



Methodology to Quantify and Attribute ATM Inefficiencies and Their Impact on Fuel Consumption

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Abstract

Air Traffic Management (ATM) is a critical component of the European air transport system; its efficiency has a significant impact on the airlines' profitability but is also a lever of the pathway towards aviation sustainability, with an expected contribution up to 8% in reducing aviation-related emissions between now and 2050. In this context, the presented work has the ambition of developing a methodology to quantify and question the aforementioned efficiency gain potential, and to categorize inefficiencies in the ATM. This paper details the initial workflow referring to one among a small number of city pairs that have been selected to cover routes of various lengths departing from Europe. Later, the complete subset of city pairs, plus broader, statistically relevant study cases will be assessed. In this perspective and as the basis of a synthetic efficiency indicator, key metrics, targeting vertical, horizontal and combined flight efficiency are revisited to contribute to the quantification of ATM inefficiency. The insight offered by these metrics enables tracking the efficiency evolution with the update of flight plans and along the complete flight execution, rather than focusing on a specific flight phase.

Keywords: ATM inefficiency; aircraft operations; sustainable air transport

Abbreviations: ATM: Air Traffic Management, FIR: Flight Information Region, IAS: Indicated Air Speed, SAF: Sustainable Aviation Fuel, SDE: Strategic Distance Efficiency, SID: Standard Instrument Departure, STAR: Standard Terminal Arrival Route, TAS: True Air Speed, TDE: Tactical Distance Efficiency, TOD: Top of Descent, TOM: Take-Off Mass, VFE: Vertical Flight Efficiency

1. Introduction

In line with its decarbonization goals, commercial air transport is already acting to reduce its greenhouse gas emissions by introducing evolutionary improvements, such as the adoption of Sustainable Aviation Fuel (SAF), fleet modernization, and the improvement of its operational efficiency. According to EUROCONTROL [1], improved operations are expected to contribute to approximately 8% of the reduction of aviation's CO₂ emissions between now and 2050. Unlike innovative aircraft technologies, which promise long-term reductions to the aviation's climate impact but require lengthy research and face uncertain outcomes, operational improvements may provide nearer-term emissions benefits, though these gains are often incremental and constrained by operational, regulatory, and infrastructural factors. In this context, the presented work has the ambition of developing a methodology to quantify and question the efficiency gain potential and categorize inefficiencies in the Air Traffic Management (ATM) by attributing the source to the various air transport stakeholders and ATM regulatory constraints. The latter goal is only briefly mentioned in this work, as it

represents a long-term objective of the project. Such an approach is also coherent with the airlines' expectations concerning ATM services, stated in [2]: airspace users want to operate their declared gate-to-gate flight schedule in an optimal manner, following individual business requirements and with transparent access to constraints at any flight phase.

The methodology is being developed and validated using a small set of airport pairs that cover short-, medium-, and long-haul routes departing from Europe to ensure a robust computation of the relevant metrics. They are introduced here referring to a single airport pair on a short-haul route. The methodology will later be applied to a comprehensive route set to obtain a statistically meaningful analysis of inefficiencies in the ATM over defined geographic or stakeholder scopes. Relevant data is obtained from open sources but it is further enriched thanks to complementary information brought in by the industrial partner of the project, Thales, as detailed in the following. Starting from this data, the quantification of the inefficiencies involves analyzing flight operations at various levels of modeling precision to gain a comprehensive understanding of the sources of inefficiency and their relative importance. To gain a complete understanding of the efficiency of a group of flights, both lateral and vertical efficiency are assessed separately first, and then together. As explained in more detail below, each efficiency indicator is assessed relative to a segment-specific reference corresponding to the flight phase it represents. Since the objective is to quantify the ATM inefficiency, we are looking for metrics that minimize or eliminate the dependency on operating aircraft.

The inefficiency analysis evaluates both the filed flight plan and the actual flown trajectories via segment-specific indicators to distinguish between two types of factors influencing the final flown trajectory: strategic constraints, such as fixed limitations in the airspace (e.g., maximum sector capacity, restricted zones, or varying airspace charges), and tactical decisions, which reflect real-time ATM responses to dynamic conditions during the flight, such as weather or fluctuating traffic levels. Following a detailed classification of the ATM context — currently under development and including organizational, technological, and economic limitations at both strategic and tactical levels — the evaluation of the local efficiency indicators allows to quantify the impact of each constraint category on the air transport efficiency. The lateral inefficiency allows grasping the impact of ATM constraints on the flight length, whereas the coupled lateral and vertical inefficiencies aim to measure the increase in fuel consumption, detailing the overall efficiency of the flight.

The long-term objective of this work is to develop a synthetic ATM efficiency indicator, based on the coherent aggregation of multiple local metrics relating to the various phases of flight, in both the vertical and horizontal planes. This compound efficiency can be applied to a single flight, a specific airport pair or a given network, and points towards realistic ATM optimization levers. We hereby describe the preliminary data manipulation steps and present the selected relevant metrics that aim to be aggregated into a single figure.

Section 2 provides an introduction to the development of the methodology covering data sources, application scenarios and data manipulation. Section 3 introduces the selected metrics, followed by the outlook on future developments presented in Section 4.

2. Context and framework of efficiency metrics

This chapter outlines the framework of development of the ATM efficiency quantification methodology, detailing the data sources, the target scenario of application of the methodology and the manipulation of flight plans and flight data.

2.1 Data sources

The core data used in the present work comes from open-source databases, with flight plans accessible from the EUROCONTROL Aviation Data Repository for Research and ADS-B flight data accessible from OpenSky [3]. However, both datasets are enriched by additional information provided by Thales AVS and Thales LAS, the industrial partners of the project:

- **Flight plan:** The time evolution of each flight plan from the first declaration is available in Thales' dataset, detailing the time and entity of flight plan modification. This information is not easily accessible from open-source databases, but it is critical for pinpointing when and why inefficiencies result from the flight planning process. Flight plans are categorized with a varying status: preactive (released before departure), active (updated during flight, reflecting, for example, the change of the approach procedure) and terminated (a single flight plan, reflecting the actual flown trajectory, represented in the format of a flight plan). The database made available by Thales contains several flight plans per flight, sometimes up to more than 50, as there is a new flight plan instance for each minor modification. To limit the analysis of flight plans to the actual planning phase, the first and last declared preactive flight plans are considered. This is enough to detect if there is a positive or negative trend in efficiency as the flight plan evolves. Any flight plan contains the following information, useful to either match the plan to its corresponding flight data or to actually perform the analysis: the unique GUTI flight identifier, departure and arrival airports, aircraft model and ICAO address, creation date and time and the trajectory points, for which a name, coordinates, flight level and time of overfly are given. Open data allows computing flight-plan-based metrics only referring to the last preactive flight plan. Instead, the comparison to previous flight plans necessitates the Thales dataset. Although the open-access data limits the depth of the analysis, little change is observed in these indicators as the declared flight plans evolve prior to departure.
- **Fuel burn:** Each flight plan instance is enriched with an estimation of the aircraft mass at take-off and along the flight, with the fuel consumption computed using BADA. This information can be easily recomputed, estimating the aircraft Take-Off Mass (TOM) and consequent fuel consumption, referring to the modeling presented in [4] and in OpenAP [5], respectively. To better match the fuel consumption available in Thales' flight plans, the fuel consumption, computed with OpenAP takes as input the initial aircraft mass proposed by Thales.
- **Flight data:** To understand the impact of wind on the performance along the flight, ADS-B data is enriched from Thales dataset with information regarding the wind speed and direction, enabling the computation of the True Air Speed (TAS) and Indicated Air Speed (IAS). To complete the OpenSky data, which does not present weather information, thus enabling a comparable analysis, the intensity and direction of wind along the route is available from fastmeteo. The TAS is obtained from the ground speed and wind direction, enabling the computation of the true fuel consumption in an open-data context.

2.2 Manipulation of flight data

Before the efficiency analysis, it is necessary to access and pre-process flight plans and flight data efficiently to ensure that the computational effort remains reasonable. Despite relying on the information-rich datasets made available by Thales, the developed data flow ensures that only flights available in OpenSky are used, thereby ensuring partial reproducibility of the results in terms of dataset coherence. Any explicit utilization of data that is not openly available will be highlighted. Once flight plans and flight data from the various sources have been imported for the relevant period and city pair, date across the various data sets is matched on a flight-by-flight basis, the following steps are undertaken:

- Import & clean Thales plans and flight data

- Import & clean OpenSky flights
- Match OpenSky to Thales flight by callsign and aircraft ICAO address
- Match remaining Thales flight data to Thales flight plans
- Compute the aircraft performance on the flight with OpenAP
- Evaluate efficiency on a flight-by-flight basis and postprocess the results

2.3 Deployment of the methodology

As part of the preliminary definition of this project, developed in the context of a partnership between the Institute of Sustainable Aviation at ISAE-SUPAERO and Thales, a list of ten city pairs representative of the European air traffic has been selected. This list of routes, with at least one end being a European airport, includes domestic and international routes, as well as two intercontinental routes, enabling the development of a methodology versatile enough for different types of operations. In this methodology assessment phase, only preliminary results concerning one month's flights for one city pair are presented, with a broader analysis still under development. The chosen route corresponds to city pair 6 (LEPA-EDDL), considering the flights of June 2023. The dataset includes 297 northbound-only flights. The route is well-representative of the hurdles in the identification of suitable efficiency metrics, given the variety of operating aircraft and trajectories in the dataset.

Potential sources of inefficiency and delay in air transport include high traffic density and adverse meteorological conditions, both of which exhibit seasonal variability. To capture these seasonal effects while maintaining a reduced computational effort and considering the data availability within the EUROCONTROL R&D Data Archive, the months of March and June are selected for the analysis of air transport inefficiencies. Besides, a comparison between these months in 2019 and 2023 will be introduced, given the significant impact that the COVID-19 crisis had on air transport, with current traffic levels and capacity still being expressed with respect to pre-COVID values.

The en-route segment is defined as the portion of route obtained excluding a radius of 40 NM around the departure and arrival airports as suggested by [6]. The initial assessment of the considered route reveals substantial variability in the horizontal trajectories, though distinct clustering patterns are observable within the data. Thus, a formal clustering methodology has been applied to the en-route segments. The proposed clustering method is K-means [7, 8], whose working logic is based on the initial identification of cluster centers whose location is iteratively identified by minimizing a cost function that computes the squared Euclidean distance between the centroids and route way points. Figure 1 represents the obtained clustering for the selected city pair, for which four clusters are obtained.

3. Efficiency metrics

This section presents the efficiency metrics developed so far, divided into vertical, horizontal and combined.

3.1 Vertical flight efficiency

Vertical flight efficiency assesses the performance of a flight trajectory by measuring its alignment with an optimal vertical flight profile and its adherence to fuel-burn minimizing procedures. Due to the substantial variability in trajectories, weather conditions, and the diverse range of aircraft operating on specific city pairs, establishing a universally applicable and robust optimal vertical flight profile, used as a benchmark for the evaluation of other performance metrics, remains challenging. At this stage, however, a reference optimal trajectory from the origin airport to the destination air-

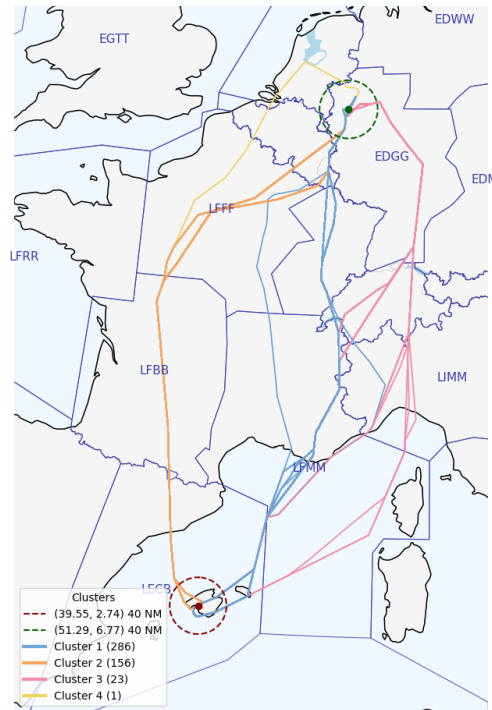


Figure 1. Cluster map for LEPA-EDDL flights in June 2023, with the 40-NM circle centered at the departure and arrival airports excluded from the en-route segment.

port is not required as the proposed primary or phase-specific metrics are referred to a particular phase or segment of the flight and each segment-specific reference is either based on a particular feature of the trajectory in this flight segment (i.e. the presence of level flight after the TOD - Top of Descent) or on the flight plan, which is considered to be the proxy of the best trajectory accounting for aircraft type, weather and airspace conditions at the time of flight. As opposed to the use of theoretical optimal (such as the great-circle path), the intent is to use segment-specific references achievable in the ATM real-world constraints and then to aggregate the consequent primary metrics into a compound one. Among the primary metrics, some are based on the estimation of the fuel consumption on the segment, whose accuracy varies across the spectrum of various aircraft types and depending on the chosen performance model. To eliminate aircraft-related uncertainties on fuel consumption and move towards ATM-specific efficiency metrics, we propose to consider all flights to be operated by one reference aircraft. For short-haul ones, considered in the present results, we resort to the Airbus A320 (and to its OpenAP performance model), which is the most common on short-haul flights. As each aircraft has indeed its own set of optimal climb, cruise and descent performance, the consequences on the output of efficiency evaluation due to the proposed deletion of the aircraft variable needs to be assessed. Figure 2 shows key performance indicators for all the aircraft types operating on the target route, LEPA-EDDL, as a post-process of real flight data on the selected city pair. More specifically, the four boxplots show, for each aircraft type, the observed climb range, cruise altitude, cruise Mach number, and descent range. The median values in red, interquartile ranges within the blue or orange boxes, and outliers (dots) illustrate the variability of operational practices between aircraft types as well as within the same type. The biggest dispersion concerns the BCS3 cruise performance, showing a lower altitude and speed, which is coherent with the fact that it is a regional aircraft. Similarly, a lot of dispersion is seen concerning the descent

range, which includes all the distance flown after the TOD, including the eventual holding. It is important to note that these indicators correspond to actual operational conditions on the selected city pair, with all aircraft types subject to the same constraints, and therefore do not represent optimal aircraft performance values. As such, the observed dispersion cannot be attributed solely to intrinsic aircraft performance, whose optimal values are very hard to find as they are proprietary to the OEMs. Enforcing fuel burn calculations based on a single reference aircraft (e.g., A320) thus appears to introduce homogenization in an attempt to adopt an aircraft-neutral approach that makes sure that uncertainties in aircraft performance models do not interfere with ATM efficiency assessment solely based on flight plans and trajectories. Further analyses and validation of such approach will follow, before a definitive implementation in the methodology.

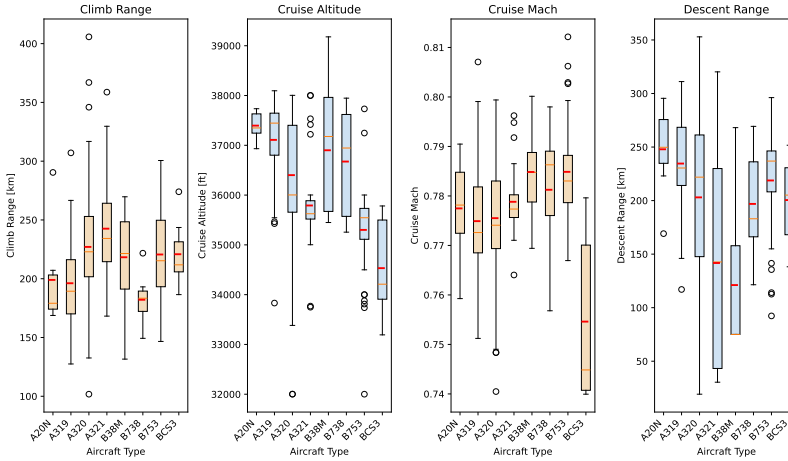


Figure 2. Box-plot of aircraft performance indicators on the route LEPA-EDDL.

Here the selected vertical flight efficiency indicators are presented, each referred to distinct portions of the flight:

- Vertical Flight Efficiency indicator (VFE): defined by EUROCONTROL [9] as the portion of cruise flown at an altitude equal or greater than 1,000 ft below the one declared in the latest preactive flight plan, whose en-route portion is taken as reference:

$$VFE = \frac{D_{Cruise|_{h \geq h_{FP-1,000ft}}}}{D_{Cruise}} \quad (1)$$

As of now, a unique VFE has been computed for the entire cruise, but it can also be computed on a per-Flight-Information-Region basis to facilitate the identification of inefficient airspaces. A similar indicator, defined VFE1, has been computed comparing the actual trajectory with the first preactive flight plan. This indicator cannot be obtained from open-access data. A VFE smaller than VFE1 means that the planned cruise flight level has increased with the evolution of the FP, meaning that a more efficient flight level has been planned. This analysis does not account for time-varying weather condition forecasts that might affect the choice of the flight level for the upcoming flight. The assumption of the VFE indicator is that the optimal cruise altitude has been selected in the planning phase, thus this altitude acts as a proxy for the most fuel-efficient trajectory, accounting for wind and aircraft mass for the specific flight. The 1,000 ft margin is representative of normal traffic separation margins. Flying above this altitude is acceptable, especially for longer flights such as the route considered here, for which the decreased fuel consumption at higher altitudes still outbalances, or is at least comparable to the increase of climb fuel to get to a higher cruise

level. Instead, flight at lower-than-optimal cruise altitude can cause a significant increase in fuel consumption, going from +2.1% at -2,000 ft to +12% at -6,000 ft for an A320 [10]. Similar values have been obtained from a regression performed on the fuel consumption in still air of a subset of flights, computed with OpenAP - centered on a distance of 1,600 km \pm 5% - for all but one aircraft - the A20N - on the route, which suffers from a limited amount of data points, as shown in fig. 3. This information does not confirm that the planned flight level is the optimal, but shows the sensitivity of fuel consumption to FL, reminding the importance of flying at the correct altitude. Confirming the importance of an optimized cruise altitude, with an eventual live update with real

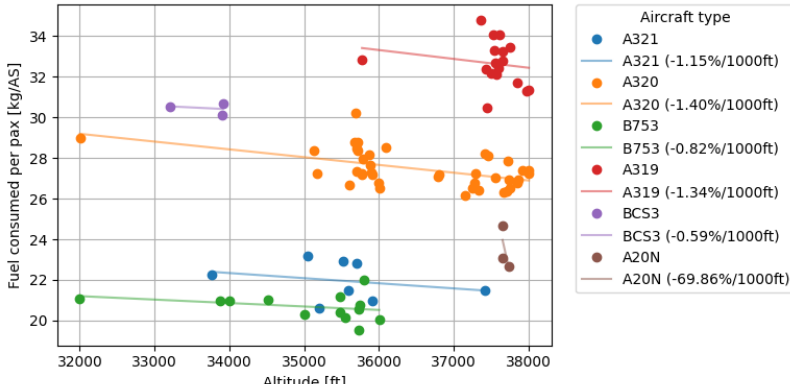


Figure 3. Fuel consumption per passenger on the entire route as a function of cruise altitude and aircraft type on the reference route.

weather information, [11] quantifies the potential reduction of fuel consumption due to a in-flight altitude optimization within a Free Flight Region (FFR) at 1.6%. Since this reference introduces FFRs, which are outside the scope of this work, and works only on the Oakland Oceanic Airspace, which has specific traffic (mostly Hawaii to continental US flights and scarce crossing trajectories), it is hard to generalize this potential reduction to European operations, in far more constrained flights regions. Nonetheless, the reference validates the importance of VFE and marks how tactical optimization is possible.

- Continuous descent: the Continuous Descent Operation (CDO) indicator has the ambition of assessing the portion of flight that follows the TOD, by identifying the distance flown in descent, over the total distance flown after the TOD as follows:

$$CDO = \frac{d_{Descent}}{d_{Descent} + d_{Level}} \quad (2)$$

[12] demonstrates that continuous descents at Chinese airports can save an average of 139 kg of descent fuel, equivalent to a 21.5% reduction in descent fuel consumption. The net savings are reduced to approximately 25 kg per flight at ZHHH and ZWWW airports, which have a large majority of narrow-body aircraft. This justifies the relevance of performing continuous descent approaches from an environmental standpoint. In the context of this analysis, the increase in fuel consumption due to non-continuous descent has been computed conservatively, considering that any level segment still provides movement in a useful direction, as no detection of holding patterns has been implemented yet:

$$\Delta F_{Descent} = \frac{F_{Level} - F_{Cruise} \frac{d_{Level}}{d_{Cruise}}}{F_{Descent}} \quad (3)$$

Figure 4 shows an example of a vertical flight profile, comparing the first (green) and last (orange) proactive FPs to the actual flown trajectory in blue. This particular flight, operated by an A321, is

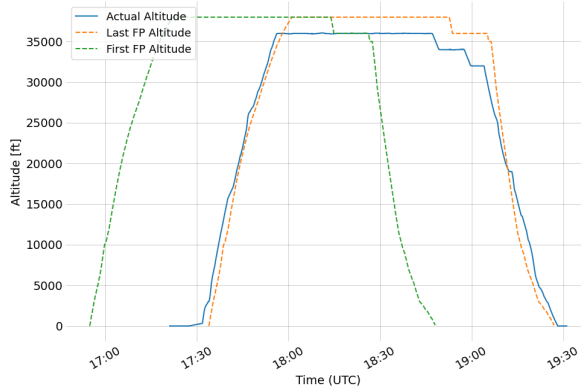


Figure 4. Comparison of the flown vertical flight profile to the first and last FP vertical profile.

very informative on the selected metrics for vertical efficiency, as both cruise at a flight level lower than planned (with respect to both the first and last preactive FPs) and a short interruption of the descent path at 19:10 can be observed. A shift of approximately 40 minutes between the initial and the last preactive FPs can also be observed, with the former matching the actual departure time. This delay has no influence on the considered metrics, which are position- and not time-based, meaning that the planned altitude is compared to the actual flown altitude at the same position. Besides, this work focuses on in-flight inefficiencies: since this particular flight has closely matched its last planned duration, the precise cause of the pre-departure delay, clearly shown by the shift between the first and last FPs, has not been investigated. For this specific flight, the indicators are as follows:

$$\begin{aligned} \text{VFE} &= 0.3061 & \text{VFE1} &= 0.3329 \\ \text{CDO} &= 0.9609 & \Delta F_{\text{Descent}} &= 4.3 \text{ kg} \end{aligned}$$

3.2 Horizontal route efficiency

This section introduces metrics useful to evaluate the horizontal flight efficiency of trajectories, which is assessed on the en-route segment to exclude the impact of terminal procedures (Standard Instrument Departure (SID), Standard Terminal Arrival Route (STAR), noise-abating trajectories...). The horizontal efficiency compares a flown route (or flight plan) with a reference. This can either be the orthodromic distance between the two terminal airports [6, 13], or can account for various ATM constraints (fixed route structures, airspace restrictions, or route charges), like in [14, 15]. The considered metrics are the following:

- Strategic Distance Efficiency (SDE): the metric compares the filed flight plan en-route distance to the corresponding shortest (within the dataset) en-route filed distance, as follows:

$$SDE = \frac{D_{ER,Filed}}{D_{ER,Filed|min}} \quad (4)$$

In the assessed study case, the shortest en-route flight plan belongs to cluster 1. The four clusters show a SDE of 1.06, 1.10, 1.13 and 1.12 respectively, showing how the shortest FP is still 6% shorter than the flights that follow comparable paths.

- Tactical Distance Efficiency (TDE): the metric compares the flown en-route distance to the corre-

sponding en-route filed distance from the last preactive plan, as follows:

$$TDE = \frac{D_{ER,Actual}}{D_{ER,Filed}} \quad (5)$$

The average TDE for all 4 clusters shows the actual flown trajectory to be shorter than the planned route, with the indicator equal to 0.92, 0.89, 0.90 and 0.88. A similar metric, called TDE1, compares the en-route flown distance to the en-route planned in the first flight plan. If TDE is greater than TDE1, it means that the planned en-route distance was reduced as the flight plan evolved before the flight, showing an increased efficiency. TDE1 for the four clusters is equal to 0.94, 0.90, 0.93 and 0.90, showing that the horizontal efficiency drops slightly as the preactive flight plans are updated.

As an example, fig. 5 shows the horizontal trajectory of the flight shown in fig. 4, which belongs to cluster 2 and sees a SDE and TDE of 1.103 and 0.888 respectively.

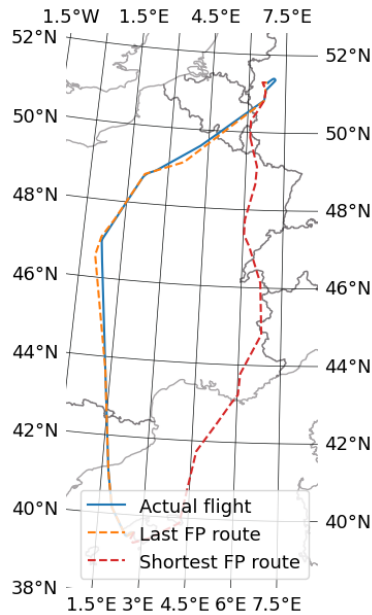


Figure 5. Comparison of the flown trajectory with its last corresponding FP (orange) and the shortest en-route FP (red).

- **FIR Cost:** the EUROCONTROL-administered airspace overfly fee has a formulation that depends on a country-related unit-rate u , on the distance in kilometers per country and on the Maximum Take-Off Mass of the operating aircraft in tons, as [16]:

$$C = \sum_c^{Country} \left(u \frac{D}{100}\right)_c \sqrt{\frac{MTOM}{50}} \quad (6)$$

A more thorough database, including the FIR cost outside of the EUROCONTROL airspace, has been implemented to account for long-haul routes. No further details are given as it is not relevant for the selected test route. If the last term of eq. (6) is neglected, a fair and straight comparison of the route cost independent of the operating aircraft is obtained, enabling to understand the rationale behind the choice of trajectory. This particular route does not seem to see a significant variability in distance, FIR cost and duration across the four identified clusters, as shown in table 1.

Table 1. Comparison of distance, FIR cost and duration of flights across clusters.

Cluster	Distance [km]	FIR cost [Euro]	Duration [min]
1	1425.3	1006.7	136
2	1493.5	1059.6	139
3	1490.4	1082.8	141
4	1498.3	1063.5	141

It is also interesting to point out that routes of clusters 2 and 4 actively avoid the Marseille FIR which is one of the 3 FIRs, together with Karlsruhe and Paris, that recorded an average en-route delay per flight greater than 2 minutes in 2023 [17]. Unlike Paris, which was mostly affected by strikes, the Marseille FIR sees 39% of the delay attributed to capacity and staffing.

- Qualitative observations on the impact of departure and arrival procedures: looking at fig. 1, the effect of arrival and, less so, departure runway direction on the flown route is easily detected. In fact, the only difference between cluster 2 and cluster 4 (consisting of only 1 flight) lies in the arrival pattern at Dusseldorf. Similarly, clusters 1 and 3 show partial correspondence, especially in the Southern part of the route, with a greater difference in the Northern part, again due to the arrival direction at the destination. The departure direction appears to be less impacting on the trajectory, as both orientations appear in clusters that are then differentiated by the arrival direction. This consideration urges to develop a more formal analysis on the impact of STARs on the efficiency of trajectories.

3.3 Combined efficiency metrics

Clearly, the overall flight efficiency can be achieved if only both high vertical and horizontal efficiencies are achieved. Figure 6 shows SDE and TDE as a function of VFE, with a color code identifying clusters. Both TDE and SDE are better if lower, whereas the optimal VFE is 1, with lower values representing suboptimal execution of the vertical flight plan. Thus, the bottom right corner represents the optimal condition in both plots. Looking at the left graph, cluster 1 has the best SDE, which is logical considering that it includes the reference flight plan, with cluster 3 scattered around and cluster 2 being 10% worse than the reference. Looking at the right plot, representing the execution of the flight plan, flights in cluster 2 achieve the highest reduction in distance compared to the plan.

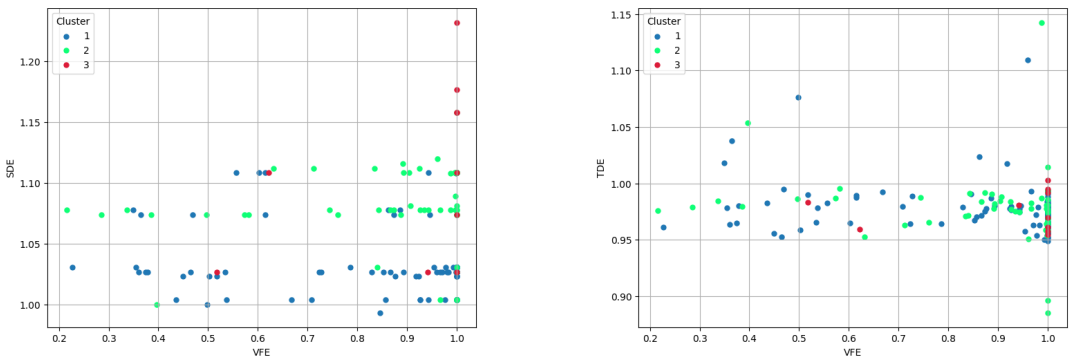


Figure 6. Comparison of SDE and TDE as a function of VFE, divided by clusters.

Another global indicator is the fuel per passenger, which is computed using OpenAP fuel consumption models and cabin capacity. This indicator is biased by aircraft-specific efficiency, but it enables the comparison of different route clusters of the city pair. Table 2 shows the results only for the A320-

operated flights. Despite not being the optimal in terms of execution of the vertical flight plan (VFE

Table 2. Indicators for A320 flights divided by clusters.

Cluster	VFE	VFE1	CDO	SDE*TDE	Fuel per pax [kg/AS]
1	0.815	0.825	0.974	0.975	28.4
2	0.719	0.713	0.963	0.979	29.7
3	0.820	0.834	0.972	1.017	29.4

and VFE1), flights in cluster 1 fly the shortest distance (lowest SDE*TDE) and consume the least fuel per passenger. All three clusters see very high CDO, indicating a good management of approach traffic at EDDL airport.

4. Conclusion

This paper offers a useful review of the main challenges in the quantification of ATM inefficiency and offers a summary of some existing metrics actively used by prominent stakeholders, such as EUROCONTROL. These metrics enable the initial development of the presented methodology; in particular, other vertical and combined metrics will be introduced to obtain a unique global insight into the potential of reduction in climate impact due to the improvement of air transport management.

These local metrics will be combined into a synthetic indicator designed to capture and quantify all sources of inefficiency along the flight. In parallel, an aggregated metric based on fuel consumption—comparing the actual flight to a median trajectory for the same city pair—will be computed to evaluate how well the combined local metrics reflect the impact on fuel consumption. Once all of the modeling of the local indicators and their aggregation is implemented, the methodology will be applied to the ten reference routes for fine-tuning and verification, to then proceed with broader analyses to quantify and perform a statistical analysis on the impact of inefficiencies in ATM in the European skies. Currently, cost-efficiency strategies are only considered in terms of FIR cost, but we have the ambition to integrate existing models of direct operating costs, to evaluate the cost index of flights. This would open the path to a transparent discussion of the inherent link between cost-efficiency and climate-efficiency with long-term established methods to warrant safety and smooth network capacity management.

Author contributions

- Gabriele Sirtori: Conceptualization, Data Curation, Formal Analysis, Acquisition, Investigation, Validation, Visualization, Writing (Original Draft),
- Laurent Joly: Conceptualization, Funding, Methodology, Project Administration, Resources, Supervision, Writing (Review and Editing), Validation,
- Melissa Hoffman: Software, Investigation, Data Curation, Formal Analysis,

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Open data statement

As already described in the text, data to perform a basic version of the proposed analysis is available from open-access sources. Nonetheless, the analysis of the effect of the evolution of FPs is not possible with open-access data.

Reproducibility statement

The code used to present the preliminary results of this paper is still under development, but it is accessible at <https://github.com/Gab97-31/JOAS-/tree/main> and will be updated as the project advances.

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