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Uncovering Hidden Inefficiencies in the Route Availability Document

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Abstract
This study investigates inefficiencies within the Route Availability Document (RAD) used in European air traffic management, focusing on flights from Zurich Airport (LSZH) to various airports in London (EGLL, EGKK, and EGLC). The RAD imposes complex restrictions that impact flight planning, which can lead to inefficiencies. By analyzing flight plans and historical aircraft trajectories, this study highlights discrepancies between filed flight plans and actual flight paths for these city pairs, with only between 2.7% and 4.5% of the flights flying as filed. The impact of EUROCONTROL's *All Together Now 2024* initiative was also assessed, revealing no improvements in adherence to the flight plans. Statistical tests were employed to quantify differences in flight distance and duration, demonstrating that deviations from the RAD constraints lead to shorter and more efficient flights. The study proposes methods for scaling this analysis to uncover inefficiencies and suggests potential RAD modifications to enhance air traffic management efficiency.

Keywords: RAD; Route Availability Document; Air Traffic Management

1. Introduction

Managing a safe and efficient air traffic flow is a challenge for which EUROCONTROL is responsible at the European level. One integral tool in Air Traffic Flow and Capacity Management (ATFCM) in Europe is the Route Availability Document (RAD). The RAD provides a common reference document containing policies and procedures for routes as well as information about free route airspace. It is applicable to flights conducted under instrument flight rules and is updated every Aeronautical Information Regulation and Control (AIRAC) cycle (28 days). The RAD integrates both structural and ATFCM (geographical and vertical) restrictions. As part of EUROCOTROL's network manager ATFCM operation, it organizes air traffic into specific flows to best use the available capacity. The network manager, air navigation service providers, and aircraft operators continuously review RAD restrictions [1].

RAD restrictions are defined in both human-readable and machine-readable formats and can contain flight level caps, geographical and routing restrictions, or requirements on the aircraft's equipment. When a flight plan is submitted to EUROCONTROL's integrated initial flight plan processing system, it will automatically be checked for compliance with RAD conditions and is usually rejected if it is in violation [2].

The sheer amount and complexity of today's RAD restrictions are difficult to handle. As an illustration, the RAD valid from 5th of September 2024 contains almost 16,000 individual conditions [3]. This is not only a challenge to humans but also to computers. The constraints established in the RAD increase the complexity of the already tricky *flight planning problem* solved by flight planning software. Mathematically speaking, some of the RAD restrictions make the flight planning problem at least as hard as the *path avoiding forbidden pairs* problem, which has been shown to be NP-hard [4].

While RAD restrictions are discussed in the scientific literature in the context of flight planning [5, 6, 4, 7], relatively little has been published on the effect of RAD restrictions on flight efficiency. One noteworthy exception is [8] by EUROCONTROL's Performance Review Unit, which assessed en-route vertical inefficiencies.

Our paper investigates one particular example of geographical inefficiencies in the RAD. Although this paper is relatively narrow in scope, it illustrates the issue at hand and provides methods to assess this type of inefficiencies. The case study focuses on the initial part of flights from Zurich Airport (LSZH) to London Heathrow (EGLL), Gatwick (EGKK), and London City (EGLC) airports. The most efficient route that meets the RAD conditions is illustrated in Figure 1. The reason for choosing this particular example was that it was suspected of being inefficient. While aircraft operators must file and plan according to RAD restrictions, flights might not follow the planned route in practice, as they receive shortcuts instead.

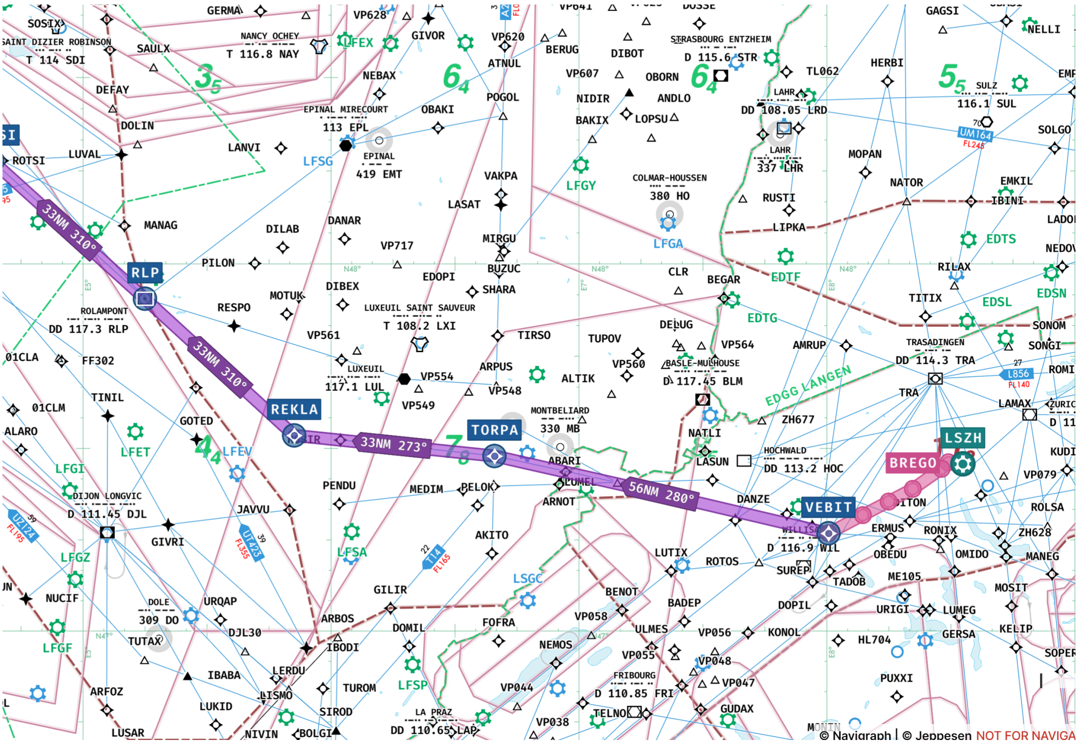


Figure 1. Planned route TORPA, REKLA, and RLP. © 2024 Navigraph / Jeppesen.

Additionally, we investigate the impact of EUROCONTROL's *All Together Now 2024* initiative [9] launched in May 2024. This initiative asks pilots to "fly what you file!" and ATCOS to "not deviate the flight from the vertical/lateral profile as filed in the flight plan" in order to minimize delays and optimize capacity. The aircrew can request deviations from the filed flight plan or they can be offered by the ATCO. Although adherence to the filed flight plans makes perfect sense to reduce complexity and makes the best use of the capacity, it provides few incentives for individual actors to do so. From an aircraft operator's point of view, it is advantageous to request a shortcut and, thus, save time and fuel, even though it might negatively affect the air traffic system.

The following section presents the case study, the data, and methods used and discusses the results of this particular example. Section 3 describes how the method can be generalized to investigate these particular inefficiencies on a larger scale, and Section 4 concludes this study.

2. Case Study

The planned route illustrated in Figure 1 meets the RAD conditions by departing Zurich via the standard instrument departure route to the waypoint VEBIT and then continuing to TORPA, REKLA, and RLP. The relevant RAD conditions are ([3], AIRAC 2409):

- Annex 3A: Aerodrome Connectivity Options:
  - LS5597
  - LS5599
  - LS5598
- Annex 2B: Local and Cross-border Capacity and Structural Rules:
  - LS2395
  - LS2813
  - ED3839
  - LF2151

The datasets used in this case study and how they were processed are described below.

2.1 Data and Processing

This case study is based on two datasets: filed flight plans submitted to EUROCONTROL and historical aircraft trajectories. Both datasets cover the period from May 01, 2023, to September 30, 2024 and, thus, include one year's worth of data before the *All Together Now 2024* initiative was launched. To allow for a more consistent statistical analysis, only flights from three airlines were used, namely Swiss International Airlines, British Airways, and EasyJet. They account for the majority of flights between Zurich and London, and as airlines, they are expected to have comparable operations. At the same time, basing this study on multiple airlines should capture the differences in operation between them.

The flight plans were provided by the EUROCONTROL Performance Review Unit in the form of SO6-M1 files. These files contain the last filed flight plan in the format of character-separated values. Each flight plan has its unique identifier, and a flight is represented by a sequence of waypoints. No additional processing was required since the provided dataset was already filtered to include only flights from Zurich to London.

The historical trajectories were obtained from the OpenSky Network [10] and were downloaded and processed using the Traffic Python library [11]. After downloading, the trajectories and the flight plans were merged and augmented with computed values (e.g., cumulative distance, routing via TORPA, REKLA, and RLP), and obvious outliers were removed. The resulting dataset is summarized in Table 1.

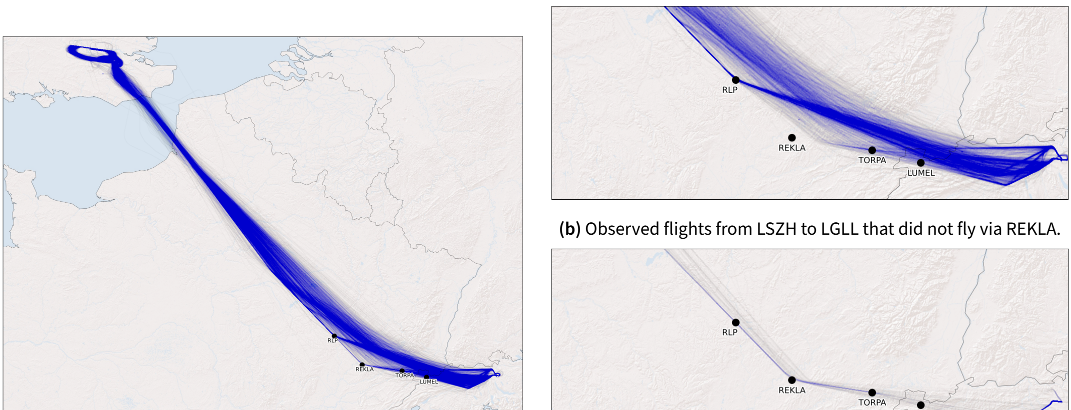
Table 1. Overview of flight plans and trajectories planned via TORPA, REKLA, and RLP.

	LSZH - EGLL	LSZH - EGKK	LSZH - EGLC	Total
Total flight plans filed	3138	680	1036	4854
Flight plans via waypoints	2953 (94.1%)	653 (96.0%)	894 (86.3%)	4500 (92.7%)
Matched trajectories via waypoints	2439 (82.6%)	585 (89.6%)	807 (90.3%)	3831 (85.1%)

Out of 4855 filed flight plans, the majority (4500 flights, or 92.7%) were planned via TORPA, REKLA, and RLP, and a total of 3831 (85.1%) historical trajectories were matched to the flight plans via these waypoints. By far the most flights were between Zurich and London Heathrow (LSZH - EGLL), where 2439 trajectories were matched to flight plans. The fairly large number of 3831 matched trajectories allows for a meaningful statistical analysis.

2.2 Adherence to the Filed Flight Plans

As mentioned earlier, it was suspected that the RAD restrictions might not be adhered to in operation, and flights might not be conducted according to the filed flight plan. To check whether the *All Together Now 2024* initiative of EUROCONTROL changed the behavior of pilots and air traffic controllers, the period before May 2024 and after were analyzed separately. The trajectories matched to flight plans filed via TORPA, REKLA, and RLP were checked to determine whether they overflew or performed a fly-by of waypoint REKLA. The results are illustrated in Figure 2 and shown in Table 2, listed separately for the period before the initiative (< 01.05.2024) and after (≥01.05.2024).



(a) Observed flights from Zurich (LSZH) to London Heathrow (LGLL), flight plans filed via TORPA, REKLA, and RLP.

(b) Observed flights from LSZH to LGLL that did not fly via REKLA.

(c) Observed flights from LSZH to LGLL that did fly via REKLA.

Figure 2. Comparison between the planned flights and the actual trajectories between Zurich and London.

The results show that only a small fraction of flights follow the filed flight plans and comply with the RAD. In the period before the *All Together Now 2024* initiative, only between 3.1% and 4.5% flew as filed, and between 1.8% and 5.6% did so after. To understand whether the initiative had a significant effect, a one-sided two-sample proportions z-test, a statistical test to compare two Bernoulli distributions, was performed [12]. As the number of *positives*, i.e., flights flying as filed, is too small for some city pairs, the statistical test might not be reliable if performed for each city pair individually. This issue is avoided by using all flights, independent of the city pair, before the initiative as one group and all the flights after the initiative as a second. The hypothesis H_o was that after the launch of the *All Together Now 2024* initiative, the adherence to the flight plan increases:

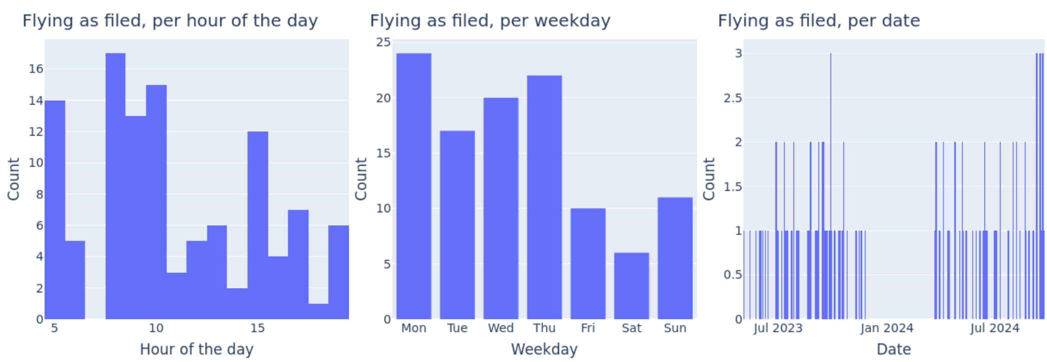
Table 2. Adherence to the filed flight plans via LUMEL, TORPA, REKLA, and RLP.

		LSZH - EGLL	LSZH - EGKK	LSZH - EGLC	Total
	Filed via REKLA	1689	354	580	2623
< 01.05.2024	Flown via REKLA	68	16	18	102
	Ratio via REKLA	4.0%	4.5%	3.1%	3.9%
	Filed via REKLA	752	231	227	1210
≥01.05.2024	Flown via REKLA	42	10	4	56
	Ratio via REKLA	5.6%	4.3%	1.8%	4.6%
	Filed via REKLA	2441	585	807	3833
Total	Flown via REKLA	110	26	22	158
	Ratio via REKLA	4.5%	4.4%	2.7%	4.1%

- H_o: $p_{\text{before}} = p_{\text{after}}$, the initiative does not affect the probability of adhering to the flight plan
- H_a: $p_{\text{before}} < p_{\text{after}}$, the probability of adhering to the flight plan is greater after the initiative

The resulting p-value of the test is 0.28. Using a significance level of $\alpha = 0.05$, the null hypothesis cannot be rejected (p-value $\not< \alpha$), indicating no significant increase in adherence to flight plans due to the initiative. In simple terms, there is no evidence that the initiative has increased adherence to flight plans on specific routes.

To better understand and potentially suggest modifications to the RAD, detecting any pattern when aircraft deviate from *flying as filed* would be beneficial. Since only relatively few aircraft adhered to the flight plan, this group is easier to study to detect any pattern. One might expect that adherence to the flight plans might be higher at certain times of the day or season. Figure 3 illustrates our simple analysis of this.



(a) Histogram of flights *flying as filed*, per hour of the day.
(b) Histogram of flights *flying as filed*, per weekday.
(c) Histogram of flights *flying as filed*, per date.

Figure 3. Histograms of flights *flying as filed*.

Unfortunately, not many patterns over time are obvious. Neither the hour of the day (see Figure 3a nor the weekday (see Figure 3b indicates any clear trends. Only the time of the year shows a clear gap of about four months between November 23$^{\text{rd}}$ and March 29$^{\text{th}}$, where not a single flight flew as filed. In the remaining month, between none and at most three flights adhered to the flight plan. The data suggests that suspending the corresponding RAD restrictions during the winter months might be an option. Of course, this would need to be coordinated and agreed upon with the involved stakeholders.

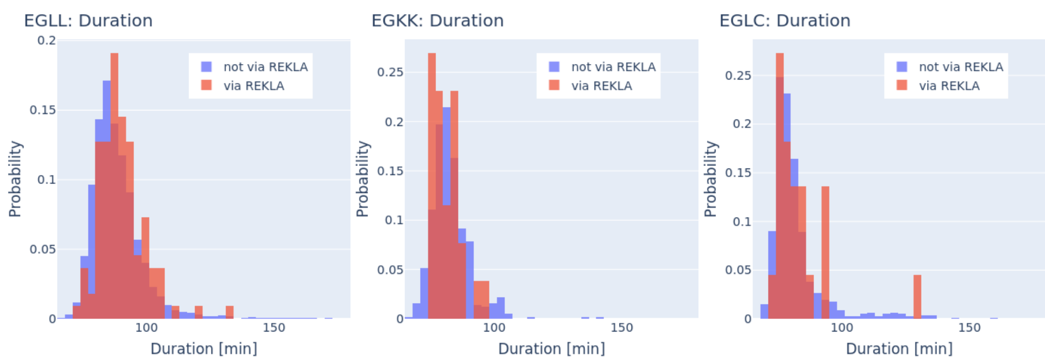
2.3 Quantifying the Inefficiencies

In the following, the inefficiencies are quantified by comparing the flights that adhere to the flight plans to the ones that do not. This effort is complicated by the fact that the absolute number of flights flying as filed is small, and a few outliers in this group can have a large impact on the statistics. The inefficiencies were quantified using two different measures between the two groups: the difference in distance flown and the difference in flight duration. These measures are computed per city pair since they would not be comparable otherwise. The difference in fuel consumption was also calculated for the two groups and per city pair, but the results are omitted here. The number of flights between the city pairs that flew via REKLA was relatively small. When these small groups are further divided into the different aircraft types (to allow for a fair comparison), the groups become too small for any meaningful statistical analysis.

To determine whether a more direct routing omitting the waypoint REKLA leads to shorter flight duration and distances flown, the one-sided *Mann-Whitney U-rank test* is applied [13]. This is a nonparametric statistical test to estimate whether the flight duration and distance are longer for the flights via REKLA compared to flights that do not fly via REKLA, i.e.

- H_o: $x_{\text{not REKLA}} = x_{\text{REKLA}}$, no difference in flight duration/distance exists between the groups
- H_a: $x_{\text{not REKLA}} < x_{\text{REKLA}}$, flights not flying via REKLA have stochastically smaller flight durations/distances compared to flights via REKLA

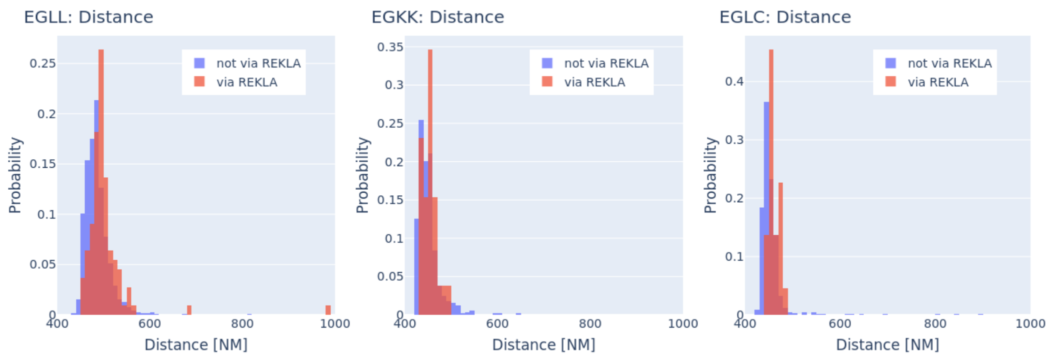
The distributions of the flight duration and the distance flown are illustrated in Figures 4 and 5. The results of the statistical analysis are summarized in Table 3.



(a) Duration of flights with destination EGLL. (b) Duration of flights with destination EGKK. (c) Duration of flights with destination EGLC.

Figure 4. Flight duration for the two groups. Red: flights via REKLA; Blue, flights not via REKLA.

The results indicate for all city pairs that flying via REKLA results in a (statistically) significantly longer flight distance than flights that do not (assuming the same significance level $\alpha = 0.05$ as above, p-value $< \alpha$). The largest effect is observed for flights to London Heathrow, with a median difference in flight distance of 12NM. This city pair also shows a significant difference in flight duration. The median duration of flights via REKLA is 2.4 minutes longer than for flights that do not fly via REKLA. On the other hand, the statistical test for the flights to London Gatwick and London City indicates that no difference between the groups exists with respect to the duration. This might be a genuine effect, but it could also be due to the relatively small sample of flights that fly via REKLA to the destination.



(a) Flown distance of flights with destination EGLL. **(b)** Flown distance of flights with destination EGKK. **(c)** Flown distance of flights with destination EGLC.

Figure 5. Flight distance for the two groups. Red: flights via REKLA; Blue: flights not via REKLA.

Table 3. Median time and distance for flights between Zurich and London. The flight count is repeated here for convenience.

		LSZH - EGLL	LSZH - EGKK	LSZH - EGLC
Duration	via REKLA [min]	88.9	79.9	79.7
	not via REKLA [min]	86.5	81.5	78.8
	difference [min]	2.4	-1.6	0.9
	p-value	0.001	0.911	0.090
Distance	via REKLA [NM]	494.5	454.1	458.4
	not via REKLA [NM]	482.5	447.3	447.7
	difference [NM]	12	6.7	10.7
	p-value	0.000	0.021	0.000
Flight count	via REKLA	110	26	22
	not via REKLA	2329	559	785

In the following discussion, we focus on the city pair Zurich - London Heathrow, for which we observed almost twice as many flights as for the other two combined. One might expect that when aircraft arrive ahead of their scheduled time at the destination airport, they might end up in holding patterns more often. To investigate this, holding patterns were identified in the trajectories. 689 out of 2329 (29.6 %) trajectories not flying via REKLA went into a holding pattern, compared to 42 out of 110 (38.2 %) of the flights via REKLA. This suggests that flights not flying as filed do not end up in holding patterns more often.

The statistically significant shorter flight duration of 2.4 minutes might not seem like a lot. But it should be considered that flight operations run on a very tight schedule. This difference represents 2.7% of the total flight time for this city pair and an even larger fraction of the aircraft turnaround time (see [14] as a reference for turnaround times). Allowing aircraft operators to file flight plans that more closely align with the actual operations would enable them to have a more optimized scheduling and could potentially save fuel and CO_2 emissions. Of course, flight plans that are more in line with the actual operation would be helpful in ATFCM and is at the core of the *All Together Now 2024* initiative.

3. Application of the Methods to Large-Scale Analysis

The proposed methods are, in principle, suitable for automated, large-scale analysis of inefficiencies in the RAD. As in this study, city pairs with sufficient traffic could be analyzed to determine the fraction of traffic not adhering to the flight plans. If a defined threshold is exceeded, differences in flight duration and distance could be further investigated. Such a two-step approach would limit the computational burden of the analysis by processing only city pairs with a low rate of flight plan adherence. Determining appropriate thresholds to define when an operation is *inefficient* could be done on a sample of city pairs with known inefficiencies. For instance, what percentage of traffic not adhering to the flight plans is worth analyzing further.

Of course, a large-scale analysis of the RAD's inefficiencies would require additional effort and is not without challenges. Large amounts of flight plans and historical trajectories would need to be processed to produce robust and representative results. Naturally, this requires a fair amount of computational resources and additional effort to implement the methods efficiently. A noteworthy pitfall might be city pairs with relatively little traffic. A long observation period would be needed to arrive at a sufficiently large number of observations, which increases the risk that the relevant airspace structure changes over time. In that case, trajectories and flight durations might not be comparable for the whole period due to changes in the airspace structure along the entire trajectory, not only around the analyzed inefficient part. However, an effort to detect inefficiencies at scale might well be worth it. Uncovering and subsequently alleviating such hidden inefficiencies would benefit everybody involved.

4. Conclusions

This study demonstrates that the current RAD restrictions, while designed to optimize air traffic flow, can lead to inefficiencies in practice. The analysis of flights from Zurich to London showed that only a small fraction of flights adhere to the RAD-mandated routes, with deviations typically resulting in shorter flight durations and distances. The *All Together Now 2024* initiative by EUROCONTROL did not significantly increase adherence rates, indicating that systemic incentives might not align with operational practices. Statistical analysis confirmed that avoiding certain waypoints, such as REKLA, could improve efficiency without increasing the probability of the involved aircraft ending up in holding patterns.

Although the methodology used in this study effectively identifies inefficiencies, its current scope is limited to a specific set of routes. A large-scale analysis could systematically assess inefficiencies across multiple city pairs, providing insights for targeted RAD modifications. Potential adjustments, such as seasonal suspensions of certain restrictions or refinements based on historical deviations, could better align regulations with actual operations. This would provide better predictability, potentially leading to time and fuel and a smoother operation.

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Author Contributions

- Raphael Monstein: Conceptualization, Formal analysis, Methodology, Software,, Writing – original draft, Writing – review & editing
- Jan Krummen: Conceptualization, Data Curation, Methodology, Software, Writing – review & editing

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Open Data Statement

All analyses in this study used open ADS-B data from the OpenSky network. Additionally, the flight plans provided by EUROCONTROL are accessible at https://zenodo.org/records/14016336.

Reproducibility Statement

The code required to reproduce all results presented in this paper can be found in a public GitHub repository under the following link: https://github.com/ZHAW-ZAV/RAD_inefficiencies_paper.

References

[1] EUROCONTROL. *ATFCM User Manual - Network Manager*. Accessed: 2024-08-28. 2023. URL: https://www.eurocontrol.int/sites/default/files/2023-03/eurocontrol-atfcm-users-manual-27-0-wef-20230425.pdf.

[2] EUROCONTROL. *NM Flight Planning Requirements - Guidelines*. Accessed: 2024-08-28. 2023. URL: https://www.eurocontrol.int/sites/default/files/2023-11/eurocontrol-nm-fpl-guidelines-v4-0.pdf.

[3] EUROCONTROL. *Route Availability Document (RAD)*. Accessed: 2024-08-29. 2024. URL: https://www.nm.eurocontrol.int/RAD/.

[4] Anders N. Knudsen, Marco Chiarandini, and Kim S. Larsen. "Heuristic Variants of A* Search for 3D Flight Planning". In: *Integration of Constraint Programming, Artificial Intelligence, and Operations Research*. Ed. by Willem-Jan van Hoeve. Cham: Springer International Publishing, 2018, pp. 361–376. ISBN: 978-3-319-93031-2.

[5] Vladyslav Alieksieiev. “Artificial Locust Swarm Routing Algorithm: An Approach to Consider both Routing via FRA and Applying RAD”. In: *2019 International Conference on Information and Digital Technologies (IDT)*. 2019, pp. 1–10. DOI: 10.1109/DT.2019.8813465.

[6] Anders Nicolai Knudsen, Marco Chiarandini, and Kim S. Larsen. “Constraint Handling in Flight Planning”. In: *Principles and Practice of Constraint Programming*. Ed. by J. Christopher Beck. Cham: Springer International Publishing, 2017, pp. 354–369. ISBN: 978-3-319-66158-2.

[7] Ítalo Romani De Oliveira, Steve Altus, Sergey Tiourine, Euclides C. Pinto Neto, Alexandre Leite, and Felipe C. F. De Azevedo. “Stochastic Flight Plan Optimization”. In: *2023 IEEE/AIAA 42nd Digital Avionics Systems Conference (DASC)*. 2023, pp. 1–8. DOI: 10.1109/DASC58513.2023.10311152.

[8] Sam Peeters, Guglielmo Guastalla, and Kevin Grant. “Analysis of en-route vertical flight efficiency”. In: *2018 Integrated Communications, Navigation, Surveillance Conference (ICNS)*. 2018, pp. 3C3-1-3C3–8. DOI: 10.1109/ICNSURV.2018.8384859.

[9] EUROCONTROL. *All together now 2024*. Accessed: 2024-08-28. 2024. URL: https://www.eurocontrol.int/all-together-now-2024#pilots.

[10] Matthias Schäfer, Martin Strohmeier, Vincent Lenders, Ivan Martinovic, and Matthias Wilhelm. “Bringing up OpenSky: A large-scale ADS-B sensor network for research”. In: *IPSN-14 Proceedings of the 13th International Symposium on Information Processing in Sensor Networks*. IEEE. 2014, pp. 83–94.

[11] Xavier Olive. “traffic, a toolbox for processing and analysing air traffic data”. In: *Journal of Open Source Software* 4.39 (2019), pp. 1518–1. DOI: 10.21105/joss.01518.

[12] statsmodels. *Equivalence test based on normal distribution*. Accessed October 23, 2024. https://www.statsmodels.org/dev/generated/statsmodels.stats.proportion.proportions_ztost.html. 2024.

[13] SciPy. *Mann-Whitney U rank test on two independent samples*. Accessed October 23, 2024. https://docs.scipy.org/doc/scipy/reference/generated/scipy.stats.mannwhitneyu.html. 2024.

[14] Paolo Malighetti, Chiara Morlotti, Renato Redondi, and Stefano Paleari. “The turnaround tactic and on-time performance: Implications for airlines’ efficiency”. In: *Research in Transportation Business and Management* 46 (2023). Themed Volume on Transport Efficiency, p. 100874. ISSN: 2210-5395. DOI: https://doi.org/10.1016/j.rtbm.2022.100874.