Advanced Flight Efficiency Key Performance Indicators to support Air Traffic Analytics: Assessment of European flight efficiency using ADS-B data

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Abstract—Flight efficiency is of great concern in the Air Traffic Management (ATM) community since today's ATM inefficiencies affect both airspace users (AUs) and Air Navigation Service Providers (ANSPs). Each actor has their own vision of flight efficiency: whereas airlines are concerned mainly with aspects that impact their business strategy (fuel consumption, schedule adherence and cost), ANSPs consider other aspects such as sector capacity, Air Traffic Controller (ATC) interventions, emissions and noise. Capturing both visions in new Key Performance Indicators (KPIs) is important to take new steps towards more sustainable air traffic operations.

The current standard KPI used to measure flight efficiency is the "horizontal flight efficiency", which measures the horizontal excess en-route distance compared to the orthodromic distance. This view of efficiency is very limited since it doesn't take into account other sources of inefficiencies, namely meteorological conditions or the vertical profile of the flight, that have a big impact on the AUs operational objectives. Therefore, advanced metrics are being developed to include these objectives in the assessment of efficiency and to analyse how the inefficiencies are distributed among them, as well as new methodologies to calculate these advanced KPIs in real time.

This paper presents a consolidated set of advanced user-centric cost-based efficiency and equity indicators which address different aspects of efficiency such as the horizontal and vertical component, fuel consumption or cost of the flight, thus introducing the airspace user's viewpoint into consideration. Also, the methodology followed for the calculation of the indicators, based on historical data and in real time, is demonstrated. For the evaluation of the indicators, Automatic Dependent Surveillance-Broadcast (ADS-B) data and a set of user-preferred trajectories (including flight plan, optimal cost and optimal distance) as reference are used. Finally, a flight efficiency and equity assessment of the European traffic flow for three different scenarios is presented, where two whole days of air traffic in the European Civil Aviation Conference (ECAC) area were used for the efficiency indicators, and one month of traffic for specific city pairs was used for the equity indicators. This proves the added value of these newly introduced indicators, showing that different indicators account for different sources of inefficiencies, and that the use of ADS-B data could serve as a reliable source for performance monitoring.

Keywords—Airlines; ANSP; Flight Efficiency; KPI; Air Traffic Management; SESAR; ADS-B.

I. INTRODUCTION

The Single European Sky (SES) Performance Scheme [1][2] is designed to drive and steer the continuous improvement of European Air Traffic Management (ATM) performance. This Performance Scheme establishes a Performance Framework that sets European Union-wide targets for four Key Performance Areas (KPAs): Safety, Cost-Efficiency, Capacity and Environment. These overall targets, which are reviewed and updated periodically in the different Reference Periods (RPs), are transposed into binding national/FAB (Functional Airspace Block) targets that are incorporated into national/FAB performance plans. The Performance Scheme defines a set of Key Performance Indicators (KPIs) for each of the KPAs. These indicators, which are obtained through air traffic-related data [5][15][16][17], allow the aggregated performance of the European ATM services and their impact on Airspace Users (AUs) to be evaluated without explicitly taking into account their requirements [20].

This set of KPIs is not thought to be static. New indicators and techniques are being continuously researched to improve the understanding of the ATM system. Following this trend, EUROCONTROL, on behalf of the European Union (EU), invests in research that will allow further improvement to the measurement of the ATM system [3][4]. In this direction, the SESAR 2020 Performance Framework [39] was recently established. In addition, the EU publishes reports with analysis and recommendations for the ATM system for each particular year [5]. Joint reports with the Federal Aviation Administration (FAA) are also published to compare both systems and to identify best practices to optimise ATM performance [6]. Being able to better understand how these new practices are really addressing the real interests of AUs is essential.

II. BACKGROUND

Flight efficiency is a generic term that can refer to different concepts and definitions. Nevertheless, due to its significant direct economic and environmental impacts flight efficiency is a vibrant research area [3][4][10][11][12][13][14]. Consequently, the monitoring of efficiency indicators to allow for a better understanding of the drivers of ATM flight efficiency is growing.

Flight efficiency indicators are currently monitored and reported by the SES Performance Scheme [8][9] as part of the Environmental KPA defined by the International Civil Aviation Organization (ICAO) [1][2]. This monitoring is done both in the U.S. and Europe [5][6][7], as well as in other countries such as Australia.

Today the mandatory KPI used by the SES Performance Scheme is "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.
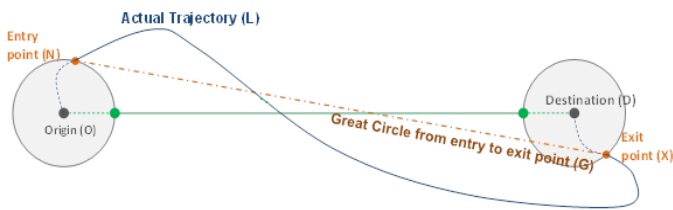

Figure 1. Flight length compared with Great Circle Distance

The Achieved Distance methodology [15] is used to calculate horizontal flight efficiency. 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 Arrival Sequencing and Metering Area (ASMA) exit point of the departure airport and the ASMA entry point of the arrival airport), named the Great Circle Distance (see Figure 1).

Studies performed by EUROCONTROL [16][17][36] have shown that this approach to calculating flight efficiency does not capture the "optimum" trajectory, as it fails to take into account meteorological factors or the operational objectives of AUs. These studies have allowed EUROCONTROL to design a vertical indicator whose introduction in SESAR RP3 has also been studied [37]. FAA's researchers also investigated the possibility of introducing the wind as a parameter for the optimum trajectory calculation [18]. 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 [19]. BR&TE and CRIDA have explored an innovative direction in a collaborative study using real operation data. As a result, a new methodology was proposed to construct an enhanced flight efficiency indicator that better captures fuel consumption [20].

All previous studies have shown that the existing Achieved Distance methodology does not fully capture the optimum or most efficient trajectories, which are a cornerstone for these calculations. These findings have opened new directions for investigating optimum trajectories, considering factors such as fuel consumption, flight time costs or schedule adherence. This study takes as starting point the previous research to overcome the gaps in the today's most common flight efficiency indicator.

III. METHODOLOGY

A. Methodology based on historical data

The evaluation of flight efficiency indicators requires the definition of several types of trajectories, each of which accounts for a loss of efficiency due to different factors. The definitions below follow the nomenclature and framework used in [20][27] and are the final set of reference trajectories[1] selected in AURORA (more thorough definitions can be found in [40][41]):

- Optimal Distance Trajectory (ODT). This is the shortest distance trajectory following the Great Circle from origin to destination.

- Optimal Cost Trajectory 1 (OCT1). This trajectory is the minimum cost trajectory (using the concept of Cost Index[2]) in free flight conditions from origin to destination. Although air navigation fees are not considered in the generation of this trajectory, they are taken into consideration in the cost-based indicators.

- Optimal Cost Trajectory 2 (OCT2). OCT2 differs from OCT1 in the fact that it takes into consideration today's airspace structure since it follows the horizontal path given in the flight plan.

- 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 by the aircraft on the day of operation.

AFT is calculated from surveillance information (ADS-B track data) using BR&TE's Aircraft Intent Inference and Trajectory Reconstruction (INTRAC) service. National Oceanic and Atmospheric Administration (NOAA) weather forecasts are used as the weather model, and Base of Aircraft DAta (BADA) is used as aircraft performance model [24]. 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

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[1] Additional reference trajectories were also calculated in previous steps of the project [30], but AUs prioritized those included in this document.
[2] The values of the Cost Index used in this paper are extracted from publicly available documents published by aircraft manufacturers [31][32][33].

the flight, such as the initial mass of the flight or fuel burnt. This reconstructed initial mass will then be used as the initial mass in all reference trajectories.

ODT and FPT are calculated 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 <u>Trajectory Generation</u> 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. The complete explanation of these processes, including the optimization used for the creation of the optimal profiles, is included in [28][40].

Trajectory Reconstruction and Trajectory Generation 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 [20][21]. 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 (latitude, longitude, altitude, mass, time and speed) of the flight and an aircraft intent[3] expressed using the Aircraft Intent Description Language (AIDL). Details on AIDL and TCI can be found in [21][22][23][25][26].

Each indicator is then obtained by selecting and comparing the relevant variables of the AFT with those of the selected reference trajectory. The process followed to calculate AURORA's efficiency indicators is summarized in Figure 2.
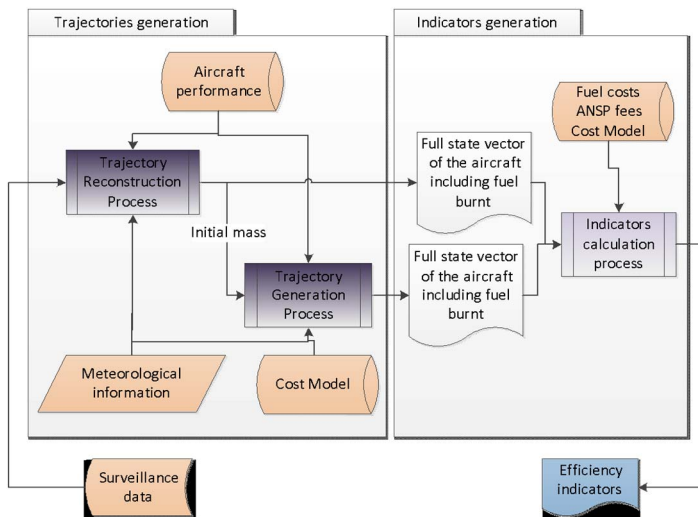

Figure 2: Service-oriented approach for calculating new efficiency indicators based on historical surveillance data

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[3] 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.

The availability of all surveillance data from origin to destination increases the feasibility and accuracy of the Trajectory Reconstruction and Generation processes. Thus, ADS-B data was identified as an appropriate source to enable the calculation of the whole trajectory for flights departing or arriving outside of European Airspace (where radar data of the whole trajectory are not necessarily available), or across multiple airspaces with different ANSPs.

B. Methodology based on on-line data

Figure 3 illustrates the architecture of the online efficiency indicator calculation 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 [34] and Apache Kafka [35].
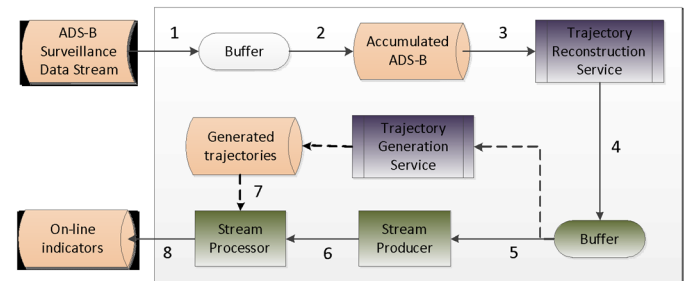

Figure 3: The architecture of the online system

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 identification. We use the callsign combined with departure time to uniquely identify a flight.

3) The Trajectory Reconstruction service is triggered periodically, for example every time there is an update of ADS-B tracks (approximately 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 a multi-threaded manner, with the unit of parallelism as each unique flight.

4) These reconstructed trajectories are sent on to an Apache Kafka [35] 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. The Trajectory Generation service creates the reference trajectories which are stored in a database. We use the estimated initial mass from the output of Trajectory Reconstruction, which leads to a periodically updated Trajectory Generation service.

6) The Stream Processor, which is implemented using Apache Spark Streaming [34], pulls the reconstructed trajectory streaming data every 30 seconds to aggregate a micro-batch. Then it computes the parameters needed to calculate 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 points.

8) The stream processor outputs the calculated on-line indicator results into a PostGIS data store for subsequent complex queries. For example, the air traffic network manager can check the evolution of an indicator in one sector (or a specific area) for a period.

C. Definition of Efficiency Indicators

Table I presents the final list of indicators consolidated in AURORA. This list differs from the indicators defined in [29] and evaluated in [30] due to the iterative process to consolidate the indicators with the AUs. The formulas used for the calculation of the indicators can be found in [40][41].

The first indicator, KEA, is equivalent to the one currently used by the PRU (Performance Review Unit) in their efficiency analysis and reports, and it is calculated for comparison purposes. For the other indicators, AURORA's nomenclature consists of four components: the first letter is for the variables being compared (K for distance, F for fuel, C for cost, V for vertical); the second letter (E) means Efficiency; the third letter means the trajectory that is assessed, in all cases A for the Actual Flown Trajectory (AFT); and the final component, separated by underscore, identifies the trajectory used as reference (P for FPT, C1 for OCT1 and C2 for OCT2). For example, CEA_C1 means Cost Efficiency indicator of the Actual Flown Trajectory versus the Optimal Cost Trajectory 1.

Ind.	Set	Ref. Traj.	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	Cost	FDT	Extra-costs of the AFT in comparison with the FPT.
CEA_C1		OCT1	Extra-costs of the AFT in comparison with the OCT1.
CEA_C2		OCT2	Extra-costs of the AFT in comparison with the OCT2.

Table I: AURORA´s indicators

It is worth noting that all indicators are calculated from origin to destination[4]. This implies that the calculation of KEA differs from the current implementation where the portion of the flight in an area of 40NM around the airports (ASMA) is excluded from the computation [15][17][20]. The AUs involved in the study expressed their interest in understanding the efficiency of their flights taking the whole trajectory, including the ASMA, into account.

Table II shows the qualitative assessment of the indicators given by the AUs. "Understanding" represents the ease with which AUs felt they could understand the meaning of an indicator, and "representativeness" indicates the degree to which AUs felt an indicator represented their view of flight efficiency. These criteria were chosen in line with the SESAR methodology to assess new indicators which could be incorporated to the SESAR 2020 Performance Framework [39].

AUs ASSESSMENT		
ID	**Understanding**	**Representativeness**
KEA	High	Low
KEA_P	High	High
VEA_P	High	Medium
VEA_C1	Medium	High
VEA_C2	Low	Low/Medium
FEA_P	High	Medium/High
FEA_C1	Low	High
FEA_C2	Low	High
CEA_P	High	Medium/High
CEA_C1	Low/Medium	High
CEA_C2	Low/Medium	High

Table II: AUs´ assessment of efficiency indicators

Although indicators of higher complexity are more representative for AUs, they are also more difficult to understand. Cost-based indicators are identified as the most relevant ones and vertical, horizontal and fuel-based indicators are considered as complementary. In addition, the indicators comparing the actual trajectory versus the flight plan (AFT versus FPT) are seen as a way to quantify current inefficiencies while indicators comparing the actual trajectory versus the cost-optimal trajectory in free route (AFT versus

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[4] With the exception of the vertical indicators that only takes into account the portion of the trajectory from Top of Climb (TOC) to Top of Descend (TOD), in line with the AUs' suggestions.

OCT1) are perceived as key indicators to assess the future ATM system.

D. Definition of Equity indicators

Equity indicators tend to capture how the inefficiencies of the system are distributed between all AUs within a certain context, such as the European Civil Aviation Conference (ECAC) region, an airport, city pair, or airspace crossed. Several equity indicators are defined and evaluated in [29] and [30], and they were iteratively refined with the AUs.

The final list of equity indicators used in AURORA can be divided in two subsets as shown Table III.

Ind.	Set	Ref. Traj.	Description
EQ_FL_P	Flight Level	FDT	Differences between AUs in terms of percentage of flights reaching the en-route flight level of the reference trajectory.
EQ_FL_C1		OCT1	
EQ_FL_C2		OCT2	
EQ_CEA_P	Costs	FDT	Differences between AUs in terms of costs of the actual flown trajectory versus the reference trajectory.
EQ_CEA_C1		OCT1	
EQ_CEA_C2		OCT2	

Table III: AURORA's equity indicators

EQ_FL_P and EQ_CEA_C1 are used as examples to explain the approach, their formulas can be found in [40][41].

As in the case of the efficiency indicators, equity indicators are evaluated by the AUs in terms of "Understanding" and "Representativeness". This evaluation is summarised in Table IV.

AUS VIEW		
ID	Understanding	Representativeness
EQ_FL_P	High	Medium
EQ_FL_C1	Medium	Medium
EQ_FL_C2	Medium	Medium
EQ_CEA_P	High	Medium
EQ_CEA_C1	Medium	Medium/High
EQ_CEA_C2	Medium	Medium/High

Table IV: AUs' assessment of equity indicators

Similar to the case for efficiency indicators; cost-based equity indicators are identified as the most representative for the AUs. EQ_FL_P is also positively assessed as it provides information about up to which point the requested flight level of the flight plan is respected.

E. Scenario Description

The scenario selected to study efficiency indicators (for both the offline and the online experiments) are two days of full ECAC traffic without major disruptions, i.e. without abnormal ATC regulations or delays: February 20th and February 24th 2017. February 24th has higher volume of flights and different predominant wind direction than February 20th. Constraints in time available to process reference trajectories made it necessary to reduce the data sets. The study considers flights departing from 12:00 to 14:00 UTC as these are the main peak hours on the selected days. Additionally, all flights operating between several city pairs along the 24 hours of the two days are also included in the data sets. These city pairs are: London Gatwick [LGW] – Madrid Barajas [MAD], London Gatwick [LGW] – Barcelona [BCN], Frankfurt [FRA] – Madrid Barajas [MAD], Paris Orly [ORY] – Toulouse [TLS], Paris Orly [ORY] – Lisbon [LIS], Istanbul [IST] – Amsterdam [AMS], Roma Fiumicino [FCO] – Amsterdam [AMS] and Barcelona [BCN] – Brussels [BRU]. This adds up to 1,583 trajectories for the 20th and 1,692 trajectories for the 24th.

To perform the study on equity indicators it was necessary to extend the number of flights to one month. We select all flights during the time period from June 22nd 2017 to July 19th 2017 for the following city pairs: London Gatwick [LGW] – Barcelona [BCN], Frankfurt [FRA] – Madrid Barajas [MAD] and Istanbul [IST] – Amsterdam [AMS]. This adds up to 1,537 flights.

IV. RESULTS

A. Flight Efficiency

Table V summarizes the mean, standard deviation and the coefficient of correlation with the horizontal indicator that has the same reference trajectory for the two selected ECAC traffic samples. It is relevant to mention that by definition positive higher values of all indicators imply higher inefficiencies.

Days	Ind.	Mean value	Std. Dev.	Linear Correl. with Horizontal Indicator[5]
20/02/2017 24/02/2017	KEA	9.3%	6.6%	
		10.0%	6.6%	
	KEA_P	-1.1%	5.0%	N/A
		-1.5%	5.6%	
	VEA_P	5.1%	3.7%	0.04
		2.9%	3.4%	0.00
	FEA_P	1.6%	6.3%	0.51
		1.8%	6.6%	0.37
	CEA_P	1.7%	5.0%	0.75
		1.4%	4.9%	0.63
	KEA_C1	9.5%	6.6%	N/A
		10.2%	6.6%	
	VEA_C1	8.0%	5.0%	0.01
		9.2%	5.2%	0.00
	FEA_C1	1.7%	7.2%	0.40
		2.0%	6.7%	0.25

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[5] Linear correlation with the horizontal indicator that has the same reference trajectory e.g. CEA_C2 is correlated with KEA_C2.

	CEA_C1	8.7%	6.1%	0.65
		9.1%	6.0%	0.59
	KEA_C2	-1.2%	5.2%	N/A
		-1.3%	5.3%	
	VEA_C2	7.5%	4.9%	0.04
		8.6%	5.4%	0.00
	FEA_C2	-0.6%	6.7%	0.29
		0.0%	6.8%	0.14
	CEA_C2	4.5%	5.7%	0.74
		5.0%	5.5%	0.55

Table V: 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), we can identify that, in terms of horizontal deviation, actual trajectories are more efficient than the flight plans (KEA_P negative). This means that flight plans are usually shortcut. AUs stated that they are often forced to plan routes that do not include shortcuts that are inevitably taken.

By contrast, the trend changes if we look at the indicator that measures costs (CEA_P). 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 of the planned trajectories as can be seen by the average values of FEA_P.

Figure 4 shows an example of the flight AEA1029 (February 20th). In blue we can see the flight plan while the flown trajectory is represented in red.
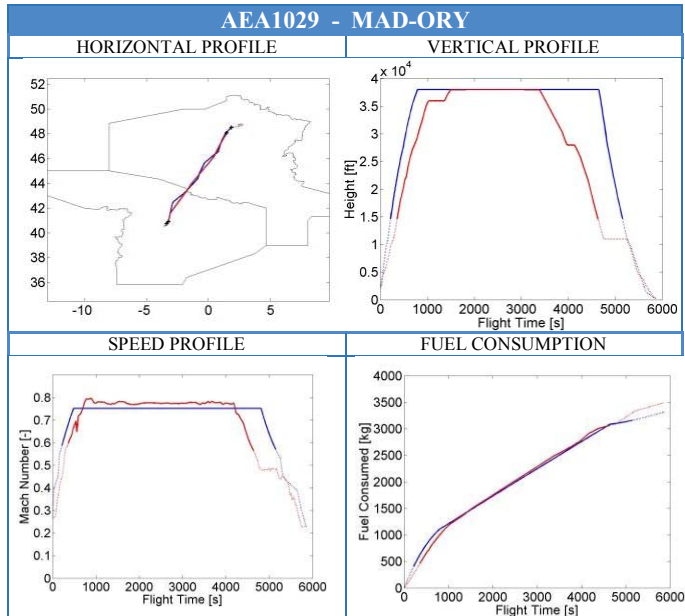

Figure 4: FPT as reference trajectory (AFT in blue, FPT in red)

AEA1029 receives various shortcuts, which are translated into 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 translated into a benefit in terms of fuel consumption: FEA_P is 5.3% which means that the actual trajectory is a 5% more inefficient than the flight plan (illustrated in the picture at the bottom right) due to the two periods in which the aircraft is levelling off in the descent phase. Vertically, the actual trajectory is more inefficient than the flight plan due to the initial level capping in the cruise phase (VEA_P equals -0.84%[6]). Finally, 2.1% for CEA_P means the actual trajectory is more inefficient in terms of cost than the flight plan, and this is mainly due to the impact of fuel consumption which cannot be balanced with the reduction of flight time or taxes.

Previous results and examples show that KEA_P, FEA_P, VEA_P and CEA_P allow the deviations of the actual trajectories with respect to the planned trajectories to be quantified, and that these deviations are not necessarily aligned with the differences in the horizontal distance between actual and planned trajectories.

OPTIMAL COST TRAJECTORY 1 (OCT1) AS REFERENCE

Focusing now on the indicators with cost-optimal trajectory in free route as reference, it is relevant to mention that KEA_C1 has a very strong positive relationship with KEA according to Pearson scale [38] (0.99 in both traffic samples). 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 indicators that are more complex (due to a more complex reference trajectory). This high correlation is explained because, for European short and medium-haul flights, weather does not cause major horizontal deviations of the cost-optimal trajectories in free route with respect to the geodesic.

In spite of this, KEA does not properly represent how good the actual trajectory is with respect to the cost-optimal trajectory. The linear correlation between KEA and CEA_C1 is around 0.70 which is identified as a strong positive relationship according to the Pearson scale [38].

Figure 5 shows the consequences of this correlation through a representative example. RYR62HJ has a KEA of 6.1%, while its value for CEA_C1 is 11.7%. This means that in terms of costs the inefficiency is almost duplicated. This is due to the fact that, although there is a high correlation between the horizontal distance and the costs, there are other parameters which are impacting costs that are not represented by KEA. The cost of fuel (FEA_C1 equals 7.98%), the vertical profile (VEA_C1 equals -9.77%) together with the cost of the time and the taxes increase the representativeness of CEA_C1. RYR62HJ does not reach its optimal flight level and the duration of the cost-optimal trajectory is almost 2,000 seconds shorter, which also implies lower fuel consumption.

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[6] Negative value of VEA indicator implies that the mean value of the en-route flight level of the actual trajectory is lower than the one of the flight plan.

We calculate the average weights of the different factors that contribute to the overall cost of a flight[7] (considering the cost-optimal trajectories in free route). The main factor impacting costs is fuel (42% of the total costs) but a strong influence of time also exists (34% of the total cost). The last place is for the taxes with 24%.

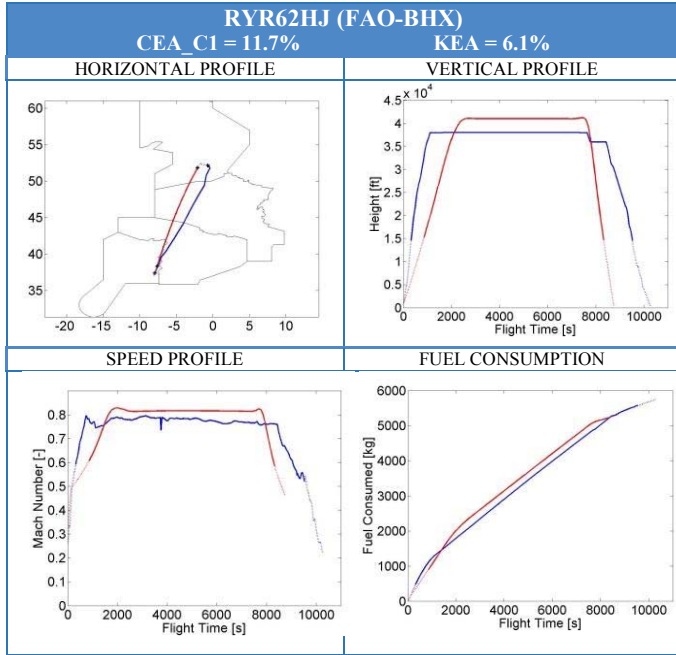| RYR62HJ (FAO-BHX)	
CEA_C1 = 11.7%	KEA = 6.1%
HORIZONTAL PROFILE	VERTICAL PROFILE
SPEED PROFILE	FUEL CONSUMPTION

Figure 5: OCT1 as reference (AFT in blue, OCT1 in red)

OPTIMAL COST TRAJECTORY 2 (OCT2) AS REFERENCE

Indicators with OCT2 as reference are an intermediate step between having as the reference the flight plan and having as reference the cost-optimal trajectory in free route. Actual trajectories in the ECAC are more efficient than expected when compared with the best possible cost-optimal trajectory following the flight plan horizontally, 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.

B. Equity

The following section deals with the results achieved for the equity indicators defined in III.D, as well as the analysis performed for them.

The definitions of the equity indicators require that their computation encompasses different AUs. For this reason, individual flights cannot be assessed in isolation and a new framework has to be set. After testing different data aggregations (whole ECAC, FIR/UIR airspace, city-pair, etc) and traffic sample characteristics[8], we focus our analyses on

relevant city-pairs over one month, analysing two of the defined indicators selected as they are the most representative for the AUs: EQ_FL_P and EQ_CEA_C1.

Table VI summarizes the results achieved for the comparison of the three city-pairs selected: MAD-FRA, LGW-BCN and AMS-IST. It is relevant to remark that, by definition, positive higher values of all indicators imply higher inefficiencies. On the other hand, although the equity indicators are defined by the standard deviation of the traffic sample, the mean values are also shown as a way of analysing the situation of each AU in comparison to the others. The rows labelled "Mean" show the resultant mean among the AUs, while the rows labelled "Value" show the actual value of the equity indicator.

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

Table VI: Equity indicators distribution for different city-pairs

The MAD-FRA and LGW-BCN city pairs have the same associated mean while having different EQ_FL_P values. This implies that the mean among the AUs is equal (thus, pure efficiency is the same for both city-pairs), but that the inefficiencies are not equally shared between them. Figure 6 shows the different means associated with each AU in each city-pair for this indicator, which is independent of the number of flights per AU. In the MAD-FRA city-pair, the inefficiencies associated with AU1 and AU3 are very dissimilar and thus the equity indicator gets higher (this is indeed worse equity). On the other hand, the LGW-BCN city-pair inefficiencies are more balanced and thus its equity indicator is lower (better equity).

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[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.

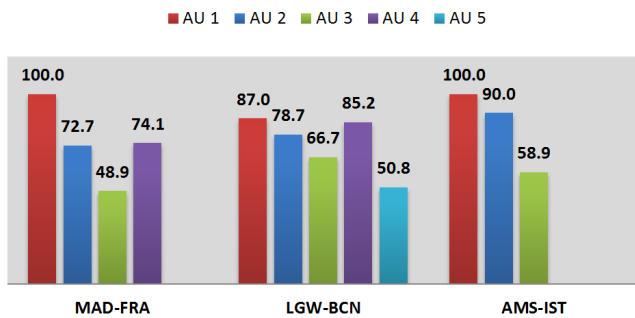[8] Further results on these traffic samples are included in [30].

Figure 6: EQ_FL_P mean values for different AUs

On the other hand, the MAD-FRA and AMS-IST city pairs have fairly similar EQ_FL_P values while having different associated means. 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 achieved the requested flight level (RFL) than the flights from MAD-FRA.

An operational example of the behaviour of different AUs can be seen in Figure 7 which shows flights on the AMS-IST city pair for AU1 and AU3. Flights reaching their RFL are shown in red and flights not reaching their RFL are shown in blue. One AU always reaches their RFL (100%) while the other does so only 58.9% of the time. This may be due to ATC constraints, but it is more likely that it shows different AU strategies in the treatment of their flight plans and their execution. These differences in behaviour and strategies impact the equity indicators, as seen in Table VI.
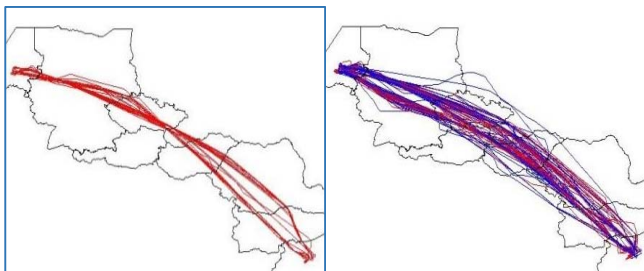

Figure 7: ADS-B tracks of AU1 and AU3 in city-pair AMS-IST

One of the analyses 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 the LGW-BCN and AMS-IST city-pairs, with 5 and 3 AUs respectively. In both cases, one AU looks far below the rest, and the indicator reflects this sensitivity (as there are 4 other AUs in LGW-BCN and 2 in 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 the EQ_CEA_C1 indicator, Table VI 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 the costs of the AFT trajectories are closer to those of the OCT1 trajectories[9].

However, the distribution of EQ_CEA_C1 is inversed with respect to the distribution of EQ_FL_P. As shown in Table VI, 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 reflects 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.

C. STAM using the output of on-line model

One of the motivations of building the stream-based data model for monitoring flight efficiency on-line is to enable better planning of STAM measures, which the air traffic controller (ATC) can use for re-routing or level-capping to alleviate any detected hotspots (i.e. in a certain airspace sector the aircraft counts during a time interval is beyond its upper limit) in tactical stage (i.e. day of operations), rather than pre-tactical or strategic stages.

This use case is tested by means of a real operational scenario. A hotspot was identified in Spanish airspace on July 2nd of 2017 at 11:30. This hotspot, identified in the sector DOMINGO UPPER, required the implementation of STAM measures to 2 flights to comply with the Occupancy level of the sector, i.e. the maximum number of aircraft that can be within the sector at the same time. The STAM measure applied to the 2 flights was level-capping, which is included in the total sample of 13 flights that are eligible for applying STAM of any type. A total number of 264 different solutions were available to be selected, including the real operational solution applied. Each solution is assessed in terms of the different efficiency indicators, by calculating the mean of the indicators of the flights comprising that solution. An optimum solution in terms of each efficiency indicator can be obtained.

The results show that, compared to the STAM measure implemented, other solutions could have improved the overall efficiency of the hotspot from a mean CEA_C1 of 8.36 to a mean 7.99. This implies a reduction of around 5% on the indicator; while in total fuel consumption of the flights, the reduction rises up to almost 250 kilograms just by applying the optimum solution.

V. CONCLUSIONS

The experiments described in this paper show that the proposed indicators can capture the different sources of flight inefficiencies better than the current "horizontal flight efficiency" indicator. Vertical and speed profiles, together with the impact of weather conditions are identified as relevant

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[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.

factors to be taken on board when quantifying the efficiency of a flight.

Indicators computing the deviations of actual trajectories versus optimal cost-optimal trajectories in free route are the ones to drive the ECAC towards the future system in which AUs could fly their optimum flight profiles in a free route environment. The CEA_C1 indicator was selected by the AUs as the most relevant one, and the others complement it in order to better understand the sources of the cost-based inefficiencies.

Indicators computing the deviations of actual trajectories versus cost-optimal trajectories following the horizontal flight plan represent improvements on efficiency that could be reached, taking into consideration the current route design. The results have shown that half of the current inefficiencies in terms of costs are due to the constraints in the route design.

Equity indicators provide an insight into how inefficiencies are distributed among AUs, allowing the detection of regions or routes that present abnormal values compared to the average. Conversely, companies' strategies can highly impact these indicators, making it difficult to recognize the causes of inequities.

Currently, flight efficiency indicators can only be calculated after the completion of a flight. By using a data streaming technology and live flight data, the new indicators can be calculated online in near real time. The dynamic calculation makes efficiency indicators available to AUs while flights are live and could be used to identify efficiency and equity problems during flights, to better plan STAM measures, and to monitor the performance of groups of flights. For this implementation, additional algorithms are necessary to ensure the consistent integration of the already flown portion of the trajectory with the predicted trajectory until destination, as a prerequisite to run the Trajectory Reconstruction and Generation processes.

VI. RECOMMENDATIONS

Based on the results and conclusions obtained from the analysis some additional activities are identified to allow implementing the proposed indicators:

- Definition of a unique optimal trajectory from the perspective of the AUs. This trajectory should represent the AUs' future preferences (i.e., free route) and should be agreed by a wide number of AUs with different business strategies, and by the ANSPs;

- Consolidation of the most relevant components of the overall flight costs to be included in the efficiency indicators with a wide number of AUs. Additional components of the overall flight costs such as delay, crew and connection costs could be relevant for the AUs and are not considered in AURORA;

- Although equity indicators provide an insight into how inefficiencies are distributed among AUs allowing the identification of specific routes or city pairs that

present abnormal inequities, further research is envisioned to allow the sources of inequities to be identified through advanced cause and effect models;

- Design of data cleaning processes as part of the stream-based data model in order to ensure that the quality of live surveillance data does not impact the generation of user-preferred trajectories in real-time.

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