Fine-Grained Evaluation of Arrival Operations

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***Abstract*—Analysis of the sequence of arriving aircraft, as well as identification of the cases of spacing violations, is an important step in evaluating performance of the Terminal Maneuvering Area (TMA) Air Navigation Services: without knowing the current performance levels, it is difficult to identify which areas could be improved.**

This work presents an enhanced data-driven methodology for evaluation of arrival aircraft sequencing and spacing inside TMA, inspired by the previous research presented by EUROCONTROL EEC [1]. On several use-case examples using historical dataset from Stokholm Arlanda airport, we illustrate how to effectively capture different aspects of flight inefficiency, as well as characterize and quantify sequencing effort and aircraft spacing. This is a contribution towards the development of the adaptive multi-dimensional key performance indicators (KPIs) tailored to the specific aspects of airspace performance, and designed to serve further airspace optimization initiatives. [1]

***Keywords*—Arrival sequencing, aircraft spacing, minimum time to final, spacing deviation, sequence pressure, data analysis**

I. INTRODUCTION

Improving efficiency of arrival operations is high on the agenda of aviation policy makers both in EU (SESAR) and the US (NextGen). While subjective expert opinion remains important in assessing the improvements, an objective evaluation of ATM modernization activities is possible only with a set of precise quantitative performance indicators. Such KPIs allow one to argue in favor of (or against) the many ongoing and envisioned initiatives, judge their effectiveness and adjust, if necessary, their direction. The development of proper KPIs correctly characterizing ATM operations is therefore a key activity for both Eurocontrol and FAA [2]. The KPIs are used to quantify tradeoffs between the (often conflicting) objectives, feeding decisions of both the managers and the operatives.

ATM development goals are often set as a collection of target numbers reflecting the desire to improve various aspects of future operations, expressed in the corresponding KPI values. Most commonly, these targets are set with respect to future, forecasted traffic/environment. The issue with this approach, however, is that the future rarely behaves as forecasted, especially in the aviation industry tightly connected to the surrounding circumstances via fuel prices, regulations, political, social, economic et al. factors.

An ongoing example is the COVID-19 pandemic which led to an unprecedented and never predicted reduction in air traffic worldwide (by up to 95%). At the same time, the main goals of the regulatory and research efforts, such as, e.g. to increase airspace throughput and reduce environmental effect of flying, were set basing on the assumption that air traffic continues to grow. The significant reduction in passenger numbers resulted in flights being cancelled or planes flying empty. With all the negative impact on all the aviation stakeholders, the main optimization and environmental goals were quickly achieved. Less aircraft flying definitely resulted in the reductions in fuel burn and noise around airports. According to [3] daily global CO_2 emissions decreased by 17% by early April 2020 compared with the mean 2019 levels. At their peak, emissions in individual countries decreased by 26% on average. In addition, airports became obviously less congested, accompanied by the improved throughput, lower traffic density, less accidents and safety violations, with the improved values of the corresponding KPIs.

Examples like the above suggest that chasing absolute values for KPIs, without taking the reality into account, may be misleading. In this work, we introduce the notion of *adaptive* KPIs, to provide the baseline for comparison of the operations against what could have been the best possible management under the given circumstances (traffic demand, weather, fleet composition, environmental regulations, airspace restrictions, staffing situation, introduction of new technologies, etc).

Any KPI is affected by a multitude of factors. By studying the effects of different factors in isolated scenarios, we will obtain a set of values each representing the KPI when some of the factors are absent/present. Comparing the values (which

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we call the *dimensions* of the KPI) will highlight the factors, which are most influential for the KPI and pinpoint where the inefficiency comes from.

This work is our first attempt to develop such adaptive multidimentional KPIs for objective assessment of the arrival aircraft sequencing and to investigate the evolution of the traffic density within TMA. We adopt and enhance the methodology proposed by EUROCONTROL EEC in [1], where the main purpose of the new KPIs was the comparison of performance of various TMAs with different metering techniques, as well as characterization of the sequencing and spacing in dense and complex environments. For that the authors used sufficiently large datasets concentrating on the peak hours.

In our work, we explore new dimensions for application of these same KPIs. We use significantly smaller datasets of various sizes to explore the dynamics of the KPIs over different time, covering different operational scenarios. On the examples of several use-cases, we demonstrate how the proposed KPIs help to explore spacing evolution and accuracy.

The rest of the paper is organized as follows. In Section II we present state of the art, in Section III we describe the proposed KPIs and details how they are calculated. Section IV describes the data we use for KPI calculations, followed by Section V presenting the data analysis for several examples of the KPI usage. Section VI concludes the paper and outlines future work directions.

II. RELATED WORK

EUROCONTROL developed the methodology used by its Performance Review Unit (PRU) for the analysis of flight efficiency during climb and descent [4]. Every year, Performance Review Commission of EUROCONTROL makes an assessment of air traffic management in Europe, where it covers all the aspects of the air traffic efficiency at the top 30 European airports, including Stockholm airport Arlanda (e.g [5]). In addition, EUROCONTOL PRU develops and maintains open access cloud based data repositories to enable stakeholders to reproduce the performance review results [6].

EUROCONTROL Experimental Center works on the development of the new performance indicators targeting to capture different aspects of flight inefficiencies in TMA [1], [7]–[10]. In [7], the authors proposed a novel approach for understanding and characterization of arrival sequencing and pressure, which relies on an analysis of spacing evolution over time between aircraft, and considers aspects as convergence, speed, and monotony. The authors extended the methodology in [1] with an analysis of spacing and pressure for four European airports—each representing a different type of operation. We apply similar methodology with several modifications to compare our optimal solutions to the real arrival routes.

Development and classification of the KPIs for en-route flight phase was considered within the APACHE project (a SESAR 2020 exploratory research project) [11], [12]. Later Prats et al. [13] proposed a family of enhanced performance indicators.

In [14]–[16] Lemetti et al. presented a detailed assessment of different aspects of Stockholm Arlanda airport performance, as well as investigated the impact of different factors influencing the efficiency of arrivals, such as various weather phenomena and traffic intensity; while aircraft sequencing and spacing characterization were not covered by this research.

Several authors proposed methods to improve separation and sequencing of aircraft within a TMA. In early works [17], NATS and EUROCOTNROL considered sequencing close to the runway with a re-categorization project aiming to replace the current standard of using only a few aircraft categories, where separation is determined by the category of leading and trailing aircraft, by a per-aircraft-type separation standard. Older tools focused on increasing runway throughput using complex models of controller behaviour. For example, in [18], the authors adjusted an aircraft's speed profile and provided a heading correction in order to obtain a fuel-efficient descent and reach the desired arrival time.

Detailed studies assessed the impact of new concepts in relation to sequencing [19], [20], [21]. The authors considered different dimensions: flight efficiency, e.g., using distance and time flown; human factors, e.g., using workload, radio communications, and instructions; and effectiveness, e.g., using achieved spacing in final using simulation data. In [21], the authors introduced an analysis of instructions and eye fixations as a function of the distance from the final point to show the geographically based nature of the aircraft sequencing activity, in particular, for late versus early sequencing actions. Regarding aircraft spacing on arrival, various studies have been performed in the context of airborne spacing when studying different algorithms [22], [23], [24], [25], [26].

III. METHODOLOGY

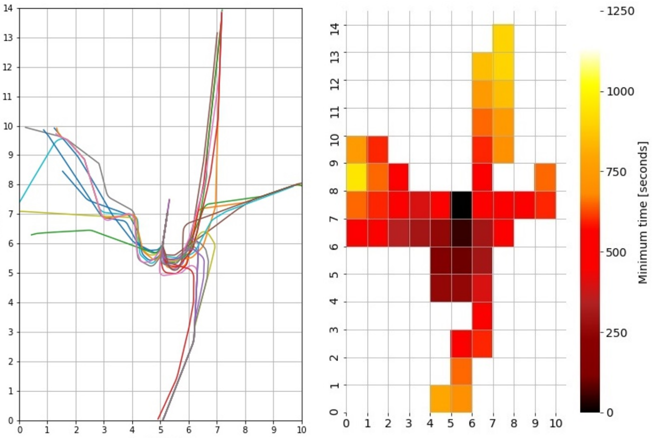
In this section, we describe the KPIs considered in this work, and detail on how they are calculated. In general, they are defined as proposed in [1], but the calculation methods slightly differ.

1) Minimum Time to Final: **Time to final** is defined as the minimum time it takes the aircraft to get from its current position to the final approach point.

We overlay a square grid over the rectangle formed by the entry points to the TMA. We calculate the **minimum time to final** for each cell of the grid, as the minimum time needed from any point within the cell of the grid to the final approach along any of the aircraft trajectories passing through the cell. We assign infinite (or a very large value) of the minimum time to final to the cells through which no trajectories pass during the considered time period.

The definition of minimum time to final used in this work is different from the definition used in [1], where the minimum time to final is defined as the minimum time along all possible paths, where a path is a succession of segments/portions of trajectories connected to each other forming a tree. Further, we apply similar methodology based on our variant of the definition of the minimum time to final.

For visualisation of the resulting assignment, we plot a heatmap of the minimum time to final on a grid. Figure 1 illustrates our approach on example of a day with average traffic intensity (over the whole 2018) at Stockholm Arlanda airport, January 29, with 28 arrivals during the peak hour of this day (6:00–7:00), where Figure 1(a) shows the actual aircraft arrival trajectories, and Figure 1(b) visualizes the resulting minimum time to final for these trajectories in the corresponding grid. In this example, the minimum time to final (here and further on, calculated for the cells through which the aircraft trajectories pass), lies between 0 and 939 seconds, with the average of 520 and standard deviation of 225.



(a) (b)

Figure 1. Flight trajectories (a) and minimum time to final heatmap (b) for the average traffic intensity day, on January 29, 6:00–7:00, with 28 flights.

2) Spacing Deviation: The **spacing** of an arriving aircraft pair at time t is defined as the difference between the respective minimum times to final. **Spacing deviation** at time t is calculated for a pair of aircraft tagged as the leader and the trailer. (The leader is the aircraft that arrives at the final point first, and the trailer is the aircraft that arrives second.) The spacing deviation captures the aircraft's mutual position in time and is calculated according to the formula:

$$\text{spacing deviation}(t) = \min\ time(\text{trailer}(t)) - \min\ time(\text{leader}(t-s)) \quad (1)$$

where s is the time separation with which the aircraft pair arrives at the runway, and $time$ is the minimum time to final. The spacing deviation reflects information about the control error, which is the accuracy of spacing around the airport.

Figure 2 shows an example of the spacing deviation, calculated for one hour of the day with average traffic intensity, January 29, 6:00-7:00. Here we choose s to be equal to the spacing of the aircraft pair with which they arrived to the final point, which obviously results in zero spacing deviation at $t = 0$. The horizontal axis shows minimum time to final of the trailer in each aircraft pair. The figure presents only the flights inside TMA within 900 seconds interval along the horizontal axis. In this scenario the spacing deviation lies between -334 and 268 with an average of 3.02 seconds and standard deviation 71.89. The maximum width of the 90th quantile (shown in turquoise in the figure) is 465, which quantifies the spread of the 90% confidence interval.

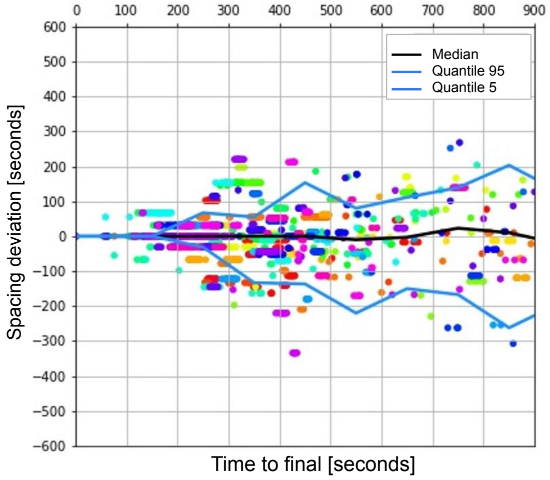


Figure 2. Spacing deviation for the average traffic intensity day, on January 29, 2018, 6:00–7:00, with 28 flights.

3) Sequence Pressure: The **sequence pressure** for an aircraft at time t is the number of aircraft with the same time to final within a given time window w; it reflects the aircraft density at different time t. It is calculated for each aircraft at any time of its presence within the TMA with the discrete time steps. Sequence pressure quantifies aircraft density and characterizes the type of metering used in this particular airport and sequencing within TMA.

For all our example scenarios we choose $w = 120$ seconds. Figure 3 shows the sequence pressure for the same one hour of the day with average traffic intensity, January 29, 6:00-7:00. In this scenario the sequence pressure lies between 1 and 3, with an average of 1.34 and standard deviation of 0.57. We can observe that up to three aircraft intended to arrive at the same time (±2 minutes), which may indicate a potential separation problem. Further investigations may need to be performed (for the corresponding aircraft), to understand what happened in each specific case, captured by the proposed KPI. We will give an example of such detailed analysis in Section V.

IV. DATASET

For obtaining the aircraft flight trajectories, we use the Historical Database of the OpenSky Network [27], [28], which provides an open-source data in a form of aircraft state vectors for every second of the trajectories inside TMA. 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. Applicability of this type of data for the performance assessment purposes is justified in [29].

For this work, we have access to data representing all the aircraft arrivals to Stockholm Arlanda airport during the year 2018. Further in the analysis we use subsets of this data

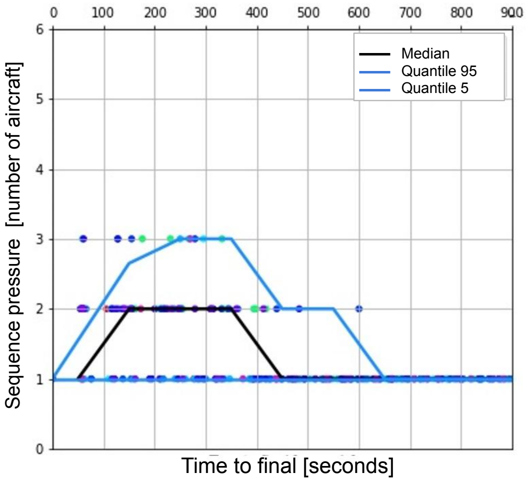


Figure 3. Sequence pressure for the average traffic intensity day, on January 29, 2018, 6:00–7:00, with 28 flights.

corresponding to different time periods in 2018. The data from Opensky network is downloaded with Python scripts using OpenSky REST API and SSH agent to access Opensky Impala Shell. We implement the functions for KPIs calculation using Python programming language in Spyder scientific environment.

Opensky state vectors are used for reconstruction of the 4D flight trajectory. High granularity of OpenSky states data allows to determine the exact seconds the aircraft enters the terminal area and reaches the final approach. However, due to the non-reliable nature of the data transmission technology and collection technique, the raw data may be incomplete and contain erroneous records. Therefore, for efficient and reliable performance analysis, the data needs to be cleaned, smoothed and filtered. For example, some records in the dataset can show that the aircraft missed the final point, performed turn-around or never landed. There are also some gaps and unreasonable fluctuations in the flight trajectories, which may cause noticeable errors in our KPIs calculations. We filter out all such erroneous data, leaving only the records representing complete aircraft trajectories from the time aircraft enter TMA to their landing on the runway.

V. EVALUATION AND DATA ANALYSIS

In this section, we demonstrate how to apply the proposed KPIs for the fine-grained evaluation of the arrival sequencing and spacing within TMA. The objective is to calculate the KPIs for different use-case scenarios and to analyze the KPIs with respect to the different traffic situations, such as: night-time versus daytime operations, similar periods with different traffic intensities, periods with heavy delays. Then we investigate the cases of potential separation violations for the hotspots captured by one of the KPIs.

A. *Night-time vs daytime operations*

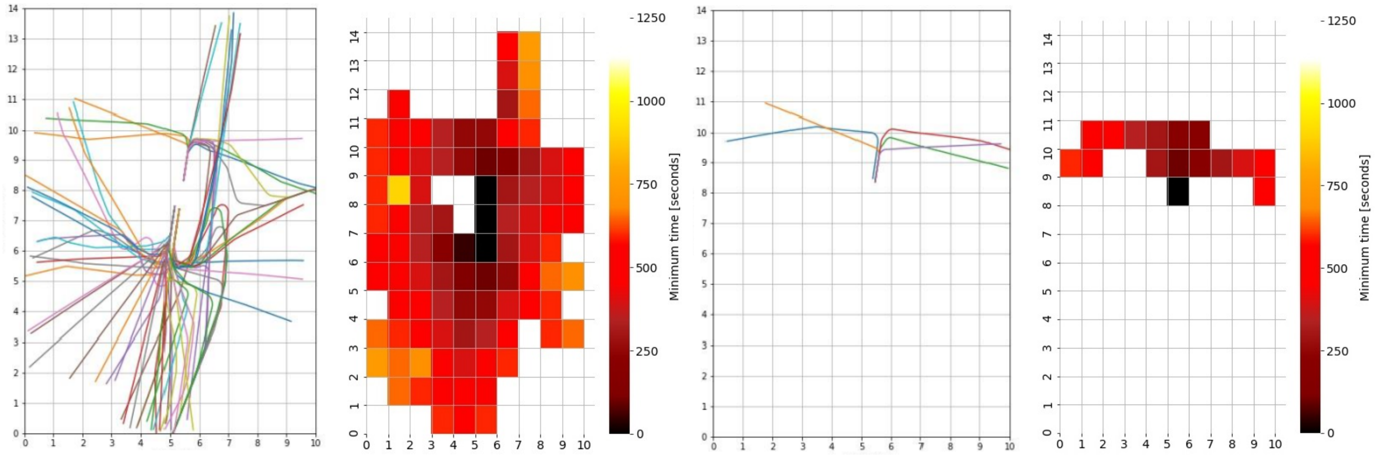
The least busy day of the year 2018 was on December 29, with only 73 aircraft landed at Stockholm Arlanda airport during that day, which is about five times less than that during the day with the highest total number of flights, on May 16 (361 flights). 68 out of the 73 arrivals landed during the daytime period, which is 6:00-24:00, and 5 landed during the night, 0:00-6:00. Figure 4 illustrates the corresponding flight trajectories and minimum time to final heatmaps. Spacing deviation and sequence pressure KPIs are shown in Figure 5. The corresponding statistics for the KPIs are presented in Table I, from which we can see that there is no significant difference in the minimum time to final KPI between the daytime and night-time operations. The higher traffic density during daytime, when compared to night-time operations, is reflected in the higher value of the 90th quantile width in the spacing deviation KPI. Due to the low volume of traffic during both time intervals, we observe that the sequence pressure values are generally low in both scenarios, which indicates that there are no signs of congestion, thus slightly higher in the daytime case. The difference in the total traffic volumes is captured by the spacing deviation, reflected in the range of the values of this KPI and in the 90th quantile width, which can be easily observed in the Figures 5 (a) and (b). The heatmaps in Figures 4 (b) and (d) also effectively visualize the difference between the daytime and night-time operations.

TABLE I. COMPARISON FOR THE DAYTIME OPERATIONS VS. NIGHT-TIME OPERATIONS ON DECEMBER 29, 2018.

Statistics	Day	Night
Time period	6:00-24:00	0:00-6:00
Number of flights	68	5
	Min. time to final	
Minimum	0	0
Maximum	882	610
Average	444	349
Standard dev.	178	175
	Spacing deviation	
Minimum	-380	-117
Maximum	353	114
Average	3.29	12.64
Standard dev.	69.37	37.79
90th quantile width	419.2	164.8
	Sequence pressure	
Window size	120	120
Minimum	1	1
Maximum	2	1
Average	1.07	1
Standard dev.	0.25	0

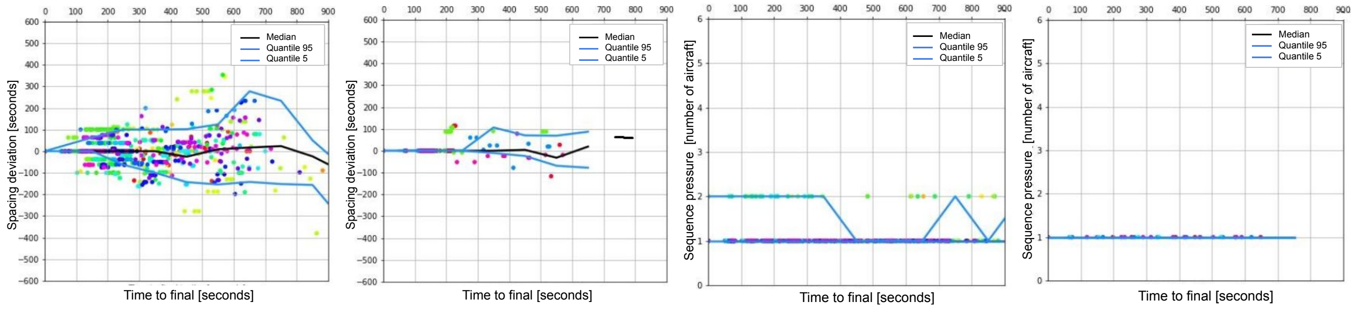
B. *Scenarios with different traffic intensity*

The busiest day of the year 2018 was on May 16, with the peak hour between 5:00-6:00, and the least busy day was on December 29, with the peak hour between 11:00-12:00. In Figure 6, flight trajectories and minimum time to final heatmaps for the two peak hours are presented, and Figure 7 shows spacing deviation and sequence pressure. Statistics for these peak hours of the two days are presented in Table II. Comparing the flight trajectories and the minimum-time to final heatmaps for the corresponding peak hours, we observe that the aircraft arriving from the west spend noticeably more



(a) (b) (c) (d)

Figure 4. Flight trajectories and minimum time to final heatmap for daytime operations, 6:00-24:00 (a, b) and night-time operations, 0:00-6:00 (c, d), on December 29, 2018.



(a) (b) (c) (d)

Figure 5. Spacing deviation and sequence pressure for daytime operations, 6:00–24:00 (a, c) and night-time operations, 0:00-6:00 (b, d), on December 29, 2018.

time in TMA. On the the least busy day, aircraft from the west do not even pass the westerly entry point ELTOK, which is not true about the aircraft from other directions.

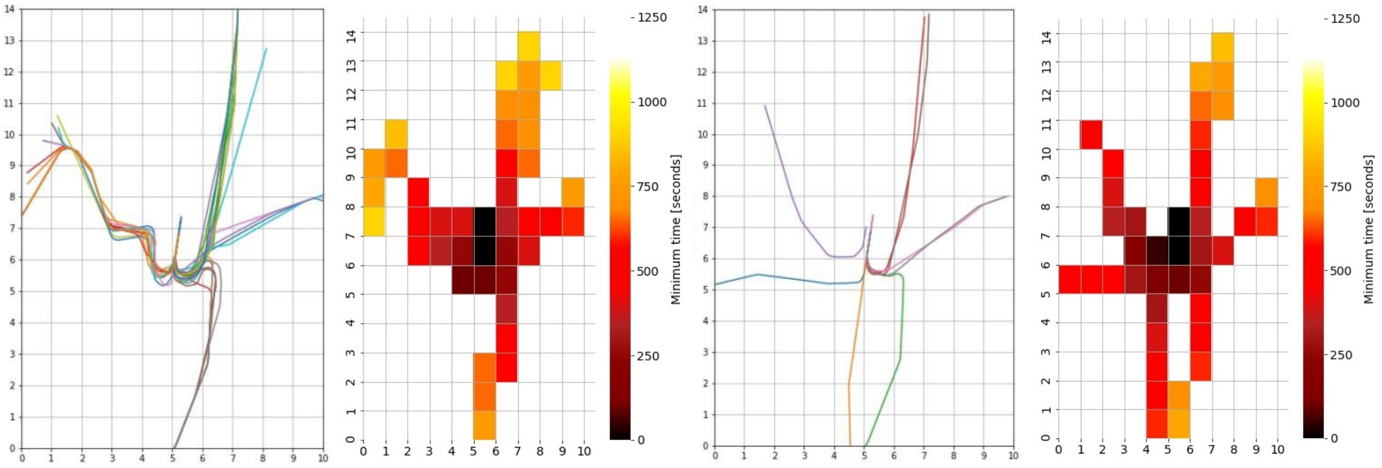
While statistics for the minimum time to final, in general, do not show significant differences, the KPIs for spacing deviation and sequence pressure clearly demonstrate that the range of the values for the peak hour for the day with high traffic, is almost twice of the range compared to the low-traffic day. The same observation holds for the standard deviation of the sequence pressure. The width of the 90th quantile for the spacing deviation also captures that the traffic intensity is higher during the peak hour of the busiest day.

C. Scenario with heavy delays

Heavy delays were recorded in Arlanda airport on February 26, 2018, caused by a severe snowfall according to [16]. The total of 217 aircraft arrived during that day. According to the Opensky data, the period with the heaviest delays was between 13:00 and 14:00. Flight trajectories and minimum time to final for that hour are illustrated in Figure 8, and the corresponding spacing deviation and sequence pressure are presented in Figure 9. The first column in Table III shows the

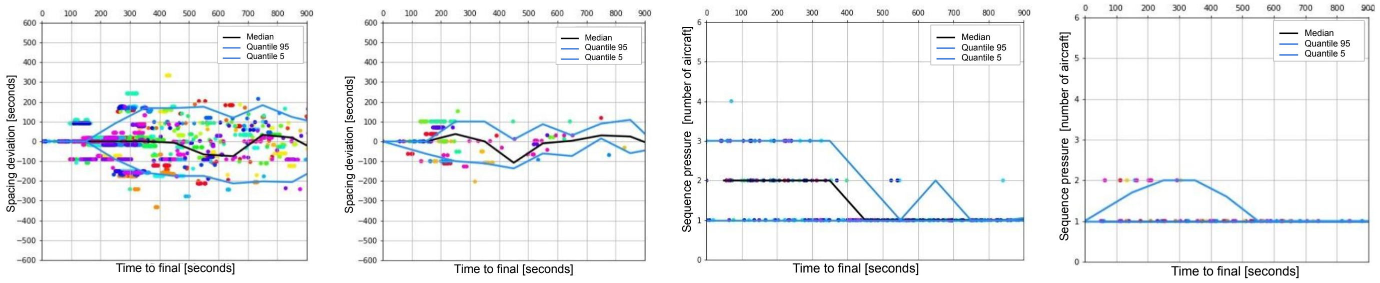
TABLE II. COMPARISON OF THE PEAK HOUR ON THE BUSIEST DAY, MAY 16, 2018, AND THE PEAK HOUR ON THE LEAST BUSY DAY, DECEMBER 29, 2018.

Statistics	The busiest day	The least busy day
Time period	5:00-6:00	11:00-12:00
Number of flights	29	8
	Min. time to final	
Minimum	0	0
Maximum	932	836
Average	508	456
Standard dev.	228	215
	Spacing deviation	
Minimum	-412	-203
Maximum	369	152
Average	0.15	0.62
Standard dev.	81.32	73.18
90th quantile width	378	211
	Sequence pressure	
Window size	120	120
Minimum	1	1
Maximum	4	2
Average	1.43	1.15
Standard dev.	0.7	0.36



(a) (b) (c) (d)

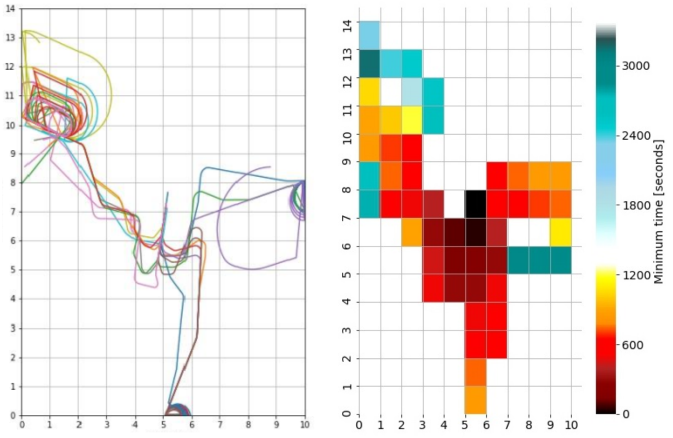
Figure 6. Flight trajectories and minimum time to final heatmap for the peak hour of the busiest day of the year 2018, May 16, 5:00-6:00 (a, b) and the peak hour of the least busy day of the year 2018, December 29, 11:00-12:00 (c, d).



(a) (b) (c) (d)

Figure 7. Spacing deviation and sequence pressure for the peak hour of the busiest day of the year 2018, May 16, 5:00-6:00 (a, c) and the peak hour of the least busy day of the year 2018, December 29, 11:00-12:00 (b, d)

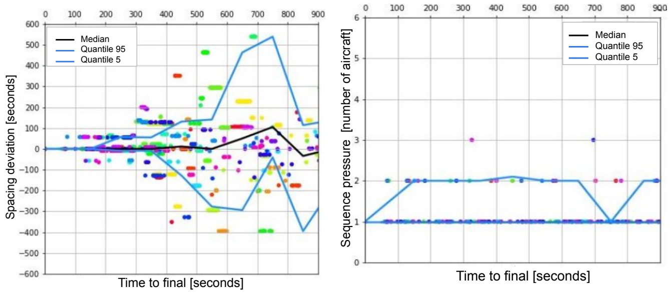
statistics for this hour. The maximum and average values of minimum time to final are quite high, which indicates that the aircraft did not fly their quickest and shortest paths from the TMA entry points to the final point. Severe snowfall requires frequent snow sweeping, which makes the runway unavailable for a duration of 8-12 minutes [30], and the capacity for arriving traffic reduces drastically. Due to this, aircraft may need to perform holding patterns and cannot fly an optimal path in the TMA, which we can clearly see in the flight trajectories in Figure 8(a). The average value of the sequence pressure is low, which indicates that a low number of aircraft arrived during the same time window, which is also to expect during periods with bad weather when air traffic controllers might want an extra buffer and do not sequence the aircraft too tight.



(a) (b)

Figure 8. Flight trajectories (a) and minimum time to final heatmap (b) for the most delayed hour, on February 26, 2018, 13:00-14:00, with 17 flights.

In addition, we study the dynamics of the KPIs when applied to different time periods during the day with heavy delays, all including the hour with the heaviest delays. For that we compare the statistics for all our KPIs corresponding to the three time periods, as shown in Table III. We see that the values for the average and standard deviation of the minimum time to final decrease with the increase of the time period. The reason is that increasing the period, we cover more and more other periods with smaller delays (or not delayed at all). This obviously leads to the lower values of the minimum



(a) (b)

Figure 9. Spacing deviation (a) and sequence pressure (b) for the most delayed hour on February 26, 2018, 13:00-14:00, with 17 flights.

time to final. Then the other two KPIs, which calculations are based on the minimum time to final, demonstrate similar trend. The range of the values for all periods and all KPIs stays unchanged, corresponding to the extremes inherited from the hour with the heaviest delays.

This use-case demonstrates that the KPIs are very sensitive to the choice of the period they are calculated for, which makes them adaptive to the actual weather and traffic conditions.

TABLE III. COMPARISON OF THE PERIODS OF DIFFERENT DURATION FOR THE DAY WITH HEAVY DELAYS ON FEBRUARY 26, 2018.

Time period	13:00–14:00	10:00–16:00	6:00–24:00
Number of flights	17	80	201
	Min. time to final		
Minimum	0	0	0
Maximum	3142	3142	3142
Average	1062	847	718
Standard deviation	902	702	650
	Spacing deviation		
Minimum	-395	-494	-544
Maximum	539	512	458
Average	22.47	0.26	1.21
Standard deviation	135.74	117	109.89
90th quantile width	757	689	612.05
	Sequence pressure		
Window size	120	120	120
Minimum	1	1	1
Maximum	3	3	3
Average	1.17	1.14	1.13
Standard deviation	0.41	0.38	0.36

D. Detecting the hotspots with potential separation violations

An additional feature of the sequence pressure KPI that it can be used to detect situations where potential separation violations occurred. In one of the scenarios (average-traffic day, January 29, 2018), the sequence pressure of three was calculated between 0 and 100 seconds to final for three aircraft (Figure 10(a), all three coincide in one point), capturing three situations with three aircraft located close to the runway within one cell of the grid. These situations should be investigated further, as they may indicate potential problems of safe separation violation.

Figure 10 illustrates these situations, The first scenario is shown in Figure 10(b), with a high sequence pressure detected for the orange aircraft at 7:02:18. By searching for the position recording with the location closest to the approximate location of the final approach point (FAP) (here defined by a point located at the FAP altitude, calculated backwards with a 3°-glide path originating at the runway threshold), we can check at what time each aircraft passed this point. The orange aircraft passed the point of interest at 7:00:34, the green at 7:01:54 and the red at 7:04:33. According to our calculations of time passage, we can see that the orange and the green aircraft are separated by only 80 seconds in time. By applying a distance based separation of 3 NM (medium wake vortex category aircraft followed by a medium), we conclude that the resulting ground speed to cover this distance is still realistic at this stage of the flight, and hence, does not indicate a separation violation problem.

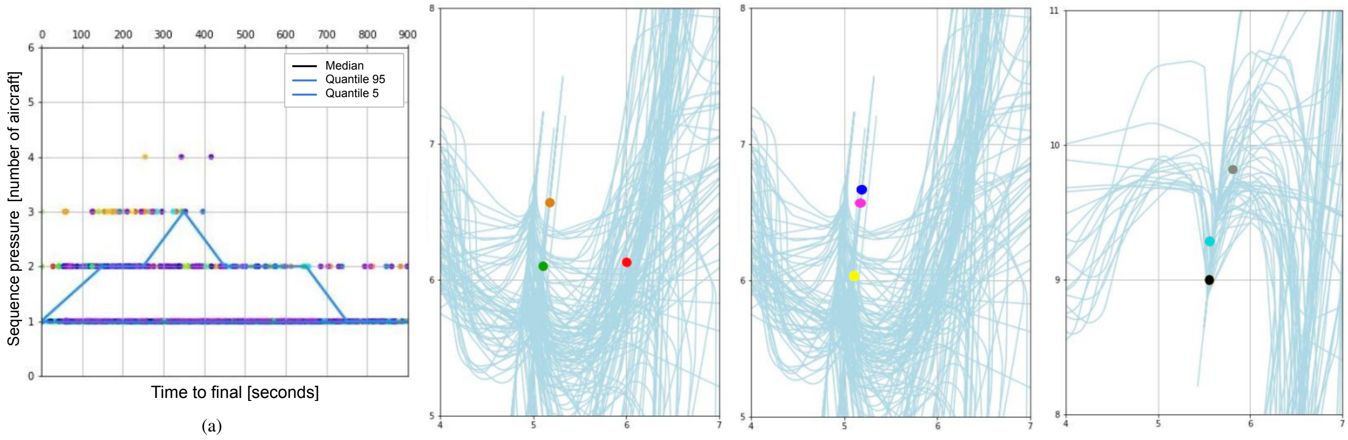
The second scenario is illustrated in Figure 10(c), with a high sequence pressure detected for the purple aircraft at 7:21:45. Analysing the corresponding data, we conclude that the purple and blue aircraft have already landed (and should not have a separation problem), and the yellow aircraft is at the safe distance and yet has time to safely land.

The third scenario is illustrated in Figure 10(d), with a high value of sequence pressure for the black aircraft at 9:32:46. The cyan aircraft passed the point of interest at 9:32:23, the black at 9:34:09 and the grey at 9:35:42. According to our calculations of time passage, we can see that the black and the cyan aircraft are separated by 106 seconds and the grey and the black aircraft are separated by 93 seconds. Again, applying a distance-based separation requirement of 3 NM (medium wake vortex category aircraft followed by a medium), we conclude that the resulting ground speed to cover this distance is still realistic and hence, does not indicate a separation violation problem.

VI. CONCLUSION AND FUTURE WORK

This work presents an analysis of arrival aircraft sequencing and spacing at Stockholm Arlanda airport. Exploring different dimensions of the sequencing and spacing KPIs we demonstrated, on several use-case examples, how to perform a fine-graned comprehensive assessment of the TMA arrival performance. In addition, we showed how the spacing pressure KPI helps to capture the cases of the potential separation violations. We conclude that the enhanced KPIs can be successfully used to uncover inefficiencies in TMA, allowing the aviation authorities to pinpoint areas where efficiency is lost and suggest directions for the improvements.

This work contributes to the development of the *multidimensional adaptive KPIs*, which will enable creating a comprehensive picture of the operations and faithfully characterizing ATM performance. Our future work will target the development of new such KPIs capturing other aspects of the TMA performance, as well as testing their applicability for evaluation of the optimization activities within TMA,



(a)

(b)

(c)

(d)

Figure 10. Sequence pressure for an average-traffic day, January 29, 6:00-24:00, with 271 flights (a), and investigation of the separation violation at the hostposts with a sequence pressure of 3 aircraft close to the runway, on January 29, 2018, for the times 7:02:18 (a), 7:21:45 (b) and 9:32:46 (c).

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