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AURORA

ADVANCED USER-CENTRIC EFFICIENCY METRICS FOR AIR TRAFFIC PERFORMANCE ANALYTICS

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Abstract

AURORA (Advanced User-centric efficiency metRics for air traffic perfORmance Analytics) project addresses the exploration of new performance indicators to assess the operational efficiency of the ATM system based on Airspace Users' needs. Automatic Dependent Surveillance-Broadcast (ADS-B) data and a set of user-preferred trajectories are the core for the computation of the new indicators. AURORA also proposes new metrics to measure how fairly the inefficiencies are distributed among the Airspace Users, as well as new methodologies to calculate these advanced indicators in real time.

The report provides a summary of AURORA accomplishments and contributions, along the feedback obtained and lessons learned, to then conclude with further developments of AURORA in the ATM Community and in the integration of Exploratory Research projects into the SESAR mainstream and the future SESAR 2020 program.

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1 Executive Summary

AURORA project addresses the exploration of new performance indicators for operational efficiency based on aircraft operators' needs. Flight efficiency indicators are currently monitored and reported by the SES Performance Scheme [22], as part of the Environmental KPA defined by ICAO [25]. Nowadays, the only mandatory KPI used by the SES Performance Scheme is the "Horizontal Flight Efficiency", which is calculated comparing the horizontal component of the flight and the geodesic route, assuming it is the most efficient one.

The main goals of the project are:

- Define a set of efficiency and equity indicators, selected through an iterative process with several airlines members of the AURORA's Airspace User (AU) group;
- Define off-line and on-line methodologies to obtain those new indicators based on surveillance and flight plan data, considering the impact of weather conditions and without the need of confidential information from the airlines. These methodologies were designed as service-oriented architectures that enable the off-line and on-line calculation of the indicators;
- Several case studies showing the feasibility of the methodologies and the benefits of AURORA's indicators in comparison with current ones. Indirectly, the potential benefits of using ADS-B data as a mean to assess the global (origin to destination) efficiency of a flight were also analysed.

AURORA's research led to the definition of a set of new indicators dealing with both efficiency of the flights and equity. The new set of efficiency indicators is compound by thirteen indicators: four indicators based on distance, three indicators based on the vertical profile of the flight, three indicators to quantify the fuel consumption and three indicators to quantify the flight costs. The new set of equity indicators is compound by six indicators: three indicators to assess the vertical profile of the flights per airline and three indicators to assess the flight costs per airline.

These indicators were evaluated using historical data and using a developed on-line process to compute indicators in-flight. Additionally, the Airspace Users' group was consulted to assess their understanding and the representativeness to their interests. According to these assessments, the overall findings of the project are:

- ADS-B data could serve as a reliable source for performance monitoring both at global level, ECAC level and local level;
- The service-oriented approach following during the project proved to be feasible and reliable;
- The on-line process to calculate indicators met the expectations of the AUs group in terms of latency and calculation accuracy;
- AUs appraised the improvement on representativeness of AURORA's indicators with respect to current efficiency indicators, at the cost of certain decrement of understanding to be addressed;

- Efficiency indicators change the current view of efficiency by including other components of the flights (as the vertical profile or the fuel consumption) rather than sticking to the horizontal profile of the flights as today. These inclusions add representativeness to the set of indicators, which are able to complement each other offering the possibility to identify inefficiencies origins;

- The introduction of AURORA's indicators into the resolution of hotspots improves its overall efficiency. Current decisions, which are not based on efficiency, on imbalance resolution may induce to increments of fuel consumption or cost increment with respect to the most efficient solutions based on AURORA's indicators;

- Equity indicators provide an insight on the distribution of inefficiencies among AUs across the ECAC area. These indicators allow identifying regions where equity principles are not applied as expected. These indicators are only representative when calculating in wide periods i.e. one month.

Before the implementation of these new indicators, further benchmark activities should be addressed:

- Definition of a unique optimum trajectory. This trajectory should represent the airspace user future preferences (free route), and should be agreed by a wide number of airlines, with different business strategies, and by the ANSP;

- Agreement with the ANSPs on how to address the local decomposition of these indicators and their affection to other airspaces;

- Definition with the Airspace Users on a common methodology to calculate the total cost of a flight. Evaluation of the need of a complex formula to include delays, crew costs, connecting passengers… or flight costs can be simplified to the computation of taxes, fuel and flight time as the major sources of costs inefficiencies.

Following the results achieved, the AURORA consortium is proposing two enablers to the SESAR ATM Master Plan:

- ”Provision of centralised trajectories reconstruction and generation services through SWIM” as a new enabler that allows obtaining new indicators based on surveillance and flight plan data, considering the impact of weather conditions and without the need of confidential information from the airlines. This enabler is considered to have reached TRL2;

- “Provision of advanced stream-based model for on-line calculation of efficiency indicators through SWIM” as an enabler that transversally contributes to the SESAR Solutions addressing DCB and STAM. This enabler is considered to have reached TRL1.

2 Project Overview

2.1 Operational/Technical Context

Flight efficiency indicators are currently monitored and reported by the SES Performance Scheme [28], [29] as part of the Environmental KPA defined by ICAO [21], [22]. This monitoring is done both in the U.S. and Europe [25]-[27] as well as in other countries such as Australia.

Flight efficiency is a generic term that can refer to different concepts and definitions. Nevertheless, flight efficiency is always considered as a relevant area under study due to the direct economic and environmental impacts it has according to well-known studies [23], [24], [30]-[34]. Consequently, efficiency indicators' monitoring is continuously growing to allow for a better understanding of the drivers of ATM flight efficiency. In this direction the Single European Sky ATM Research (SESAR), through the SESAR 2020 Performance Framework, refines the selection of KPAs from ICAO and introduces different indicators for SESAR 2020 Validation Targets and Assessments in order to help quantify the impact of a SESAR Solution. The SESAR 2020 Performance Framework divides flight efficiency between Fuel efficiency (inside the Environment KPA and with a Performance Target measured by the average fuel burnt per flight), ANS Cost efficiency and Airspace User Cost efficiency (both in the Cost-Efficiency KPA and with the Performance Targets of the ATCO hour on duty and the Technology Cost per flight).

Today's mandatory KPI used by the SES Performance Scheme is the "Horizontal Flight Efficiency". This KPI limits the calculation of flight efficiency to the horizontal component of the flight, and considers the geodesic route as the most efficient reference.

The method to calculate this indicator is named "the Achieved Distance Methodology" [35]. This methodology calculates the average en-route additional distance with respect to the Achieved Distance, which is an apportionment of the most direct route between two airports (between the ASMA exit point of the departure airport and the ASMA entry point of the arrival airport), named the Great Circle Distance.

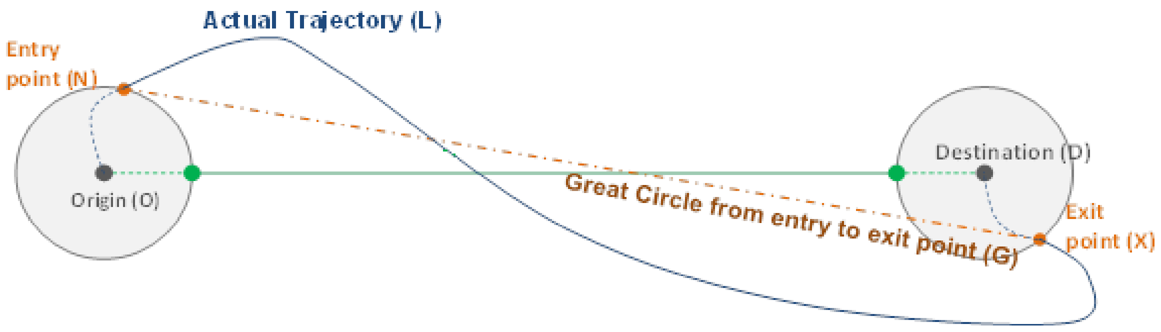

Figure 1: Flight length compared with Great Circle Distance.

Some studies performed by EUROCONTROL [36], [37], [56] have shown that this approach for the calculation of flight efficiency, based only on the horizontal component of the flight, does not capture the "optimum" trajectory when considering meteorological factors or the airspace users' operational objectives. These studies encouraged EUROCONTROL to propose a complementary vertical indicator whose introduction in SESAR RP3 is currently being evaluated [36], [37] and [57]. In US, FAA's researchers have studied the possibility of introducing wind as a parameter for the flight efficiency evaluation in the trajectory calculation [38]. On the other hand, European ANSPs are also trying to improve the representativeness of flight efficiency indicators. As an example, NATS has developed the 3Di metric that may provide a good measure of the ATM influence on fuel efficiency [39]. BR&TE and CRIDA began exploring an innovative direction in a collaborative study using real operation data; as a result, a new methodology was explored to construct an Enhanced Flight Efficiency indicator that better captures the fuel consumption [40]. All previous studies showed that the existing Horizontal Flight Efficiency methodology based on the Great Circle Distance trajectory does not fully capture the optimum or more efficient trajectories, which are the cornerstone for the calculations.

These findings open a new way for investigation on optimum trajectories, considering factors such as fuel consumption, flight time costs or weather conditions impact. AURORA's study takes as starting point the previous research to overcome the gaps of the today's most common flight efficiency indicator.

2.2 Project Scope and Objectives

AURORA addressed the need to explore promising new performance indicators for operational efficiency, based on aircraft operators' needs. Its scope was to investigate new indicators for flight efficiency and equity as well as to explore innovative methodologies to calculate these indicators based on centralized trajectory generation services, in where any user could verify the calculation and the reference trajectories used in the evaluation of the metrics. Additionally, AURORA explored the use of these services for the on-line monitoring of efficiency and the design requirements needed.

The goals of AURORA are summarized in:

- A set of efficiency and equity indicators that were selected as outcome of an iterative process carried out with several airlines members of the AURORA's Airspace User group;
- Off-line and on-line methodologies to obtain those new indicators based on surveillance and flight plan data, considering the impact of weather conditions and without the need of confidential information from the airlines. These methodologies were designed as service-oriented architectures that enable the off-line and on-line calculation of the indicators;
- Several case studies showing the feasibility of the methodologies and the benefits of AURORA's indicators in comparison with current ones. Indirectly, the potential benefits of using ADS-B data as a mean to assess the global (origin to destination) efficiency of a flight were also analysed.

2.3 Work Performed

2.3.1 Definition of AURORA's efficiency and equity indicators

The calculation of AURORA's efficiency indicators requires the definition of several types of trajectories, each of them accounting for a loss of efficiency due to different factors. The definitions below follow the nomenclature and framework used in [40], [47] and are the final set of the reference trajectories[1] selected in AURORA:

- Optimal Distance Trajectory (ODT). This is the shortest distance trajectory, the one that follows the Great Circle from origin to destination. The ODT does not consider the impact from other traffic or from any airspace structure restrictions. This trajectory is aligned with how efficiency is currently measured by SES Performance Scheme through the Achieved Distance methodology, as explained in [35], [37] [40];
- Optimal Cost Trajectory 1 (OCT1). This trajectory represents a possible futuristic free flight from origin to destination in where the Airspace User can freely minimise costs of fuel and flight time (using the concept of Cost Index) as if it was flying alone. It does not take into consideration any airspace or ATC restrictions and represents the theoretical minimum cost incurred by the Airspace User to operate that route. Although air navigation fees are not considered in the optimization of this trajectory, they are taken into consideration in the calculation of the associated cost-based indicators. The Cost Indexes used in the project are a mean value for each aircraft extracted from publicly available documents published by aircraft manufacturers [51], [52], [53];
- Optimal Cost Trajectory 2 (OCT2). The OCT2 differs from the OCT1 in the fact that it takes into consideration today's airspace structure since it follows the horizontal path given in the flight plan. It represents the minimum cost possible following the current route structure but neglecting any vertical restriction or minimum separation.
- Flight Plan Trajectory (FPT). This trajectory corresponds to the last filed flight plan and contains all procedural constraints. The aircraft would fly this trajectory if no ATC tactical interventions took place.
- Actual Flown Trajectory (AFT). This trajectory corresponds to the true trajectory flown obeying objectives specified in the filed flight plan, but also considering ground delays, tactical ATC interventions and weather diversions. All these factors contribute to the actual flown trajectory being different to what was planned (the FPT).

AURORA's indicators are structured in several subsets to increase progressively the representativeness of the measure (from only horizontal distance into the more complex indicators based on costs). The subsets are the following:

1 Additional reference trajectories were also calculated in AURORA in previous steps of the project such as the Optimal Fuel Trajectory (OFT), i.e. trajectory that minimizes fuel consumption in free flight conditions, among others. These can be seen in the D3.2. [4]

- Indicators to improve the analysis of the horizontal component of the flight;
- Indicators to address the vertical component of the flight;
- Indicators which are focused on the fuel consumption;
- Indicators which are focused on the airlines' costs dealing with flight time, fuel consumption and taxes.

The following table presents the final list of efficiency indicators consolidated in AURORA. This list differs from the indicators defined in the D3.1 [3] and evaluated in D3.2 [4] due to the iterative process with the participants in the AURORA's Airspace User Group along the whole duration of the project.

The first indicator, KEA, is equivalent to the one currently used by the PRU in their efficiency analysis and reports. KEA is only calculated for comparison purposes. For the rest, AURORA's nomenclature consists of four letters:

1. The first letter is for the variables being compared (K for distance, F for fuel, C for cost, V, for vertical);
2. Second letter (E) means efficiency;
3. Third letter means the trajectory that is assessed, in all cases A for the Actual Flown Trajectory (AFT);
4. Finally, the fourth, separated by underscore, identify the trajectory used as reference (P for FPT, C1 for OCT1 and C2 for OCT2). As an example, CEA_C1 means Cost Efficiency indicator of the Actual Flown Trajectory versus the Optimum Cost Trajectory.

Indicator	Subset	Reference Trajectory	Description
KEA	Horizontal	ODT	Difference of the horizontal distance of the AFT with the ODT.
KEA_P		FDT	Difference of the horizontal distance of the AFT with the FPT.
KEA_C1		OCT1	Difference of the horizontal distance of the AFT with the OCT1.
KEA_C2		OCT2	Difference of the horizontal distance of the AFT with the OCT2.
VEA_P	Vertical	FDT	Difference of the average en-route flight level of the AFT with the FPT.
VEA_C1		OCT1	Difference of the average en-route flight level of the AFT with the OCT1.
VEA_C2		OCT2	Difference of the average en-route flight level of the AFT with the OCT2.
FEA_P	Fuel	FDT	Extra-fuel consumption of AFT in comparison with the FPT.
FEA_C1		OCT1	Extra-fuel consumption of AFT in comparison with the OCT1.
FEA_C2		OCT2	Extra-fuel consumption of the AFT in comparison with the OCT2.
CEA_P	Costs	FDT	Extra-costs of the AFT in comparison with the FPT.
CEA_C1		OCT1	Extra-costs of the AFT in comparison with the OCT1.

Indicator	Subset	Reference Trajectory	Description
CEA_C2		OCT2	Extra-costs of the AFT in comparison with the OCT2.

Table 1: AURORA´s indicators

It is important to clarify that, all the indicators are calculated from origin-destination[2]. This implies that the calculation of KEA differs from the current implementation indicated by the PRU to ANSPs, where the portion of the flight in an area of 40NM around the airports (ASMA) is excluded from the evaluation of the indicators [35], [37], [40]. The airlines involved in the study mentioned their interest to understand the efficiency of their flights by considering the whole trajectory, including the ASMA. The formulas used to calculate the indicators are described in the D3.2 [4].

Equity indicators are based on the efficiency ones and capture how the inefficiencies of the system are distributed between all Airspace Users within a certain context (e.g. ECAC region, airport, city pair or airspace crossed). The computation of all Equity indicators is done by using the standard deviation of the mean values of each Airspace Users' flights. The consolidated Equity indicators are structured in two subsets, flight level usage and costs comparison.

Indicator	Subset	Reference Trajectory	Description
EQ_FL_P	Flight Level	FDT	Differences between airlines in terms of percentage of flights reaching the flight level of a specific reference trajectory.
EQ_FL_C1		OCT1	
EQ_FL_C2		OCT2	
EQ_CEA_P	Costs	FDT	Differences between airlines in terms of costs of the AFTs versus a specific reference trajectory.
EQ_CEA_C1		OCT1	
EQ_CEA_C2		OCT2	

Table 2: AURORA's Equity indicators.

2.3.2 Methodology to obtain the indicators

2.3.2.1 Computation of indicators based on historical data (OFFLINE CALCULATION)

The methodology and process followed in the calculation of AURORA's efficiency indicators is summarised in the Figure 2.

2 Excepting for the vertical ones that according to AUs suggestions only takes into account the portion of the trajectory from Top of Climb (TOC) to Top of Descend (TOD).

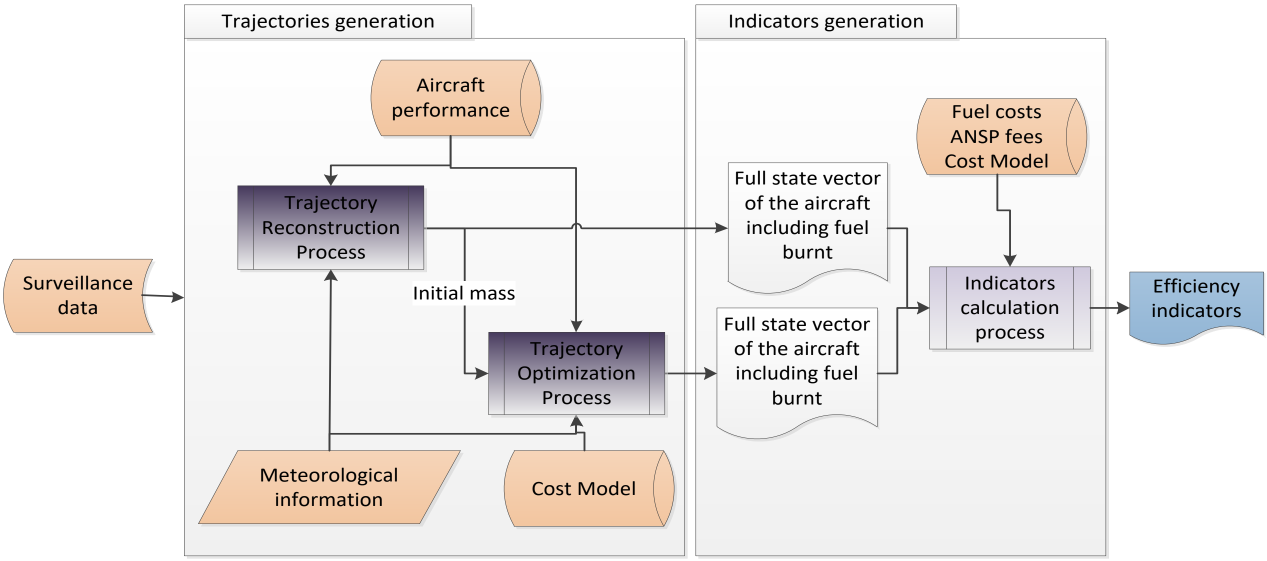

Figure 2: Service-oriented approach for the calculation of new efficiency indicators.

AFT is calculated from surveillance information (ADS-B track data) using BR&TE's Aircraft Intent Inference and Trajectory Reconstruction (INTRACT) service. National Oceanic and Atmospheric Administration (NOAA) weather forecasts is used as the weather model and Base of Aircraft DAta (BADA) is used as aircraft performance model [44][3]. This process, which is named **Trajectory Reconstruction**, enables the acquisition of the full state vector of the aircraft, including variables that are not explicitly included in the surveillance data and are needed to analyse the efficiency of the flight, such as the initial mass of the flight or fuel burnt. This reconstructed initial mass is then used as the initial mass in all the different reference trajectories.

ODT and FPT are calculated for each flight using the Aircraft Intent Generation and Trajectory Synthesis (INCEPT) service and finally, OCT1 and OCT2 are calculated in the Intent-based Trajectory Optimization (INTRO) service. The process of calculating these trajectories is called **Trajectory Generation** since, these are synthetic trajectories never flown by the aircraft, but used as references for comparison purposes. The cornerstone of this process is the initial mass extracted from the reconstruction process. Each indicator is then obtained by selecting and comparing the proper variables of Actual Flown Trajectory with those of the reference trajectories.

Both processes were carried out using PERCEPT (Predictive assEssment of the impact of new aiR traffiC concEpts on current oPeraTions), which is a flexible air traffic modelling tool proprietary of BR&TE [40], [41]. In PERCEPT, Trajectory Reconstruction and Generation processes rely on a common Trajectory Computation Infrastructure (TCI) that produces a trajectory using as input the initial conditions

3 The services used to generate all the trajectories that were used in AURORA can equally use BADA 3.X or BADA 4.X. AURORA study uses BADA 3.10 to maximize the number of flights analysed in the traffic samples since BADA 3.10 currently has higher aircraft type coverage for the ECAC area than the latest BADA 4 version (BADA 4.2).

(latitude, longitude, altitude, mass, time and speed) of the flight and an aircraft intent[4] expressed using the Aircraft Intent Description Language (AIDL). Details on the AIDL and the TCI used can be found in [41], [42], [43], [45] and [46]. The main idea behind the concept of Trajectory Reconstruction using PERCEPT is to find an instance of AIDL that fits the ADS-B track and then feed the resulting aircraft intent to the TCI that integrates the full trajectory.

In the Trajectory Generation process, the AIDL instance that is fed into the TCI to obtain the aircraft trajectory is created depending on the trajectory that is sought after. The AIDL instance comes from flight intent information and initial conditions. Flight intent[5] information condenses all the restrictions and objectives that affect a particular flight that have a direct impact on the resulting trajectory. For the same origin and destination, depending if the final trajectory needs to comply with the operational flight plan or should follow an optimal profile, different instance of AIDL will be created. The complete processes of Trajectory Reconstruction and Generation, including the optimization process used for the creation of the optimal profiles, are explained in detail in [12].

To improve performance and allow access of the different partners to the reconstruction and generation processes, they were set up in different services mentioned before.

2.3.2.2 Computation of indicators based on data streaming (ONLINE CALCULATION)

Figure 3 illustrates the architecture of the online efficiency indicator system. The main components in this architecture are an input ADS-B surveillance data stream; the trajectory reconstruction service which can generate a reconstructed trajectory (including initial mass estimates) given a sequence of surveillance points; the stream processor that calculates efficiency indicators based on surveillance data; a store of generated reference trajectories calculated once flight plan data becomes available; and a persistent store in which the calculated efficiency indicators are stored. The key technologies used in the implementation of the system are Apache Spark Streaming [54] and Apache Kafka [55].

4 Aircraft intent is the information that describes how the aircraft is to be operated within a certain time interval. An instance of aircraft intent defines the aircraft behaviour that has an impact on the aircraft trajectory.

5 Flight intent can be seen as a generalization of the concept of flight plan. Details on the flight intent can be found in [25].

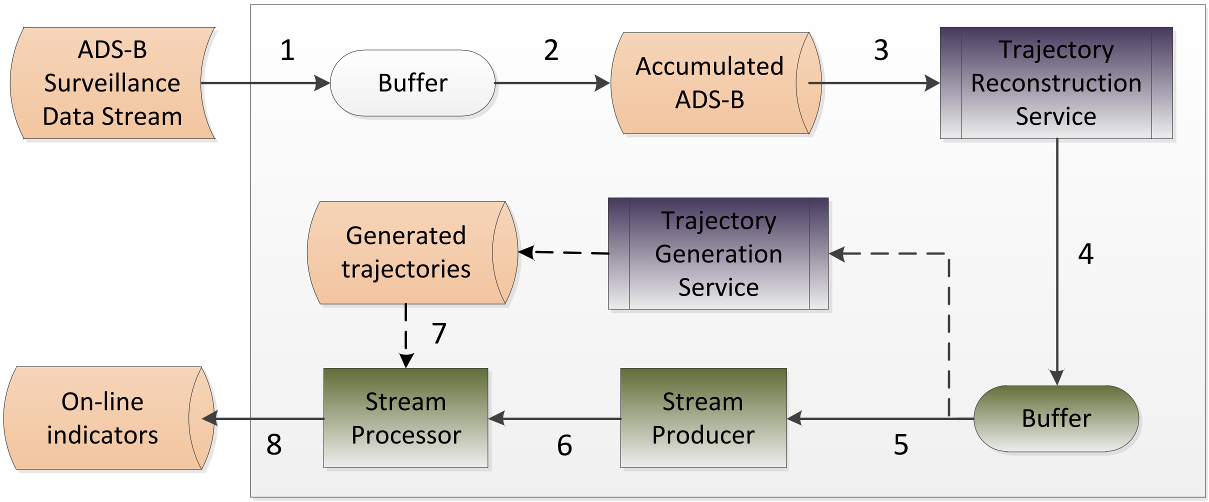

Figure 3: architecture of the online efficiency indicator system.

Key points in the data flow of this architecture are labelled with digits 1 to 8. These are explained as follows:

1. The ADS-B surveillance data stream is sent to a buffer to adapt to the receiving rate and the subsequent processing rate;
2. The contents of this buffer are then cleared and appended on the accumulated ADS-B data store which is partitioned by flight id. We use the "call sign number" combined with "departure time" to uniquely identify a flight;
3. The trajectory reconstruction service is triggered periodically, for example every 5 seconds, to derive extra states (i.e. mass) for all updated actual trajectory points. To avoid a performance bottleneck, this reconstruction service is called in multi-threaded manner, with the unit of parallelism as each unique flight;
4. These reconstructed trajectories are sent on to an Apache Kafka buffer. This reliable buffer can ingest data with high throughput and low latency for more complicated processing tasks afterwards;
5. The Kafka stream producer reads reconstructed trajectory streams from the buffer and sends them to the stream processor. This stream producer guarantees reliable message transmission with no duplication, no data loss, and no out-of-sequence messages;
6. The Stream Processor, which is implemented using Apache Spark Streaming [54], pulls the reconstructed trajectory streaming data every 30 seconds to aggregate a micro-batch and computes the efficiency indicators that correspond to all new reconstructed trajectory points, such as travelled distance, consumed fuel, and overall cost;
7. This stream processor also retrieves the relevant optimum value using nearest point search from pre-loaded in-memory generated trajectories data, then calculates required flight efficiency indicators with the actual value from reconstructed trajectory point. The broadcast mechanism in Spark is used for pre-loading generated trajectory data to avoid sending copies to all worker machines every time a new micro-batch is formed. The calculation so far is

defined with a set of "stateful" transformations (rather than actions) to avoid generating large intermediate datasets;

8. The stream processor uses the "for each" action to finally output the calculated on-line indicator results on to PostGIS for subsequent complex queries. For example, the air traffic network manager can check the evolution of an indicator - KEA in one sector - to see if it is relatively fairly distributed among airlines.

Additionally, we use the estimated initial mass from the output of trajectory reconstruction, which lead to a periodically updated trajectory generation service.

2.3.3 Description of experiments

Verification and validation exercises were performed with the objective of verifying the feasibility of the proposed methodologies (both off-line and on-line) to obtain the indicators and to validate the applicability of AURORA's indicators in the real ATM environment. These exercises are structured according to the addressed objectives in:

- Verification of the off-line processes to generate trajectories and associated indicators. The goal of this first exercise was to assess the data, tools and methodology to calculate the trajectories used for the computation of indicators based on historical data. The findings of this exercise can be found in D3.2 [4];
- Validation of efficiency and equity indicators. This exercise assessed the benefits of the newly introduced indicators in comparison of existing ones as a way of historically monitoring the network performance related to efficiency and equity. The findings of this exercise can be found in D3.2 [4];
- Verification of the on-line processes to calculate the AURORA's efficiency indicators. The goal of the verification of the on-line process was to calculate the time evolution of the indicators and to compare the values of the indicators calculated off-line with those calculated in real time. Latency and throughput of the processes were also tested. The findings of this exercise can be found in D3.3 [5];
- Validation of the use of on-line efficiency indicators in the application of STAMs measures in SESAR. This exercise assessed the benefits of AURORA's indicators in the processes for the identification and assessment of hotspots along the day of operation. The fact of continuous on-line monitoring of efficiency indicators will facilitate the analysis of the hotspots from the perspective of the Airspace Users. This will allow selecting the most suitable STAM measure by balancing the ATM network perspective with the Airspace Users' needs.

All experiments analysed actual ADS-B equipped flights whose whole track remains inside the European Civil Aviation Conference (ECAC) area. ADS-B data were used in time intervals of less than 5 seconds, to ensure maximum level of granularity in the generation of trajectories as starting point for the computation of indicators.

Three traffic samples were selected for the analysis, one day considering flights of the airlines participating in the Airspace Users Group, and two days of full ECAC area traffic without major disruptions, i.e. without abnormal ATC regulations or delays. The selected days were: 2017 January 10th, 2017 February 20th and February 24th respectively. February 24th had higher magnitude and different predominant wind direction than February 20th, therefore different distribution of inefficiencies was expected. The main study focused on flights departing from 12:00 to 14:00 as these are the main peak hours of the selected days. Additionally, all flights operating several city pairs along the 24 hours of the two days were also included in the final data sets. These city pairs, which were identified by the members of the AURORA's Airspace Users Group, are: London Gatwick – Madrid Barajas, London Gatwick – Barcelona, Frankfurt – Madrid Barajas, Paris Orly – Toulouse, Paris Orly – Lisbon, Istanbul – Amsterdam, Roma Fiumicino – Amsterdam and Barcelona – Brussels. This adds up to 400 trajectories for the 10th; 1,583 trajectories for the 20th; 1,692 trajectories for the 24th. Efficiency results of the two last traffic samples are included in this document. January 10th was selected to perform a preliminary experiment and its results are included in D3.2 [4].

It is important to mention that, in the case of the Equity indicators, an additional traffic sample was selected to increase the representativeness of the results as it was identified the need of measuring Equity in longer time periods than one single day. The new days for the analysis of equity indicators (only for the off-line experiments) were: time period of June 22nd 2017 to July 19th 2017 for the city pairs London Gatwick – Barcelona, Frankfurt – Madrid Barajas and Istanbul – Amsterdam. This adds up to 1537 flights. Results of this new traffic sample are included in this document.

Additionally, the last experiment focused on the use of efficiency indicators with STAM used a different traffic sample, as it was necessary to address the resolution of hotspots. The traffic sample was comprised by the flights initially flying through the sector LECMDGU (Domingo Upper) in the Spanish Airspace the day 2017 July 2nd at 11:30.

2.4 Key Project Results

Results are structured according to the different experiments that were performed in AURORA: Experiments to assess the feasibility of the off-line and on-line methodologies i.e. verification exercises, and experiments to show the benefits of AURORA's indicators in comparison with the current ones i.e. validation exercises.

2.4.1 Feasibility of the off-line processes to compute efficiency indicators

The main objective, set for the verification experiment described in D3.1 [3], was to obtain at least 70% of success rate in the reconstruction and generation of trajectories. The overall figures are summarised in the following table, where it can be seen that the previous objective was achieved.

Trajectory Type	Success rate
AFT	95%
FPT	80%
ODT	94%
OCT1	91%
OCT2	73%

Table 3: Success rates in trajectory reconstruction and generation.

As a complementary analysis, some of the resulting trajectories were compared to real data provided by the AURORA's Airspace Users. A set of 40 flights per airline was selected and compared to the values of initial mass and fuel consumption as stated in the Operational Flight Plans (OFPs) of those flights. The results showed that the reconstruction process underestimates the initial mass and fuel consumption by 17%. These results were improved to 9% when comparing with Quick Access Recorder (QAR) data since we were able to pinpoint the initial and final points of the flight. The reasons for these deviations are:

- The representativeness of the aircraft model used (since BADA provides a model for aircrafts as they are when leaving the factory, engine and systems wear is not considered and therefore BADA models will always underestimate the fuel consumption);
- The use of weather forecast instead of actual weather;
- The sensibility of the reconstruction algorithm to the initial guess of mass estimation.

It was verified that these mass differences did not extremely affect the indicators since this initial mass is the same for the two trajectories to be compared in all the indicators. This was achieved by running a set of 3,000 flights with different values of initial mass (the mass extracted from the reconstruction process, decreasing the mass by 5% until -15% of that reference mass, and increasing the mass by 5% until +15% of that reference mass). Figure 4 shows the percentage of flights in which the indicator values changed more than a certain number of units for each mass variation in respect to the reference mass values for one of the indicators. In dark blue we have the percentage of flights whose indicator changed more than 3 points (without exceeding the 5 point difference), in cyan we have the percentage of flights whose indicator changed more than 5 points, in green we have the flights that changed more than 10 points, and in yellow those which changed more than 15 points. It should be noted that the total percentage of flights that varied their indicator over 3 points is the sum of all the heights of the different colour bars. Results showed that only in few cases the change in the indicator was significant.

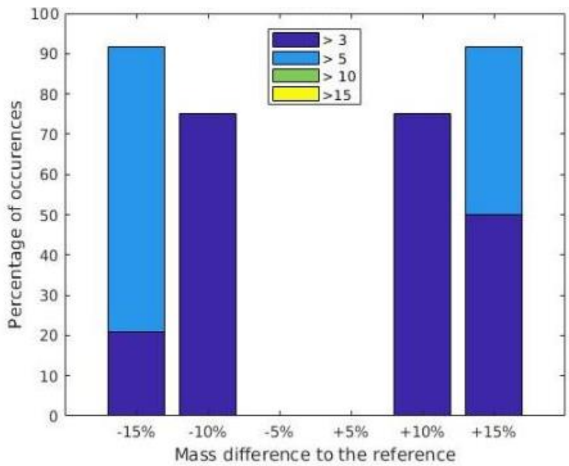

Figure 4: Mass difference.

D3.1 [3] identified also a specific objective dealing with the throughput of the off-line process, stating that efficiency and equity indicators for all flights in the ECAC area in one month had to be processed in less than two weeks, including the aggregation of data to obtain the indicators. Although throughput was progressively increased in the subsequent traffic samples, this objective was not reached. The results of February 20th were obtained in less than one week using a remote server with 8 cores. The results of February 24th were obtained in three days using a remote server with 16 cores.

2.4.2 Monitoring of efficiency and equity indicators based on historical data

2.4.2.1 Efficiency indicators

Table 4 shows the mean values, the standard deviations and the coefficients of correlation with the horizontal indicators for the two most representative ECAC traffic samples , 2017 February 20th and 2017 February 24th. Coefficients of correlation allowed assessing if it is necessary to calculate complex indicators to assess the efficiency from the perspective of the Airspace Users or simple indicators such as the horizontal ones are representative enough.

The table shows also the Airlines´ qualitative assessment of the added value of AURORA´s new indicators, based on their interests. Understanding represents if it is easy to understand the indicator, and representativeness means if it is representative enough of their interests. These criteria were chosen in line with the SESAR process to assess new indicators. Indicators that are more complex are harder to understand but are more representativeness of AUs interests.

Days	Indicator	Mean value	Standard Deviation	Linear Correlation with Horizontal Indicator	Understanding	Representativeness
20/02/2017 24/02/2017	KEA	9.3% 10.0%	6.6% 6.6%		High	Low
	KEA_P	-1.1% -1.5%	5.0% 5.6%	N/A	High	High
	VEA_P	-1.8% -1.9%	4.3% 4.0%	0.03 0.01	High	Medium
	FEA_P	1.6% 1.8%	6.3% 6.6%	0.51 0.37	High	Medium/High
	CEA_P	1.7% 1.4%	5.0% 4.9%	0.75 0.63	High	Medium/High
	KEA_C1	9.5% 10.2%	6.6% 6.6%	N/A		
	VEA_C1	-6.1% -7.5%	7.2% 7.4%	0.01 0.01	Medium	High
	FEA_C1	1.7% 2.0%	7.2% 6.7%	0.40 0.25	Low	High
	CEA_C1	8.7% 9.1%	6.1% 6.0%	0.65 0.59	Low/Medium	High
	KEA_C2	-1.2% -1.3%	5.2% 5.3%	N/A		

Days	Indicator	Mean value	Standard Deviation	Linear Correlation with Horizontal Indicator	Understanding	Representativeness
	VEA_C2	-4.9% -6.3%	7.5% 8.0%	0.01 0.01	Low	Low/Medium
	FEA_C2	-0.6% 0.0%	6.7% 6.8%	0.29 0.14	Low	High
	CEA_C2	4.5% 5.0%	5.7% 5.5%	0.74 0.55	Low/Medium	High

Table 4: Statistical values and relationships between indicators.

Flight Plan Trajectory (FPT) as reference

Focusing on the indicators with the flight plan as reference trajectory (KEA_P, VEA_P, FEA_P and CEA_P), the first thing that can be seen is that in terms of horizontal deviation, actual flights are more efficient than the flights plans (KEA_P negative). This means that flights are usually shortcutted. These results are in line with AUs comments during AURORA workshops, in which they stated that they are forced to plan a route that later is not flied due to often shortcuts. However, they cannot plan the route with the shortcuts when submitting the flight plan.

By contrast, if we look at the indicator that measures costs (CEA_P), the situation changes and on both days the average values indicate that the actual trajectory is more inefficient than the flight plan trajectory. One of the reasons is that fuel consumption of the actual trajectories is higher than the fuel consumed by the planned trajectory as average values of FEA_P show.

Figure 5 shows an example of the flight AEA1029 (for the 20/02/2017). In blue, we can see the flight plan while in red is the flown trajectory. On the top left, the horizontal profiles of the trajectories are represented.

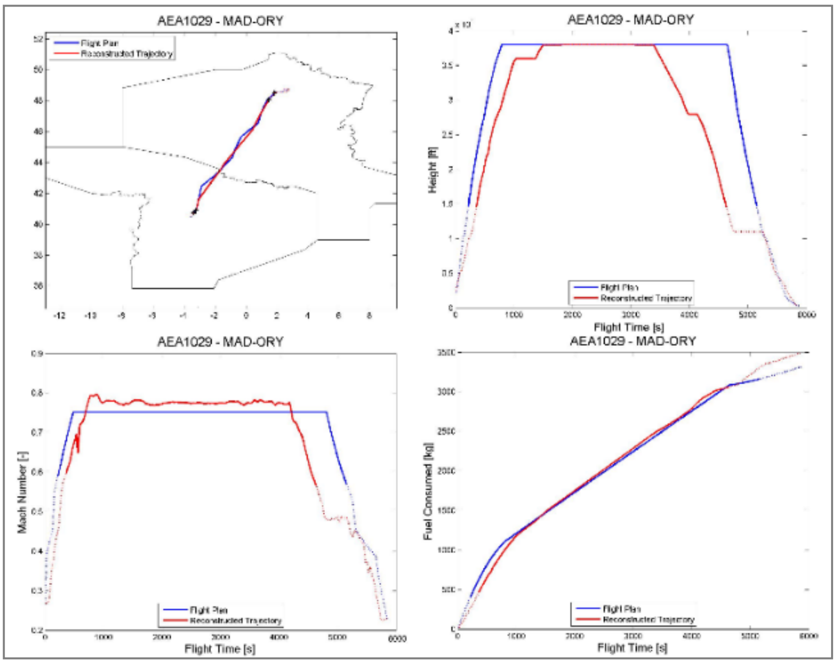

Figure 5: FPT as reference

It can be seen that the flight received various shortcuts. This is translated in a KEA_P of -1.9%. The actual trajectory is more efficient in terms of horizontal distance than the flight plan. However, this improvement on the horizontal distance is not aligned with benefits in terms of fuel consumption. As FEA_P is 5.3%, the actual trajectory is a 5% more inefficient that the flight plan (button right picture) due to the two periods in which the aircraft is levelled-off in the descend phase. In terms of vertical efficiency, actual trajectory is 0.8% inefficient in comparison with the planned trajectory due to the initial level capping in the cruise phase (VEA_P equals -0.84%[6]). Finally looking at the indicator measuring the costs (taking into account all the factors like fuel, time and taxes) CEA_P value is 2.1% that means the actual trajectory is a 2% more inefficient in terms of costs than the flight plan.

Previous results and example show that KEA_P, FEA_P, VEA_P and CEA_P allows quantifying the deviations of the actual trajectories with respect to the planned trajectories proposed in the flight plans. These deviations are not necessarily aligned with the differences in the horizontal distance between actual and planned trajectories, and on the contrary, the trend can change due to other factors, which are not considered in the horizontal indicator.

Optimal Cost Trajectory 1 (OCT1) as reference

Focusing now on the indicators with the optimum free route as reference trajectory (KEA_C1, VEA_C1, FEA_C1 and CEA_C1), KEA and KEA_C1 have a high correlation factor of 0.92. This implies that an easy-to-obtain indicator such as KEA could be representative enough to estimate KEA_C1 and there is no need of defining horizontal indicators that are more complex (due to a more complex reference

[6] Negative value of VEA indicator means that the flight is flown below the flight level of the specific reference trajectory while positives values means that the flight flown above the flight level of the reference trajectory.

trajectory). This high correlation is explained because, in Europe, weather (wind, pressure and temperature) is not causing major horizontal deviations of the optimal cost-based trajectories in free route with respect to the geodesic for short and medium-haul flights.

In spite of this, neither KEA nor KEA_C1 are properly representing how good is the actual trajectory with respect to the optimal cost-based trajectories. The linear correlation between KEA and CEA_C1 is around 0.70 and between KEA_C1 and CEA_C1 is around 0.60 as it is shown in previous table. This is identified as a medium-strong correlation according to Pearson scale. Figure 6 shows CEA_C1 scatter for similar values of KEA.

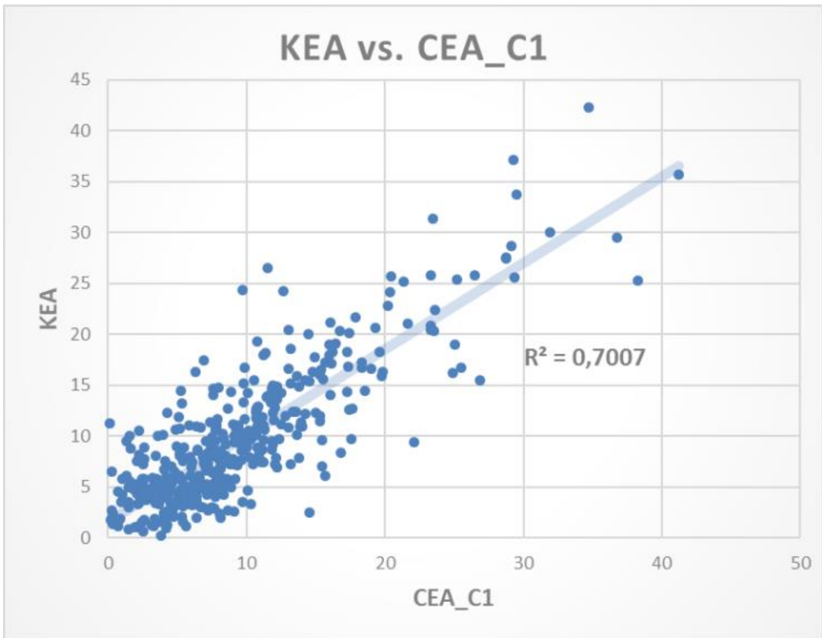

Figure 6: Scatter of CEA_C1 values correlated with KEA for February 20th.

An example of this scattering is shown in Figure 7. Flight RYR62HJ has a KEA of 6.1%, while its value for CEA_C1 is an 11.7%. Thus, in terms of costs the inefficiency is almost the double. Although there is a high correlation between the horizontal distance and the costs, other factors which are not represented in KEA, have strong influence on the new cost-based indicator. The fuel efficiency, FEA_C1 equals 7.98%, the vertical profile, VEA_C1 equals -9.77%, together with the cost of the time and the taxes are increasing the representativeness of the CEA_C1. In the example, it can be seen that the flight didn´t reached its optimal flight level and the duration of the flight is almost 2,000 second shorter, which implies lower fuel consumption.

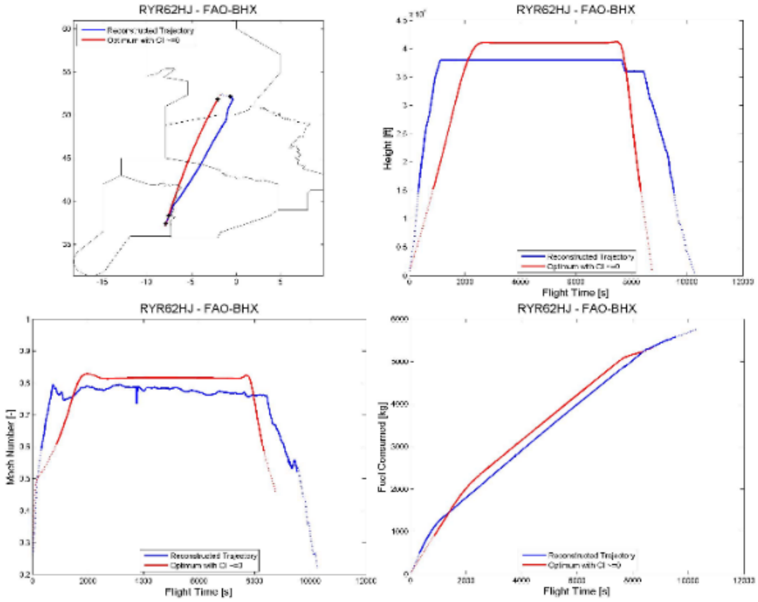

Figure 7: OCT1 as reference

Figure 8 shows the average weights of the different factors that contribute to the costs of a flight[7] (considering the free route cost-based trajectory). As it can be seen, the main factor is the fuel but a strong influence of the time also exists. This is the reason why the correlation between FEA_C1 and CEA_C1, 0.52, is not very high.

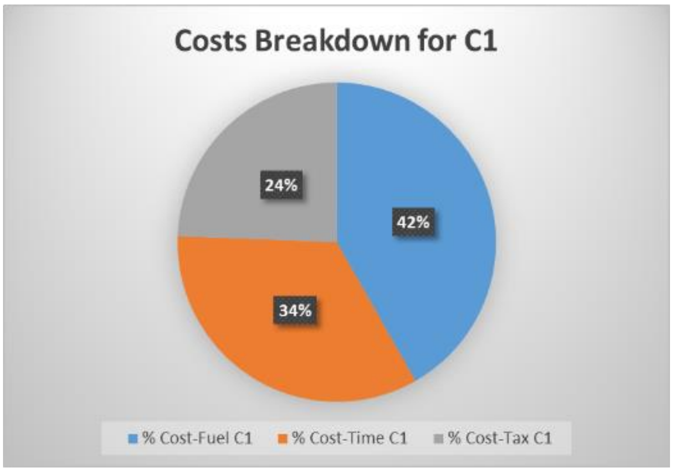

Figure 8: Breakdown of costs for trajectory OCT1.

[7] In AURORA only time, fuel and taxes are considered. Other factors which are impacting the cost of a flight such as delays or cost of connections are not taken into consideration.

CEA_C1 can also change the global picture of local inefficiencies. Figure 9 represents the inefficiencies in the ECAC area for February 20th. For example, flights in Germany, Austria and Czech Republic have values in the range of CEA_C1 from 10% to 25%, while KEA values are in the range of 0% to 25%.

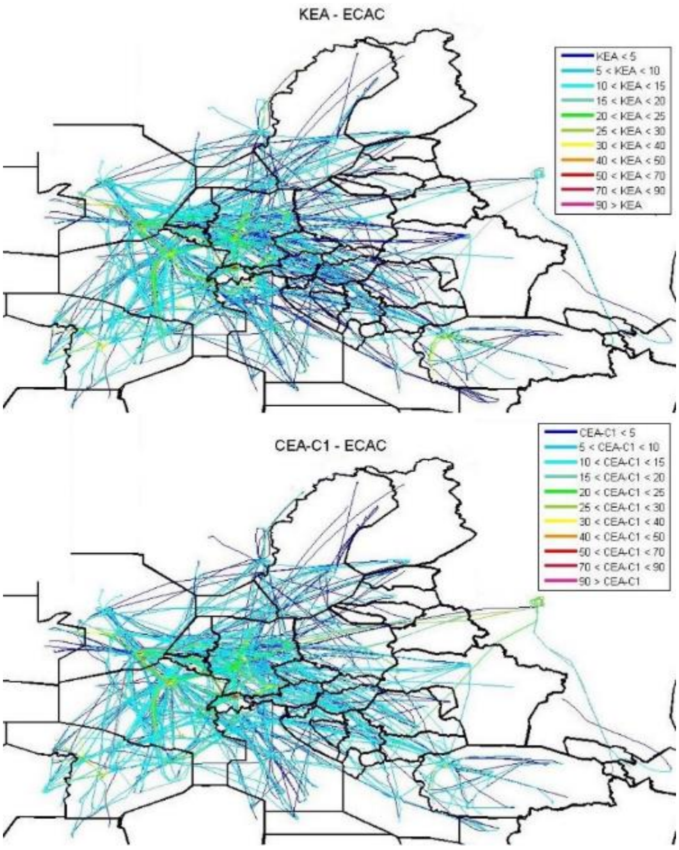

Figure 9. Cost-based and Distance indicators comparison

These indicators, FEA_C1, VEA_C1 and CEA_C1, could be the ones to drive the ECAC towards the future system in which airlines could flight their optimum flight in a free route environment. In terms of representativeness, the one that provide a more complete view of the AUs inefficiencies is the CEA_C1.

Optimal Cost Trajectory 2 (OCT2) as reference

Indicators with OCT2 as reference are a step between having the flight plan as reference and having the optimum free route trajectory. Actual trajectories in the ECAC are more efficient than expected when comparing with the best possible cost-efficient trajectory following the flight plan, i.e. OCT2, as it can be seen in the difference between CEA_C2 and KEA mean values. In fact, KEA and CEA_C1 mean values are around 50% higher than CEA_C2 in the two traffic samples. This indicates that half of the ECAC inefficiencies in terms of costs are due to the constraints of the route design.

Local decomposition of the indicators

AURORA efficiency indicators reveal the efficiency of the whole flight. However, there is a need to decompose the total values into local values, to identify in which portion of the flight these inefficiencies are produced, such as, for example, the portion of the flight within a given airspace (FIR/UIR, FAB, etc).

The current approach to isolate local efficiency, used by EUROCONTROL, is the methodology called the "Achieved Distance Methodology" [35]. ADM only takes into account horizontal profile (distance) and thus, only KEA indicator can be calculated. For this reason, AURORA's project proposes a different methodology to allow the decomposition of global indicators into local values without the need of considering exclusively geographical considerations.

The main difference with the ADM is that AURORA's approach is applicable for different reference trajectories, like optimum trajectories based on costs. Therefore, all efficiency indicators of each region could be calculated and it could be possible to obtain the cost and fuel of each portion of the flight. On the contrary, it needs more time to compute because it is necessary to generate multiple optimal trajectories from each entry point into a region.

In order to do the calculations it was necessary to generate different reference trajectories (ODT, OCT1 or OCT2): one origin-destination trajectory (plotted in red in Figure 10), and a set of new reference trajectories from each entry point to a region, to destination (plotted in green in Figure 10).

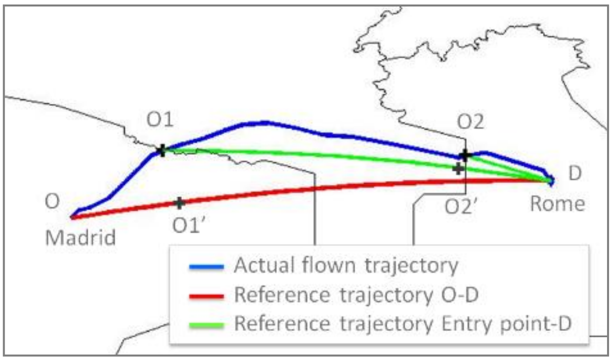

Figure 10. AURORA's approach (reference trajectories).

This methodology detects the first transition point (O1) from one region to the next over the real trajectory, and projects this point over the reference trajectory O-D (O1'). This section (O-O1') will be taken into account for the indicator's calculations in this region. The process followed is repeated for the second section of the flight over the second region (O1-O2'), and finally for the last region (O2-D).

The new methodology to capture local efficiency should be obtained similar results to the one of EUROCONTROL in terms of distance. The KEA results obtained by both methodologies over only five flights with origin and destination in Europe were analysed. At first sight, AURORA's approach offer fairly similar results as the "Achieved Distance Methodology", with a 90% of correlation. Thus, AURORA's approach could be a good approach to obtain local efficiency. Figure 11 shows the comparison of KEA indicator yielded by both methodologies for the regions of the flights analysed.

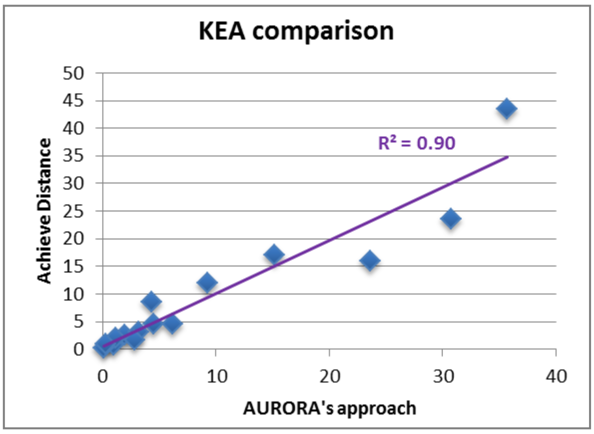

Figure 11. Local decomposition of KEA indicator with current and AURORA's method.

Moreover, it was applied AURORA's approach in order to obtain the local decomposition of KEA and CEA_C1 for the flights shown before. Comparison between the local values of both indicators showed the same trend over the crossed regions. This is reasonable as distance-based inefficiencies and cost-based inefficiency have a medium-strong correlation as it was explained in previous sections. Figure 12 shows a comparison between KEA indicator in green and CEA-C1 indicator in blue for one flight.

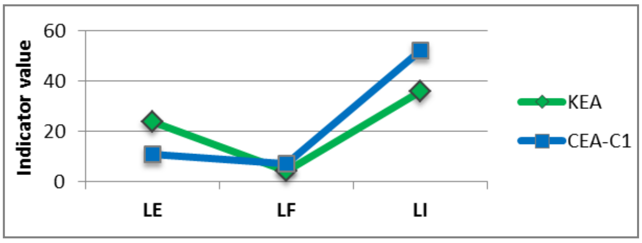

Figure 12. Local cost efficiency by AURORA's approach.

2.4.2.2 Equity indicators

The Equity definition's nature requires that its computation encompass different Airspace Users. For this reason, individual flights cannot be assessed and a new framework had to be set. After completing several studies[8], the analysis of Equity by city pair was selected by the Airspace Users as the most promising approach to Equity.

Two of the defined indicators were studies in depth for being the most representative for the AUs: EQ_FL_P and EQ_CEA_C1. The following table summarizes the results achieved for the three selected city-pair (FRA-MAD, LGW-BCN and AMS-IST).

The "Mean" rows show the resultant mean among the Airspace Users, while the "Value" rows show the actual value of the Equity indicator, i.e. the standard deviation.

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8 Different data aggregations were evaluated and researched: whole ECAC results, FIR/UIR airspace, city-pair, etc. Further results on these traffic samples are included in the D3.2 [4].

As happened to the efficiency indicators, equity indicators were evaluated by Airspace Users in the final AURORA's AU Workshop. This evaluation was done in terms of understanding and representativeness, following the same principles as stated above for the efficiency indicators. This evaluation is summarised in Table 5. Similar to what happened to efficiency indicators, cost-based Equity indicators kept being the most representative, while flight level equity was complementary and it could be impacted by the different company strategies.

[%]	MAD-FRA	LGW-BCN	AMS-IST	Understanding	Representativeness
EQ_FL_P Mean	73.9	73.7	83.0	High	Medium
EQ_FL_P Value	**20.9**	**15.1**	**21.4**		
EQ_FL_C1 Mean	7.3	34.3	34.5	Medium	Medium
EQ_FL_C1 Value	**7.7**	**25.6**	**14.7**		
EQ_FL_C2 Mean	7.3	31.9	34.5	Medium	Medium
EQ_FL_C2 Value	**7.7**	**22.4**	**16.7**		
EQ_CEA_P Mean	1.5	4.5	1.5	High	Medium
EQ_CEA_P Value	**1.5**	**0.9**	**1.2**		
EQ_CEA_C1 Mean	13.4	13.3	8.3	Medium	Medium/High
EQ_CEA_C1 Value	**0.7**	**1.1**	**0.6**		
EQ_CEA_C2 Mean	4.6	7.1	3.5	Medium	Medium/High
EQ_CEA_C2 Value	**1.1**	**0.9**	**0.4**		

Table 5: Equity indicators distribution for different city-pairs.

The MAD-FRA and LGW-BCN have the same mean values of EQ_FL_P while having different EQ_FL_P values. This implies that the pure efficiency is the same for both city-pairs if the efficiency aggregation was performed by Airspace User, but that the inefficiencies are not equally shared between them. Figure 13 shows the different means associated to each Airspace User (AU) in each city-pair for this indicator. It should be mention that AUs are not necessarily the same in each city-pair.

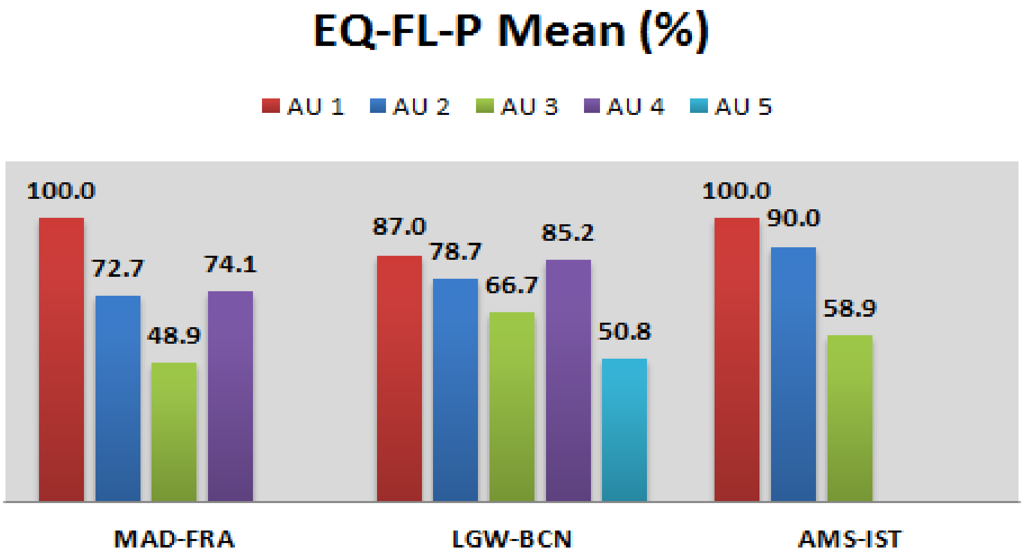

Figure 13: EQ-FL-P Mean values for each city-pair separated by AUs.

Independent of the number of flights, each AU receives an efficiency value and then their main differences can be observed. In the MAD-FRA city-pair, the inefficiencies associated to AU1 and AU3 are very dissimilar and thus the equity indicator gets higher (this is indeed worse Equity). On the other hand, LGW-BCN city-pair inefficiencies are more balanced and thus its Equity indicator is lower (better equity).

On the other hand, the MAD-FRA and AMS-IST have similar EQ_FL_P values while having different associated mean. This implies that the inefficiencies are equally shared between them, but in the case of AMS-IST the AUs have better associated mean. This means that more flights from AMS-IST achieve the requested flight level than the flights from MAD-FRA, although their distribution is not shared equally among AUs.

An operational example on the behaviour of different AUs in the same city-pair can be seen in Figure 14. In red, flights reaching their RFL are shown; while in blue flights not reaching their RFL are shown.

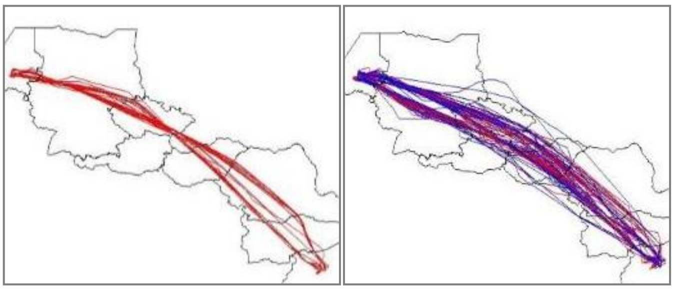

Figure 14: ADS-B tracks of AU1 and AU2 in city-pair AMS-IST

In these figures, the behaviour of both AUs can be appreciated in the same city-pair, as one airline always reaches their RFL (100%) and the other does not even get 60% (58.9%). This may be due to ATC constraints, but it is more likely that is showing different AUs strategies in the treatment of their flight plans and their execution. These differences in behaviour and strategies will affect the Equity indicators.

One of the analysis that may attract the reader's attention is the sensitivity of the indicator to the number of AUs in the city-pair. The differences can be seen in both LGW-BCN and AMS-IST city-pairs, with five and three AUs respectively. In both cases, one airline looks far below the rest, and the indicator reflects this sensitivity (as there are four left AU's in LGW-BCN and 2 in the AMS-IST). The values of the indicators (15.1% and 21.4%, respectively) are then a combination of the issue reported previously (disparities between AUs) and this sensitivity to the number of AUs in a city-pair.

In the case of EQ_CEA_C1 indicator, Table 5 shows the same trend in terms of the associated mean with respect to EQ_FL_P. MAD-FRA and LGW-BCN have the same associated mean, while AMS-IST has the best associated mean among the three. Thus, flights from AMS-IST has better CEA-C1 indicator and consequently costs of the AFT trajectories are closer to those of the OCT1 trajectories[9].

However, EQ_CEA_C1 distribution is inverse than the EQ_FL_P. As shown in Table 5, LGW-BCN has the better EQ_FL_P value between city-pairs, but it has the worst EQ_CEA_C1 value. This may be seen as another point of view of inefficiency. While EQ_FL_P may provide "bad" results in terms of Equity, EQ_CEA_C1 will reflect how cost inefficiencies are distributed without taking a specific look at the flight levels but the whole flight, as these cost inefficiencies are not always due to lower flight levels where more fuel is consumed.

2.4.3 Feasibility of the on-line processes to compute efficiency indicators

In this experiment, we first analysed the calculated values of the newly proposed indicators and how they evolve over time. To assess the accuracy of the online indicators we compared the indicator value calculated offline for each full trajectory to the online indicators calculated by on-line platform at the final point of each trajectory. To demonstrate that on-line processes can operate in near real-time we evaluated its performance in terms of throughput and latency.

The indicator values for each time stamp over a flight's duration was obtained. As an example, for a flight that departs from Dublin to London on the day of 2017 February 20th, the evolution of three of the flight efficiency indicators is plotted in Figure 15. The figure illustrates the trend after removing the first 200 trajectory points (roughly the taking-off stage, about 12minutes). After the indicators value converges and drops gradually to their lowest point, then it finally increases slightly during the landing phase of a flight. One thing worth of noting: Although some oscillations occur, which are due to differing resolution between the reconstructed actual trajectory and the generated optimal trajectories, the aforementioned general trend in most indicators is clear enough.

9 EQ_FL_P mean value is better in higher results, as it considers percentage of flights reaching the RFL. On the other hand, EQ_CEA_C1 mean compares deviations to optimum, which makes 0% the best possible outcome. In the case of the Equity indicators themselves, low values are always desirable.

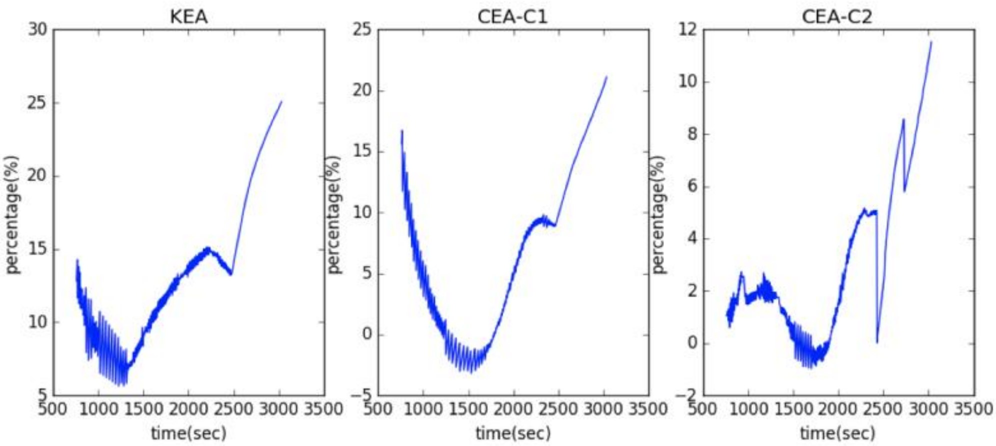

Figure 15: Evolution of indicators.

The accuracy of our proposed on-line indicator calculation method is measured in absolute error between offline (accurate) and online (approximate) indicator values. Compared with off-line indicator calculation, the on-line results are calculated using several approximations for obtaining good system performance. As the off-line indicator results have only one value for each flight (indicators are calculated only when the flight is completed), we choose the last on-line indicator value for each flight to compare. As shown in Figure 16, most of the on-line indicator values are very close to the accurate off-line value, especially for CEA_C2 that covers the overall excessive cost of the flight following horizontally the flight plan.

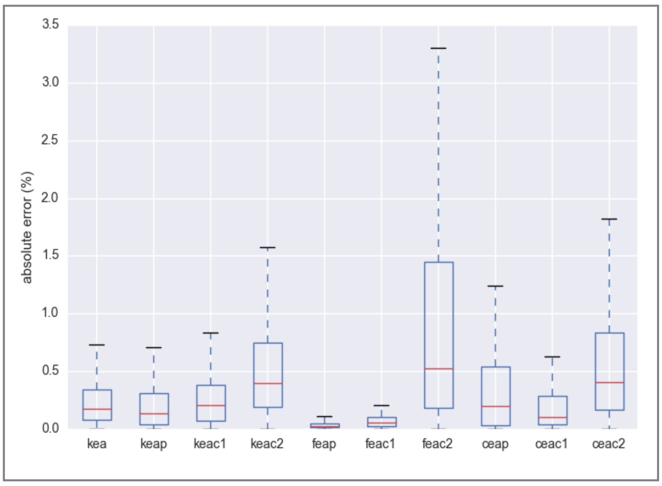

Figure 16: The distribution of absolute errors between off-line and on-line indicators value.

We define throughput as the number of data records processed by on-line platform per 10 minutes from the ADS-B surveillance data source. The throughput taken in the whole system is shown in Figure 17. The peak traffic is equivalent to about 345 records per second. Considering a lot of subsequent spatial computations (e.g. great circle distance calculation, nearest point search, point-in-polygon query), which are more computationally expensive than typical map and reduce operations in most big data applications, this throughput can still be considered heavy. Under such throughput, the latency that on-line platform achieves is shown in Figure 18. This latency accounts for the time spent for each message, from when a surveillance trajectory point is received by on-line platform, to the moment when a corresponding updated set of efficiency indicators is written in sink data store. It is worth nothing that the latency in this study contains the 5 seconds batch interval for the buffer between ADS-B data stream source and trajectory reconstruction service, the delay when reconstructing the trajectory, and the 15 seconds batch interval for Spark Streaming. A panel of expert airspace users, has recently set an update frequency (and so maximum allowed latency) target on efficiency indicator calculation of 5 minutes. The results of this show performance much better than this target. The mean latency for messages processed by on-line platform is 16.48 seconds, while the maximum latency observed for a message in our current dataset is just 35.79 seconds.

More information about this can be found in D3.3 [5].

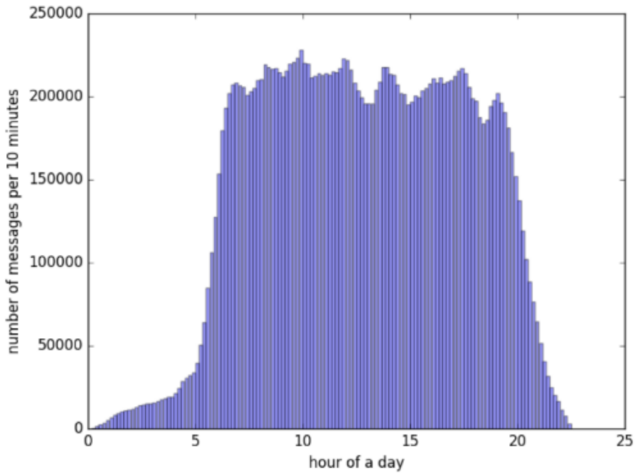

Figure 17: System throughput

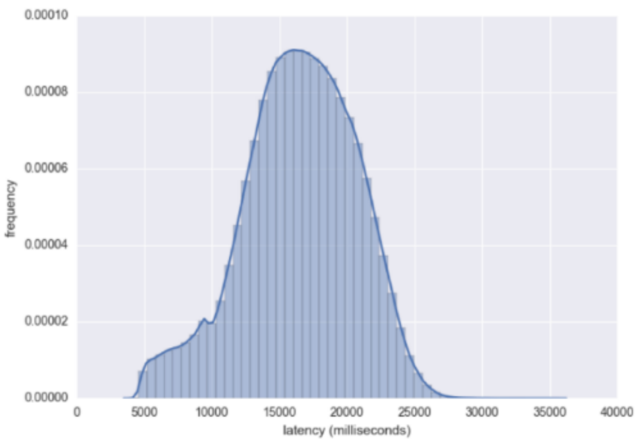

Figure 18: System latency

2.4.4 On-line monitoring of efficiency indicators in STAM solutions

One of the motivations of building the on-line platform for monitoring flight efficiency on-line is to enable better planning of STAM measures, which an air traffic controller (ATC) can use for re-routing or level-capping to alleviate any detected hotspots in tactical stage, rather than pre-tactical or strategic stages. An example of using the output of on-line platform to facilitate STAM decision-making is presented here.

A hotspot was identified in the Spanish airspace the day of July 2nd of 2017 at 11:30. This hotspot, identified in the sector DOMINGO UPPER, required the implementation of two STAMs in order to comply with the Occupancy Count of the sector. The 2 STAMs actually applied where two level-capping, which are also included in the total sample of 13 flights that are eligible for applying STAMs of any type in the selected traffic sample. Assuming that all flights follow the flight plan until the point of application of the STAM, 2 STAMs are selected among the 13 flights providing a total amount of 264 solution scenarios to be selected, including the real operational solution applied (which is referred as the reference scenario).

Each solution is measured in terms of the different efficiency indicators and an optimum solution in terms of each of them can be obtained.

Figure 19 shows all the possibilities of two STAM implementation ordered by its correspondent indicator value. As it can be seen in the figure in red colour, the actual STAM (which is indeed one of the possible solutions), can still be improved if efficiency was considered to take the decision. The results show that compared to the reference scenario, optimum efficient-based solutions may improve the overall efficiency of the hotspot from a mean CEA_C1 of 8.36 to a mean of 7.99. This implies a reduction of around 5% on the indicator. In total fuel consumption of the flights, the reduction rises up to almost 250 kilograms just by applying this optimum solution.

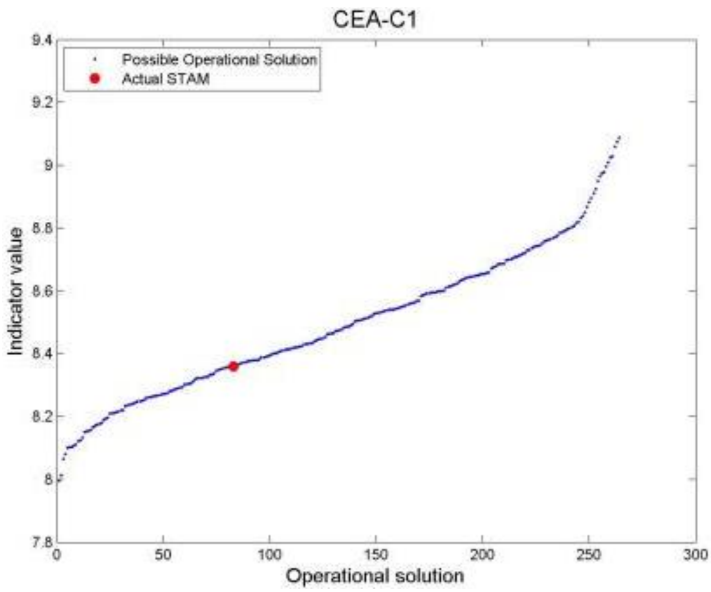

Figure 19: CEA_C1 indicator of every possible operational solution. Ordered by CEA_C1 value.

More information about this can be found in D5.1 [8].

2.5 Technical Deliverables

Reference	Title	Delivery Date[10]	Dissemination Level
	Description		
D1.1	Project Management Plan	29/09/2016	Public
This document is the Project Management Plan. It identifies and describes the procedures, the activities and the tools needed to organize, control, plan and coordinate the project. It addresses the following areas: scope, timing, costs, quality, resources, communications, and risk management.			
D2.1	Definition of user-centric air traffic efficiency indicators	20/02/2017	Public
This document describes the objectives and development of Work Package 2. It presents a study of the state of the art indicators, including a gap analysis of these indicators, the definition of advanced new metrics to improve flight efficiency measurement and the methodology followed for their calculation using historical data. It also includes the findings coming from AURORA's first workshop carried out in October 17th, 2016 in Madrid with AURORA's airspace users group.			
D3.1	Description of experimental plans	22/02/2017	Public
This document describes the verification and validation plan of AURORA's indicators and the methods to calculate them, defining the strategy followed to verify the feasibility of the proposed methods to obtain the new indicators, and to validate the expected operational benefits in the real environment. In the document, the experiments chosen for the verification of the off-line and on-line processes are stated, as well as the objectives selected for their verification. It also includes the validation scenarios and traffic samples, and the description of both processes, the data flow and data sources.			
D3.2	Report on testing of user-centric air traffic efficiency indicators and local targets	28/07/2017	Public
This report shows the outcome of AURORA's verification and validation plan for the methods based on historical data. This document evaluates the representativeness of the indicators in terms of fuel consumption or cost. It presents a summary of the experimental plan, the scenarios and assumptions used. During the course of Work Package 3, some difficulties were encountered which forced some deviations from the planned activities which are also presented here. Finally, an extensive analysis and the conclusions of the technical feasibility and the operational benefits of AURORA's indicators is presented, including the Airspace Users point of view on these indicators.			
D3.3	Report on testing of advanced performance data model	12/03/2018	Public
This report shows the outcome of AURORA's verification and validation plan for the methods based the on-line calculation. It describes and explains the methodology and results of testing the advanced performance data model developed. In particular, the overall motivation and evaluation plan and key results of proposed advanced performance data model are firstly introduced, followed by a detailed description of the stream-based data model testing results against the success criteria defined in the experimental plan. Finally, the conclusions of the full testing are represented along with the limitations when applied in production / realistic operation level.			

[10] Delivery data of latest edition

Reference	Title	Delivery Date[10]	Dissemination Level
	Description		
D4.1	Technical requirements for the data-stream analytics framework	15/03/2017	Public
This document describes the requirements of the AURORA online analytics platform that will be built both to calculate online efficiency and equity indicators and to perform experiments on these indicators. It describes the system architecture, the collection, storage, manipulation and requirements for each of the key data sources involved in the platform, and the processing requirements for each of the key tasks that the platform performs.			
D4.2	Stream-based data model	11/08/2017	Public
This document addresses the availability of stream-based data model prototype in support of the online calculation of user centric air traffic efficiency indicators. It confirms that the stream-based data model prototype was developed in conformance with the technical requirements of the D4.1, and was tested in conformance with the Experimental Plan fulfilling the defined Acceptance Criteria.			
D5.1	Performance assessment of the real-time performance monitoring framework.		Public
This document describes the process followed to analyse the influence of using AURORA's efficiency indicators in the application of STAMs. The document provides examples of actual STAM application compared to the most efficient solution according to AURORA's indicators, together with different analysis based on this scenario. It also evaluates the validation objectives according to the Experimental Plan.			
D6.3	Website	18/11/2016	Public
This website includes a summary of the project, the consortium and the work packages in the project. All technical deliverables and publications can also be found. www.aurora-er.eu			
D6.4	Final Project Results Report	31/03/2018	Public
This report explains in detail the scientific work performed so that the reader can identify which deliverables might be of interest in case he wants to read more detail			

Table 6: Technical Deliverables

3 Links to SESAR Programme

3.1 Contribution to the ATM Master Plan

AURORA delivers a set of advanced user-centric cost-based efficiency and equity indicators which address different aspects of efficiency such as the vertical component, fuel consumption or cost of the flight, thus introducing the Airspace User's viewpoint into consideration. These new indicators, together with the methodologies and advanced tools to calculate them, **cannot be considered as a SESAR solution by themselves**. No specific Operational Improvements (OIs) are addressing the definition of new indicators in the ATM Master Plan. This is due to the fact that no performance improvements can be directly derived from the implementation of new indicators to measure the network behaviour. The performance improvements will be indirectly obtained thanks to better strategic decisions when implementing new SESAR Solutions through the use of indicators that are better reproducing AUs' expectations. Thus, AURORA' indicators are transversal to the different SESAR solutions and, given the nature of the work, it is not possible to neither link the indicators to an existing OI Step nor define a new one. Our proposal is to identify **the set of AURORA's services** (Trajectories Reconstruction and Generation) as a **new enabler of the ATM Master Plan** that allows obtaining new indicators based on surveillance and flight plan data, considering the impact of weather conditions and without the need of confidential information from the airlines.

On the other hand, AURORA also delivers an advanced stream-based data model designed for calculating on-line efficiency indicators. This model is supported by techniques borrowed from the data science and information management fields for the collection and aggregation of data. The model is supported by the previously designed Trajectories Reconstruction and Generation Services. The use of this model for the resolution of Demand & Capacity imbalances will allow identifying those flights which will be less penalized in terms of fuel consumption or costs. This will allow implementing DCB or STAM measures considering Airspace Users' view on efficiency. Our proposal is to conside**r this model as a new enabler that transversally contributes to the SESAR Solutions addressing DCB and STAM**, which are those included in S2020 project "PJ09 Advanced DCB". This model will complement the existing enablers but cannot increase in isolation the maturity of the OIs.

- Solution PJ09-01 "Network Prediction and Performance" develops shared situation awareness with respect to demand, capacity and performance impacts. Network Operations will be continuously monitored through Network Performance KPAs/KPIs. AURORA's indicators will be added to these KPIs.

- Solution PJ09-02 "Integrated Local DCB Processes" represents the core functionality for the Integrated Network ATM Planning (INAP) process through an enhanced Local DCB tool set. The solution will improve the efficiency of ATM resource management, as well as the effectiveness of complexity resolutions by closing the gap between local network management and extended ATC planning.

- Solution PJ09-03 "Collaborative Network Management Functions" delivers subsidiary Network Management facilitated by a rolling NOP planning. Network Operations planning and Execution is managed by an agreed set of rules and procedures, guiding subsidiary DCB and UDPP measures under consideration of trade-offs and network performance targets.

The following table identified the enablers proposed by AURORA and existing OIs derived from previous solutions.

Code	Name	Project contribution	Maturity at project start	Maturity at project end
N/A	Increase awareness of Airspace Users' efficiency targets and how inefficiencies are distributed between Airspace Users.	New performance indicators for operational efficiency based on aircraft operators' needs.	TRL1	TRL2
SWIM-XX	Provision of centralised trajectories reconstruction and generation services through SWIM	1.- Trajectory Reconstruction enables the acquisition of the full state vector of the aircraft, including variables that are not explicitly included in the surveillance data and are needed to analyse the efficiency of the flight, such as the initial mass of the flight or fuel burnt. 2.- Trajectory Generation enables the production of synthetic trajectories never flown by the aircraft, but used as references for comparison purposes. Specific optimization criteria are considered for the generation of these synthetic trajectories.	TRL1	TRL2
DCB-0212	Network Performance Assessment for Distributed Network Operation	Network Operations performed at local, sub-regional and regional levels will be continuously monitored through Network Performance KPA/KPI. Stakeholders will be allowed to evaluate the impact of their intentions and decisions on capacity and QoS performance (flight efficiency, predictability, flexibility) at Network Level, using what if tools and Network Impact Assessment function.	TRL2	TRL2
CM-0104-B	Automated support to INAP (Integrated Network Management and ATC Planning)	The local roles within INAP (corresponding to Local Traffic Management and Extended ATC Planning) will be able to assess and resolve local complex situations (e.g. hotspots) through assessment of evolving traffic situation and evaluation of opportunities, in order to identify and manage the best performing option between Dynamic Airspace Configuration measures, flow management measures	TRL4	TRL4

Code	Name	Project contribution	Maturity at project start	Maturity at project end
		and trajectory measures (e.g. strategic de-confliction/synchronization).		
DCB-0215	Consolidation of imbalances and arbitration of Trajectory Management Solutions.	Measures from Airports (including Multi-APOC), ACCs, AUs and NM will be integrated and coordinated within SBT and RBT mechanisms to ensure the stability and performance of the network.	TRL4	TRL4
SWIM-XX	Provision of advanced stream-based data model for on-line calculation of efficiency indicators through SWIM	Advanced stream-based data model designed for calculating on-line efficiency indicators. This model is supported by techniques borrowed from the data science and information management fields for the collection and aggregation of data. The model is supported by the previously designed Trajectories Reconstruction and Generation Services	TRL0	TRL1

Table 7: Project Maturity

3.2 Maturity Assessment

The following table (Table 8) shows the maturity assessment of the enabler “Provision of centralised trajectories reconstruction and generation services through SWIM” proposed by AURORA project

ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRL-1.1	Has the ATM problem/challenge/need(s) that innovation would contribute to solve been identified? Where does the problem lie?	Achieved	Yes. The challenge is to overcome the limitations of the current indicator for the quantification of efficiency. Current indicator (KEA) measures the horizontal deviations of the flight with respect to the geodesic distance. KEA does not capture other factors influencing efficiency such as the weather conditions, the vertical component of the flight, the speed profile or the flight time. These factors are influencing the fuel consumption and costs of the flight and consequently, the efficiency from the perspective of the Airspace Users. D2.1 “Definition of user-centric air traffic efficiency indicators” summarizes all these limitations and defines new indicators to overcome these limitations.
TRL-1.2	Has the ATM problem/challenge/need(s) been quantified?	Achieved	Yes. Half of the inefficiencies are directly due to the constraints of the route design and they can be measured with current efficiency indicator (KEA). On the contrary, inefficiencies associated to the weather conditions, flight time or vertical profile among other factors are generating the other half of the inefficiencies and cannot be quantified with KEA. D3.2 “Final Project Results Report” summarizes these results (Exercise 1-2.- Benefits on the identification and monitoring of ECAC and local targets).
TRL-1.3	Are potential weaknesses and constraints identified related to the exploratory topic/solution under research? - The problem/challenge/need under research may be bound by certain constraints, such as time, geographical location, environment, cost of solutions or others.	Partially – Non blocking	There are no limitations to time, geographical location or environment for the implementation of the Centralised Trajectories Reconstruction and Generation Services. The costs of implementing this enabler were not quantified through a CBA but this is not identified as a blocking point.

ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRL-1.4	Has the concept/technology under research defined, described, analysed and reported?	Achieved	Yes. The technologies used for the enabler Centralised Trajectories Reconstruction and Generation Services are described in D3.1 “Description of Experimental Plans”. These technologies are verified and results are reported in D3.2 “Final Project Results Report”. In particular, Exercise 1-1 “Verification of the methods for the off-line calculation of indicators” assesses the proposed technologies.
TRL-1.5	Do fundamental research results show contribution to the Programme strategic objectives e.g. performance ambitions identified at the ATM MP Level?	Not applicable	Current SESAR performance ambitions are not specifically addressed. AURORA can help to define new ambitions or targets making reference to the Airspace Users’ expectations.
TRL-1.6	Do the obtained results from the fundamental research activities suggest innovative solutions/concepts/ capabilities? - What are these new capabilities? - Can they be technically implemented?	Achieved	Yes. The enabler Centralised Trajectories Reconstruction and Generation Services will allow obtaining a set of high-detailed user-preferred trajectories when the services are called and a collection of surveillance data (ADS-B or radar) are submitted.
TRL-1.7	Are physical laws and assumptions used in the innovative concept/technology defined?	Achieved	Yes. Physical laws and assumptions for the enabler Centralised Trajectories Reconstruction and Generation Services are described in D3.1 “Description of Experimental Plans”.
TRL-1.8	Have the potential strengths and benefits identified? Have the potential limitations and disbenefits identified? - Qualitative assessment on potential benefits/limitations. This will help orientate future validation activities. It may be that quantitative information	Achieved	Yes. Benefits and limitations of the Centralised Trajectories Reconstruction and Generation Services were quantified. In particular, there is room for improvements in the following areas: • Requested time to process all flights per month in the ECAC area.

ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
	already exists, in which case it should be used if possible.		• Ratio of optimal trajectories that are well generated. • Deviations of the calculated initial mass of the flight and fuel consumption with respect to the real data (provided by the airlines participating in the Airspace Users' Group). D3.2 "Final Project Results Report" summarizes these results (Exercise 1-1 "Verification of the methods for the off-line calculation of indicators" assesses the feasibility of the proposed Services and Exercise 1.2 "Benefits on the identification and monitoring of ECAC and local targets" assesses the operational benefits of using the new indicators associated to the generated trajectories).
TRL-1.9	Have Initial scientific observations been reported in technical reports (or journals/conference papers)?	Achieved	Yes. Results are reported in D3.2 "Final Project Results Report".
TRL-1.10	Have the research hypothesis been formulated and documented?	Achieved	Yes. D3.1 "Description of Experimental Plans" describes this research hypothesis.
TRL-1.11	Is there further scientific research possible and necessary in the future?	Achieved	Even though the results are strongly promising, further research is needed to address mainly: • Systematically evaluate the indicators in wider samples; • Wider consensus between stakeholders in the notion of optimal cost-based trajectory for comparison purposes;

ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
			• Further refinement of the initial mass and fuel consumption calculation to reduce current deviations. We believe that a research project at TRL 2-4 is the natural next step to take.
TRL-1.12	Are stakeholder's interested about the technology (customer, funding source, etc.)?	Achieved	Yes. AURORA has iteratively presented its results to an Airspace Users Group composed by Iberia, Air Europa, KLM, Turkish Airlines and Novair to ensure the commitment with the approach.

Table 8: ER Fund / AO Research Maturity Assessment for offline process.

Table 9 shows the maturity of the enabler “Provision of advanced stream-data model for on-line calculation of efficiency indicators through SWIM”.

ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRL-1.1	Has the ATM problem/challenge/need(s) that innovation would contribute to solve been identified? Where does the problem lie?	Achieved	Yes. The challenge is to take short-term ATM decisions for demand and capacity balancing which consider also the Airspace Users' interest and not only the network and ANSPs' views. AURORA proposes to take decisions on which aircrafts will be affected by a STAM measure and how they will be affected (rerouting, level-capping) by considering the efficiency of each impacted flight. This application will be based on the on-line calculation of efficiency indicators and predictions at the end of the flight. D3.1 "Description of Experimental Plans" summarizes current limitations and proposes changes in the current use case for the resolution of hotspots through STAM measures.

ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRL-1.2	Has the ATM problem/challenge/need(s) been quantified?	Partial - Non Blocking	Yes. It was quantified how the resolution of one real hotspot in the Spanish airspace is impacting the efficiency indicators of the flights involved. However, this experiment was only performed with a unique hotspot. D5.1 “Report on on-line monitoring of user-centric efficiency and equity indicators”describes the results of this experiment.
TRL-1.3	Are potential weaknesses and constraints identified related to the exploratory topic/solution under research? - The problem/challenge/need under research may be bound by certain constraints, such as time, geographical location, environment, cost of solutions or others.	Partial - Non Blocking	There are no limitations to time, geographical location or environment for the implementation of advanced stream-data models for on-line calculation of efficiency indicators. The costs of implementing this enabler were not quantified through a CBA but this is not identified as a blocking point.
TRL-1.4	Has the concept/technology under research defined, described, analysed and reported?	Partial - Non Blocking	Yes. The concept with the associated use case is detailed in D3.1 "Description of experimental plan". The requirements and technologies used for the enabler are described in D4.1 "Data Streaming Requirements". The verification and validation activities are described in D3.1 "Description of experimental plan". The results are reported in D3.3 "Report on testing of advanced performance data model" (verification) and in D5.1 "Report on on-line monitoring of user-centric efficiency and equity indicators" (validation in a real environment). As it was not possible to do the full integration between the enabler "Provision of centralised trajectories reconstruction and generation services through SWIM” and this enabler for the on-line calculation of indicators, it was necessary to do some assumptions on latency and throughput to perform the experiments to verify the proposed technologies. This was not identified as a blocking point.

ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRL-1.5	Do fundamental research results show contribution to the Programme strategic objectives e.g. performance ambitions identified at the ATM MP Level?	Not Applicable	Current SESAR performance ambitions are not specifically addressed. AURORA can help to define new ambitions or targets referring to the Airspace Users' expectations.
TRL-1.6	Do the obtained results from the fundamental research activities suggest innovative solutions/concepts/ capabilities? - What are these new capabilities? - Can they be technically implemented?	Achieved	Yes. The proposed enabler will allow extending the scope of several SESAR solutions within the Demand and Capacity field. This new enabler will allow introducing new performance targets dealing with efficiency in these solutions. AURORA demonstrated that the proposed enabler can be technically implemented.
TRL-1.7	Are physical laws and assumptions used in the innovative concept/technology defined?	Achieved	Yes. Physical laws and assumptions for the proposed enabler are described in D3.1 "Description of Experimental Plans" and in D4.1 "Data Streaming Requirements".
TRL-1.8	Have the potential strengths and benefits identified? Have the potential limitations and disbenefits identified? - Qualitative assessment on potential benefits/limitations. This will help orientate future validation activities. It may be that quantitative information already exists, in which case it should be used if possible.	Partial - Non Blocking	Yes. Benefits and limitations of the proposed enabler were quantified. This critiriom is considered as partially achieved as it was not possible for planning constraints to do the full integration between the enabler "Provision of centralised trajectories reconstruction and generation services through SWIM" and this enabler for the on-line calculation of indicators. D3.3 "Report on testing of user-centric air traffic efficiency indicators and local targets" summarizes the assessment of the feasibility of the proposed enabler and D5.1 "Report on on-line monitoring of efficiency and equity indicators" describes the operational benefits.
TRL-1.9	Have Initial scientific observations been reported in technical reports (or journals/conference papers)?	Achieved	Yes. Results are reported in D3.3 "Report on testing of advanced performance data model".

ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRL-1.10	Have the research hypothesis been formulated and documented?	Achieved	Yes. D3.1 "Description of Experimental Plans" describes this research hypothesis.
TRL-1.11	Is there further scientific research possible and necessary in the future?	Achieved	Further research is needed to address mainly: • Full integration of the Centralized Trajectories Generation Services within the data streaming model. • Introduction of algorithms to predict the values of the indicators at the end of the flight and not only the value at the point in which the flight is. We believe that a research project at TRL 1-2 is the natural next step to take.
TRL-1.12	Are stakeholder's interested about the technology (customer, funding source, etc.)?	Partial - Non Blocking	AURORA Airspace Users Group composed by Iberia, Air Europa, KLM, Turkish Airlines and Novair showed their interest in this application for different use cases such as for instance the use in the cockpit to monitor the evolution of the efficiency of the flight. However, ANSPs and network manager should assess this technology and results.

Table 9: ER Fund / AO Research Maturity Assessment for online process.

4 Conclusion and Lessons Learned

4.1 Conclusions

Conclusions are structured in twofold. First, we will detail the conclusions dealing with the set of AURORA's services (Trajectories Reconstruction and Generation) that allows obtaining new efficiency and equity indicators based on surveillance and flight plan data. Second, we will summarise the conclusions related to the advanced stream-based data model designed for calculating on-line efficiency indicators and its use for the application of STAM measures.

4.1.1 Trajectories reconstruction and generation services for the off-line computation of indicators

ADS-B data are a reliable source for the performance monitoring at the ECAC level, providing a new paradigm where ANSP's performance is not only evaluated locally, i.e., at the level of an ANSP area of responsibility, but also globally, assessing how the actions of an ANSP impact the overall efficiency of a flight.

As stated in the section 2.4, the process to calculate the AURORA's indicators (trajectory reconstruction, trajectory generation and indicators calculation) was proven as **technically feasible.** ADS-B data and flight plans for more than 30,000 flights were processed with a success rate higher than 90% for reconstructed trajectories and higher than 70% for all the generated trajectories. The proposed service-oriented approach allowed obtaining the full state vector of the aircraft and generating several optimal trajectories, considering the impact of weather conditions and without the need of confidential information from the airlines.

Although the trajectories used for the calculation of the indicators may have some errors in their variables (as mass or speeds), these do not affect the indicators significantly, as they are defined as differences of the different parameters of the trajectories.

Computation power and automation of the trajectory reconstruction and generation process were identified as key issues to properly address the objective of performing the calculation of AURORA indicators for wider periods e.g. one month. Throughput of the trajectories reconstruction and generation services needs to be improved by using several remote serves to calculate the trajectories in parallel.

Isolation of TMA and en-route effects may imply the generation of trajectories considering SIDs and STARs and runway configurations. At this point, the only generated trajectories considering the SIDs and STARs are the flight plan trajectories. Geodesic and free route trajectories do not take them into consideration, nor the initial or final turns to align the aircraft with the runway. These turns are very short in time and do not affect the fuel consumption by much.

AURORA's approach to decompose the efficiency of the whole flight from origin to destination into local values was applicable for the different efficiency indicators. Unlike the current approach to isolate local efficiency used by EUROCONTROL, the *Achieved Distance Methodology*, the proposed methodology decomposes global indicators into local values without considering exclusively geographical considerations and thus is applicable for the set of optimal reference trajectories proposed by AURORA. Conversely, the methodology needs more time to compute than the *Achieved Distance Methodology* because it is necessary to generate multiple optimal reference trajectories from each entry point into each region crossed by the flight.

As stated in the section 2.4, AURORA results proved the **benefits of the indicators** computing the deviations of actual trajectories versus flight plans (KEA_P, FEA_P, VEA_P and CEA_P) to monitor the flight efficiency taking into consideration the restrictions of the current network. Deviations in terms of costs or fuel consumption are not necessary aligned with the differences in the horizontal distance between actual and planned trajectories.

Vertical and speed profiles together with the impact of weather conditions (wind, temperature and pressure) are relevant factors to be taken on board in order to quantify how cost-efficient a flight is, and this is not considered in today's indicator, i.e. KEA. These factors are influencing both fuel consumption and flight time as the most relevant components of the flight costs, as it was presented in section 2.4.

Indicators computing the deviations of actual trajectories versus optimal cost-based trajectories in free route (KEA_C1, FEA_C1, VEA_C1 and CEA_C1) could be the ones to drive the ECAC towards the future system in which airlines could flight their optimum flight profiles in a free route environment. In terms of representativeness, the one that provides a more complete view of the Airspace Users' inefficiencies is the CEA_C1, and AUs selected it as the most promising one in the AURORA's workshops. On the contrary, KEA_C1 does not provide benefits with respect to the current indicator to monitor horizontal deviations i.e. KEA. Results proved that weather (wind, pressure and temperature) is not causing major horizontal deviations of the optimal cost-based trajectories in free route with respect to the geodesic for short and medium-haul flights.

Indicators computing the deviations of actual trajectories versus optimal cost-based trajectories following horizontally the flight plan (KEA_C2, FEA_C2 VEA_C2 and CEA_C2) represents the improvements on efficiency that could be reached taking into consideration the current route design. AURORA's results showed that half of the inefficiencies in terms of costs are due to the constraints in the route design.

Through an Airspace User perspective, Equity indicators' target was to capture equity in terms of flight level and costs. The main relevant and useful analysis on equity indicators was to focus in the division by city-pair. Different flows and ATCO shifts were analysed too concluding that these have a strong impact on the Equity.

Equity indicators provide an insight on how inefficiencies are distributed among airlines, allowing the detection of regions or routes that present abnormal values comparing with the average. However, Airspace Users highlighted that not always is easy to recognize the causes of these inequities, which could respond in some cases to the companies strategies.

4.1.2 Stream-based data model for the on-line computation of efficiency indicators

The stream-based data model to calculate the indicators met the expectations set by the AURORA Airspace Users Group in terms of latency and throughput. The system can cope with high volume of ingesting surveillance data stream up to 361 messages per second with no data loss, no duplicated data, and no out-of-sequence data results. Additionally, the system can response to each surveillance trajectory point with its corresponding 10 efficiency indicators' results within only 33 seconds on average, and for over 99% case less than 77 seconds.

The last point of on-line flight efficiency results calculated by the stream-based data model was very close to its off-line value. In particular, for 10 flight efficiency indicators over 1000 test flights, the maximum absolute error found so far is less than 3.5%. Thus, the accuracy of this on-line process was found as acceptable.

Using proposed "nearest point search" methodology, the on-line system provided corresponding flight efficiency indicator values for each given flight surveillance data. Thus for each flight there are roughly thousands of indicator values (depends on the number of flight efficiency indicators and the number of reconstructed trajectory points) over the full course of a flight, rather than only one indicator value when a flight is landed.

There was a wide range of possible STAM solutions for the resolution of a hotspot and each of them provided different efficiency values. The use of AURORA' efficiency indicators in the resolution of hotspots through the application of STAM measures allows selecting the most efficient solution from the perspective of the Airspace Users. Depending on the decision on which STAM measure to apply, the fuel consumption of all affected flights can be reduced in nearly 500 kilograms.

4.2 Technical Lessons Learned

4.2.1 Trajectories reconstruction and generation services for the off-line computation of indicators

ADS-B coverage is a key point for the entire process. Since the reconstructed trajectories come directly from the ADS-B data, and since the generated trajectories take as input some of the parameters from these trajectories (e.g. initial mass), it is necessary to have full ADS-B coverage of the trajectories to accurately calculate the aircraft state vector.

Uncompleted trajectories (over-flights and trajectories that started or finished outside of the ECAC area) can be calculated using ADS-B data. If full ADS-B coverage is used, it is possible to calculate the initial mass at destination although destinations or origins are out of the ECAC area. This is an advantage with respect to radar data which is dependent on the local ANSP.

Additional information provided by the Airspace Users would result in an improvement of the process. Unknown parameters, such as the initial mass or the cost index, would improve the trajectory reconstruction and generation process. The estimation of these parameters was not identified as a blocking issue to reconstruct and generate reliable trajectories for the indicators calculation.

The service-oriented approach to the trajectory reconstruction and generation processes will increase confident on the Airspace Users on the proposed efficiency indicators, as they will be able to remotely access and test their own performances.

Ensuring appropriate understanding of the new efficiency and equity indicators was an issue during the early stages of the project. Close cooperation between partners and airlines participating in the Airspace User Group allowed overcoming this issue, but nomenclature and definition of the indicators need to be improved to ensure the proper dissemination to a wider audience of stakeholders.

Dimension of traffic samples must be adapted to the specific indicator in place. As an example, traffic sample requirements for efficiency and for equity indicators were different. In the case of equity, one single day of operations was not enough to obtain consolidated conclusions and traffic sample was extended to one month of data to have airlines with several flights in each city pair.

4.2.2 Stream-based data model for the on-line computation of efficiency indicators

The data pre-processing should never be underestimated. Many noisy surveillance data points could fail the trajectory reconstruction service. This makes necessary to develop processes to pre-process and refine ADS-B data prior to the execution of the services.

The on-line data pipeline should be tested carefully and the test of the whole pipeline can be passed only when ingesting large enough data set. Different software versions may cause incompatibility when testing on-line data pipeline. The more components included in the pipeline, the more unexpected errors could occur when testing the whole pipeline. Thus, it is recommended to add components only when it is necessary.

To achieve decent system performance, disk I/O operations should be avoided over the processing duration of data pipeline. Any intermediate data generated in the pipeline should be quickly pushed to the following component. These accounts the assumptions that were made to integrate the trajectory reconstruction and generation services in the stream-based data model.

4.3 Recommendations for future R&D activities (Next steps)

Inside AURORA, there are 3 main activities that should be carried out in the future to continue with this R&D:

1. The first activity consists in the definition of a unique optimum trajectory. This trajectory should represent the airspace user future preferences (free route), and should be agreed by a wide number of airlines, with different business strategies, and by the ANSP.

2. The second activity consist in the evaluation of the local decomposition of the efficiency indicators together with the ANSPs, to agree how inefficiencies in previous sectors affects in the next sectors or ACC.

3. In addition, the last activity consist in the definition together with airlines of a methodology to calculate, the cost of a flight. It should be assessed if we need a complex formula to include delays, crew costs, connecting passengers… or, on the other hand, it is enough to quantify just the taxes, the price of the fuel and the time as the major sources of costs identified in AURORA.

As project related to performance, AURORA was invited to attend to the Performance Work Forum celebrated on February 7th 2018. One of the objectives of the meeting was to break the gap between ER and IR, in particular the objective was focus on how to incorporate ER results, related to performance, in the IR PJ19.04.

Related to AURORA two activities were set for future research:

1. One related to the definition of a unique optimum trajectory that is the same activity that was explained above.

2. The second activity is to evaluate the feasibility of the process describe in AURORA in order to calculate the new indicators proposed. In that sense, it was proposed and agreed to identify a volunteer project, initially PJ06, to test if the process is feasible.

5 References

5.1 Project Deliverables

[1] AURORA D1.1, “Project Management Plan”, Edition 00.01.01, Jun 2016.

[2] AURORA D2.1, “Definition of User-Centric Air Traffic Efficiency Indicators”, Edition 00.0.1.01, Feb 2017.

[3] AURORA D3.1, “Description of experimental plans”, Edition 00.01.00, Feb 2017.

[4] AURORA D3.2, “Report on testing of user-centric air traffic efficiency indicators and local targets”, Edition 00.01.00, Jul 2017.

[5] AURORA D3.3, “Report on testing of advanced performance data model”, Edition 00.01.00, Mar 2018.

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Appendix A

A.1 Glossary of terms

Term	Definition	Source of the definition

Table 10: Glossary.

A.2 Acronyms and Terminology

Term	Definition
ACC	Area Control Center
ADS	Automatic Dependent Surveillance
ADS-B	Automatic Dependent Surveillance - Broadcast
AEA	Air Europa ICAO Code
AFT	Actual Flown Trajectory
AIDL	Android Interface Definition Language
ANS	Air Navigation Sistem
ANSP	Air Navigation Service Provider
ASMA	Arrival Sequencing and Metering Area
ATC	Air Traffic Control
ATCFM	Air Traffic Control and Flow Management
ATCO	Air Traffic Controller
ATFCM	Air Traffic Flow and Capacity Management
ATM	Air Traffic Management
AU	Airspace User
AURORA	Advanced User-centric efficiency metRics for air traffic perfORmance Analytics
BADA	Base of Aircraft Data
CANSO	Civil Air Navigation Services Organization
CBA	Cost-Benefit Analysis
ECAC	European Civil Aviation Conference
ECML PKDD	European Conference on Machine Learning and Principles and Practice of Knowledge Discovery in Databases
ER	Exploratory Research

EU	European Union
FAA	Federal Aviation Administration
FIR	Flight Information Region
FL	Flight Level
FPT	Flight Plan Trajectory
HMI	Human-Machine Interface
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
INCEPT	Boeing's aircraft intent generation and trajectory synthetizer
INTRACT	Boeing's aircraft intent inference and trajectory reconstructor
INTRO	Boeing's intent-based trajectory optimizer
KPA	Key Performance Area
KPI	Key Performance Indicator
LC	Level-Capping
NM	Network Manager
NOAA	National Oceanic and Atmospheric Administration
OCT1	Optimal Cost-Based Trajectory 1 (Fuel & Time)
OCT2	Optimal Cost-Based Trajectory 2 (Fuel & Time & Taxes)
ODT	Optimal Distance Trajectory
OI	Operational Improvement
PRU	Performance Review Unit
RFL	Reference Flight Level
RR	Re-Routing
SESAR	Single European Sky ATM Research Programme
SIDS	SESAR Innovation Days
SJU	SESAR Joint Undertaking (Agency of the European Commission)
STAM	Short-Term ATCFM Measures
SWIM	System-wide Information Management
TMA	Terminal Manoeuvring Area

Table 11: Acronyms and terminology.

Appendix B Set of consolidated indicators

The following table summarizes the set of indicators that has been consolidated on AURORA's project together with their description, the required data and the specific formula used for its computation.

Code	Description	Formula
KEA	Horizontal flight efficiency of actual trajectory taking as reference the minimum flown distance	$KEA = \left(\frac{L_{AFT}}{L_{ODT}} - 1\right)\%$ where L_{AFT} is the horizontal distance flown by the reconstructed trajectory based on surveillance data and L_{ODT} is the great-circle distance between origin and destination
KEA_P	Horizontal flight efficiency of actual trajectory taking as reference the flight plan flown distance	$KEA\_P = \left(\frac{L_{AFT}}{L_{FPT}} - 1\right)\%$ where L_{FPT} is the horizontal distance flown by the flight plan
KEA_C1	Horizontal flight efficiency of actual trajectory taking as reference the minimum cost trajectory in free flight	$KEA\_C1 = \left(\frac{L_{AFT}}{L_{OCT1}} - 1\right)\%$ where L_{OCT1} is the horizontal distance flown by the minimum cost trajectory in free flight
KEA_C2	Horizontal flight efficiency of actual trajectory taking as reference the minimum cost trajectory following horizontally the flight plan	$KEA\_C2 = \left(\frac{L_{AFT}}{L_{OCT2}} - 1\right)\%$ where L_{OCT2} is the horizontal distance flown by the minimum cost trajectory following horizontally the flight plan
FEA_P	Comparison between calculated fuel consumption of the actual trajectory and fuel consumption calculated of the flight plan	$FEA\_P = \left(\frac{\Delta m_{AFT}}{\Delta m_{FPT}} - 1\right)\%$ where Δm_{AFT} is the fuel consumption of the reconstructed trajectory based on surveillance data, and Δm_{FPT} is the fuel consumption of the flight plan
FEA_C1	Comparison between calculated fuel consumption of the actual trajectory and fuel consumption of the minimum cost trajectory in free flight	$FEA\_C1 = \left(\frac{\Delta m_{AFT}}{\Delta m_{OCT1}} - 1\right)\%$ where Δm_{OCT1} is the fuel consumption of the minimum cost trajectory in free flight
FEA_C2	Comparison between calculated fuel consumption of the actual trajectory and fuel consumption of the minimum cost trajectory following horizontally the flight plan	$FEA\_C2 = \left(\frac{\Delta m_{AFT}}{\Delta m_{OCT2}} - 1\right)\%$ where Δm_{OCT2} is the fuel consumption of the minimum cost trajectory following horizontally the flight plan
CEA_P	Comparison between calculated costs of actual trajectory and calculated costs of the flight plan	$CEA\_P = \left(\frac{C_{AFT}}{C_{FPT}} - 1\right)\%$ $C = p_{FUEL} \cdot (\Delta m + CI \cdot \Delta t) + RC$ where C_{AFT} is the calculated cost of the reconstructed trajectory based on surveillance data, C_{FPT} is the calculated cost of the flight plan, p_{FUEL}

Code	Description	Formula
		is the average fuel price, CI is the Cost Index and RC are the route charges
CEA_C1	Comparison between calculated costs of actual trajectory and calculated costs of the minimum cost trajectory in free flight	$CEA\_C1 = \left(\frac{C_{AFT}}{C_{OCT1}} - 1\right)\%$ $C = p_{FUEL} \cdot (\Delta m + CI \cdot \Delta t) + RC$ where C_{OCT1} is the calculated cost of the minimum cost trajectory in free flight
CEA_C2	Comparison between calculated costs of actual trajectory and calculated costs of the minimum cost trajectory following horizontally the flight plan	$CEA\_C2 = \left(\frac{C_{AFT}}{C_{OCT2}} - 1\right)\%$ $C = p_{FUEL} \cdot (\Delta m + CI \cdot \Delta t) + RC$ where C_{OCT2} is the calculated cost of the minimum cost trajectory following horizontally the flight plan
VEA_P	It quantifies the vertical flight efficiency comparing average cruise flight level of the actual trajectory with average cruise[11] flight level of the planned trajectory.	$VEA\_P = \left(\frac{avgFL_{AFT}}{avgFL_{FPT}} - 1\right)\%$ where $avgFL_{AFT}$ is the cruise average flight level of the reconstructed trajectory based on surveillance data and $avgFL_{FPT}$ is the reference flight level
VEA_C1	It quantifies the vertical flight efficiency comparing average flight cruise level of the actual trajectory with average cruise flight level of the minimum cost trajectory in free flight.	$VEA\_C1 = \left(\frac{avgFL_{AFT}}{avgFL_{OCT1}} - 1\right)\%$ where $avgFL_{OCT1}$ is the cruise average flight level of the OCT1
VEA_C2	It quantifies the vertical flight efficiency comparing average en-route flight level of the actual trajectory with average en-route flight level of the minimum cost trajectory following horizontally the flight plan).	$VEA\_C2 = \left(\frac{avgFL_{AFT}}{avgFL_{OCT2}} - 1\right)\%$ where $avgFL_{OCT2}$ is the cruise average flight level of the OCT2
EQ_FL_P	It quantifies the differences between airlines in the percentage of flights that achieve the requested flight level[12].	$EQ\_FL\_P = \sqrt{\sum_{j=1}^{n} \frac{\left(x_{AUj} - \overline{x_{FL}}\right)^2}{n-1}}$ with $x_{AUj} = \frac{\sum_{\forall flights \in AU_j} \cdot FL}{number\ of\ flights \in AU_j}\%$ $FL = 1\ if\ maxCL \geq RFL$

11 The portion of the trajectory from Top of Climb (TOC) to Top of Descend (TOD).

12 Requested flight level is assumed as the optimum for the airline.

Code	Description	Formula
	It compares maximum flight level of actual trajectory with maximum flight level of the flight plan trajectory.	$FL = 0\ if\ maxCL < RFL$ $\overline{x_{FL}} = \sum_{j=1}^{n} \frac{x_{AU\,j}}{n}$ where $maxCL$ is the maximum clearance level, n is the number of airspace users and RFL is reference level from last filed flight plan
EQ_FL_C1	It quantifies the differences between airlines in the percentage of flights that achieve the optimum flight level. It compares maximum flight level of actual trajectory with maximum flight level of the minimum cost trajectory in free flight.	$EQ\_FL\_C1 = \sqrt{\sum_{j=1}^{n} \frac{\left(x_{AU\,j} - \overline{x_{FL}}\right)^2}{n-1}}$ with $x_{AU\,j} = \frac{\sum_{\forall flights \in AU_j} FL}{number\ of\ flights \in AU_j}\%$ $FL = 1\ if\ maxCL \geq FL_{OCT1}$ $FL = 0\ if\ maxCL < FL_{OCT1}$ $\overline{x_{FL}} = \sum_{j=1}^{n} \frac{x_{AU\,j}}{n}$ where $maxCL$ is the maximum clearance level, n is the number of airspace users and FL_{OCT1} is the maximum level of the OCT1
EQ_FL_C2	It quantifies the differences between airlines in the percentage of flights that achieve the optimum flight level. It compares maximum flight level of actual trajectory with maximum flight level of the minimum cost trajectory following horizontally the flight plan.	$EQ\_FL\_C2 = \sqrt{\sum_{j=1}^{n} \frac{\left(x_{AU\,j} - \overline{x_{FL}}\right)^2}{n-1}}$ with $x_{AU\,j} = \frac{\sum_{\forall flights \in AU_j} FL}{number\ of\ flights \in AU_j}\%$ $FL = 1\ if\ maxCL \geq FL_{OCT2}$ $FL = 0\ if\ maxCL < FL_{OCT2}$ $\overline{x_{FL}} = \sum_{j=1}^{n} \frac{x_{AU\,j}}{n}$ where $maxCL$ is the maximum clearance level, n is the number of airspace users and FL_{OCT2} is the maximum level of the OCT2
EQ_CEA_P	It quantifies the differences between airlines in terms of costs. It compares costs of actual trajectories with cost of planned trajectories.	$EQ\_CEA\_P = \sqrt{\sum_{j=1}^{n} \frac{\left(x_{AU\,j} - \overline{x_C}\right)^2}{n-1}}$ $x_{AU\,j} = \frac{\sum_{\forall flights \in AU_j} C_{AFT}/C_{FPT}}{number\ of\ flights\ \in\ AU_j}\%$ $\overline{x_C} = \sum_{j=1}^{n} \frac{x_{AU\,j}}{n}$ $C = p_{FUEL} \cdot (\Delta m + CI \cdot \Delta t) + RC$ where CI is Cost Index, Δt is flight time, p_{FUEL} is the average fuel price and RC are the route charges, and C_{AFT} are total costs of actual trajectory and C_{FPT} are total costs of FPT
EQ_CEA_C1	It quantifies the differences between airlines in terms of costs.	$EQ\_CEA\_C1 = \sqrt{\sum_{j=1}^{n} \frac{\left(x_{AU\,j} - \overline{x_C}\right)^2}{n-1}}$

Code	Description	Formula
	It compares costs of actual trajectories with costs of the minimum cost trajectory in free flight.	$x_{AUj} = \frac{\sum_{\forall flights \in AU_j} C_{AFT}/C_{OCT1}}{number\ of\ flights\ \in\ AU_j} \%$ $\overline{x_C} = \sum_{j=1}^{n} \frac{x_{AUj}}{n}$ $C = p_{FUEL} \cdot (\Delta m + CI \cdot \Delta t) + RC$ where CI is Cost Index, Δt is flight time, $p_{FUEL}$is the average fuel price and RC are the route charges, and C_{AFT} are total costs of actual trajectory and C_{OCT1} are total costs of OCT1
EQ_CEA_C2	It quantifies the differences between airlines in terms of costs. It compares costs of actual trajectories with costs of the minimum cost trajectory following horizontally the flight plan.	$EQ\_CEA\_C2 = \sqrt{\sum_{j=1}^{n} \frac{(x_{AUj} - \overline{x_C})^2}{n-1}}$ $x_{AUj} = \frac{\sum_{\forall flights \in AU_j} C_{AFT}/C_{OCT2}}{number\ of\ flights\ \in\ AU_j} \%$ $\overline{x_C} = \sum_{j=1}^{n} \frac{x_{AUj}}{n}$ $C = p_{FUEL} \cdot (\Delta m + CI \cdot \Delta t) + RC$ where CI is Cost Index, Δt is flight time, $p_{FUEL}$is the average fuel price and RC are the route charges, and C_{AFT} are total costs of actual trajectory and C_{OCT2} are total costs of OCT2

Table 12: AURORA´s Indicators.