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# New Insight Towards Characterization of the Terminal Areas

Tatiana Polishchuk and Lucie Smetanová
*Communications and Transport Systems, ITN,*
*Linköping University (LiU), Norrköping, Sweden*
*firstname.lastname@liu.se*

**Terminal areas often experience significant performance degradation due to limited airspace capacity and operational resources, which unavoidably contributes to the increased environmental footprint of the aviation sector. In this paper, we present our work on the development of the new performance evaluation metrics for efficient, fair and comprehensive quantitative assessment of the arrival operations within the Terminal Maneuvering Areas (TMAs). We investigate existing metrics, develop new ones and study dependencies between them, targeting creation of the comprehensive performance assessment framework. Using open-source historical flight data, we test the framework on several airports in Europe which implement different arrival procedures. The newly introduced performance metrics have a potential to predict the TMA performance based of the characteristics of the arrival flows to TMA.**

## I. Introduction

EUROCONTROL developed the methodology used by its Performance Review Unit (PRU) for the yearly assessment of the air traffic management in Europe [1]. EUROCONTROL Innovation Hub (formerly Experimental Centre) constantly works on investigation of the new metrics for better understanding of the reasons for performance inefficiencies within TMAs [2], [3], [4], with the most recent development on this topic [5], where the authors applied an extensive statistical analysis to identify the most relevant indicators for evaluation of arrivals.

The authors of [6], [7] suggested a set of metrics for comprehensive assessment of the arrival flight performance in TMA, and tested it on three European airports implementing different arrival procedures such as vectoring, trombone and point merge. These proposed metrics describe the overall TMA operations and help to identify the areas of inefficiencies. In this work, we use the existing metrics, complementing with the new ones characterising the arrival performance, and analyse the dependencies between them, targeting creation of the comprehensive performance assessment tailored to the given scope or for the specified purpose.

## II. Related Work

Significant inefficiencies were reported in the Terminal Maneuvering Areas (TMAs) [8] due to their increased complexity. For sequencing and spacing aircraft in TMA, different procedures are in place at airports around the world [9], with the most recent technique being point merge, developed by EUROCONTROL [10]. Other means of sequencing and spacing are trombone procedures, described in detail in [11, 12], and vectoring [13], where the Air Traffic Control Officers (ATCOs) manually assign heading instructions to aircraft in order to adjust the aircraft routes. TMA operation is subject to both horizontal trajectory challenges, that influences the time the aircraft spend in TMA, and vertical trajectory challenges, that influence the efficiency of the descent. Both parts have in common that they are directly related to fuel consumption and emissions, and preferably, one would want arriving aircraft to fly the shortest route from TMA entry to the runway, performing a continuous descent at a minimum engine thrust setting.

The author of [14] described the flight inefficiency metric options with focus on quantifying the difference between the ideal and actual performance, and used them to analyze flight data from European airline A320 family, proving that the flight inefficiency metrics are effective at quantifying ATM performance. In [15], the authors analysed technical efficiencies and tested their components at three New York's airports. The authors of [16] studied system-level risks and vulnerabilities of TMAs on Sydney Kingsford-Smith airport by proposing a methodology to identify ground-air network bottlenecks. In [4], the authors investigated the factors affecting the vertical efficiency in descent phase of flight for 30 top European airports in order to identify potential areas of improvement for each airport.

Ryerson et al. [17] analyzed flight-level fuel consumption data to study possible fuel savings. To do so, they isolated different flight phases, among them the terminal area inefficiencies, and ranked different terminal areas based on Terminal Inefficiency metric of fuel consumption variation in them.

In [18], the authors proposed approach for understanding and characterization of arrival sequencing and pressure, which relies on an analysis of spacing evolution overtime between aircraft, and considers aspects as convergence, speed, and monotony. We use a subset of the performance metrics proposed in this work, as a base for defining a new one for characterization of arrival sequencing in TMA.

Development and classification of the KPIs for en-route flight phase was considered within the APACHE project (a SESAR 2020 exploratory research project) [19], [20]. Later Prats et al. [21] proposed a family of enhanced performance indicators. In [22] authors conducted analysis on performance metrics in pre-TMA area with a goal to set a baseline characterization of pre-TMA metrics in order to support the operational field evaluation. The authors in [23] applied statistical learning methods to assess the impact of different weather conditions on the arrival flight efficiency. They further used the methodology to assess arrival flight efficiency in pre- and post-Covid 19 Pandemics [24]. We utilize the statistical methods detailed in this work to investigate the relationships between the efficiency indicators.

# III. Methodology

In this work, we focus on the busy-time periods for the arrivals to Dublin (EIDW), Vienna (LOWW), and Stockholm Arlanda (ESSA) airports. In this section, we describe the dataset and provide a brief description of the airports.

## A. Data

We utilize the historical open-access database of the Opensky Network [25], [26], which provides an accurate trajectory data in form of aircraft state vectors for every second aircraft spend inside the terminal area. The data is transmitted by the Automatic Dependent Surveillance Broadcast (ADS-B) aircraft transponders, and collected via sensors on the ground, supported by volunteers, industrial supporters, and academic or governmental organizations.

Our dataset contains all the aircraft arrivals to EIDW, LOWW, and ESSA during October 2019 (the busiest month of the last pre-pandemics year), covering only the busy hours, defined according to the following procedure. We calculate the average time aircraft spend in TMA per hour and remove the 0.7th percentile from this set of values. For each airport, we consider only arrivals to one most-used runway during the studied period. The chosen runways are: 28L for Dublin airport (used about 88% of the time), 01R for Stockholm Arlanda airport (35%), and 16 for Vienna airport (44%).

The performance metrics we consider are designed mainly for the TMAs, but during our analysis, we noticed that significant parts of the descent phase at Dublin airport start outside the TMA border. Due to the observed inconsistencies, we decided to consider 50NM circle around runway 28L for Dublin airport to enable capturing the whole parts of the descent for the traffic arriving from south-eastern direction.

The raw data required cleaning and filtering to remove incomplete or erroneous records, and non-typical flights. The cleaning and filtering methods include removing fluctuations in latitude, longitude and altitude, smoothing of altitude profiles, removing incomplete trajectories, and removing flights such as go-arounds, helicopters and non-commercial traffic (described in details in [6]).

The resulting dataset contains 2587, 1641, and 1045 arrival flights to Dublin, Vienna, and Stockholm Arlanda airports, respectively.

## B. Airports

In this study, we focus on three European airports with different arrival procedures to widen the scope of our analysis. The three airports are Stockholm Arlanda airport (ESSA) with open-loop vectoring arrival procedures, Vienna airport (LOWW) with trombone arrival procedures, and Dublin airport (EIDW) with point merge arrival procedure. The three airports feature similar TMA sizes of the TMAs (between 4500 and 6000 $NM^2$) and operate similar amount of yearly traffic (between 220,000 and 270,000 movements).

### *1. Stockholm Arlanda airport*

Stockholm Arlanda airport is the largest airport in Sweden located approximately 40 kilometers north from Stockholm city. According to [27] there was 116.529 arrivals to Stockholm Arlanda airport during the year 2019.

Stockholm Arlanda airport constitutes of three runways, two parallel (01R/19L and 01L/19R) and one intersecting both (08/26), the runway configuration is shown in Figure 1 - (a). Runway 01L/19R is equipped to accommodate landings and take-offs of the heaviest aircraft in use today. The parallel runways are independent on each other and can operate take-offs and landings simultaneously [28].

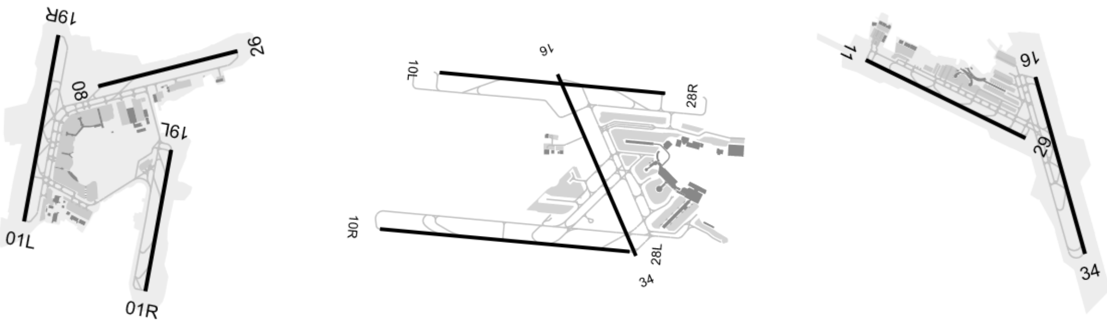
*2. Dublin airport*

Dublin airport is located approximately 10 kilometers north of Dublin city and is the busiest of Ireland's airports. According to [29] there was 114,626 arrivals to Dublin airport during the year 2019. In 2019, Dublin had two intersecting runways (16/34 and 10/28) which are rarely used simultaneously, their configuration is shown in Figure 1 - (b). However, the airport operated mostly with single runway (16/28). In August 2022, the runway 10/28 was redesigned to 10R/28L and opened for regular utilization, which is expected to increase the airport capacity [30].

*3. Vienna airport*

Vienna airport is located approximately 20 kilometers south-east from Vienna city and is Austria's largest airport [31]. There were 133,405 arrivals registered during the year 2019 [32].

Vienna airport has two intersecting runways, 16/34 and 11/29, used simultaneously to split the departure and arrival traffic flows. The runway configuration in shown in Figure 1 - (c).



(a) (b) (c)

**Fig. 1 Runway layout for Stockholm Arlanda (a), Dublin (b) and Vienna airport (c) [33].**

### C. Arrival Procedures

Most TMAs today operate open-loop vectoring, but the point merge system is becoming more popular in air space design. Open-loop vectoring arrival procedure is conducted by air traffic controllers, which monitor the TMA and manually assign heading instructions to aircraft in order to adjust the aircraft routes and deconflict them. Stockholm Arlanda airport operates the open-loop vectoring.

More recent techniques develop predefined paths to lower the workload of air traffic controllers. Point merge arrival procedure, is designed to accommodate high-traffic loads without radar vectoring. It provides benefits of improved safety and increased capacity of the airport. Point merge features sequencing legs and a common merge point. Dublin's point merge system is shown in Figure 2 - (a). The aircraft enter the PM system along the sequencing legs and follow them until they are given clear to approach instruction. Dublin was the second airport after Oslo Gardermoen, to adopt the point merge in 2012 [34].

The trombone arrival procedure, as well as point merge, consists of predefined paths for arrival. The paths have a shape of trombone and they allow aircraft to either fly the whole path or to take shortcuts to adjust its timing to final approach [11]. Vienna airport uses trombone arrival procedure for arrivals, the corresponding chart is shown in Figure 2 - (b).

## IV. Performance Evaluation Metrics

TMA performance vary noticeably during the day depending on the traffic intensity, weather and many other factors. The entry conditions are also different at the airport during the day, influenced by the amount of traffic crossing the TMA border. We differentiate between the metrics characterizing the overall TMA performance, which capture the temporal component, horizontal and vertical efficiency, environmental impact and the efficiency of the sequencing and spacing operations, and the metrics which describe the entry conditions to TMA.

We construct two sets of metrics (*A* and *B*) listed in Table 1. Set *A* contains the candidate metrics for describing the entry conditions to TMA, and set *B* contains the indicators used for characterization of the overall TMA performance.

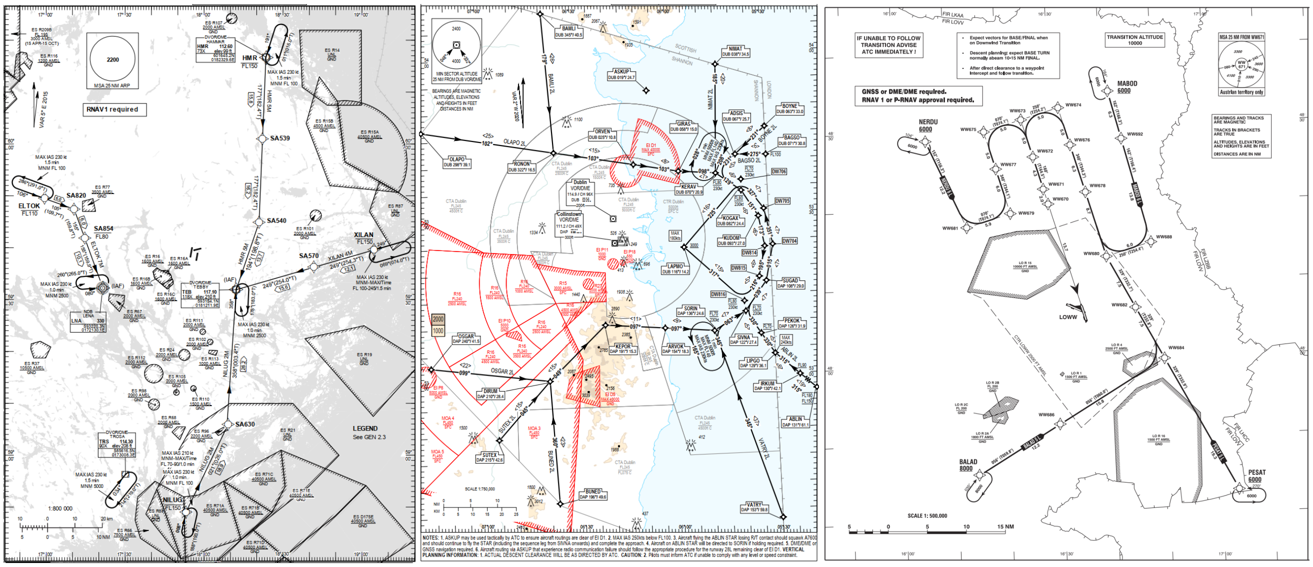


**Fig. 2 Published STARS at Stockholm Arlanda runway 01L/01R (a), Point Merge procedures at Dublin runway 28L (b) and trombone procedures at Vienna runway 16 (c) (Sources: Swedish [35], Irish [36] and Austrian AIP [37]).**

The idea is to study the dependencies between the metrics in two sets with the goal of finding the ones in set *A* which correlate with the most metrics in set *B*, targeting simplification and unification in defining the entry-to-TMA conditions.

**Table 1 Two sets of metrics describing entry conditions (Set A) and the overall TMA performance (Set B)**

| Set A | Set B |
|---|---|
| Threshold | Time in TMA |
| Aircraft within the band | Distance in TMA |
| Interarrival time | Sequencing effort |
| | Vertical Deviation |
| | Additional fuel burn |

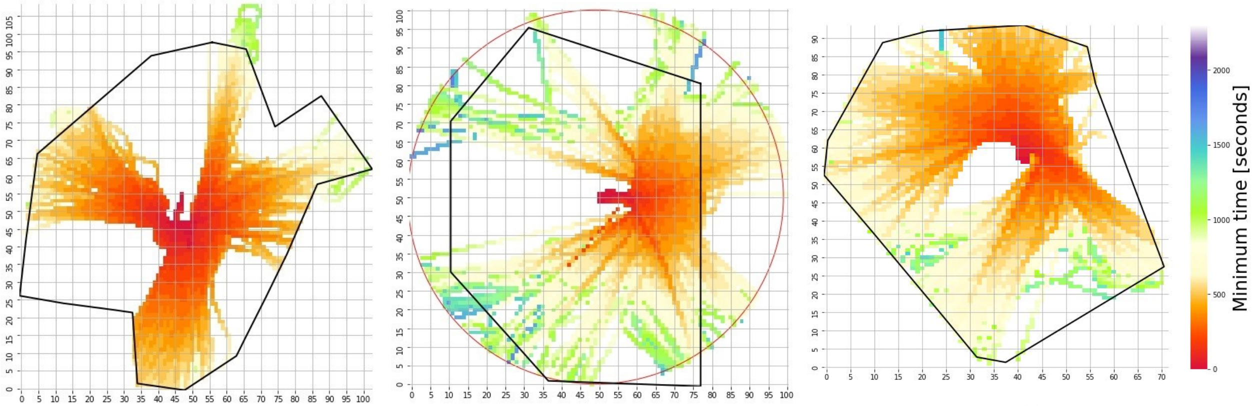
## A. Set *A* metrics

To the best of our knowledge, there are no performance evaluation metrics designed specifically for characterization of the entry-to-TMA conditions. In set A we gather the metrics which have a potential to play this role. The set consists of the new metric Threshold, the number aircraft in the band and the time between the arrivals defined as follows.

### *Threshold for the Minimum Time to Final at TMA Entry*

This new metric is constructed based on the earlier introduced Minimum Time to Final indicator ([18], [38]), which denotes the minimum time flown by aircraft within TMA during the given time period. To construct this metric, we overlay rectangular grid over the aircraft trajectories and normalize their latitude and longitude coordinates to fit the dimensions of the grid. The dimensions of the grid may vary over different TMAs as we set them to obtain $approx$ 1NM cell size. The dimensions of the grids of our studied TMAs in this work are: 103X109, 100X100, and 71X94 for Stockholm Arlanda, Dublin, and Vienna airports respectively. Then, for each cell and each part of trajectory inside, we calculate the *Time to Final* which is the difference between the current timestamp and timestamp at the runway. The Minimum Time to Final value for that cell is then the minimum value of all the Time to Final values inside that cell.

Example visualization of the Minimum Time to Final with heatmap is shown in Figure 3.



(a)

(b)

(c)

**Fig. 3 Minimum Time to Final heatmaps for Stockholm Arlanda (a), Dublin (b), and Vienna (c) airports.**

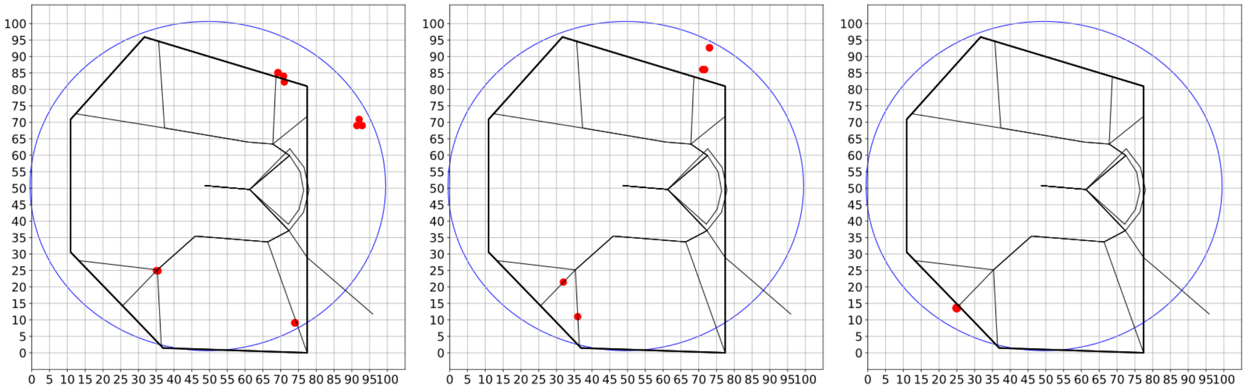


**Fig. 4 Aircraft positions (red dots) in the TMA within different iso-bands for the different threshold values: (left) 700s, (middle) 800s, (right) 900s.**

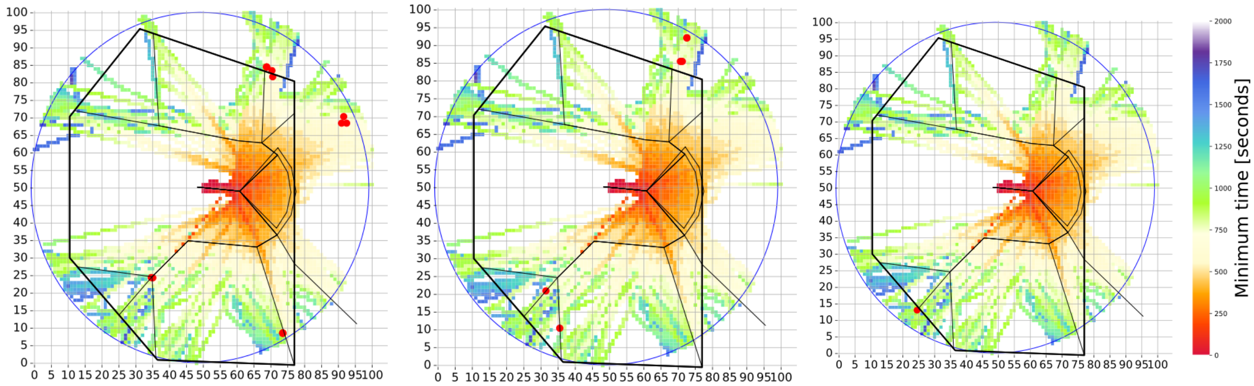


**Fig. 5 Aircraft positions (red dots) in the TMA within different iso-bands (illustrated with the heatmap of the Minimum Time to Final) for the different threshold values: (left) 700s, (middle) 800s, (right) 900s.**

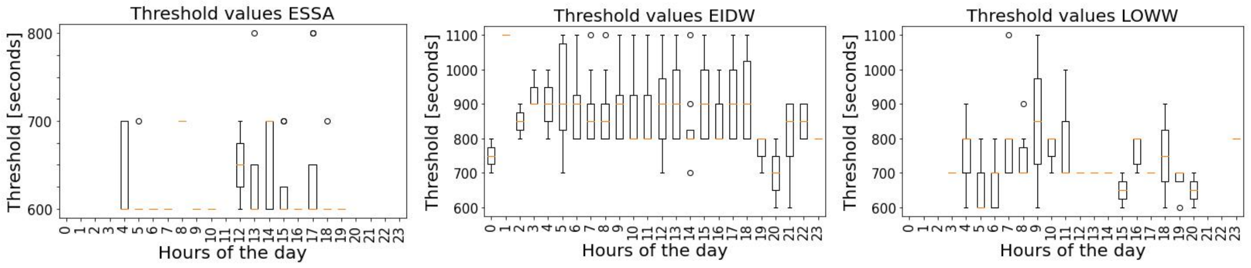
The value of the Minimum Time to Final metric varies during the day: in general, in a busy hour aircraft tend to spend more time in TMA than during the off-peak hours. Our goal is to find such a value for the Minimum Time to

Final, for which most of the aircraft are present in the TMA during the given hour, but still are close to the border. This will help to connect the time component and the actual aircraft location information in order to understand the conditions aircraft should anticipate when they enter the TMA. This information can also be a good indicator for the air traffic controllers about the expected traffic intensity and, hence, the required sequencing and spacing effort needed to manage this traffic amount.

We chose *Threshold* value of the Minimum Time to Final for the given hour by identifying the positions of aircraft when they enter the TMA, when most of them (out of the total for this hour) have already entered the TMA. We test this **new metric** as a candidate for identification of the conditions aircraft experience at the TMA entry.

Figures 4 and 5 show the aircraft positions at three different threshold iso-bands at 700, 800, and 900 seconds of Minimum Time to Final calculated for arrivals to Dublin airport between 16:00 and 17:00 on the 8th of October 2019. The total number of arriving aircraft during this hour is 16. The number of aircraft captured in the different threshold iso-bands are 16, 16, and 1 respectively. The threshold iso-band of 900 seconds of minimum time to final corresponds to the aircraft position closest to the TMA border, but it captured only 1 out of 16 aircraft. Both 700 and 800 seconds threshold bands captured all 16 aircraft, but the aircraft first positions at the 800 threshold iso-band are closer to the TMA border. Hence, we choose the threshold value of 800 seconds of Minimum Time to Final.

Figure 6 illustrates the distributions of the Threshold values calculated for the datasets representing arrivals to the three airports in our studies. High values of the Threshold correspond to busy hours. High variations of the Threshold values, as for example, at 9 am. at Vienna airport, indicate different situations during the same hour on different days. Comparing the plots for the three airports, we can roughly conclude that the aircraft entering Dublin TMA should anticipate longer transit time in TMA than the ones arriving to the other two airports (with the exception at some hours in Vienna with high Threshold values). Maximum values of the Threshold are similar at Dublin and Vienna, while the maximum value of the Threshold in Stockholm Arlanda is significantly smaller for all hours, which may indicate that in general, Stockholm Arlanda TMA is less congested.



**(a)** **(b)** **(c)**

**Fig. 6 Distribution of the Threshold values during the day for a) Stockholm Arlanda, b) Dublin, and c) Vienna airports**

*Aircraft within the band:* We count the number of aircraft within the given 100-seconds-width iso-band corresponding to the Threshold value for each one-hour period.

*Interarrival times:* The metric provides information about the time between the consecutive arrivals to the TMA entry. First, we order all arriving aircraft according to the time they appear within the specific iso-band corresponding to the given threshold. Then, we calculate the time intervals between those arrivals.

### B. Set *B* metrics

The set contains the metrics characterizing the overall TMA performance, which capture the temporal component, horizontal and vertical efficiency, environmental impact and the efficiency of the sequencing and spacing operations. Most of the metrics in this set were previously proposed for TMA evaluation [7]. We complement this set with a newly proposed metric Sequencing Effort described later in this subsection.

*Time in TMA* is characterizing the temporal efficiency and is capturing the time aircraft actually spend in TMA, starting from the entry of TMA and ending when the aircraft lands and reaches zero altitude.

*Distance in TMA* is characterizing the horizontal efficiency and is calculated as the track-mile distance which aircraft fly within TMA, starting from the entry of TMA and ending when the aircraft lands and reaches zero altitude.

To capture vertical efficiency, we calculate the *Vertical Deviation* for each aircraft as the difference between the actual vertical profile flown and the reference vertical profile. We use the continuous descent operation (CDO) as the reference vertical profile, calculated using the methodology provided by Eurocontrol Base of Aircraft Data v 4.2 [39], along the trajectory of the actual flight.

The *Additional Fuel Burn* indicator is used for characterization of the environmental impact of the flights within TMA, and is calculated as the difference between the fuel consumption calculated for the real trajectory and the one for reference vertical profile. For the real flights, we use the Total Energy Model (TEM) from BADA to find the thrust force, from which we derive the thrust coefficient. We use the actual wind and temperature data from ERA5 [40] for the reference vertical profile.

The full description of the methodology for calculation of the Vertical Deviation and Additional Fuel Burn metrics is presented in [7].

To characterize the efficiency of the sequencing methods used to safely manage the aircraft flows, we propose a new performance metric Sequencing Effort, which is defined based on the previously proposed Minimum Time to Final (described in Subsection IV.A) and Spacing Deviation initially defined in [18].

*Spacing Deviation* is defined for a pair of consecutive aircraft sorted by their time of arrival to the runway, tagged as the leader and the trailer according to which aircraft landed first. The Spacing Deviation is calculated as the difference between their respective minimum times to final at time $t$ of aircraft pair, using the following equation:

$$\mathrm{sd}(t) = \mathit{min\_time}(\mathrm{trailer}(t)) - \mathit{min\_time}(\mathrm{leader}(t - s_{rwy}))$$

where $s_{rwy}$ is the temporal separation at the runway, and *min_time* is the minimum time to final. The spacing deviation reflects information about the control error, reflecting the accuracy of spacing within the arrival flows.

Here we define a **new metric** *Sequencing Effort*, which is calculated as a difference between the spacing deviation at the given time horizon (we use the 95-th quantile in this work to exclude outliers) and the one close to the final (30 $s$ in this work). Figures 7 and 8 illustrate the Spacing Deviation and the Sequencing Effort for the three airports in this study, respectively. The slope of the Sequencing Effort curve illustrates the intensity of the control action applied by the controller or a control system to organize the aircraft in the desired order for landing, and also gives the information about the time to the final approach when this action is applied.

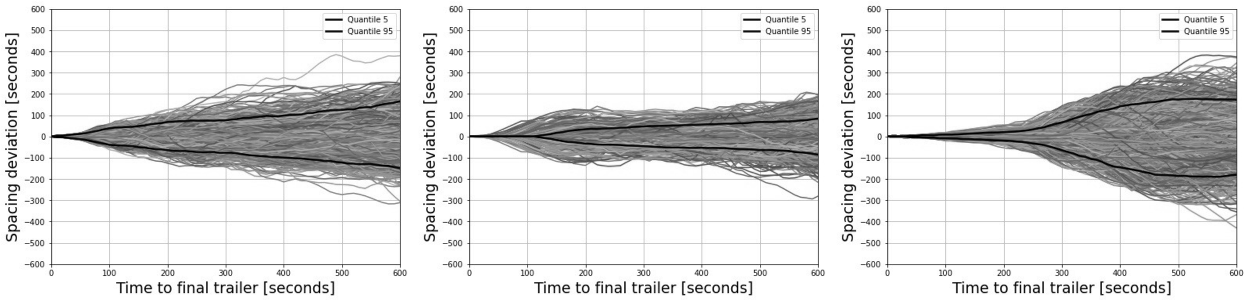


**Fig. 7 Spacing Deviation for Stockholm Arlanda (left), Dublin (middle), and Vienna airport (right).**

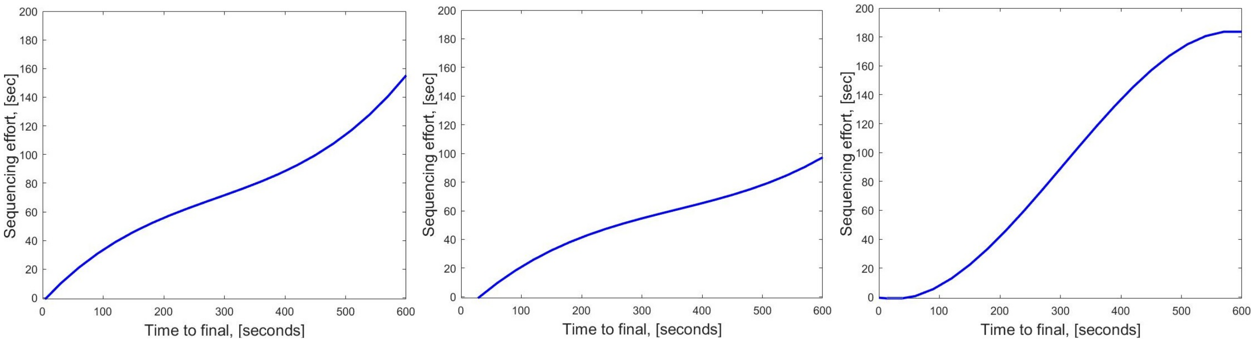


**Fig. 8 Seqencing Effort for Stockholm Arlanda (left), Dublin (middle), and Vienna airport (right).**

# V. Results

In this section, we present the correlation results between the metrics in the sets *A* and *B* for Stockholm Arlanda (Table 2), Dublin (Table 3) and Vienna (4) airports. Statistical values for the metrics in set *B* are calculated for the arrivals over one hour period, as well as for the Interrarival time metric from set *A*. The number of Aircraft within the band and the Threshold metrics are represented by one value per one-hour period. We highlight strong correlation (above 0.8) with green text color, moderate correlation (between 0.6 and 0.8) with red text color, and keep black text color for weaker correlations (below 0.6). Again, we are targeting to identify the performance indicators which strongly correlate with most of the performance metrics traditionally used for the evaluation of the overall TMA performance.

To avoid the effect of outliers, we consider the 90th quantile of the statistical values. The initial results of the regression analysis based on the Pearson and Spearman tests did not show significant dependencies between the metrics. Hence, in this work, we apply the technique described in [24], which is implemented with the use the Python Ordinary Least Squares Regression function. First, we categorize the metric from set *A* into 10 bins. Then, we run the OLS correlation test and output the results.

First of all, we observe strong or moderate correlations between the newly introduced Threshold metric from set *A* with most of the metrics from the set *B* for all three airports. This result makes the proposed metric a promising and unique candidate for representing the conditions within TMA, and the fact that this metric can be calculated already when the aircraft enter the TMA, gives an insight into further implementation of this metrics for predictions of the overall TMA performance basing on the entry flow patterns only. In future work, we plan to validate this metric on different datasets and for several other airports, and investigate on how it can be used in operational environment.

Another interesting observation is that the Threshold correlates strongly with the new Sequencing Effort metric for most of the airports (strong correlations are observed at Arlanda and Vienna airport, and moderate at Dublin). Despite the fact that these two metrics are calculated based on the same Minimum Time to Final, they are quite different and represent the phenomena of completely different nature. While Threshold reflects the overall traffic intensity, Sequencing effort is representing the mutual dependencies between the aircraft pairs. The first metric is calculated for the whole hour, the second is defined for the consequent aircraft pairs. Strong correlations between these two uncover the interplay between the way how the arrival sequence is organized and the control effort required to arrange this sequence in suitable order at the final approach.

The median of the Interarrival times metric demonstrates some promising correlations with most of the metrics at Arlanda airport, with some metrics at Dublin airport and only with maximum Sequencing Effort at Vienna. The usability of this metric is to be investigated further, as it is quite intuitive and relatively easy to implement, which makes it a promising candidate for characterization of the arrival aircraft sequence at the TMA border.

In addition, the Number of aircraft in the band correlates strongly with the maximum Time and Distance in TMA at Arlanda airport, and demonstrates moderate correlations with the maximum values of the Sequencing Effort and Vertical deviation. However, these dependencies are not confirmed at Dublin and Vienna airports.

To summarize, the newly introduced Threshold metric is the only one which correlates with most of the outlined metrics in set *B* for all three airports, what makes it the best candidate to uniquely describe the conditions at the TMA entry. Median values of the Interarrival time demonstrate strong and moderate correlations with many metrics from set *B* for Stockholm Arlanda and Dublin, but not for Vienna airport, and this fact is to be investigated further. In general, significantly less dependencies between the metrics are observed at Vienna airport than at Stockholm and Dublin. We suggest that the key for understanding the differences lies in the difference of the arrival procedures implemented in these three airport. Trombone procedures in Vienna demonstrate significantly different performance results from the Stockholm Arlanda implementing open-loop vectoring and Dublin with point merge. It is interesting to validate this assumption on other airports implementing trombone arrival procedures, and compare to what we obtained for Vienna airport.

# VI. Conclusion

The proposed work contributes to the development of the performance evaluation framework targeting a comprehensive quantitative assessment of the terminal areas. We gathered a number of performance indicators previously proposed for efficient evaluation of the TMA performance, and introduced several new ones to complement this set. Studying the dependencies between two sets of metrics calculated for three airports in Europe (we chose the airports with the similar amount of yearly movements implementing different arrival sequencing and metering techniques), we searched for the descriptive indicators serving simplification of the description of the entry conditions to TMAs. The newly introduced Threshold metric, which showed significant dependencies with the majority of other performance indicators, gives insight to understanding of how to predict the overall TMA performance based of the entry conditions to TMA. In further studies, we will continue testing these candidate indicators on different datasets to validate their usability.

**Table 2 Correlations between set *A* and set B metrics at Arlanda Airport - r-squared values**

| Metrics | | Aircraft in band | Threshold | Interarrival t. (min) | Interarrival t. (max) | Interarrival t. (avg) | Interarrival t. (median) | Interarrival t. (std) |
|---|---|---|---|---|---|---|---|---|
| Time in TMA | MIN | 0.022 | 0.998 | 0.303 | 0.455 | 0.276 | 0.615 | 0.332 |
| | MAX | 0.839 | 0.505 | 0.081 | 0.034 | 0.604 | 0.780 | 0 |
| | AVG | 0.122 | 0.920 | 0.067 | 0.089 | 0.611 | 0.679 | 0.093 |
| | MEDIAN | 0.044 | 0.688 | 0.281 | 0.210 | 0.470 | 0.368 | 0.096 |
| Dist. in TMA | MIN | 0.017 | 0.606 | 0 | 0.318 | 0.821 | 0.495 | 0.644 |
| | MAX | 0.841 | 0.911 | 0.803 | 0.012 | 0.768 | 0.844 | 0.040 |
| | AVG | 0.276 | 0.843 | 0.768 | 0.136 | 0.742 | 0.856 | 0.159 |
| | MEDIAN | 0.085 | 0.931 | 0.790 | 0.651 | 0.384 | 0.368 | 0.054 |
| Sequencing Effort | MAX | 0.781 | 0.995 | 0.026 | 0.146 | 0.128 | 0.252 | 0.012 |
| | AVG | 0.552 | 0.990 | 0.718 | 0.413 | 0.100 | 0.330 | 0.133 |
| | MEDIAN | 0.545 | 0.995 | 0.681 | 0.509 | 0.044 | 0.319 | 0.197 |
| | STD | 0.474 | 0.991 | 0.075 | 0.193 | 0.103 | 0.223 | 0.027 |
| Vertical Deviation | MIN | 0.013 | 0.748 | 0.227 | 0.008 | 0.134 | 0.639 | 0.149 |
| | MAX | 0.602 | 0.756 | 0.055 | 0.451 | 0.409 | 0.785 | 0.030 |
| | AVG | 0.049 | 0.325 | 0.206 | 0.179 | 0.495 | 0.867 | 0.166 |
| | MEDIAN | 0.017 | 0.130 | 0.238 | 0.110 | 0.009 | 0.487 | 0.161 |
| | STD | 0.040 | 0.975 | 0.250 | 0.022 | 0.141 | 0.197 | 0.052 |
| Additional Fuel Burn | MIN | 0.589 | 0.357 | 0.048 | 0.461 | 0.037 | 0.192 | 0.233 |
| | MAX | 0.222 | 0.414 | 0.311 | 0.313 | 0.544 | 0.960 | 0.064 |
| | AVG | 0.014 | 0.438 | 0.033 | 0.116 | 0.660 | 0.903 | 0.035 |
| | MEDIAN | 0.034 | 0.983 | 0.021 | 0.016 | 0.830 | 0.965 | 0.212 |
| | STD | 0.047 | 0.624 | 0.195 | 0.015 | 0.286 | 0.495 | 0.007 |

**Table 3 Correlations between Set A and Set B metrics for Dublin airport (R-square values)**

| Metrics | | Aircraft in band | Threshold | Interarrival t. (min) | Interarrival t. (max) | Interarrival t. (avg) | Interarrival t. (med) | Interarrival t. (std) |
|---|---|---|---|---|---|---|---|---|
| Time in TMA | MIN | 0.042 | 0.869 | 0.035 | 0.277 | 0.113 | 0.17 | 0.055 |
| | MAX | 0.509 | 0.647 | 0.042 | 0.034 | 0.095 | 0.001 | 0.001 |
| | AVG | 0.36 | 0.95 | 0.108 | 0.016 | 0.48 | 0.333 | 0.013 |
| | MEDIAN | 0.7 | 0.959 | 0.174 | 0.025 | 0.382 | 0.24 | 0.394 |
| Dist. in TMA | MIN | 0.337 | 0.856 | 0.368 | 0.178 | 0.6 | 0.745 | 0.157 |
| | MAX | 0.633 | 0.546 | 0.001 | 0.159 | 0.036 | 0.037 | 0.131 |
| | AVG | 0.473 | 0.97 | 0.348 | 0.001 | 0.702 | 0.631 | 0.213 |
| | MEDIAN | 0.574 | 0.971 | 0.247 | 0.008 | 0.564 | 0.478 | 0.173 |
| Sequencing Effort | MAX | 0.427 | 0.600 | 0.131 | 0.090 | 0.131 | 0.455 | 0.021 |
| | AVG | 0.649 | 0.482 | 0.054 | 0.135 | 0.163 | 0.165 | 0.090 |
| | MEDIAN | 0.490 | 0.015 | 0.108 | 0.163 | 0.123 | 0.088 | 0.026 |
| | STD | 0.504 | 0.682 | 0.248 | 0.072 | 0.128 | 0.356 | 0.001 |
| Vertical Deviation | MIN | 0.163 | 0.431 | 0.246 | 0.501 | 0.217 | 0.784 | 0.005 |
| | MAX | 0.517 | 0.661 | 0.205 | 0.173 | 0.268 | 0.146 | 0.114 |
| | AVG | 0.295 | 0.298 | 0.172 | 0.417 | 0.125 | 0.122 | 0.778 |
| | MEDIAN | 0.056 | 0.014 | 0.170 | 0.287 | 0.113 | 0.037 | 0.484 |
| | STD | 0.022 | 0.169 | 0.162 | 0.248 | 0.312 | 0.533 | 0.247 |
| Additional Fuel Burn | MIN | 0.491 | 0.820 | 0.003 | 0.198 | 0.419 | 0.726 | 0.249 |
| | MAX | 0.073 | 0.363 | 0.099 | 0.891 | 0.086 | 0.028 | 0.905 |
| | AVG | 0.107 | 0.049 | 0.207 | 0.770 | 0.222 | 0.233 | 0.817 |
| | MEDIAN | 0.213 | 0.159 | 0.147 | 0.535 | 0.250 | 0.227 | 0.517 |
| | STD | 0.064 | 0.167 | 0.422 | 0.963 | 0.120 | 0.201 | 0.802 |

**Table 4 Correlations between Set *A* and Set B metrics Vienna Airport - r-squared values**

| Metrics | | Aircraft in band | Threshold | Interarrival t. (min) | Interarrival t. (max) | Interarrival t. (avg) | Interarrival t. (median) | Interarrival t. (std) |
|---|---|---|---|---|---|---|---|---|
| Time in TMA | MIN | 0.404 | 0.160 | 0.013 | 0.018 | 0.074 | 0.084 | 0.092 |
| | MAX | 0.028 | 0.815 | 0.268 | 0.107 | 0.457 | 0.414 | 0.029 |
| | AVG | 0.063 | 0.663 | 0.089 | 0.053 | 0.095 | 0.034 | 0.125 |
| | MEDIAN | 0.083 | 0.747 | 0.010 | 0.360 | 0.024 | 0.048 | 0.123 |
| Dist. in TMA | MIN | 0.321 | 0.427 | 0.005 | 0.064 | 0.058 | 0.110 | 0.121 |
| | MAX | 0.025 | 0.749 | 0.402 | 0.114 | 0.733 | 0.568 | 0.130 |
| | AVG | 0.019 | 0.880 | 0.374 | 0.130 | 0.446 | 0.523 | 0.124 |
| | MEDIAN | 0.098 | 0.956 | 0.043 | 0.019 | 0.138 | 0.124 | 0.117 |
| Sequencing Effort | MAX | 0.580 | 0.964 | 0.973 | 0.049 | 0.497 | 0.675 | 0.117 |
| | AVG | 0.460 | 0.912 | 0.680 | 0.066 | 0.471 | 0.572 | 0.193 |
| | MEDIAN | 0.182 | 0.997 | 0.619 | 0.057 | 0.320 | 0.486 | 0.189 |
| | STD | 0.572 | 0.912 | 0.378 | 0.053 | 0.500 | 0.323 | 0.165 |
| Vertical Deviation | MIN | 0.556 | 0.631 | 0.188 | 0.077 | 0.187 | 0.047 | 0.095 |
| | MAX | 0.218 | 0.058 | 0.070 | 0.045 | 0.113 | 0.217 | 0.092 |
| | AVG | 0.021 | 0.619 | 0.027 | 0.043 | 0.265 | 0.075 | 0.077 |
| | MEDIAN | 0.010 | 0.403 | 0.088 | 0.103 | 0.305 | 0.053 | 0.122 |
| | STD | 0.269 | 0.394 | 0.199 | 0.167 | 0.152 | 0.080 | 0.044 |
| Additional Fuel Burn | MIN | 0.704 | 0.445 | 0.267 | 0.140 | 0.129 | 0.059 | 0.121 |
| | MAX | 0.280 | 0.424 | 0.066 | 0.128 | 0.015 | 0.003 | 0.125 |
| | AVG | 0.021 | 0.125 | 0.074 | 0.249 | 0.065 | 0.200 | 0.128 |
| | MEDIAN | 0.124 | 0.265 | 0.282 | 0.099 | 0.463 | 0.318 | 0.110 |
| | STD | 0.118 | 0.357 | 0.079 | 0.035 | 0.032 | 0.041 | 0.046 |

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## References

[1] EUROCONTROL, "Performance Review Report: An Assessment of Air Traffic Management in Europe during the Calendar Year 2021," , 2021.

[2] Christien, R., Hoffman, E., and Zeghal, K., "Spacing and Pressure to Characterise Arrival Sequencing," *ATM Seminar*, 2019.

[3] Christien, R., Hoffman, E., and Zeghal, K., "Towards a characterization of arrival metering. Case study on a variety of European airports," *17th AIAA Aviation Technology, Integration, and Operations Conference (ATIO)*, 2020.

[4] Pasutto, P., Zeghal, K., and Hoffman, E. G., "Vertical efficiency in descent: assessing the potential for improvements at the top 30 European airports," *AIAA AVIATION FORUM*, 2020.

[5] Pasutto, P., and Zeghal, K., "Exploring and evaluating flight efficiency indicators for arrivals, Edition 02-00," Tech. rep., February 2023.

[6] Polishchuk, T., Lemetti, A., Hardell, H., and Smetanová, L., "Evaluation of the Sequencing and Merging Procedures at Three European Airports Using Opensky Data," *OpenSky Network Symposium 2021*, 2021.

[7] Lemetti, A., Polishchuk, T., Hardell, H., Zeghal, K., and Smetanova, L., "Towards a Comprehensive Characterization of the Arrival Operations in the Terminal Area." *SIDs*, 2021.

[8] Pasutto, P., Zeghal, K., and Hoffman, E. G., "Flight inefficiency in descent: mapping where it happens," *AIAA AVIATION FORUM*, 2021.

[9] Klooster, J., Amo, A., and Mani, P., "Controlled time-of-arrival flight trails," *8th USA/Europe Air Traffic Management Research and Development Seminar*, 2009.

[10] EUROCONTROL, "Point Merge Implementation: A quick guide," , 2020.

[11] Sprong, K., Halti, B., J., D., and S., B., "Improving flight efficiency through terminal area RNAV." *6th USA/Europe Air Traffic Management Research and Development Seminar, EUROCONTROL and FAA*, 2005.

[12] EUROCONTROL, *Guidance Material for the Design of Terminal Procedures for Area Navigation (DME/DME, B-GNSS, Baro-VNAV  RNP-RNAV)*, EUROCONTROL, Ed. 3.0, March 2003.

[13] SKYbrary, "Basic Controller Techniques: Vectoring," , last accessed 12.01.2023. URL `https://www.skybrary.aero/articles/basic-controller-techniques-vectoring`.

[14] Reynolds, T. G., "Development of flight inefficiency metrics for environmental performance assessment of ATM," *8th USA/Europe Seminar on Air Traffic Management Research and Development (ATM2009)*, 2009.

[15] Diana, T., "Can we explain airport performance? A case study of selected New York airports using a stochastic frontier model," *Journal of Air Transport Management - J AIR TRANSP MANAG*, Vol. 16, 2010, pp. 310–314. https://doi.org/10.1016/j.jairtraman.2010.03.006.

[16] Zhao, W., Alam, S., and Abbass, H., "Evaluating ground–air network vulnerabilities in an integrated terminal maneuvering area using co-evolutionary computational red teaming," *Transportation Research Part C: Emerging Technologies*, Vol. 29, 2013, p. 32–54. https://doi.org/10.1016/j.trc.2012.12.003.

[17] Ryerson, M. S., Hansen, M., and Bonn, J., "Time to burn: Flight delay, terminal efficiency, and fuel consumption in the National Airspace System," *Transportation Research Part A: Policy and Practice*, Vol. 69, 2014, pp. 286–298.

[18] Christien, R., Hoffman, E., Trzmiel, A., and Zeghal, K., "Toward the characterisation of sequencing arrivals," *ATM Seminar 2017*, 2017.

[19] Prats, X., Barrado, C., Netjasov, F., Crnogorac, D., Pavlovic, G., Agüi, I., and Vidosavljevic, A., "Enhanced Indicators to Monitor ATM Performance in Europe," *SIDs 2018, 8th SESAR Innovation Days*, 2018.

[20] Prats, X., Agüi, I., Netjasov, F., Pavlovic, G., and Vidosavljevic, A., "APACHE-Final project results report," 2018.

[21] Prats, X., Dalmau, R., and Barrado, C., "Identifying the sources of flight inefficiency from historical aircraft trajectories," *ATM Seminar*, 2019.

[22] Kim, D. C. J., "TMA Integrated Metrics Assessment Model," Tech. rep., October 2006.

[23] Lemetti, A., Polishchuk, T., Polishchuk, V., Sáez, R., and Prats, X., "Identification of Significant Impact Factors on Arrival Flight Efficiency within TMA," *ICRAT 2020, 9th International Conference for Research in Air Transportation*, 2020.

[24] Lemetti, A., Polishchuk, T., and Hardell, H., "Arrival Flight Efficiency in Pre- and Post-Covid-19 Pandemics," 2022. https://doi.org/https://doi.org/10.1016/j.jairtraman.2022.102327, available online 10.11.2022.

[25] Opensky Network, 2022. Https://opensky-network.org/, last accessed 10.11.2022.

[26] Schäfer, M., Strohmeier, M., Lenders, V., Martinovic, I., and Wilhelm, M., "Bringing Up OpenSky: A Large-scale ADS-B Sensor Network for Research," *IPSN'14*, 2014.

[27] Statista, "Number of aircraft landings at Stockholm Arlanda airport," , last accessed April 19, 2023. URL https://www.statista.com/statistics/796854/number-of-aircraft-landings-at-stockholm-arlanda-airport.

[28] Wikipedia, "Stockholm Arlanda airport," , last accessed April 19, 2023. URL https://sv.wikipedia.org/wiki/Arlanda.

[29] Office, C. S., "Aviation Statistics quarter 4 and year 2019," , last accessed April 19, 2023. URL https://www.cso.ie/en/releasesandpublications/er/as/aviationstatisticsquarter4andyear2019/.

[30] Wikipedia, "Dublin Airport," , last accessed April 21, 2023. URL https://en.wikipedia.org/wiki/Dublin_Airport.

[31] Wikipedia, "Flughafen Wien Schwechat," , last accessed April 20, 2023. URL https://de.wikipedia.org/wiki/Flughafen_Wien-Schwechat.

[32] Statista, "Fluege auf dem flughafen Wien," , last accessed April 19, 2023. URL https://de.statista.com/statistik/daten/studie/296473/umfrage/fluege-auf-dem-flughafen-wien/.

[33] Olive, X., "traffic, a toolbox for processing and analysing air traffic data," *Journal of Open Source Software*, Vol. 4, 2019, p. 1518. https://doi.org/10.21105/joss.01518.

[34] EUROCONTROL, "Point Merge," , last accessed Aprl 20, 2023. URL https://www.eurocontrol.int/concept/point-merge.

[35] "Swedish AIP," , last accessed 08.07.2021. Https://aro.lfv.se/Editorial/View/IAIP?folderId=79/.

[36] "Irish AIP," , last accesed 08.10.2021. URL http://iaip.iaa.ie/iaip/aip_directory.htm/.

[37] "Austrian AIP," , last accessed 08.10.2021. URL https://eaip.austrocontrol.at/.

[38] Hardell, H., Polishchuk, T., and Smetanova, L., " Fine-Grained Evaluation of Arrival Operations." *SIDs*, 2020.

[39] EUROCONTROL, "User Manual for the Base of Aricraft Data (BADA) Family 4," , 2014.

[40] ECMWF, "Copernicus Climate Change Service (C3S) Data Store, European Centre for Medium-Range Weather Forecasts (ECMWF)," https://cds.climate.copernicus.eu, last accessed on 07.10.2021.