ensure that the future global ATM system is **performance driven** (ICAO, 2008; 2009). Consequently, the ongoing ATM modernisation programmes, such as SESAR in Europe and NextGEN in North-America, build on top of this ICAO concept and worldwide support to this initiative is also given by the Civil Air Navigation Services Organisation (CANSO, 2015). A performance-based approach, as defined by (ICAO, 2009), shall be based on strong focus on desired/required results, informed decision making driven by the desired/required results, and reliance on facts and data for appropriate decision making. This consequently entails the need for new methodologies and tools for performance **measurement**, performance **evaluation** and **decision support**.

In line with these initiatives, **current ATM performance assessment** is addressed in Europe through the Single European Sky **(SES) Performance Scheme**, which establishes an agreed methodological framework for performance **targeting**, **measuring**, **baselining** and **benchmarking** in ATM (European Commission, 2015).

Within SESAR 2020 activities, **Project 19 (PJ-19)** is devoted to the Content Integration, with work package 4 (noted PJ-19.04) being responsible for Performance Management within the Program. PJ-19.04 is structured in three main pillars:

- **Validation Targets setting**, which apportions the high-level **Performance Ambitions from the ATM Master Plan** among the different SESAR 2020 Solutions, considering the expected impact on different KPAs and in different Operating Environments. These targets are an indication to Solutions of which KPAs they need to assess in their validation activities.
- **Performance Framework (PF)**, understood as the formal set of KPIs, performance indicators (PIs) and metrics per KPA to be used in SESAR activities, including Industrial and Exploratory Research (ER).
- **Consolidated Performance Assessment and Gap Analysis:** gathering the inputs from the different Solutions and consolidating them at ECAC level, taking into account the complex interdependencies between Solutions themselves, as well as between KPAs. It includes the gap analysis between the achieved consolidated program results and the targets.

These tools, together with the Performance Management processes and methodologies and reference material per KPA or Transversal Area (Operational Performance, Safety, Security, and Human Performance), constitute the global **SESAR Performance Framework**[2].

[2] References to Performance Framework by default refer to the overall set of tools, processes, methodologies and material.

The SESAR Programme includes research and innovation projects ranging in maturity from exploratory research through to very large scale demonstrations. The mission of **SESAR 2020 Exploratory Research (ER) program** is to turn Europe's ATM excellent science into a globally competitive advantage for the next generation of the European ATM System.

Exploratory Research activities are organised in different periodical calls, each one addressing different topics. The first call of Exploratory Research in SESAR 2020 was released in June 2015, **including ATM Performance (ER-11-2015)** among other topics. One of the awarded projects was **APACHE**. This chapter aims to give a general overview of the APACHE Project, its scope and objectives, the proposed approach and a summary of the work performed during the 2-year duration of the Project. Chapter 4, in turn, summarises the principal contributions of the Project aiming at advancing the state of the art in ATM performance assessment.

3.1 Motivation of the Project

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

Moreover, the SESAR target concept of operations (SESAR Joint Undertaking, 2016) introduces new paradigms, such as TBO (**trajectory based operations**) and PBO (**performance based operations**); where a more dynamic optimisation and allocation of ATM resources is foreseen, in order to enable the airspace users (AUs) to fly with the minimum amount of constraints. It is expected these new concepts will bring a significant positive impact in ATM performance. Current performance frameworks and PIs, however, might not be able to properly capture the benefits of the new operational improvements that will arise from the implementation of TBO/PBO.

It is also worth noting that a very important aspect in ATM performance management is balancing between various KPAs by including their **interdependencies** into the analysis. These interdependencies present a high level of complexity, due to the interaction of different regulations, stakeholders, technologies and systems and market conditions. Trade-offs arise not only between KPAs but also between stakeholders and even between SESAR Solutions. To the best of our knowledge, there is no performance scorecard to track achievements versus goals, such that also captures the effects of promoting one PI versus other PIs belonging to different KPAs, or even to the same KPA.

3.2 Project scope and objectives

Aiming to address the open questions identified in the previous section, the **main objective** of the APACHE Project is to explore the potential of **advanced simulation and optimisation tools** in order to improve ATM performance assessment across a wide range of KPAs in a holistic approach, filling in this way some of the gaps of current state-of-the-art methodologies. The specific objectives of the Project are:

- to propose **new (or enhanced) metrics** and **performance indicators** capable of effectively capture ATM performance, under either current or future concepts of operation, with the aim to enable a progressive performance-driven introduction of new operational and technical concepts in ATM in line with the SESAR 2020 goals;

- to analyse some **interdependencies between KPAs**, capturing the Pareto-front for different trade-offs; and
- to estimate the theoretical **optimal limits** for certain KPA, under different optimality assumptions.

In order to fulfil these objectives, the APACHE project revolves around a novel framework that:

- generates **optimal aircraft trajectories** under different optimisation criteria and which is able to consider the business models of the airspace users (AU) and realistic weather conditions;
- generates **optimal airspace configurations**, considering the needs and constraints of the air navigation service providers (ANSP); and
- integrates both into an **advanced air traffic flow management** (ATFM) scheme.

This 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:**

- trajectories generated using
    - the current structured en-route network and published free route areas (FRA) and direct routes (DCT); or
    - assuming an ideal enhanced FRA scenario (full free route operations from origin to destination airports), in line with SEASAR 2020 solutions PJ06 and PJ07-01;
- trajectories generated using
    - the current flight level allocation and orientation schemes; or
    - assuming an ideal scenario with continuous cruise climb (CCC) operations;
- airspace sectorisations generated using
    - the current ANSP practices, where different pre-established sector configurations are used; or
    - assuming dynamic airspace configuration mechanisms in line with SESAR 2020 solution PJ08; and
- ATFM methodologies using
    - current practices, where demand is regulated by issuing ground delays; or
    - assuming a new advanced demand and capacity balance (ADCB) mechanism involving more interactions between the network manager and the AUs, inspired by SESAR 2020 solution PJ09 and the collaborative trajectory options program (CTOP) of the FAA.

Moreover, this System is also used to **synthesise some of the scenarios** used in the validation activities of the Project in order to make an initial impact assessment of these SESAR 2020 solutions (pre-ops assessment).

3.3 Project approach

Figure 3-1 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 (if any) to be considered.

Two types of performance assessment were foreseen APACHE: **"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, the (initial) assessment of some SESAR2020 solutions, or the assessment of different ATM performance trade-offs.

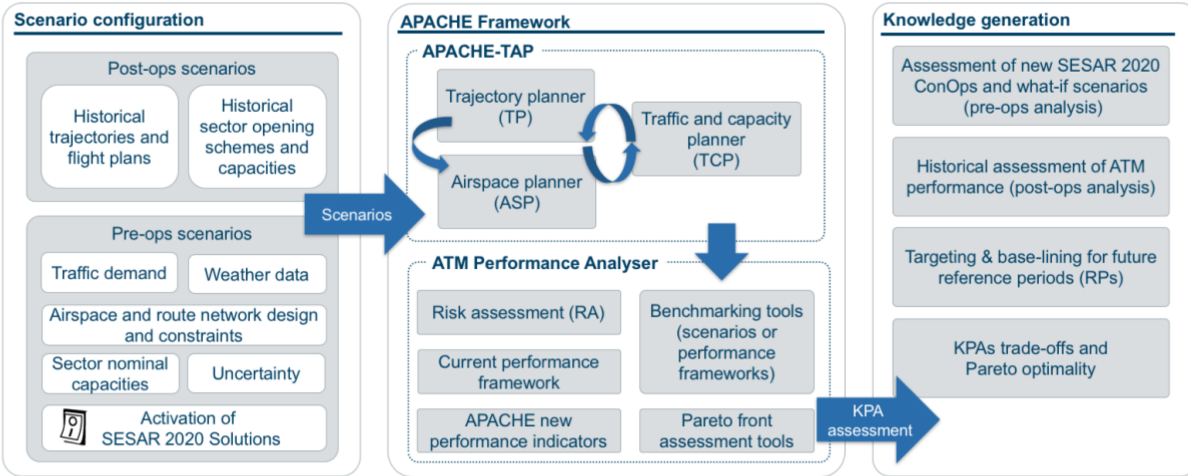


Figure 3-1. Context of the APACHE Framework within the APACHE Project

As seen in Figure 3-1, 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 **synthesize traffic and airspace scenarios** representative enough of current operations; or emulating future operational concepts in line with the SESAR 2020 ConOps (i.e. one or more SESAR solutions enabled).

This double functionality of the APACHE-TAP is also shown in the block diagram of Figure 3-2.

APACHE Deliverable D4.1 (APACHE Consortium, 2018a) details the integration of the different software components that compose the APACHE Framework, including the integration and verification tests as well as the individual (component) validation tests. Deliverable D5.1 (APACHE Consortium, 2018e), in turn, details the Project Validation exercises that were carried out, in order to show the appropriateness of the APACHE Framework to assess ATM performance towards achieving the objectives of the Project.

The latest stage of the APACHE Project focuses on **knowledge generation**. In this regard, the Performance Indicator results derived from the APACHE System can be analysed following the defined post-ops and pre-ops scenarios. The **analysis of the pre-ops scenarios** would lead to the assessment of new SESAR2020 ConOps and what-if scenarios, evaluating the impact of specific SESAR Solutions on the overall ATM performance. On the other side, the **analysis of the post-ops scenario** entails a historical assessment of ATM performance (based on historic data) using APACHE Framework performance indicators.

Based on the assessment of the APACHE Framework Results, **targeting and base-lining for future reference periods (RPs)** can be defined for the different KPAs considered in the assessment. The applicability of the new APACHE Framework performance indicators can be more easily assessed based on the APACHE Framework Results (post-ops and pre-ops).

Finally, the APACHE Project also provides a knowledge generation contribution in terms of capturing ATM **KPAs trade-offs and interdependencies**. Specific Pareto-Front assessments are to be conducted in order to demonstrate the capabilities of the APACHE Framework in this regard. Overall, seven tailored case studies were planned to assess performance trade-offs and Pareto front (besides comparisons among scenarios).

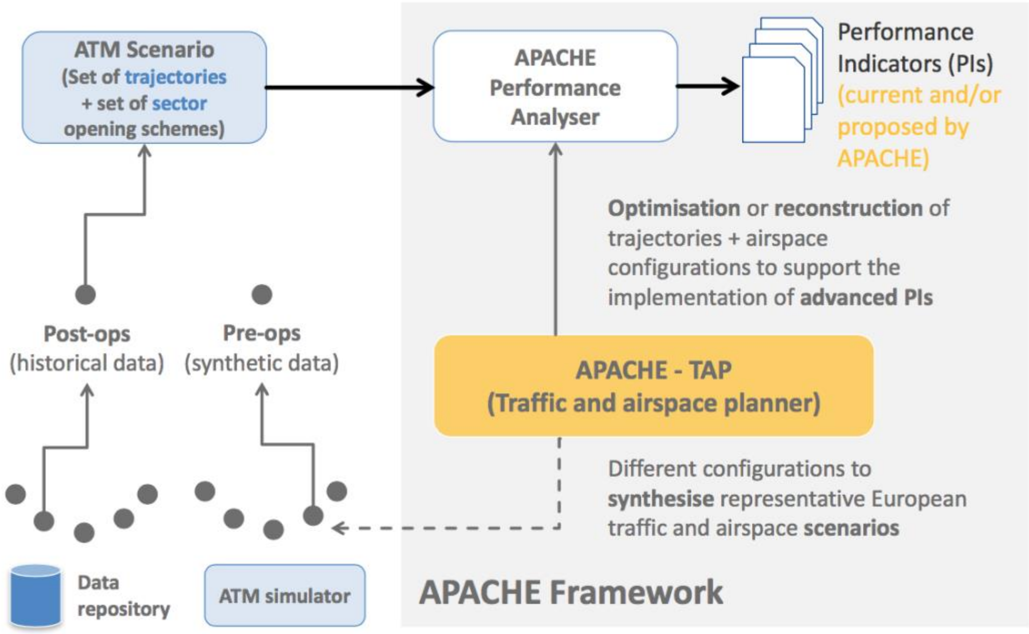


Figure 3-2. Double usage of the APACHE-TAP within the APACHE Framework

3.4 Work performed

The methodology followed in the APACHE project is shown in Figure 3-3. The current state of the art with regards to ATM performance frameworks (PF), metrics and performance Indicators (PIs) was carefully analysed in order to propose the new APACHE Framework, built on this previous knowledge. Furthermore, since APACHE is willing to propose PIs that might be useful in the future, current and SESAR 2020 target concept of operation (ConOps) were also reviewed in the first stage of the project (see section 4.1 for the principal contributions on this topic).

New PIs, or enhanced PIs adapted from state-of-the-art indicators, were proposed in a second stage of the project, aiming at better capturing key microscale and macroscale factors affecting ATM performance, as well as better identifying interdependencies between KPA (see section 4.3 for the principal contributions on this topic).

As explained before, the majority of the new (or enhanced) PIs proposed by APACHE require from advanced simulation and/or optimisation features. This was achieved by bringing together some background tools from different partners of the APACHE consortium. These tools were enhanced and integrated into a low TRL prototype (the APACHE Framework shown in Figures 3-1 and 3-2), but mature enough to fulfil the requirements of this Project (see section 4.2 for the principal contributions on this topic).

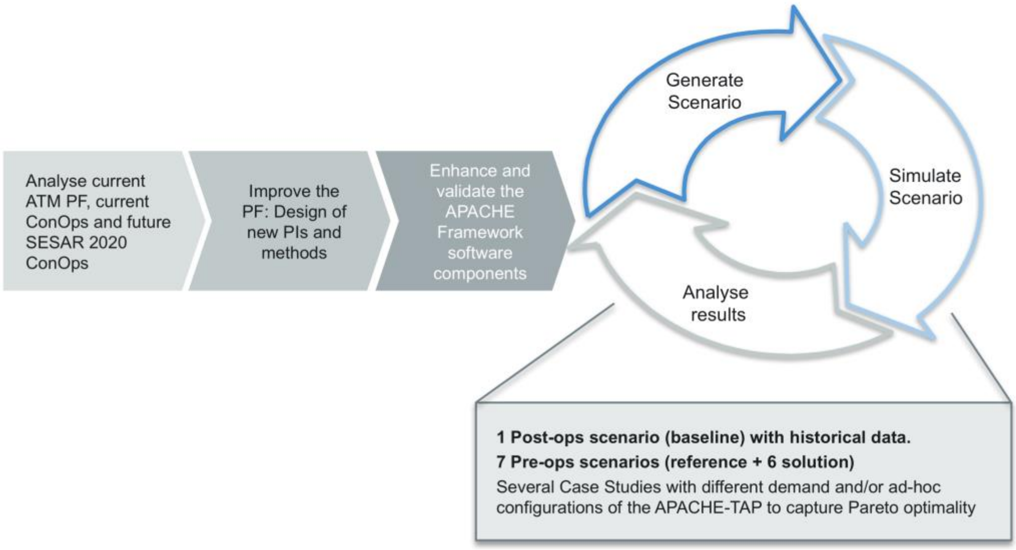


Figure 3-3. Double usage of the APACHE-TAP within the APACHE Framework

The following scenarios were finally assessed in the APACHE Project validation activities (APACHE Consortium, 2018e):

- **Post-ops scenario S0 (Baseline)**: Historic trajectory data from DDR2 (Eurocontrol, 2016) or PRU Correlated Position reports (Spinelli et al., 2017) for actual, regulated and planned trajectories.
- **Pre-ops scenario S1 (Reference)**: Synthesised/simulated trajectories and airspace sectorisations using the APACHE-TAP for current ConOps.
- **Pre-ops scenario S2 (Solution):** 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.
- **Pre-ops scenario S3 (Solution):** Continuous Cruise Climbs (CCC) scenario, pushing vertical flight efficiency to the theoretical limits by removing any constraint in the vertical trajectory.
- **Pre-ops scenario S5 (Solution):** 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.

The synthesised scenarios (pre-ops assessment) were based on the current ConOps and the new SESAR 2020 ConOps described in the latest edition of the SESAR B4.2 ConOps (SESAR Joint Undertaking, 2016), selecting the most relevant ATM functionalities for the overall purpose of the project. This enabled a comparison between the way that current metrics and methodologies capture performance in these new scenarios and the way the new framework could do it. This also allowed the assessment of current and future concepts of operations and also benchmarking among them.

For the **pre-ops assessments**, three specific Case Studies were defined for each Scenario, changing only the traffic demand (defined only by the flight ID, aircraft type, origin/destination airports and date/time of departure):

- Low demand (24h of traffic demand recorded in February 20th 2017).

- Medium demand (24h of traffic demand recorded in July 28th 2016).
- High demand (24h of traffic demand estimated for July 21st 2023)[3].

For the **post-ops Scenario**, two Case Studies were considered taking the actual/regulated/planned historical trajectories and airspace sectorisations for in February 20th 2017 and July 28th 2016.

For all scenarios, only trajectories crossing FABEC airspace were considered by the APACHE-TP and only the FABEC airspace was considered by the APACHE-ASP.

APACHE Deliverable D5.1 (APACHE Consortium, 2018e) contains the precise specification of all Scenarios and Case Studies used in the Project Validation exercises, as well as all the results, analysis and conclusions drawn.

[3] generated by Eurocontrol's STATFOR tool configured to give the maximum amount of demand for that representative day.

4 Principal project contributions and key results

This section summarises the principal contributions of this project and highlights the most promising or meaningful results, pointing when appropriate to the Project deliverable that contains more details or discussions. Appendix A of this document lists and summarises all the public deliverables of the APACHE Project.

4.1 ConOps and Performance Frameworks review

In APACHE Deliverable D2.1 (APACHE Consortium, 2017a), the Concept of Operations (ConOps) for the project was defined. This deliverable aimed to set the different contexts of operations (baseline and SESAR2020 target operations) to be considered in the new APACHE System developed within the Project. From this operational context, the scope of the Project was concreted and a set of SESAR solutions were identified to be subject of study during the assessing activities of the Project. Thanks to this, the traceability of the APACHE Project scope within the context of the SESAR programme could be settled. This traceability was carried out as per SESAR solutions to be assessed, that could be assessed or that enable other solutions to be assessed within the Project. Finally, the work performed for this deliverable aimed to set up the pavement of the potential evolution of the concept towards higher levels of maturity.

Overall, the SESAR 2020 programme output is defined and packed in the form of “SESAR Solutions”. SESAR Solutions contain outputs from R&I activities which relate to either an Operational Improvement (OI) step or group of OI steps and associated enablers which have been designed, developed and validated in response to validation targets that when implemented, will deliver performance improvements to European ATM (SESAR Joint Undertaking, 2016). In total, 66 SESAR1 and 85 SESAR2020 Solutions were identified in the course of activities of APACHE WP2.

The objective of APACHE Deliverable D3.1 (APACHE Consortium, 2017b), in turn, was twofold:

- to review the current KPIs and PIs used by the SESAR, Performance Review Body (PRB) and other relevant institutions (ICAO, CANSO, and SES PRU); and
- to propose new (or enhanced) PIs, which could be computed/measured using the new APACHE framework, and aiming.

For this purpose, past reports and guidance material were reviewed in order to determine which KPAs are covered and which specific KPIs/PIs are used in Europe. Apart from that, relevant ICAO and CANSO documents were also reviewed, among others. Special attention was given to the **SESAR Performance Framework**, which is quite specific in its purpose and perspective as it aims to estimate the performance benefits of SESAR solutions before the execution phase of operations (in line with

APACHE **pre-ops** assessments). **SES PRU** indicators were also reviewed, which in turn are aiming to monitor performance from realised operations (in line with APACHE **post-ops** assessments).

A comprehensive list of all indicators used by the different organizations worldwide is summarized in (APACHE Consortium, 2017b). This overview showed over 150 different PIs distributed in 11 different KPAs. This could result from different understanding of the ICAO high-level goals, but it is also highly related to specific characteristics of the systems observed. It is likely that the same set of indicators cannot successfully catch the performances of different ATM systems (e.g. US and European ATM system), due to differences in air traffic system organization, airspace management, air traffic flow management practices, etc.

This comprehensive review of the state of the art in ATM performance measurement allowed the APACHE consortium to **propose a set of new PIs (or enhanced versions of existing PIs)** aiming to to bridge some gaps in current state-of-the-art methodologies, either to better capture ATM performance or to identify the complex interdependencies among different KPAs. Details on the new indicators are given in section 4.3 of this report.

4.2 The APACHE Framework

As seen in Figure 3-1 the APACHE Framework is mainly composed by the APACHE traffic and airspace planner (APACHE-TAP) and by the APACHE performance analyser (PA). As commented above, the APACHE-TAP has a double functionality in the project (see Figure 3-2): to support the APACHE PA with the computation of optimal trajectories and/or airspace sectorisations needed to build certain ATM performance PIs; and to synthesise pre-ops scenarios representative of current of future operations.

The APACHE Framework was build using existing background software:

- *Dynamo,* a trajectory prediction and optimisation tool from UPC, integrated into the APACHE trajectory planner (TP) component;
- a suite of tools to compute optimal sectorisations from ENAC, integrated into the APACHE airspace planner (ASP) component; and
- a risk assessment methodology and a TCAS collision model from UB-FTTE, integrated in to the APACHE risk assessment (RA) component.

Some other software components were developed from scratch for the purposes of the APACHE project, such as the traffic and capacity planner (TCP) and the APACHE PA.

The integration of these independent components into a unified platform or framework is one of the main contributions of the APACHE Project. This Platform could be seen as a prototype of an ATM simulator, which brings together different expertise and backgrounds. A first step towards a powerful tool useful for ATM simulation and ATM performance assessment, as demonstrated in this Project.

Next sections summarise the main software developments carried out within the APACHE project for each of the APACHE Framework software components. More details are given in APACHE Deliverable D4.1 (APACHE Consortium, 2018a), including the verification and validation tests performed, as well as the list of limitations and assumptions for each of the components.

4.2.1 The APACHE framework integration

Besides developing or enhancing new software components, a big effort in APACHE was devoted to integrate these components (coming from different backgrounds and not designed to be part of an integrated and bigger system) into a single prototype. Figure 4-1 shows a block diagram depicting this APACHE Framework integration, where the components workflow is shown, along with the different files serving as interface among components.

As seen in the Figure, the main sources of data used in this Project were Eurocontrol's Demand Data Repository 2 (DDR2) (Eurocontrol, 2016), which contained all traffic demand information needed to reconstruct trajectories (in post-ops) or synthesise them (in pre-ops). In order to generate these trajectories, the TP also needed aircraft performance data, taken from the Base of Aircraft Data (BADA) v4.1 also from Eurocontrol (Nuic et al., 2010) and weather data taken from ECMWF (European Centre for Medium-Range Weather Forecasts) database. The ASP, in turn, takes also airspace structure and capacity data from the DDR2 but due to missing and wrong data in this particular repository, additional sources were used to amend and complement the DDR2 data, like the Aeronautical Information Publication (AIP), available through Eurocontrol's European AIS Database (EAD), as well as French national aeronautical data repository (CAUTRA) and different ACC internal documentation.

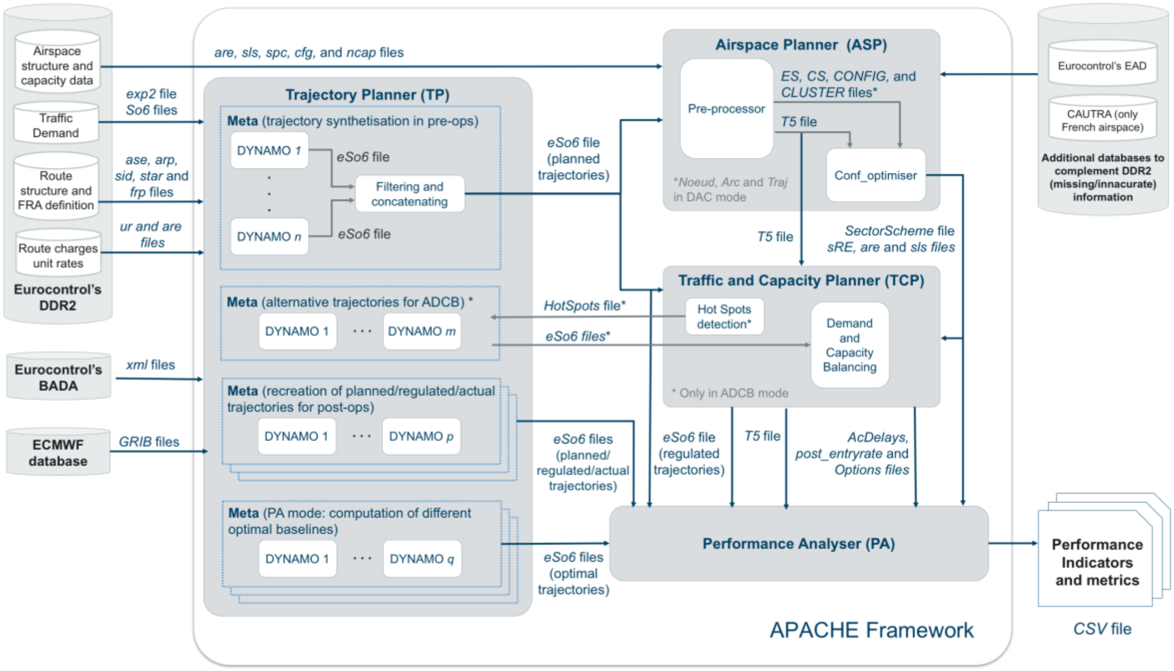


Figure 4-1. APACHE Framework workflow

The workflow starts by executing **Meta**, a component of the APACHE TP developed from scratch in this Project that allows a distributed computation of trajectories using high performance computing (HPC) techniques. **This component enabled the massive computation of trajectories needed in APACHE validation exercises (around 1 million).** The workflow continues with the ASP module, which takes airspace structure and trajectory data to compute optimal sector schemes.

In pots-ops assessments, these two modules (TP and ASP) provide the required information to the APACHE-PA to compute the different PIs and assess ATM performance and trade-offs. As explained before, in pre-ops mode, the TP and ASP (together with the TCP) are used to synthesise scenarios (traffic and airspace structures) according to the global configuration parameters (day of operations, activation of one or several SESAR Solutions, etc).

The following sections highlight the principal contributions for each particular module of the APACHE Framework.

4.2.2 The APACHE trajectory planner (TP)

The APACHE TP is composed by two main software components: The DYNAMIC Optimiser (**DYNAMO**) and the **Meta** Launcher mentioned above. In APACHE, DYNAMO was used for four different purposes (see Figure 4-1):

- **Trajectory synthetisation for pre-ops scenarios**: different realistic traffic sets were synthesised under different concepts of operation and taking different inputs for traffic demand and/or weather conditions.
- **Alternative trajectories for ADCB Case Studies:** For those Case Studies where the TCP was configured in ADCB mode, the TP (emulating the AUs) provided to the TCP (emulating the NM) with a set of alternative trajecotries to avoid congested sectors (hotspots) in the lateral domain (re-routings) or in the vertical domain (level cappings).
- **Trajectory recreation for post-ops scenarios**: Taking as input the planned, regulated or actual trajectories from DDR2 (containing for each flight only 3D coordinates at different time stamps) DYNAMO was configured to estimate the take-off mass, the Cost Index and the fuel burnt for each flight in order to reconstruct a full 4D trajectory with this extended data.
- **Trajectory optimisation under different optimality criteria and/or constraints**: Different PIs implemented in the APACHE-PA require from different trajectory baselines, which are optimal trajectories under different criteria/constraints.

An initial version of DYNAMO was brought as background by UPC in the APACHE project and was significantly enhanced with the following new features in order to fulfil the previous four high-level functionalities:

- Inclusion of realistic weather processing data directly from ECMWF database.
- Inclusion of state-of-the-art aircraft performance models by using BADA 4.1.
- Optimisation of the lateral component of the trajectory.
- Optimisation of the vertical component of the trajectory by means of pre-processed look-up tables in order to enable massive computations of trajectory and guarantee the stability of the algorithm (Dalmau et al., 2018).
- Optimisation under different concepts of operations: following the structured en-route network, assuming full free-route operations, following flight level allocation/orientation schemes, or assuming continuous cruise climbs (CCC).
- Optimisation with different cost functions and in particular, taking into account AU business needs.
- Optimisation with sector avoidance in the lateral or vertical component of the trajectory.
- Reconstruction of 4D trajectories (including aircraft mass, cost index and fuel flow estimation) based on surveillance data (for executed trajectories) or flight plan data (for planned/regulated trajectories) and without requiring confidential or proprietary data.

For illustrative purposes, Figures 4-2 to 4-5 show some example trajectories using DYNAMO and showing the principal key features. The APACHE TP was validated with the Airbus performance engineering programs (PEP) suite and compared with a similar trajectory planner module developed by Boeing in the context of the AURORA SESAR 2020 Exploratory Research Project. More details are found in D4.1 (APACHE Consortium, 2018a).

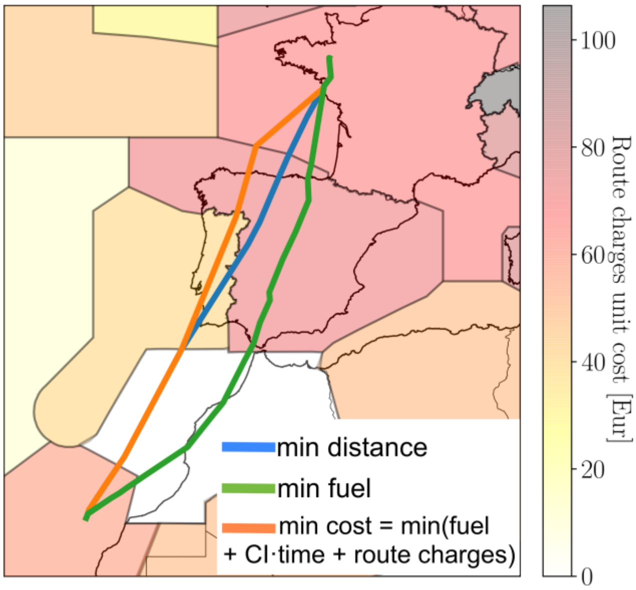
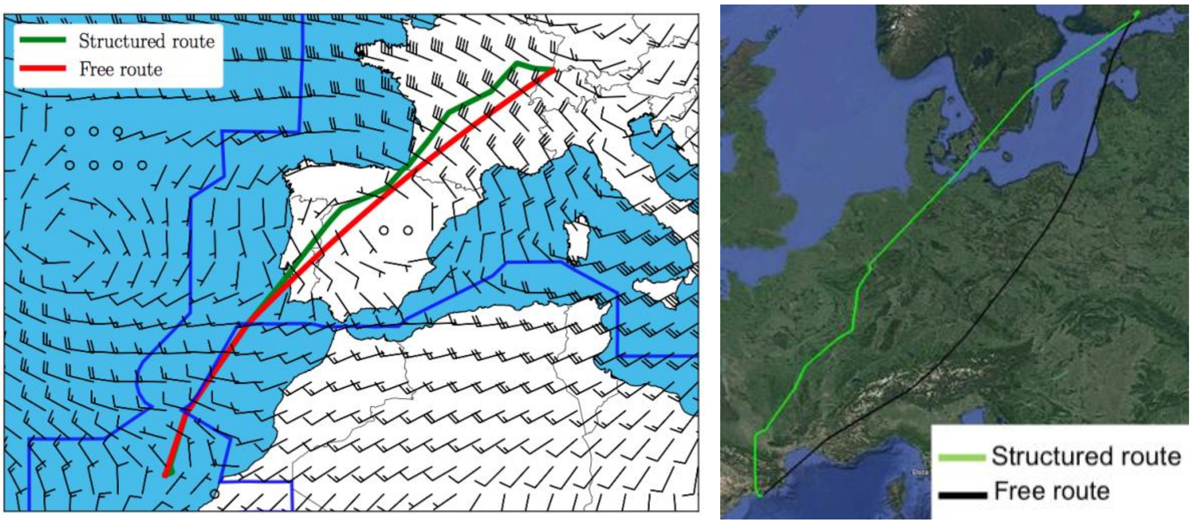
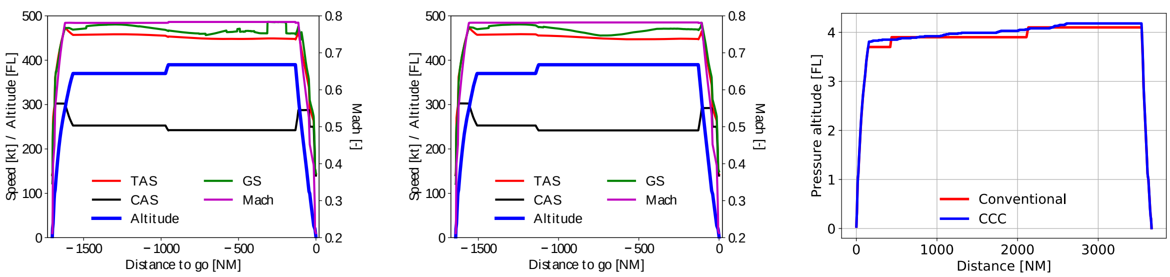


Figure 4-2. APACHE TP generating 3 different optimal trajectories according to 3 different optimisation criteria



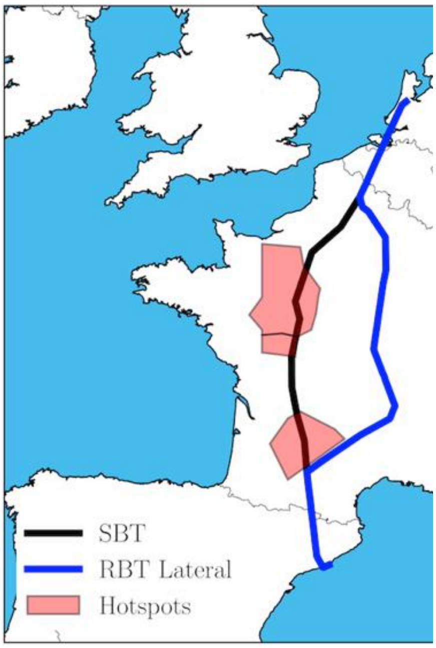
a) Example 1: from GCLP to LFSB b) Example 2: from LEBL to EFHK

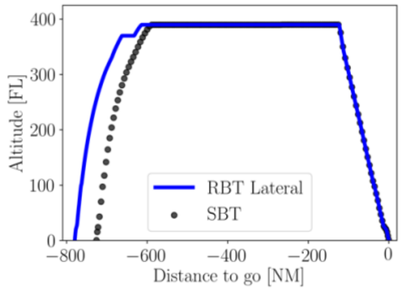
Figure 4-3. APACHE TP generating weather-optimal routes with different lateral ConOps



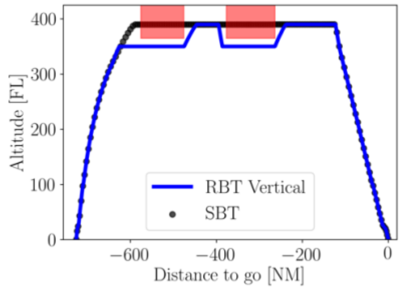
a) Structured route in Fig 4-3a a) Free-route in Fig 4-3a b) Conventional vs. CCC

Figure 4-4. APACHE TP generating weather-optimal vertical profiles with different vertical ConOps





(b) New vertical profile resulting from lateral avoidance



(a) Lateral avoidance (re-routing) (b) Vertical avoidance (level capping)

Figure 4-5. APACHE TP generating weather-optimal alternative trajectories to avoid hotspots.

4.2.3 The APACHE airspace planner (ASP)

The APACHE ASP was brought as background by ENAC in the APACHE project and was enhanced and adapted for the integration with other modules of the APACHE framework.

It takes as input traffic data (trajectories coming from the APACHE TP module) and airspace structure/capacity data and produces the optimal sector opening scheme for the given mode of operations, demand and operational constraints. The APACHE ASP is composed by two main software components: the data pre-processing module (**preprocessor**) and airspace configuration module (**conf_optimizer**), both being able to work in two modes representing current and future ConOps.

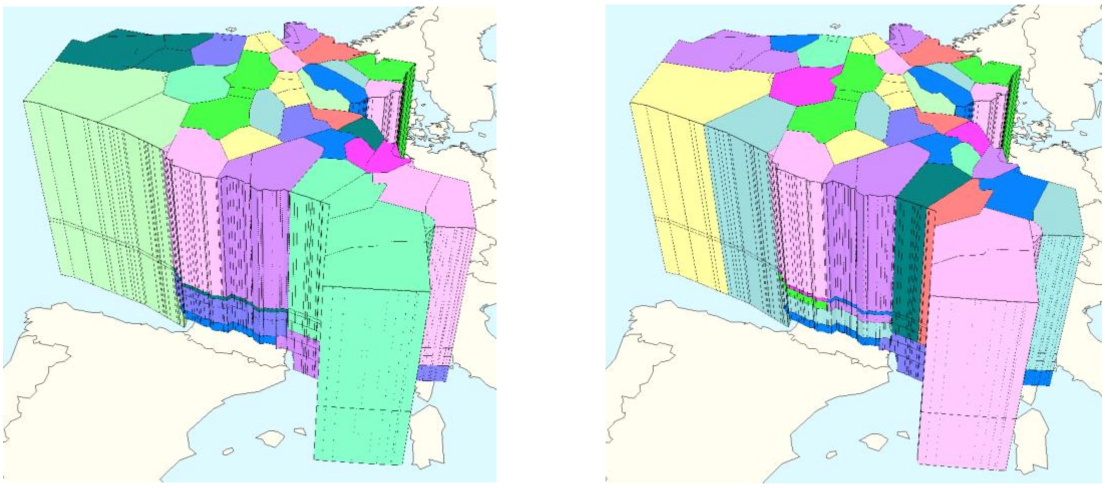
Preprocessor takes raw input data (internal and/or external) and computes constraints and objectives for the optimization problem. It has following functionalities, of which some are completely developed for the APACHE project:

- Extraction of the nominal sector capacities in the current operation mode from different data sources (new functionality);
- Computation of the airspace-traffic intersection and sector entry counts (new functionality) needed for the evaluation of the sector load and finally evaluation of the airspace configurations feasibility and objective;
- Computation of configuration transitions that model operational constraints of sector grouping/degrouping in the current operations (existing functionality adapted for unsupervised/without-expert-knowledge transition computation);
- Sector complexity computation for the future mode of operation (existing functionality);
- The controller workload limit, in terms of traffic complexity, extraction (new functionality);
- Neighbouring computation between elementary sectors (adaptation of the existing functionality).

After the **preprocessor** has finished, the **conf_optimizer** is launched computing an optimal sector opening scheme and generating different outputs used for other modules in downstream (namely TCP and PA), ASP module verification and validation, results analysis, etc.

The optimization problem of finding optimal sector opening scheme is modelled differently for the current and future ConOps, and therefore solved by two different optimization techniques as explained in D4.1 (APACHE Consortium, 2018a).

For illustrative purposes, Figure 4-6 shows the (optimal) output of the ASP at two different time intervals for the same day of operations. Notice the change of active sectors (in number and/or redistribution of elementary sectors) due to the change in the traffic demand: an increase of incoming traffic at 11h (if compared with 9h) leads to a degrouping (splitting) of collapsed sectors into smaller sectors to better handle the new demand.



(a) Airspace configuration at 9h　　(b) Airspace configuration at 11h

Figure 4-6. APACHE ASP generating optimal sectorisations (opening schemes). Example for two different time periods of the same day (visualized with Eurocontrol NEST)

Although brought as background by ENAC in the project, to enable the optimization of large geographical areas that were of the scope of APACHE project (FABs, ECAC), the used techniques of the ASP in APACHE were adapted and enhanced in order to solve the problem more efficiently in terms of computational load.

4.2.4 The APACHE traffic and capacity planner (TCP)

The APACHE TCP was developed from scratch for the APACHE Project and it is only enabled when the APACHE-TAP is used to synthesise Case Studies for the **pre-ops scenarios**.

Once the ASP has generated an optimum sectorisation, trying to better allocate airspace capacity for a given traffic demand, the TCP is responsible to regulate the demand avoiding to exceed the maximum nominal capacity in any sector. The TCP has two different modes of execution:

- "current ConOps" replicating the Computer Assisted Slot Allocation (CASA) algorithm, assigning delays when a demand and capacity imbalance occurs; and

- "future ConOps" implementing an advanced demand and capacity (ADCB) algorithm, allowing for optimal delay and trajectory amendments at pre-tactical level), inspired by SESAR 2020 solution PJ09 and the collaborative trajectory options program (CTOP) of the FAA.

The CASA implementation was validated with a similar tool used by Eurocontrol's NEST. It should be noted, however, that nominal capacities as published in the DDR2 were used to regulated remand in this Project. This is far from actual operations, where each flow management position (FMP) have different strategies and criteria to finally decide whether a regulation should be applied or not, if a new (higher) capacity should be declared for a certain period of time, if some overload (i.e. demand above nominal capacity) is allowed for certain sectors in certain periods of time, etc. This behaviour strongly relies on (expert) human intervention and decision making (the staff working at the FMP) and was out of the scope of the TCP modelling. Consequently, delays computed by the APACHE TCP are significantly higher that those obserded nowadays in real operations.

The ADCB implementation included some degree of collaborative trajectory planning between the AUs and the network manager (NM). In this mode of operation, the TCP module performed the following functionalities:

- detection of time-varying hotspots (i.e. airspace volumes with demand greater than capacity);
- generation of hotspot avoidance information, for each affected flight, for trajectory negotiation with the TP; and
- demand and capacity balancing through optimising trajectory alternative selections and delay assignments by using linear optimisation to incorporate a series of options to manage the traffic flow in a high flexible way. The possible measures consist of (alternative) trajectory options (given by the TP once the hotspots are detected) and different delay strategies (including ground holding, airborne holding, linear holding and delay recovery after the regulated airspace). The objective is to minimise the overall deviation to the initial status which is composed of all the user-preferred trajectories, whilst maintaining.

Figure 4-5 corresponds to an example of a trajectory affected by two hotspots and shows the original trajectory along with the (optimal) lateral and vertical re-routings computed by the TP. More details are found in D4.1 (APACHE Consortium, 2018a).

4.2.5 The APACHE performance analyser (PA)

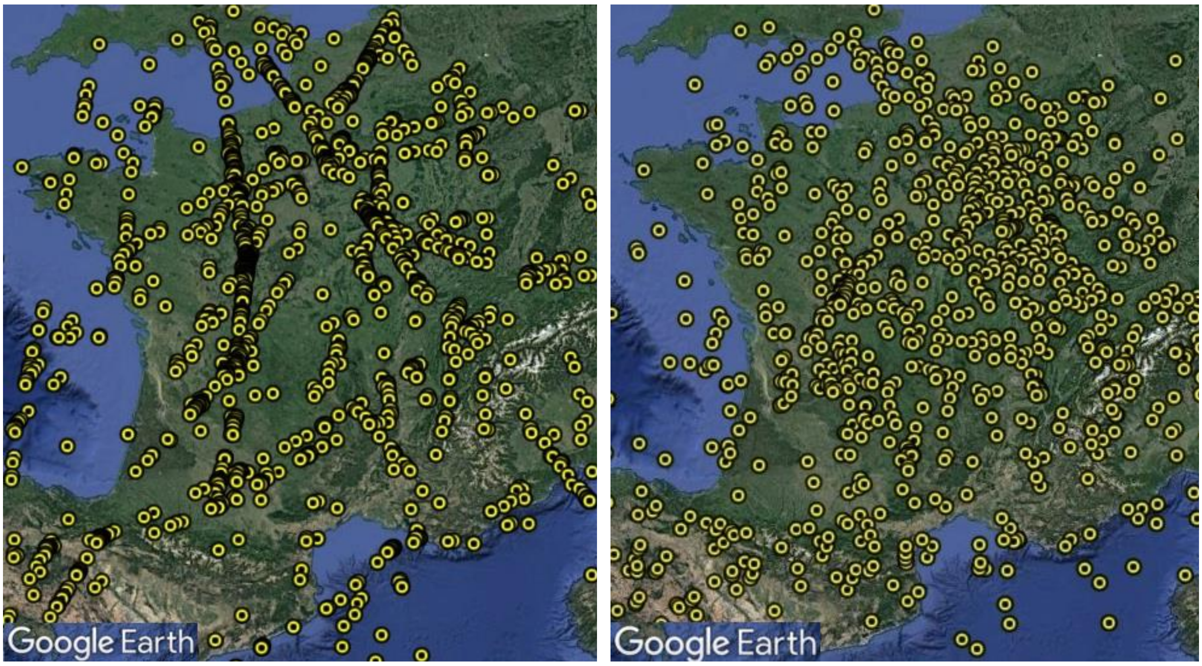
The APACHE PA was developed from scratch for the APACHE Project and calculates the different performance indicators (PIs) used in the APACHE Framework. As mentioned above (see also Figure 4-1), the PA implements some complex indicators that require inputs from optimisation tools provided by the APACHE-TAP, such as optimal trajectory baselines (TP) or optimal sectorisations (ASP).

Moreover, the PA embeds the **Risk Assessment (RA) module**, which is a specific module that computes all Safety PIs and was developed by UB-FTTE using some tools brought as background. This module is formed, in turn, by:

- a separation violation detection module;
- a TCAS activation module; and
- a risk of conflict/accident assessment module.

The RA component is based on the assumption that conflict between pair of aircraft exists when either horizontal and/or vertical separation minima are violated. This loss of separation might activate the TCAS module, which counts traffic alerts and resolution advisories warnings. The risk of conflict/accident assessment module is based on calculation of “elementary risk” which is defined as the area between the surface limited by the minimum separation line and the function representing the change of aircraft separation. The risk of conflict/accident is then defined as the ratio between the “elementary risk” and the observed period of time. Apart from the risk between specific aircraft pairs, an assessment of the total risk in a given sector is also considered.

As illustrative example, Figure 4-7 shows the geographical location of the closest points of approach (CPA) that were below 5NM in the horizontal plane or 1000ft in the vertical plane for an example set of 24h traffic. It should be noted that this traffic came from planned 4D trajectories (synthesised by the APACHE TP), which were not subject to any ATC intervention (this explains the relatively big number of conflicts in the Figures). Figure 4-7a corresponds to a set of traffic synthesised under current en-route network structure, while Figure 4-7b corresponds to the same traffic synthesised under the assumption of full free route operations. As expected the location of the conflicts are much more spread in the latter case.



(a) Structured en-route network **(b) Full free-route operations**

Figure 4-7 Location of conflicts (CPA below 5NM horizontal or 1000 ft vertical) for an example Test Case.

4.3 Proposal of new performance indicators

Following the SESAR 2020 Performance Framework, the APACHE project tried to cover all the KPAs defined there, not necessarily at the same level of detail, but not limiting the research to the “classical” Capacity, Safety, Environment, and Cost-efficiency, as in the SES Performance Scheme. Thus, new (or enhanced) PIs were proposed aiming at filling some of the gaps identified in state-of-the-art methodologies for ATM performance assessment.

A total of 89 new, or enhanced, PIs have been proposed in the Project. Among them, 16 PIs were not finally implemented in the APACHE System, due to its low level of maturity and/or to the lack of data required to implement these indicators. Thus, they were not assessed nor considered in the scope of the Validation activities of the Project. Nevertheless, they are candidates for implementation in future evolutions of the APACHE System.

The APACHE System finally implements a total of 73 new (or enhanced) PIs: 2 for the Access and Equity KPA; 3 for the Capacity KPA; 10 for the AU Cost-efficiency focus area; 2 for the ANS Cost-efficiency focus area; 45 for the Environment KPA; 4 for the Flexibility KPA; and 7 for the Safety KPA. Details on these PIs are given in (APACHE Consortium, 2017b; 2018d), such that:

- they are capable of measuring the performance of the current and future ATM for the purpose of planning (solution validation) and monitoring;
- they could be implemented by the APACHE System providing the data for calculation of PIs can be obtained from the (existing, somewhat modified) tools that will integrate the APACHE System; and
- a meaningful relationship between KPAs can be established based on the selected PIs.

The following approach was applied:

- The four major KPAs (the most frequently assessed ones and covered by both SESAR and SES Performance Schemes) and associated PIs are considered first. Existing PIs are adopted as they are or certain enhancements are suggested. Also, new indicators are possibly proposed;
- in line with SESAR2020 PF, which addresses a wider range of KPAs, seven additional KPAs are also considered, where the same approach as above is applied: some of existing performance indicators are found appropriate as they are or with certain enhancement, or new indicators are proposed; and
- in line with APACHE goals, possible introduction of new KPAs (out of those 11 previously mentioned) and their corresponding indicators are also considered.

Next sections summarise the principal contributions done for each KPA. Since in the SESAR 2020 PF, the cost-efficiency KPA is divided in two big focus areas, those measuring cost-efficiency for the AUs and those focused in the air navigation services (ANS), this distinction has also been made here.

4.3.1 Environment KPA

The main contribution in the environment KPA was to propose indicators that **take into account optimal trajectories as baseline references** to derive environmental flight inefficiencies measured in terms of extra distance flown or extra fuel burnt. Thus, in APACHE, actual or planned trajectories are compared with **optimal trajectories that take into account weather conditions and might consider different optimality criteria and/or optimisation constraints**.

Current state-of-the-art indicators used in the SES PRU compute these inefficiencies by comparing the actual or planned trajectory with the **geodesic distance** (i.e. the minimum ground between origin and destination airports)[4]. The SESAR 2020 PF, in turn, already proposes fuel-based indicators, but for pre-ops assessment only (i.e. when both reference and solution trajectories are synthesised and therefore the fuel consumption can be easily computed). **The main contribution in APACHE is to extend these concepts for post-ops analysis**, where fuel is estimated only from observed radar tracks. Thus, the difficulty lies in the fuel estimation of the observed trajectory without requiring confidential or sensitive data from the AUs (such as the take-off mass of the aircraft, cost index, etc.).

The new environment PIs proposed in APACHE are divided in two big families: distance-based indicators (ENV-1 family) and fuel-based indicators (ENV-2 family):

- **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, but represent already a step beyond current state-of-the-art indicators used by the SES PRU for monitoring purposes (which use geodesic distances as baselines).
- **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 from complex fuel estimation algorithms (fuel is estimated only from observed radar tracks only).

Each family has several indicators aiming to **capture different sources of environmental inefficiencies**, such as inefficiencies in the vertical or lateral domain of the trajectory (only for ENV-2.x) or inefficiencies due to different layers of the ATM (strategic, tactical or both). Moreover, each of these indicators, in turn, can be computed by using different baseline reference trajectories, allowing to better isolate the different sources of environmental inefficiencies, leading at the end to 45 different indicators for the Environment KPA.

4.3.1.1 Contributions for post-ops assessments

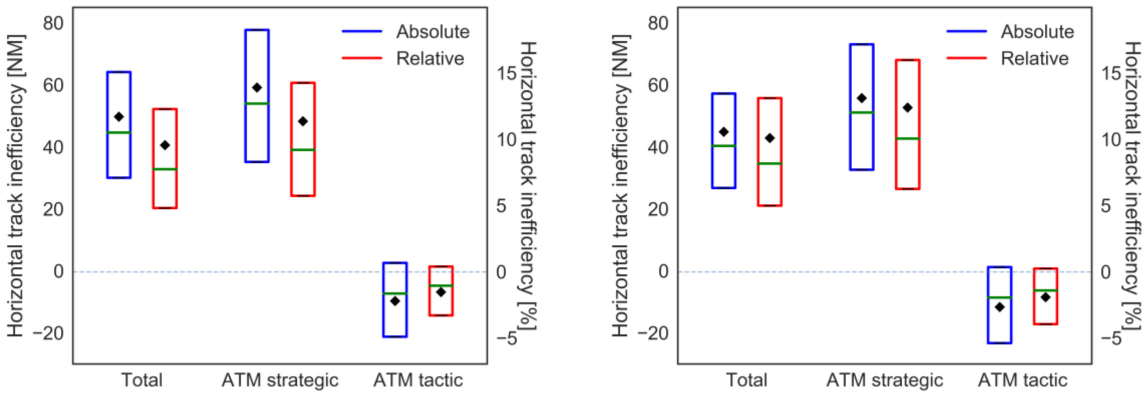
Figure 4-8 shows the environmental inefficiencies computed with the APACHE distance-based PIs for the two post-ops Case Studies. As commented before, different PIs are proposed to capture different sources of inefficiency, in this case decoupling the tactical layer of ATM (i.e. ATC intervention) to the strategic layer (i.e. the fact that AUs are still forced to use a structured en-route networks to plan and execute their flights). It is worth noting how the tactical layer introduces, for most of the flights, a "negative inefficiency", meaning that ATC contribute to reduce route extension by short-cutting the planned trajectory

Figure 4-9 shows the same assessment using fuel-based PIs. An advantage of the fuel-based indicators proposed in APACHE is the possibility to decouple the vertical and horizontal sources of fuel inefficiency, besides differentiating, as well, inefficiencies originating in the tactical layer or the strategic layer of the ATM. This leads to 9 different indicators, as observed in Figure 4-9.

Results show how 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

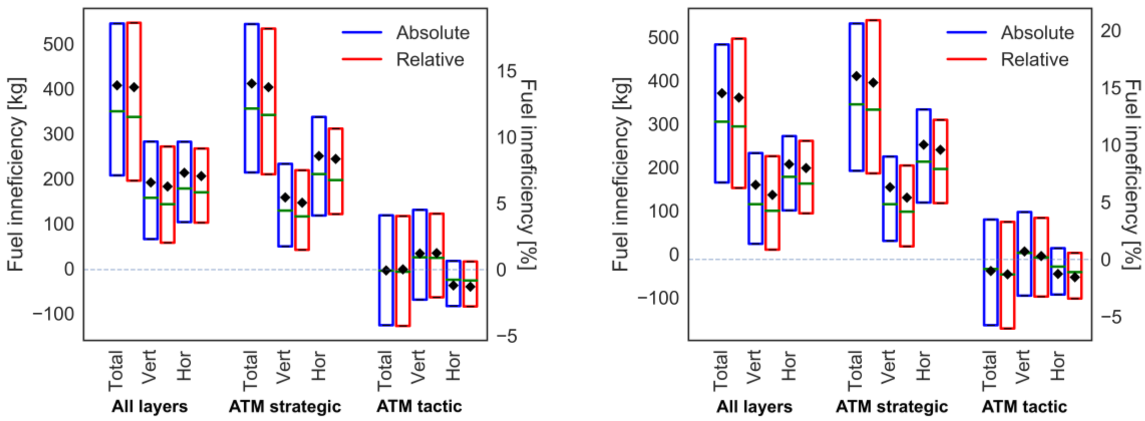
[4] More precisely, current SES PRU indicators KEP and KEA, exclude the segments of trajectory within a 40NM radius around the origin and destination airports and they also show results in percentages of flight efficiency, taking into account the route length when aggregating results at ANSP/network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

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 4-8: Post-ops results with distance-based environmental indicators (ENV-1 family)



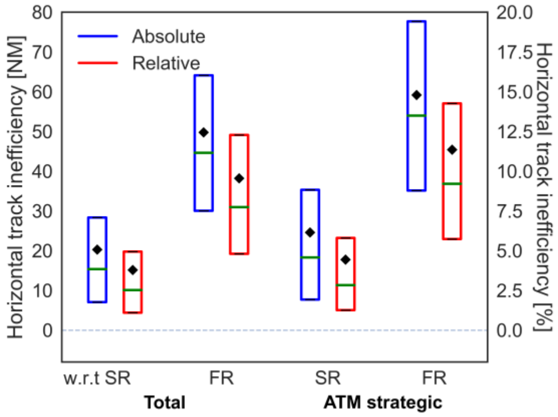
a) S001 (24h FABEC Jul 28th 2016) a) S003 (24h FABEC Feb 20th 2017)

Figure 4-9: Post-ops results with fuel-based environmental indicators (ENV-2 family)

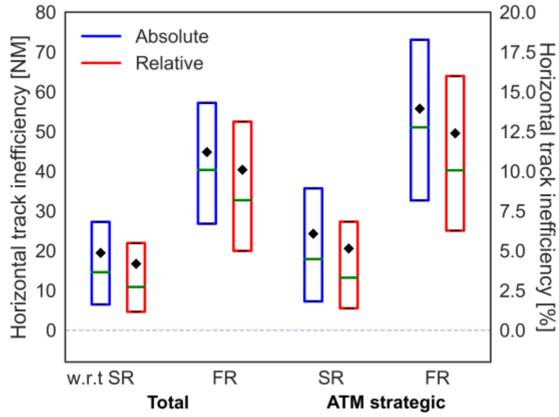
The optimal trajectory used as baseline for the previous twelve indicators has been computed assuming a full-free route airspace with a flat route-charges scheme and maximum range operations (i.e. Cost Index zero) and considering weather conditions for the day of study. **Different trajectory baselines could be considered**, however, such as:

- 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).

This leads to multiple additional performance indicators in the environment KPA that **capture different sources or types of inefficiency.** Figures 4-10 and 4-11 show, respectively for the distance- and fuel-based indicators, the results for the same two post-ops Case Studies presented above when changing the trajectory baseline to compute the PIs.

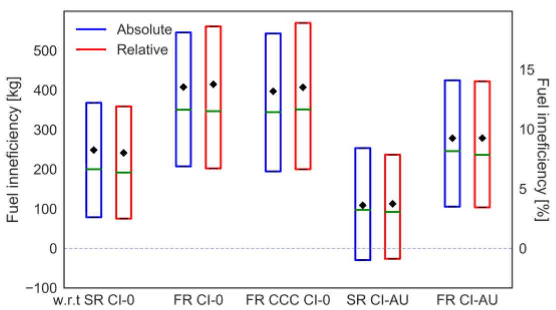


a) S001 (24h FABEC Jul 28th 2016)

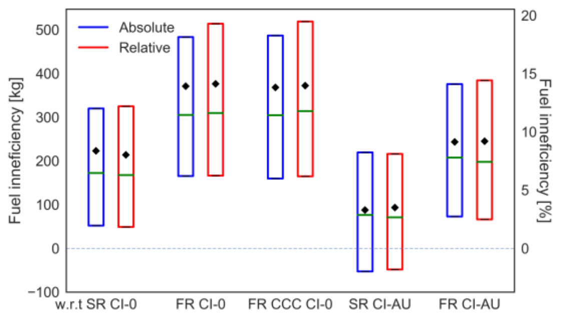


a) S003 (24h FABEC Feb 20th 2017)

Figure 4-10: Post-ops results with distance-based environmental indicators (ENV-1 family) using different trajectory baselines



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



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

Figure 4-11: Post-ops results with distance-based environmental indicators (ENV-2 family) using different trajectory baselines

As expected, inefficiencies for the SR (structured routes) cases are lower, since the optimal trajectory baseline is also constrained to follow segments of the current route network. 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 in current operations.

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 observed before**, since part 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.

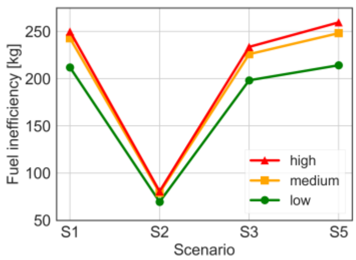
As observed in Figure 4-11, the inefficiencies that could be attributable to ATM go down to approximately 250 kg (7.8%) if a full free route scenario is considered for the baseline trajectories (instead of 350 kg – 11%), or 97 kg (3.0%) if the structured route network is considered (instead of 200 kg – 6.3%). In other words, AU's induced fuel inefficiencies (due to flying faster than the maximum range speed) have a mean around 100 kg (3% in relative terms approximately) for the two days of study considered.

Finally, it is worth noting that inefficiencies captured by the SR CI-AU indicator are due to discrepancies between the APACHE optimisation tool and those used by the AU at the moment of planning their flights. These discrepancies could have different nature: different weather data, an inappropriate mass and/or Cost Index estimation by the APACHE trajectory reconstruction tool, the AU planning deliberately a route, which is not the best route in the network, etc.

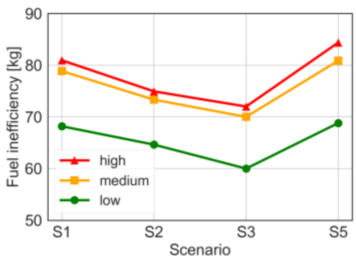
4.3.1.2 Contributions for pre-ops assessments

Figure 4-12 shows the environmental inefficiencies (median of the data set) computed with the APACHE fuel-based PIs for the four pre-ops scenarios[5]: ENV-2.3 (total inefficiency); ENV-2.4 (vertical inefficiency); and ENV-2.5 (horizontal inefficiency). Since the APACHE PIs can capture (and decouple) vertical and horizontal fuel inefficiencies, the benefits of flying continuous cruise climb operations (CCC) can be assessed (Scenario S3), something that could not be done with distance-based indicators or using current SES PRU indicators.

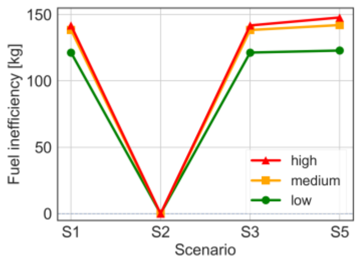
Similarly, the **APACHE indicators can better capture fuel inefficiencies in Scenario S5**, which implements the ADCB algorithm that allows for re-routings and level cappings when regulating demand. All level cappings would not be captured using distance-based indicators or using current SES PRU indicators.



a) ENV-2.3 (Total inefficiency)



b) ENV-2.4 (Vertical inefficiency)



c) ENV-2.5 (Horizontal inefficiency)

Figure 4-12: Pre-ops results for the Environment KPA (fuel-based PIs)

4.3.2 Airspace User cost-efficiency focus area

The main contribution of APACHE in the AU cost-efficiency focus area was to propose indicators that take into account **flight time** and **cost for the AU,** opening the door to consider **optimal trajectories as baseline references** as done for the PIs of the Environment KPA**.** Current state-of-the-art indicators used in the SES PRU compute the share of regulated flights as a macroscopic measure of the system efficiency. The SESAR 2020 PF, in turn, proposes similar AU cost-based indicators, but for pre-ops

[5] S1: Reference Scenario: Reproducing current operations – S2: Solution scenario with enhanced free route areas (full free route from origin to destination in ECAC) – S3: Solution scenario allowing continuous cruise climbs (but still following the structured route network) – S5: Solution scenario implementing an advanced demand and capacity balancing algorithm allowing for global optimal allocation of delays, re-routings and level cappings.

assessment only (i.e. when both reference and solution trajectories are synthesised and therefore the AU related cost can be easily computed).

The main contribution in APACHE is to extend these concepts for post-ops analysis, where AU cost is estimated only from observed radar tracks. Thus, the difficulty lies in the cost estimation of the observed trajectory without requiring confidential or sensitive data from the AUs (such as the take-off mass of the aircraft, cost index, etc.). This means that estimation of flight cost might not be accurate for certain AUs or flights, but these indicators are still very useful for relative comparison between two or more scenarios or case studies.

The new AU cost-efficiency PIs proposed in APACHE are divided in two big families: cost-based indicators (CE-1 family) and trip-time-based indicators (CE-4):

- **Cost-based indicators** try to estimate the cost inefficiencies in terms of extra fuel burnt, extra flight time and ATFM delay (if any). The have the advantage to be a more direct estimate on the impact for the AU but their computation is more difficult since they require from complex fuel estimation algorithms. 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.
- **Trip-time-based indicators** have the advantage that they much easier to compute, if compared with cost-based indicators, and directly capture performance in one of the aspiration levels set in the ATM Master Plan (SESAR Joint Undertaking, 2015)[6]: trip-time. Although trip-time is one of the key aspects in the AU cost-breakdown structure it is not the only one and therefore, this PIs may show partial information of the ATM System performance.

Each family has several indicators aiming to capture AU cost-inefficiencies due to different layers of the ATM (strategic, tactical or both) or can be computed by using different optimal trajectories as baseline "optimal" references to compute the PI. This variability leads, at the end, to 10 different indicators for the AU cost-efficiency focus area.

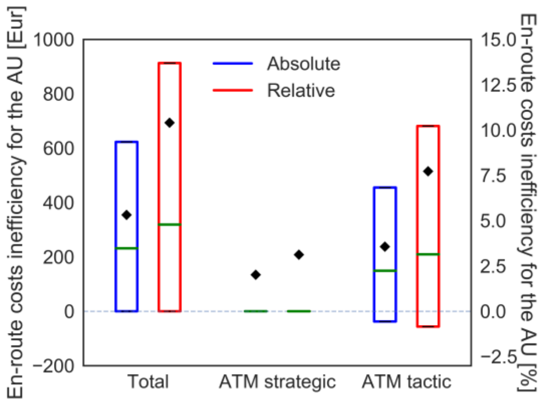
4.3.2.1 Contributions for post-ops assessments

Figure 4-13 shows the inefficiencies computed with the APACHE AU cost-based PIs for the two post-ops Case Studies. As commented before, different PIs are proposed to capture different sources of inefficiency (decoupling tactical and strategic layers of ATM) and also can be computed by using different baseline trajectories.

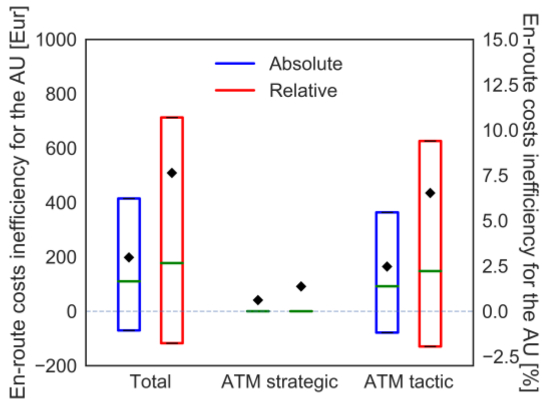
The results presented in Figures 4-13a and 4-13b used the last filed flight plan by the AU (the first SBT according to the SESAR 2020 ConOps) as baseline trajectory (i.e. the trajectory that is used to compare with the actual trajectory and compute the cost inefficiency). This is an important hypothesis, 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

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

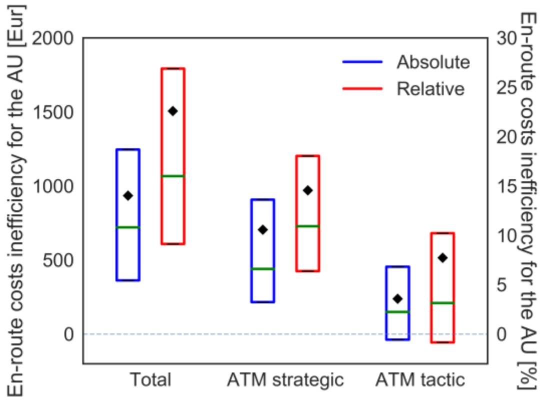
operations, however, it is not always the case that the last filed flight plan by the AU truly represents its real intentions, since, for example, they might intentionally submit a flight plan avoiding a certain airspace likely to experience congestion. Results shown in Figures 4-13c and 4-13d, in turn, 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).



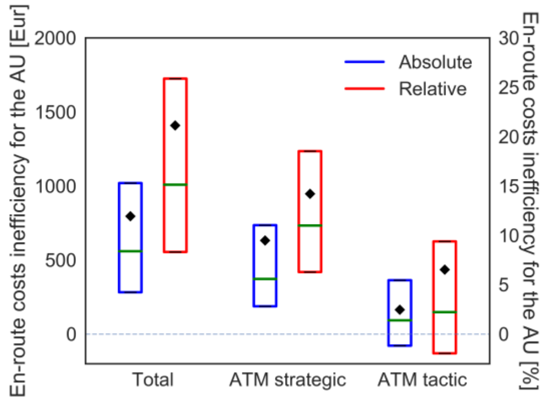
a) S001 (24h FABEC Jul 28th 2016) with last filed flight plan as baseline trajectory



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



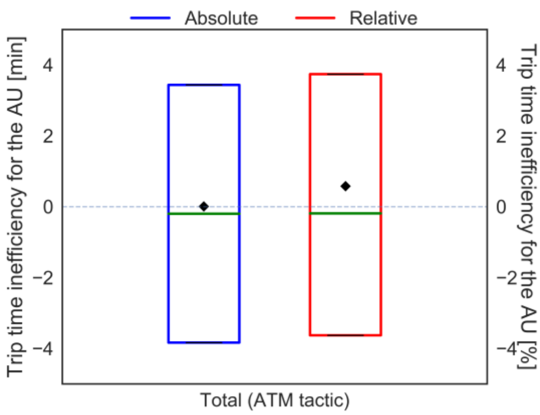
c) S001 (24h FABEC Jul 28th 2016) with optimal full free route trajectory as baseline



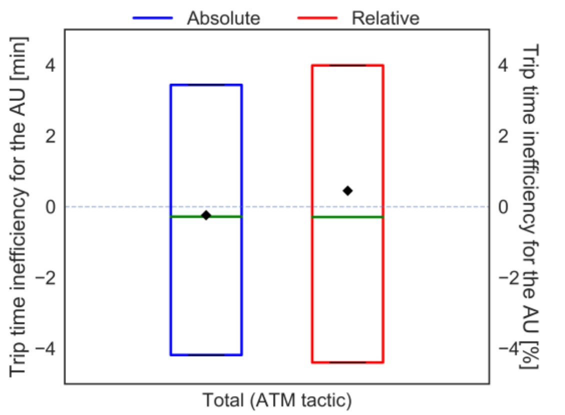
d) S003 (24h FABEC Feb 20th 2017) with optimal full free route trajectory as baseline

Figure 4-13: Post-ops results with cost-based AU cost-efficiency indicators (CE-1 family)

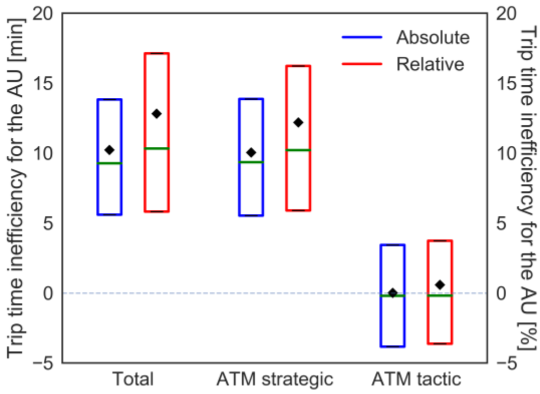
Figure 4-14 shows the assessment of the two post-ops Case Studies using the AU time-based indicators. Like in Figure 4-13, the results presented in Figures 4-14a and 4-14b use the last filed flight plan by the AU (or the first SBT) as baseline trajectory, while results shown in Figures 4-14c and 4-14d assume that the baseline trajectory is an ideal full-free route trajectory (from origin to destination) flown at the AU's desired Cost Index. Since in Figures 4-14a and 4-43b 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).



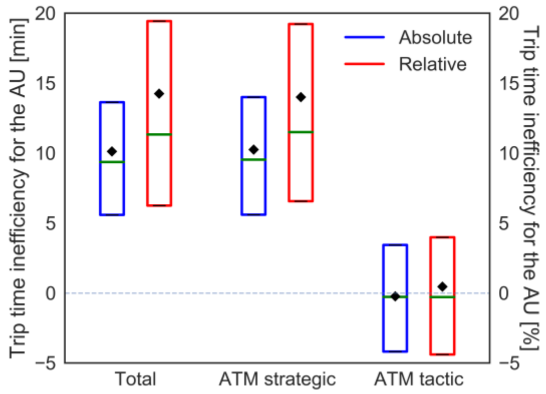
a) S001 (24h FABEC Jul 28th 2016) with last filed flight plan as baseline trajectory



a) 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



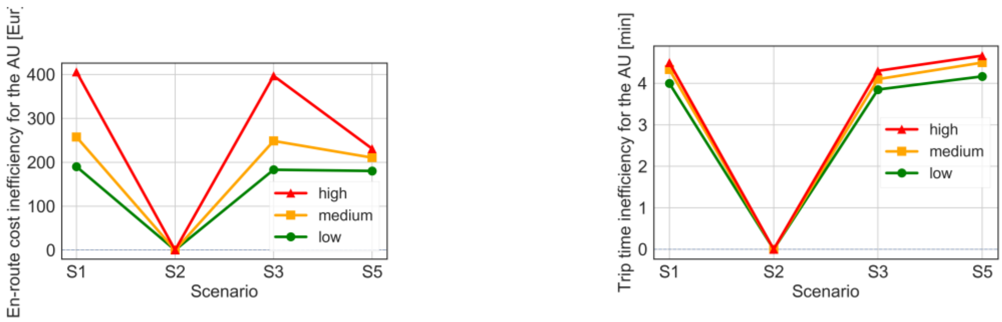
d) S003 (24h FABEC Feb 20th 2017) with optimal full free route trajectory as baseline

Figure 4-14: Post-ops results with time-based AU cost-efficiency indicators (CE-4 family)

4.3.2.2 Contributions for pre-ops assessments

Figure 4-15 shows the AU cost inefficiencies (median of the data set) computed using the optimal full free route trajectory as baseline for the indicator (if the last filed flight plan, or first SBT, is used as baseline for the indicator the median is zero, meaning that for all more than the 50% of the flights were not regulated).

Since the APACHE PIs estimate the cost for the AU in terms of extra distance flown (fuel and time), delay and route charges, **these indicators capture very well the benefits of flying in a full free-route scenario** (S2) **or if an ADCB algorithm is used to regulate demand** (S5). This last example is particularly interesting since current SES PRU only accounts for the share or regulated flights. In S5, although more aircraft are regulated if compared with the reference scenario (S1), which uses only delay to regulate demand, the impact in terms of cost for the AUs is much lower than in S1. Indeed, allowing re-routings and level cappings allows to reduce the delays significantly and the overall AU cost figures are also reduced significantly. Yet, due to these re-routes the environmental impact is higher as it was already observed in Figure 4-12.



a) AU cost-based indicator (CE-1.1) a) Trip time indicator (CE-4.1)

Figure 4-15: Pre-ops results for the AU cost-efficiency indicators with optimal full free route trajectory as baseline

4.3.3 ANS cost-efficiency focus area

The main contribution of APACHE in the AU cost-efficiency focus area was to propose new approaches to estimate the cost of providing air traffic services. In this context, 2 PIs are proposed:

- CE-2: **Sectorisation costs:** trying to capture if the airspace is sectorised in the optimal way, since it compares the actual/planned opening scheme with the optimal opening scheme generated by the APACHE ASP component.
- CE-3: **Flights per ATCO hour on duty**, evaluates the overall amount of flights handled versus the total number of ATCO hours of ATCOs on duty.

4.3.3.1 Contributions for post-ops assessments

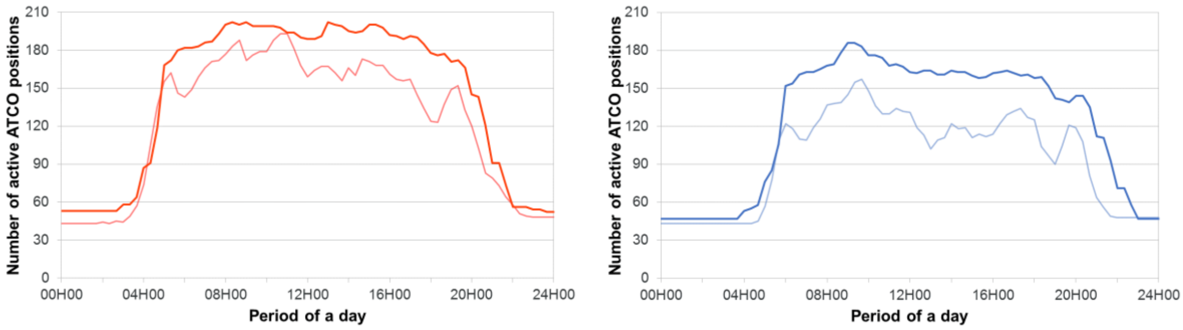
The proposed indicators were able to capture the effects of seasonal demand (analysing one full day of operations in summer and another in winter), showing that the cost-efficiency in terms of sectorisation costs is higher for the summer day assessed rather than for the winter day.

In winter, much lower sectorisation costs could be achieved using the optimal airspace sectorisation. However, this cost reduction is not visible in reality. See Figure 4-16, where the number or active ATCO positions is compared with the optimal number of ATCO positions (as computed by the APACHE ASP).

With the increase of the traffic demand the sectorisation cost of the optimal sectorisation scheme are increased as well (Figure 4-16), driven by the main ATM objective to accommodate demand without imposing significant penalties to the traffic demand. Therefore, the summer Case Study requires higher optimal sectorisation costs than the low demand. However, the increase in the optimal sectorisation cost is not followed by proportionally increase in actual sectorisation cost, which is why the summer Case Study shows higher cost-efficiency.

4.3.3.2 Contributions for pre-ops assessments

APACHE indicators were able to capture that an eventual full free route scenario (Scenario S2), assuming current ANSP practices to organise airspace, might lead to much lower cost-efficiency for the ANSPs. In this full free route paradigm, a higher number of ATCO positions is needed to serve the same traffic demand as in the reference scenario (using current conventional ATS route network). This fact leads, consequently, to a lower ANS cost-efficiency.



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

Figure 4-16: Comparison of the realised and optimal sectorisations for the two post-ops Case Studies.

4.3.4 Equity

The main contribution of APACHE in the equity KPA was to propose an indicator (AEQ-2) that takes into account **cost penalties per AU**. The main difficulty for this indicator, lies in the cost estimation mechanism, like with the AU cost-efficiency indicators presented above. **For post-ops assessments, this is a clear contribution** beyond current state-of-the-art practices.

It should be noted, however, the Equity PIs proposed in APACHE show partial information of the equity of the ATM system, since regulations are strongly related to the geographic location of the eventual hotspots or demand imbalances. Thus, if an 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; A will consequently experience more regulations than 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 left for future research.

4.3.5 Safety

In the Safety KPA, APACHE proposed some new indicators compliant with the Performance Objective One stated in (Performance Review Commission, 2016): Reduction of loss of separation incidents both horizontally and vertically by **focusing on system risk**, which can be estimated in pre-tactical phase in order to identify hotspots on the network and take measures to increase safety (APACHE Consortium, 2017b).

The PRU is currently assessing a range of PIs in the field of safety, e.g. number of accidents and serious incidents, number of reported unauthorised penetrations of airspace, number of reported separation minima infringements, etc., among which two are used as KPIs: *total commercial air transport accidents*; and *the number of accidents with air navigation service contribution*. All PIs and KPIs are based on accident/incident investigation reports (post operation analysis, reactive safety approach) and are aggregated at annual level. Conversely, **APACHE proposes 7 PIs which are measurable either in pre-ops simulations or by automatically analysing post-ops traffic.** These post-ops PIs could be measured in a real system on a daily or hourly level, and are not dependent on accident/incident reporting (i.e. proactive safety approach).

APACHE safety PIs are presented in absolute or relative terms. Indicators with absolute values are given as counts of specific occurrences: Traffic Alert (TA) warnings (SAF-1), Resolution Advisories (RA) issued (SAF-2), Near Mid Air Collisions (NMAC) (SAF-3). TAs/RAs, NMACs occur very often. So, count of those occurrences could be a good proxy of what could happen in the airspace. Of course, TAs/RAs, NMACs are based on anticipation of distance at closest point of approach (CPA) between two aircraft when this anticipation is time-based. Similarly, the number of potential separation violations (SV) i.e. conflicts, is used to indicate safety (SAF-4). Its determination is based on actual distance between two aircraft and depends on separation minima applied.

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

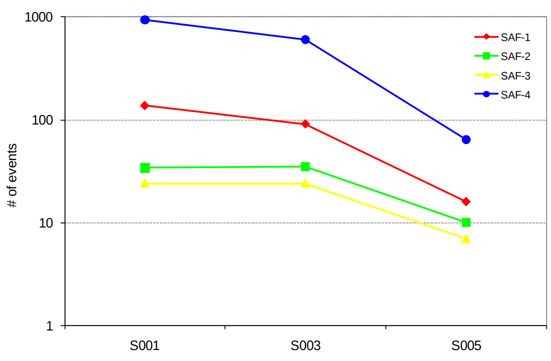
Apart from these indicators, and related to SAF-4, it is proposed to measure separation violation severity for aircraft in conflict (SAF-5), in situations when either horizontal, vertical or both separation minima are violated, as well as duration of conflict situations (SAF-6). Duration of separation violation situation (SAF-6) is measured as a time period in which actual separation is lower than separation minima, while severity (SAF-5) presents a measure of how close the difference between actual separation and separation minima is to zero. Based on these two indicators (different combinations of conflict duration and severity) it is possible to calculate a risk of conflicts (SAF-7) in a given airspace. More details are given in (APACHE Consortium, 2017b).

4.3.5.1 Contributions for post-ops assessments

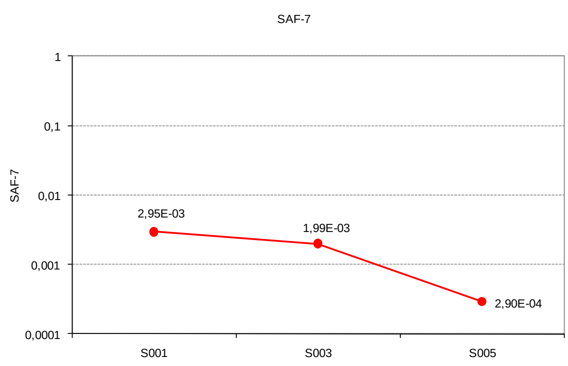
Regarding SAF-1, SAF-2, SAF-3 and SAF-4, Post-OPS indicators may rely on reporting by the airlines and ANSPs, but it is more likely to expect that they might be reluctant to disclose information on alerts triggered. In order to avoid getting unreliable results from the incomplete reports, APACHE System aims in performing post-ops analysis by simulating realised (executed) traffic.

In such a way, indicators are derived based on the TAs, RAs, NMACs and SVs that should have been occurred under the given conditions, regardless of whether they have been or not reported. The same applies for relative values of these indicators.

Detailed assessment results for different traffic demands are given in (APACHE Consortium, 2018c), while an example comparison of some safety PIs for different traffic demands (from two different sources) is given. For illustrative purposes here, Figure 4-17 shows this comparison with five safety PIs and for 3 different Case Studies: winter day and summer day using Eurocontrol DDR2 data as input; and the same summer day using Eurocontrol PRU CPR data as input.



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

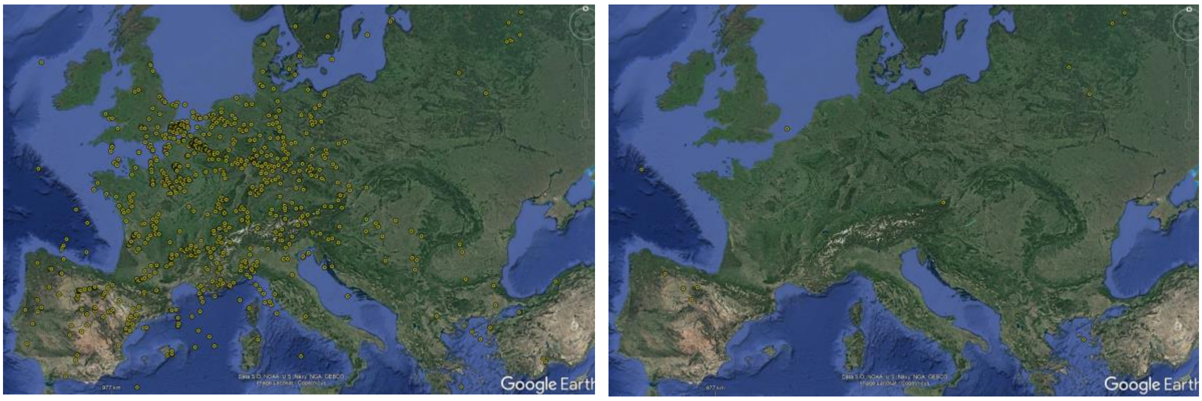


b) SAF-7

Figure 4-17: Comparison of the different safety PIs for the three post-ops Case Studies considered (S001: summer day, taken from DDR2; S003: winter day, taken from DDR2; S005: summer day taken from PRU CPR)

Figure Figure 4-18 shows the geographical distribution of SAF-4 (number of separation violations) for the same (summer) day of historical operations, comparing the two data sources (DDR2 vs. PRU CPR) and showing 24 hour of aggregated data in a single figure. 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 (CPR) 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.



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

Figure 4-18: Spatial distribution of SAF-4

4.3.5.2 Contributions for pre-ops assessments

All safety indicators used in pre-ops are derived from simulating planned traffic. Activating or deactivating certain SESAR solution in simulations it is possible to see their influence (hopefully benefits) on safety. Yet, since the APACHE Framework in pre-ops was not simulating the tactical layer (i.e. the ATC behaviour in separating traffic), these indicators only showed the inherent system risk at planning level. See (APACHE Consortium, 2018c) for details.

4.3.6 Capacity

The main contribution of APACHE in the capacity KPA is twofold:

- First, proposing a new indicator (CAP-1) to be considered jointly with the existing SES PRU indicator: *Average en-route ATFM delay per flight*, that complements information lost when using C-CAP-1 due to delay averaging; and
- secondly, proposing a new indicator as a replacement of the existing one, in line with SESAR trajectory-based operations paradigm.

Current state-of-the-art indicator used in the SES PRU (labelled C-CAP-1 in the APACHE Project) computes yearly average en-route delay per flight caused by the ATFM. If considering that current approach in Europe is to hold controlled flights on the ground whenever capacities declared by control centres along their routes are exceeded; this justifies use of **ATFM delays as a proxy for the capacity**, since any imbalance between capacity and demand directly materializes in ATFM delays. This approach, however, presents several drawbacks that were discussed in (APACHE consortium, 2017b).

The most important one results from delay averaging, done on the purpose of establishing a metric invariant to the level of demand (setting targets). By averaging, the information of the delay distribution, important in identifying small demand/capacity imbalances vs. significant capacity pitfalls, is lost. Furthermore, due to heterogeneous demand distribution (spatial or temporal) decrease in the average delay is not always result of system performance improvement but caused by the increase of the demand (denominator). The new indicator, **CAP-1** *Robust maximum en-route delay*, proposed in APACHE **aims at complementing information loss of C-CAP-1** due to delay averaging. Naturally, the indicators are considered as post-operational. Yet, considering the APACHE framework capabilities to synthesize scenarios (i.e. the APACHE-TAP) indicators were also tested in the pre-ops analysis too.

In line with SESAR trajectory-based operations paradigm, initial shared business trajectory may be changed spatially and/or temporally in the search for the system acceptable solution (agreed RBT), through the collaborative decision-making process. The use of the existing indicator (C-CAP-1) is insufficient since **not all operational penalties are captured**. In APACHE, the concept of the average (departure) en-route ATFM delay is extended to the **average arrival delay (CAP-2),** aiming to capture total delay compared to the user preferred route caused by slot allocation, rerouting, speed/level change, etc. In the SESAR trajectory-based operations, trajectory information will be available for the pre- and post-ops analysis. Conversely, in current operations the only means to identify the agreed (regulated) trajectory for the pre-ops analysis is by simulation, which is the main contribution of the APACHE framework. Still, the difficulty lies in the identification of the “real” AU initial (wished) demand which is a topic for future research.

An additional contribution of the APACHE project in the capacity KPA was made by proposing **additional indirect macroscopic indicators,** capturing all demand management measures by including AU business decisions, and new direct method for evaluation of the airspace capacity (by simulation) and not as a proxy based on the ATFM delay. However, due to complex evaluation/validation process and/or missing input data (AU decisions possibly confidential/sensitive data) they were excluded from the APACHE validation exercises.

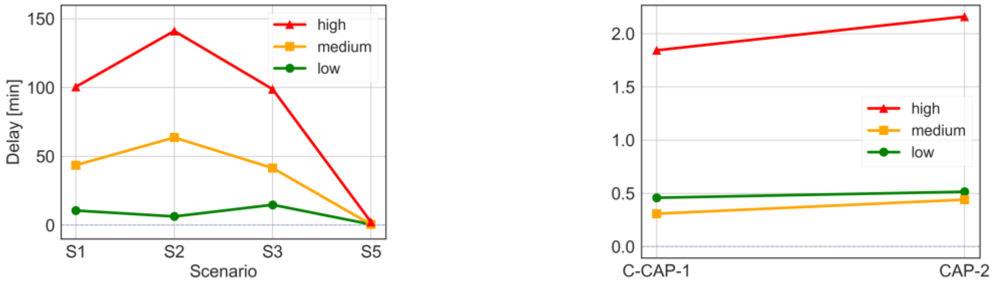
4.3.6.1 Contributions for post-ops assessments

In line with the mentioned contribution of the APACHE project in the capacity KPA, the most important contribution for the post-ops assessment is in establishing **a reliable indicator that can be used for monitoring of the system capacity performance and setting-up targets**. Additionally, computation of the **arrival delay** of regulated trajectory (excluding all tactical controller/pilot interaction) would in certain situation require trajectory to be synthetized rather than taken from the historical repository. This is even more true for the initial user demand that is usually unknown but could be regenerated knowing to some extent the AU business models.

4.3.6.2 Contributions for pre-ops assessments

In the line of performance-based operations, pre-operational assessment of the system capacity would allow the selection of the modus-operandi that is the most adapted for the given traffic demand and airspace restrictions, as shown in figure 4-19. Here, 4 post-ops scenarios[7] are compared for three levels of traffic demand showing how the APACHE

Although such assessment would be possible with trajectory information available in the SESAR trajectory-based operations, today it is not possible without capabilities brought by the APACHE framework. Thus, Figure 4-19b reveals that the APACHE indicator (CAP-2) better captures the system capacity in Scenario S5, where re-routings and level cappings are also part of the demand and capacity balance mechanisms. These delays caused by changes is the trajectory (RBT) would not be captured by the existing indicator (C-CAP-1).



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

Figure 4-19: Pre-ops results for the Capacity KPA

4.3.7 Flexibility

The flexibility KPA addresses the ability of the airspace users to modify their flight trajectories, in order to exploit occurring operational opportunities and is one of the areas which have been poorly covered in ATM performance assessments so far. During the comprehensive review of Performance Frameworks performed by APACHE (see section 4.1), only a few indicators were identified in this KPA, which have not been widely used in performance assessments, mostly due to data availability issues. This lack of data is largely caused by the tactical nature of requested flight changes, which is why APACHE proposes another approach when considering this KPA.

Namely, there is a strong link between flexibility and capacity, because the latter is needed to accommodate potential changes in demand. Therefore, it seems **reasonable to assess flexibility in an indirect way by estimating the excess capacity which can be exploited in order to absorb changes that occur on the day of operations.**

The main contributions of APACHE in this KPA are the 4 new indicators that, in general, can be used both for pre-ops and post-ops assessments (although one of them, FLEX-4, could only be used in pre-ops in APACHE since it makes only sense in a full TBO environment (it accounts for the total number of possible DCB solutions to solve the same demand and capacity imbalance problem).

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,

[7] S1: Reference Scenario: Reproducing current operations – S2: Solution scenario with enhanced free route areas (full free route from origin to destination in ECAC) – S3: Solution scenario allowing continuous cruise climbs (but still following the structured route network) – S5: Solution scenario implementing an advanced demand and capacity balancing algorithm allowing for global optimal allocation of delays, re-routings and level cappings.

minimizing the negative effects on the AU 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 this KPA.

The applicability of these PIs is detailed in (APACHE Consortium, 2018c), where different post-ops and pre-ops Case Studies were analysed.

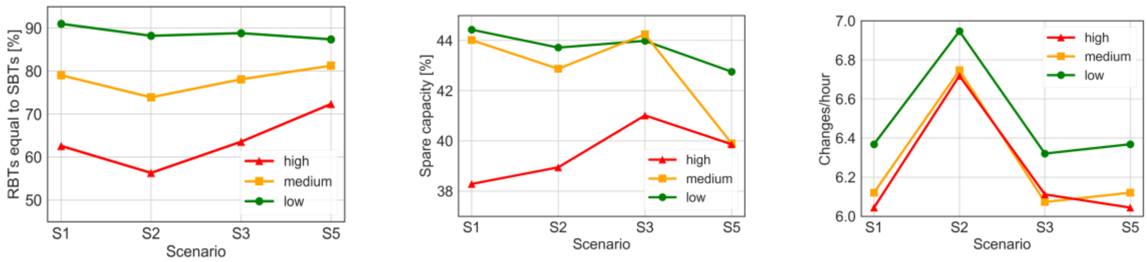
4.3.7.1 Contributions for post-ops assessments

The applicability of these PIs in post-ops is detailed in (APACHE Consortium, 2018c), where two different Case Studies were analysed: a winter (low demand) day and a summer (high demand day). The high demand day showed more regulations and APACHE new flexibility indicators showed less "system flexibility" accordingly.

4.3.7.2 Contributions for pre-ops assessments

The APACHE new flexibility indicators were also used in pre-ops assessments[8], as shown in Figure 4-20. FLEX-1 captures the effect of ATM regulations imposed on air traffic demand. It is clearly notable that the most constraining is the full free-route scenario (S2), having the lowest percentage of non-regulated flights. Related to FLEX-2, although the results obtained do not suggest any clear conclusion regarding the cross-scenario comparison, it is notable that spare capacity expectedly decreases with the increase of traffic demand. FLEX-3 reaches its maximum values in full free-route scenario (S2). This is because more sectors have to be open in order to accommodate challenging traffic, which causes an increase of the number of sector changes and, consequently, ATCO coordination workload.

FLEX-4 indicator, 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 was also tested, capturing different flexibility levels in the S5 scenario (where an ADCB algorithm was simulated).



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

Figure 4-20: Pre-ops results for the Flexibility KPA

[8] S1: Reference Scenario: Reproducing current operations – S2: Solution scenario with enhanced free route areas (full free route from origin to destination in ECAC) – S3: Solution scenario allowing continuous cruise climbs (but still following the structured route network) – S5: Solution scenario implementing an advanced demand and capacity balancing algorithm allowing for global optimal allocation of delays, re-routings and level cappings.

4.4 Assessment of ATM performance and trade-offs

Beside those interdependencies directly observed by comparing the different pre-ops scenarios (for instance, comparing various KPA for a full free route scenario vs. the same scenario using the conventional ATS route network), in APACHE a series of trade-offs were 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). The overall objective of these assessments was to **show the capabilities of the APACHE Framework to capture interdependencies among KPAs**, quantify them and assess Pareto optimality.

A couple of illustrative examples are reported below. More details can be found in APACHE Deliverable D5.1 (APACHE Consortium, 2018e).

4.4.1 Example 1: reducing the number of ATCOs

The existing trade-offs between the cost-efficiency KPA (considering both ANS and AU focus areas) and capacity KPA were investigated by changing the **availability of sector configurations, by reducing the maximum number of ATCO per cluster.** Figure 4-21 shows the results for Scenario **S1** (reference, using **CASA** to regulate excess of traffic demand), while Figure 4-22 shows the results for Scenario **S5** (using **ADCB** to regulate the demand, allowing re-routings and level cappings, besides delay, into a global optimisation process).

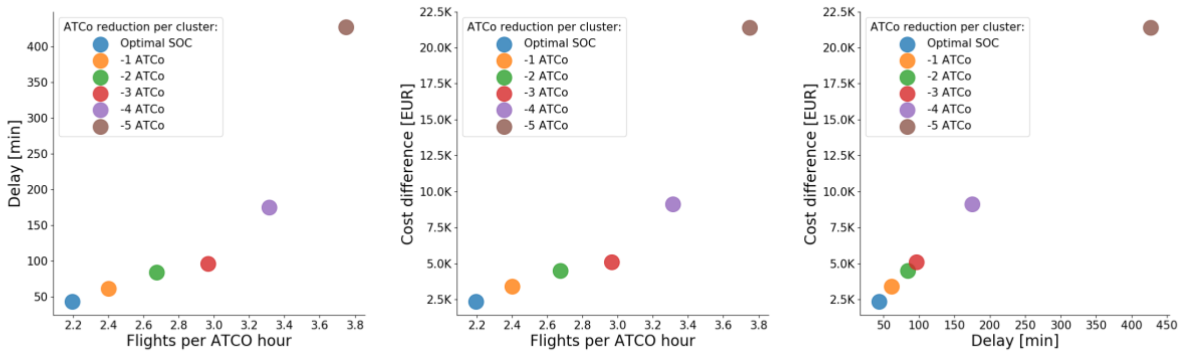
As seen in Figure 4-21, the reduction in the number of ATCOs per cluster, which improves the ANS cost-efficiency by increasing the number of flights per ATCO hour, entails an increase in en-route ATFM delay (C-CAP-1) and in the cost due to strategic ANS actions for the airspace user (CE-1.1). This increase 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).

Figure 4-21c 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. Thus, a reduction of 3 or 4 ATCOs per cluster would be considered probably the best trade-off for this particular example.

For the ADCB case (Figure 4-22), the reduction the number of available ATCOs positions per cluster also affects the ANSP cost-efficiency by increasing flights per ATCO hour. This reduction, however, is followed by the increase in the flights regulations represented by the increase of the average en-route ATFM delay (see Figure 4-22a). CASA and ADCB scenarios experience an equivalent increase of the ANS cost-efficiency, but the ADCB scenario shows lower increase of delay if compared to the CASA scenario, 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).

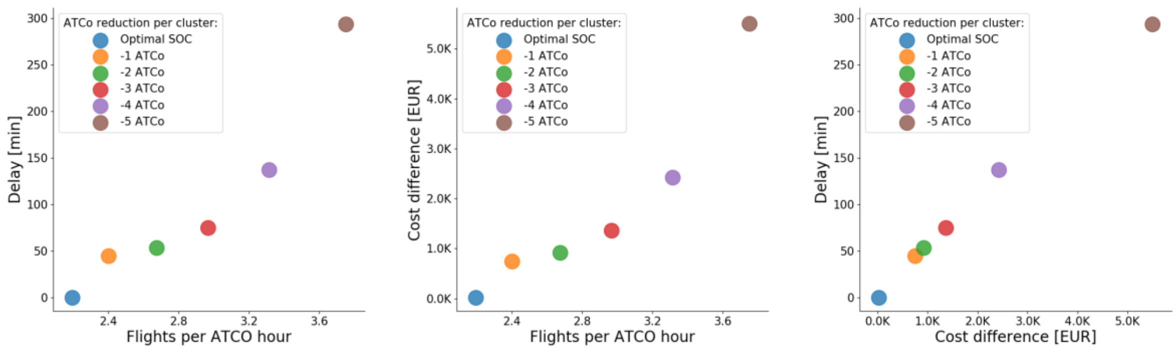
The ADCB scenario also shows significant reductions in the AU cost if compared with the CASA scenario (Figure 4-22b vs. Figure 4-21b). For this particular example, the AU cost inefficiency is reduced from 22.5kEur to 5KEur for the highest Pareto-Front Case Study.

Like in the CASA scenario, Figure 4-22c suggest that 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.



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

Figure 4-21: Interdependencies when reducing the number of ATCO (availability of sector configurations) – Reference Scenario (network manager implementing CASA).



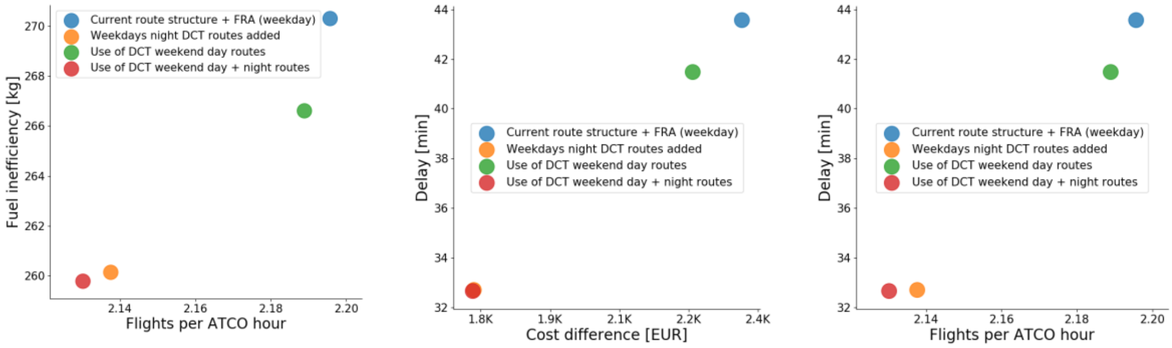
a) CE(ANS) vs. CAP b) CE(ANS) vs. CE(AU) c) CE(AU) vs. CAP

Figure 4-22: Interdependencies when reducing the number of ATCO (availability of sector configurations) – Solution scenario (network manager implementing an ADCB algorithm).

4.4.2 Example 2: changing the availability of direct routes (DCT)

In this example, the interdependencies between different KPAs when varying the **availability of direct routes (DCT)** for trajectory planning are investigated. Four simulations have been done: 24h availability of current Night DCT; inclusion of current weekend-only DCT (only during the day); 24h availability of current weekend-only DCT; and using the current route structure (including current FRA during weekdays) as baseline case.

As observed in Figure 4-23a, the use of DCT entails substantial fuel efficiency gains in exchange of a small reduction of ANS cost-efficiency. Consequently, AU cost-efficiency is also improved (see Figure 4-23b). Major benefits are when using those DCT routes currently available only in night periods. In terms of en-route ATFM delay, the use of DCT routes leads to delay reductions since less bottle necks in the network are found (see Figures 4-23b and 4-23c).



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

Figure 4-23: Interdependencies when changing the availability of direct routes (DCT)

5 Links to SESAR programme

The SESAR ATM concept and the European ATM Master Plan provide a clear and high-level overview of a new ATM paradigm that shall bring benefits on all of the currently four main ATM KPAs, namely safety, capacity, cost-efficiency, and flight efficiency. However, the opportunities and limits of these KPAs, as well as their complex interdependencies, are not yet well understood by the ATM scientific community.

The APACHE Project brings the opportunity to study (through simulation and optimization mechanisms) the theoretical limits for each KPA as well as assessing how they may actually reduce the performance of the other KPAs (and in which proportion). The developed APACHE System can contribute to reproduce the future ATM concepts envisioned by SESAR in order to anticipate and support the activities of targeting, monitoring, measuring, base-lining and benchmarking for the holistic enhancement of the overall ATM performance.

5.1 Contributions to the ATM Master Plan

Within the framework of the Single European Sky (SES), the European Air Traffic Management Master Plan is the main planning tool for defining ATM modernisation priorities and ensuring that the SESAR Target Concept (SESAR Joint Undertaking, 2016) becomes a reality. The Master Plan is an evolving roadmap and the result of strong collaboration between all ATM stakeholders.

The Master Plan details not only a high-level view of what is needed to be done in order to deliver a high-performing ATM system, but also explains why and by when. In order to do so, the SESAR Performance Ambitions were defined. The performance ambition supported by SESAR refers to the performance capability that may be achieved if SESAR Solutions are made available through R&D activities, deployed in a timely and synchronised way. While acknowledging that the performance gains at local level will also depend on local conditions, it shows that significant performance gains can be achieved in Europe in a number of KPAs, namely environment, capacity, cost efficiency, operational efficiency, in addition to safety and security (SESAR Joint Undertaking, 2015),

Figure 5-1 depicts the specific KPAs, SES High-Level Goals, KPIs and SESAR ambitions as contained in the European ATM Master Plan. The expected targets are also included for each KPI, stating the absolute and relative saving targets.

Performance indicators used in the current Performance Scheme are not sufficient to describe with an accurate and holistic perspective the performance of future ATM concepts, in which the management of trajectories and the relaxation of airspace constraints will allow introducing user-preferred 4D trajectories, while at the same time the separation of flights will be anticipated and carried out in a more strategic phase. **The APACHE Project contributes to enhance these current performance indicators, even defining new ones, which are expected to capture the benefits and performance trade-offs of such new operational concepts**.

Key performance area	SES High-Level Goals vs. 2005	Key performance indicator	SESAR ambition vs. baseline 2012: Absolute saving	SESAR ambition vs. baseline 2012: Relative saving
Cost efficiency: ANS productivity	Reduce ATM services unit cost by 50% or more	• Gate-to-gate direct ANS cost per flight - Determined unit cost for en-route ANS* - Determined unit cost for terminal ANS*	EUR 290-380	30-40%
Operational efficiency	-	• Fuel burn per flight (tonne/flight) • Flight time per flight (min/flight)	0.25 -0.5 tonne 4-8 min	5-10% 3-6%
Capacity	Enable 3-fold increase in ATM capacity	• Departure delay (min/dep) - En-route air traffic flow management delay* - Primary and reactionary delays all causes • Additional flights at congested airports (million) • Networkthroughput additional flights (million)	1-3 min 0.2 -0.4 (million) 7.6 -9.5 (million) Additional flights, not saving	10-30% 5-10% [1] 80-100% [2]
Environment	Enable 10 % reduction in the effects flights have on the environment	• CO_2 emissions (tonne/flight) - Horizontal flight efficiency (actual trajectory)* - Vertical efficiency - Taxi-out phase	0.79 -1.6 tonne	5-10%
Safety	Improve safety by factor 10	• Accidents with ATM contribution	No increase in accidents	Improvement by a factor 3-4
Security	-	• ATM related security incidents resulting in traffic disruptions	No increase in incidents	

Metrics with monetary value in business view

* Targeted by the Performance Scheme

1. Additional flights that can be accommodated at congested airports, representing 5-10% of flights at congested airports (~31% of14,4 (million) flights in 2035).

2. Additional traffic accommodated in 2035 in comparison with 2012 and associated with ANSP productivity gains, enabled by SESAR. Note: Numbers are rounded.

Source: Eurocontrol PRB, SES, EC ACE report (2012), Master Plan Campaign Expert Workshops.

Figure 5-1: SESAR Performance Ambition levels for 2035 including KPI (SESAR Joint Undertaking, 2015)

The newly defined APACHE Framework performance indicators could be further investigated in order to assess their applicability and could be potentially considered for the review of the SESAR Performance Ambitions for some KPAs.

5.2 Links with the SESAR 2020 performance framework and uptake exploitation of results into industrial research

The project has opened the door to **a more integrated and holistic methodology to assess ATM performance**, enabling the following potential application use cases:

- support the **validation exercises** of certain **SESAR solutions**, providing
    - a **unified and homogeneous Framework** to compute certain performance indicators on demand (via web services, for instance);
    - assessment of **interdependencies** between SESAR solutions;
    - intensive **model-based simulations,** allowing performance assessment, sensitivity and robustness analysis in several KPAs;
    - the computation of **optimal** (under different constraints to assess different KPAs, focus areas or specific stakeholder needs) **trajectories** and/or **sector opening schemes** on demand (via web services, for instance);
- support the definition of the **high-level performance ambitions** for the European ATM master plan, or even contribute to SESAR validation target setting;
- recreate **tailored simulations** to test and validate the appropriateness of certain performance indicators or refine some of them; and

- **benchmarking/complementation** of different Performance Frameworks.

The main SESAR Solution related with these activities is PJ-19.04.

5.3 Maturity assessment

The APACHE Framework has been assessed according to the SESAR Maturity Assessment Criteria, which is based on material from E-OCVM version 3.0 and Technology Readiness Levels (TRL) provided by Horizon 2020, adapted to the specificities of SESAR 2020 programme.

The SESAR Maturity Criteria provides a set of maturity criteria applicable to the topics under the scope of the Exploratory Research Projects (both fundamental and applied oriented ones) and for the three E-OCVM phases that are the scope of SESAR2020, V1, V2 and V3 phases.

The APACHE Project has been assessed towards initial maturity levels: TRL-1 Basic principles observed and TRL-2 Technology concept formulated. According to these TRL levels, **APACHE has achieved TRL-2** at the end of the project as the technology concept and its application has been formulated. The theory and scientific principles described in the various Project Deliverables focus on very specific application areas, the characteristics of the application have been described, including the functional specifications. In addition, the connection between specific tools has been developed for simulation and analysis of the application.

The assessment of the APACHE results' maturity is presented in Table 5-1 below. This indicates the maturity of the project to evolve from Exploratory Research to Industrial Research, assuming that APACHE has achieved TRL-2.

OPS	OPS.ER.1	Has a potential new idea or concept been identified that employs a new scientific fact/principle?	Achieved	- APACHE revolves around a novel framework that is able to generate optimal trajectories and sectorisations to support the implementation of novel and/or more accurate performance indicators for pre-ops and post-ops assessments. - This framework can also synthesise traffic and airspace scenarios, considering AUs business models and realistic ANSP practices, simulating different operational contexts and enabling the possibility to perform what-if assessments.	D3.1, D3.2, D4.1
OPS	OPS.ER.2	Have the basic scientific principles underpinning the idea/concept been identified?	Achieved	The APACHE framework is able to reproduce current and future operations, which reflect the understanding and full knowledge of the basic principles in terms of ATM performance, airspace structure and flight trajectories.	D2.1, D4.1
OPS	OPS.ER.3	Does the analysis of the "state of the art" show that the new concept / idea / technology fills a need?	Achieved	The project analyses the current ATM situation in Europe, identified the links with SESAR programme, in particular with several SESAR Solutions, and identified the benefits it could bring and the answers it could provide to existing issues and gaps in ATM performance analysis. In this context, a review of different performance frameworks is also provided. Validation exercises support this advance beyond the state of the art.	D2.1, D3.1, D5.1
OPS	OPS.ER.4	Has the new concept or technology been described with sufficient detail? Does it describe a potentially useful new capability for the ATM system?	Achieved	Requirements of the APACHE Framework are properly identified in D3.2. The APACHE Framework is described in detail in D4.1 and verification and integration tests are reported, along with individual components validation.	D3.2, D4.1
OPS	OPS.ER.5	Are the relevant stakeholders and their expectations identified?	Achieved	The stakeholders relevant in the APACHE project are mainly ANSPs and Airspace Users. In addition, the Advisory board meetings included the participation of ATM main stakeholders which provided valuable and constructive feedback to the project.	D2.1, D6.2
OPS	OPS.ER.6	Are there potential (sub)operating environments identified where, if deployed, the concept would bring performance benefits?	Achieved	- The SESAR Operating Environment (OE) applicable to the APACHE project and thus to the Operational Context defined in this document is **en-route.** The subcategories of this OE are Low, Medium, High complexity (SESAR Joint Undertaking, 2016). - Integration of the novel indicators into the SESAR Performance Framework would bring benefits in performance assessment.	D2.1, D5.1

SYS	SYS.ER.1	Has the potential impact of the concept/idea on the target architecture been identified and described?	Not Applicable	-	-
SYS	SYS.ER.2	Have automation needs e.g. tools required to support the concept/idea been identified and described?	Achieved	For the development of the APACHE framework, a set of existing tools has been used, being previously developed by the different partners that compose the APACHE consortium. Some other tools have been developed from scratch. All these components have been integrated into a prototype of the APACHE Framework, with a very low level of automation. Automation needs are identified and described and may be subject of future work to raise the TRL of the APACHE Framework.	D3.2, D4.1
SYS	SYS.ER.3	Have initial functional requirements been documented?	Achieved	The specifications of the interface and the requirements of the APACHE assessment framework have been defined including: interfaces between the different existing or newly proposed modules (module on trajectory optimisation, module on sectorisation, module on safety assessment, etc.), in order to harmonize data formats, input/outputs, user requirements.	D3.2
PER	PER.ER.1	Has a feasibility study been performed to confirm the potential feasibility and usefulness of the new concept / idea / Technology being identified?	Achieved	- The benefits of the new concepts simulated through the APACHE System have been quantified and analysed in detail in different validation Case Studies (D5.1). - Applicability considerations of the new proposed indicators have also been identified (D3.1).	D3.1, D5.1
PER	PER.ER.2	Is there a documented analysis and description of the benefit and costs mechanisms and associated Influence Factors?	Not Applicable		
PER	PER.ER.3	Has an initial cost / benefit assessment been produced?	Partial - Non Blocking	D5.1 provides an indication of the benefits APACHE could bring, but a comprehensive assessment of the benefits and implementation cost has not been elaborated.	D5.1
PER	PER.ER.4	Have the conceptual safety benefits and risks been identified?	Not Applicable		
PER	PER.ER.5	Have the conceptual security risks and benefits been identified?	Not Applicable		
PER	PER.ER.6	Have the conceptual environmental impacts been identified?	Not Applicable		

PER	PER.ER.7	Have the conceptual Human Performance aspects been identified?	Not Applicable		
VAL	VAL.ER.1	Are the relevant R&D needs identified and documented? Note: R&D needs state major questions and open issues to be addressed during the development, verification and validation of a SESAR Solution. They justify the need to continue research on a given SESAR Solution once Exploratory Research activities have been completed, and the definition of validation exercises and validation objectives in following maturity phases.	Achieved	Future research and innovation needs for the APACHE results have been identified and included in D6.3 (Exploitation Plan) and D1.2 (Final project results report)	D1.2, D6.3
TRA	TRA.ER.1	Are there recommendations proposed for completing V1 (TRL-2)?	Achieved	Future research and innovation needs for the APACHE results have been identified.	D4.1, D.6.3

Table 5-1. ER fund / AO research maturity assessment

6 Conclusions

APACHE is a SESAR 2020 Exploratory Research project that has explored the potential of advanced **simulation and optimisation tools** to improve ATM performance assessment across a wide range of KPAs. In this context, APACHE has:

- proposed **new (or enhanced) metrics and performance indicators** capable of effectively capture ATM performance, under either current or future concepts of operation, with the aim to enable a progressive performance-driven introduction of new operational and technical concepts in ATM in line with the SESAR 2020 goals;
- analysed **interdependencies between KPAs**, capturing the Pareto-front for different trade-offs; and
- estimated the theoretical **optimal limits** for certain performance indicators, under different optimality assumptions.

A key element in APACHE is the development of a novel **ATM simulation framework, a service-oriented software** that has been used in the project for two different purposes:

- to synthesise traffic and airspace scenarios, simulating different operational contexts and enabling the possibility to perform what-if assessments (**"Pre-ops"** ATM performance assessment); and
- to provide advanced models and optimisation tools that can support the implementation of novel and/or more accurate metrics and performance indicators, which can be used for "Pre-ops" but also for **"Post-ops"** (monitoring) purposes

6.1 Main contributions

The APACHE framework enables proactive and predictive analysis of the current and future ATM system, as a first step towards Performance Based Operations. The project has proven the **usefulness of advanced simulation and optimisation tools to improve or define new performance indicators** overcoming some of the current limitations in performance assessment. It has been shown how the APACHE Framework can better capture:

- the **impact of new concepts** (such as SESAR solutions);
- complex **interdependencies** between different KPA and/or SESAR solutions**;**
- the **theoretical limits** for certain KPAs.

Some performance indicators proposed by APACHE are mature enough for **a potential uptake to industrial research** with little effort (develop specific web services, front-ends, interfaces, integration into wider platforms, etc.). Examples are some safety indicators; some environment or AU cost-efficiency indicators for pre-ops analysis; or some equity and capacity indicators.

Other indicators still require **further research** to refine certain models, to gather the appropriate input data or to envisage alternatives to avoid requiring confidential or proprietary data. Examples of this category of indicators are some flexibility indicators; ANSP cost-efficiency indicators; and certain environment and AU cost-efficiency indicators for post-ops assessment.

Finally, the APACHE project has also identified some indicators that would require **long term research** and were just mentioned, but not implemented in the APACHE Framework prototype. These include indicators requiring complex or very specific models (global warming models, for instance) and indicators requiring a deeper understanding of certain stakeholders' behaviour or a complex set of input data (to derive, for instance passenger-centric metrics).

The project has opened the door to **a more integrated and holistic methodology to assess ATM performance**, enabling several application use cases.

6.2 Future lines for research and next steps

APACHE has identified some questions that still deserve further research. These are briefly summarised as follows:

- Methodologies to better capture and infer **preferences and operational practices of airspace users and air navigation service providers**, without requiring confidential or non-available data. This would allow a more accurate and robust computation of "advanced" Performance Indicators. This research embraces the following topics:
    - infer certain **aircraft state variables** or **airspace user preferences** needed to estimate fuel consumption from only surveillance data;
    - Better integrate complex (and more accurate) models for the **cost of delay** in the AU cost-efficiency indicators;
    - Better estimate ANSP or flow management positions (FMP) practices when managing airspace **capacity** and ATFM **regulations**; and
    - better link **capacity** and **safety** indicators with airspace **complexity**.
- Methodologies to better isolate the contribution of ANS in certain KPAs (for instance environmental impact or AUs cost-efficiency) and to better identify reactive/preventive AU behaviours.
- Perform in-depth analyses (sensitivity, trade-offs, cause-effect, robustness, etc.) with statistically significant amounts of data.
- Upscale the APAHCE Framework prototype to the whole ECAC area.
- Perform a detailed feasibility assessment and cost-benefit analysis to raise the TRL of the APACHE Framework.

6.3 Lessons Learnt

APACHE has brought the opportunity to UPC, ALG, UB-FTTE and ENAC (and the SJU) to work together with a common objective in the first wave of exploratory research projects of SESAR 2020. The principal (technical and implementation) lessons learnt are highlighted as follows:

- Development of APACHE simulation and optimization platform has proven to be very challenging in such a short period of time and due to diversity of problems appearing during the development of different modules. Yet, a first prototype could be integrated and successfully tested.

- The quality of input data for traffic/airspace (mainly from Eurocontrol's DDR2) seems to be not accurate enough for certain post-ops analysis (namely in the safety and capacity KPAs). Other sources of data shall be investigated.
- The geographical simulation scope used in the APACHE validation exercises (FABEC) was not enough to derive certain conclusions about KPA interdependencies. Widening this scope is necessary in the future (e.g., the whole ECAC area).
- Inclusion of external experts from the beginning of the project is more than necessary, but is very hard to sustain their homogeneity during the project which could cause return to explain the "basics" of the project even when it is in its most advanced stages.

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Appendix A Summary of APACHE public deliverables

D1.2	Final Project Results Report						
Related WP	WP1	Leader	UPC	Latest version:	v00.02.00	July 2018	
Abstract	This report summarises all the research activities performed by the APACHE project and highlights the main project outcomes and contributions. The APACHE Project 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). Besides performing a thorough review on the SESAR 2020 Concept of Operations and different Performance Frameworks, the main contributions of the Project are the integration of several background tools into a single platform, enabling the "APACHE Framework"; the proposal and validation of 73 new (or enhanced) performance indicators; and the assessment of ATM interdependencies by using this Framework. This report briefly describes these contributions, highlighting the progress done beyond state-of-the-art methodologies in ATM performance assessment. This report also outlines the links with the SESAR programme, identifying potential uptake of results to Industrial research and outlines potential future research and innovation activities.						
D2.1	Scope and definition of the Concept of operations for the project						
Related WP	WP2	Leader	ALG	Latest version:	v01.00.00	February 2017	
Abstract	The APACHE project proposes a new approach to assess European ATM performance based on simulation, optimization and performance assessment tools that will be able to capture the complex interdependencies between KPAs at different modelling scales. This document is the baseline for the Project and defines the operational context which encompasses the evaluation studies that will be carried out in the Project. The baseline and SESAR 2020 target operations definition within the context of APACHE will permit to settle the scope of the project and trace it within the context of the SESAR programme. This traceability is carried out as per SESAR solutions to be assessed, that could be assessed or that enable other solutions to be assessed within the Project.						
D3.1	Review of current KPIs and proposal for new ones						
Related WP	WP3	Leader	UB-FTTE	Latest version:	v01.01.00	October 2017	
Abstract	The main objective of this report is to review the current KPIs and PIs used by the SESAR, Performance Review Body (PRB) and other relevant institutions and to propose new PIs which could be measured using the new framework proposed by the APACHE project. For this purpose, past reports and guidance material is reviewed in order to determine which KPAs are covered and specific KPIs/PIs used in Europe. Apart from that, relevant ICAO and CANSO documents are also reviewed, among others. Special attention is given to SESAR Performance Framework which is quite specific in its purpose and perspective as it aims to estimate the performance benefits of SESAR solutions before the execution phase of operations, which is in line with the APACHE project as it focuses mainly on Pre-OPS ATM performance assessment. Based on current KPIs/PIs review and objectives of ATM performance assessment framework from WP2, a set of novel PIs which could be measured using new framework introduced by the APACHE project are proposed in collaboration with the SJU and the PRB considering their valuable feedback. From this assessment, the APACHE System will implement a total of 42 new (or enhanced) performance indicators (25 main indicators and 17 variants).						
D3.2	Functional requirements and specifications for the ATM performance assessment framework						
Related WP	WP3	Leader	UPC	Latest version:	v01.01.00	June 2018	
Abstract	The APACHE project proposes a new framework to assess European ATM (air traffic management) performance based on simulation, optimization and performance assessment tools that will be able to capture the complex interdependencies between KPAs at different modelling scales. This document presents the software requirements for the APACHE System. The APACHE System is the platform, build up with different software components (existing and to be developed) implementing a wide set of performance indicators across several key performance areas (KPA). Moreover, the APACHE System can be configured to synthetize aircraft trajectories and airspace sectorisation for future scenarios, in line with the SESAR 2020 scope, where input data is not available (and also for hypothetical scenarios based in the current concept of operations).						

<table>
<tr><td></td><td colspan="7">The software requirements presented in the current document are classified as functional requirements, non-functional requirements and domain requirements. These requirements relate to the first phase of the software development cycle, depicted as Requirements Analysis. This is the base for the following phases: Design, Development, Testing and Implementation.</td></tr>
<tr><td>D4.1</td><td colspan="7">Report on the availability of the APACHE framework</td></tr>
<tr><td>Related WP</td><td>WP4</td><td>Leader</td><td>UPC</td><td>Latest version:</td><td>v00.01.00</td><td>May 2018</td><td></td></tr>
<tr><td></td><td colspan="7">The APACHE project proposes a new framework to assess European ATM (air traffic management) performance based on simulation, optimization and performance assessment tools that will be able to capture the complex interdependencies between KPAs at different modelling scales. 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. This deliverable is the software availability note of the APACHE Framework.

This document firstly describes how the different system components have been integrated into a single workflow, aiming at fulfilling the requirements of the Project. Verification and integration tests of the whole APACHE Framework are presented, showing the successful integration of the different components. Then, validation tests of the individual components of the APACHE Framework are described, taking into account that the validation at system level (i.e. the validation of the whole APACHE Framework as a unified tool to assess ATM performance) is out of the scope of this Deliverable and will be reported in D5.1.

Supported by all these tests, the evaluation of the requirements identified in previous Deliverable D3.2 is presented, showing the evidences that proof the fulfilment of requirements and giving a rationale for those (very few) requirements not fulfilled or changed. Finally, this report concludes with a summary of all limitations and assumptions taken when developing the APACHE Framework, aiming at clearly identifying the maturity level of the developed Framework and pointing towards future enhancements and developments of the tool.</td></tr>
<tr><td>D5.1</td><td colspan="7">Results from simulation and analysis of results</td></tr>
<tr><td>Basic information</td><td>WP5</td><td>Leader</td><td>ALG</td><td>Latest version:</td><td>v00.02.00</td><td>July 2018</td><td></td></tr>
<tr><td>Abstract</td><td colspan="7">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.</td></tr>
<tr><td>D6.2</td><td colspan="7">Final report on communication and dissemination</td></tr>
<tr><td>Related WP</td><td>WP6</td><td>Leader</td><td>UPC</td><td>Latest version:</td><td>v00.01.00</td><td>May 2018</td><td></td></tr>
<tr><td>Abstract</td><td colspan="7">This document reviews the communication and dissemination plan for the APACHE Project and reports on the specific actions performed during whole duration of the Project (9 May 2016 to 8 May 2018). The success of these activities is measured against different metrics that were established beforehand in the APACHE Project communication and dissemination plan. Targets achieved include the Participation in the SESAR innovation days; publications in conference proceedings; dedicated stakeholder consultation activities and workshops; consultation with the APACHE external experts advisory board; dissemination</td></tr>
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	towards Industrial Research and SESAR scientific committee; and visitors of the APACHE public web site. Conversely, some other targets were not achieved, namely: journal papers published; targets set for social media communication (twitter and LinkedIn), press releases; communication to general public; and the APACHE final event, which was finally cancelled. The report concludes with recommendations and specific actions that are foreseen after the closure of the project, once the final results will be available and additional dissemination and communication actions will be done, especially aiming to address some of the abovementioned unachieved targets.						
D6.3	Exploitation plan						
Related WP	WP6	**Leader**	ALG	**Latest version:**	v00.02.00	June 2018	
Abstract	This document is the Exploitation Plan of the APACHE project. Its purpose is to identify, describe and assesses the different exploitable results and foreground generated by 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 that will be able to capture the complex interdependencies between KPAs at different modelling scales. 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. The importance of this report resides in the description of the exploitation of the project results, as they are the basis for future research. Each partner has provided its own exploitation intentions identifying exploitable services and all the exploitable results of the project, which are foreseen to be further developed in the future. Also, each partner has identified the research challenges from lessons learnt to take into account for their own research activities and services.						

APACHE consortium