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PERFORMANCE EVALUATION OF THE ARRIVAL OPERATIONS IN TERMINAL AREA

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Abstract

This paper describes performance analysis in Stockholm TMA for the arrival flows to Stockholm-Arlanda airport in Sweden. The TMA is a complex piece of airspace and one of the main contributors to inefficiencies in air transportation. Aircraft in the TMA may experience both horizontal and vertical flight inefficiency, due to extended routing and inability to perform a Continuous Descent Operation (CDO), respectively. In previous work, we uncovered significant performance inefficiencies resulting in excessive fuel consumption at Arlanda airport in 2019 and 2020, and the goal with this paper is to identify areas of flight inefficiency by assessing horizontal, vertical and fuel efficiency of all the arrivals during the busiest month in 2019 per flow, utilizing a clustering technique. Clustering the arriving traffic allows us to assess different flows individually and pinpoint areas of improvement. Using ADS-B-based open-source flight data, we calculate the additional fuel burn compared to two different reference profiles and try to identify whether any fuel inefficiency stems from the flight being horizontally or vertically inefficient, or a combination of both. Additionally, we study the impact of traffic intensity and weather on arrival performance for the whole year of 2019. The results uncover variable performance of the arrival flows and depending on which runway is in use, with median additional distance ranging from 0 to 6.9%, median time flown level from 0 to 5.2%, vertical deviation between 20700 to 33600 ft·minutes, and the resulting additional fuel burn of 37.0 to 125.2%. High impact of the traffic intensity factor was observed for most of the clusters and runways in use. [1]

Keywords: Terminal airspace, performance evaluation, clusterization, arrival flows.

1. Introduction

Capacity limitations as well as overall traffic complexity of the Terminal Maneuvering Areas (TMAs), make them the main contributors to inefficiencies in air transportation. TMA performance is influenced by a multitude of different factors including geographical location of the corresponding airport, surrounding terrain, and to a large extent by the organization and distribution of the arriving flows.

Previous work uncovered significant performance inefficiencies resulting in excessive fuel consumption at Stockholm-Arlanda airport in 2019 and 2020 [1], [2]. In this work, we investigate the arrival performance at this airport per cluster (or arrival flow).

Inefficient operations in the TMA may be attributed to both the horizontal and the vertical flight performance of an aircraft. While it is desirable to fly the shortest route from entry to the TMA, until the final approach segment, the importance of the vertical flight performance must not be neglected. Horizontal inefficient trajectories result in more time spent in TMA, thus, increasing the time that an aircraft burns fuel. For the vertical part of the trajectory, the most efficient descent is when the engines are operating at an idle thrust setting, in combination with no speed-brakes usage. Such an operation is called Continuous Descent Operation (CDO). Executing a perfect CDO requires full knowledge of the

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expected flight route, as the vertical trajectory is highly dependent on the amount of distance that is required to the final approach.
In this work, we characterize the horizontal and vertical flight efficiency using a set of performance indicators, and relate it to the additional fuel burn, with the goal to identify the sources of fuel inefficiencies within TMA. We cluster the terminal area in order to divide the arriving traffic into several parts, representing the main arrival flows to the Stockholm TMA. The clustering approach makes it possible to identify the specific areas of inefficiencies inside TMA. In addition, we analyse the impact of different factors, such as weather and traffic intensity, to understand which of the factors cause which aspects of performance degradation.

2. Related Work

Evaluation of flight efficiency, and in particular TMA performance, has been a topic of interest in recent years. International Civil Aviation Organization (ICAO) proposed a set of metrics to enable analysis of TMA performance [3]. EUROCONTROL developed the methodology used by its Performance Review Unit (PRU) for the analysis of flight efficiency within the areas of safety, capacity, cost-effectiveness and environment, reflected in the yearly assessment reports, reviewing the flight inefficiency within TMA at the top 30 European airports [4].
Pasutto et al. [5] analyzed the factors affecting vertical efficiency in descent, with the aim to determine where exactly the inefficiencies occur. They developed a method to isolate and quantify the respective contributions of airspace versus operations, with the varying horizon around the airport. The studies confirm that the airspace is generally the main source of inefficiencies, due to the complexity in and around these terminal areas. The authors proposed to combine the deviation from the ideal vertical profile and the time into one metric, which we adopted and slightly modified in this work.
Estimation of the flight inefficiencies in terms of extra fuel burn calculated based on the algorithm proposed in [6] was considered in the scope of APACHE project [7]. Later Prats et al. [8] proposed a family of performance indicators to measure fuel inefficiencies.
In [9], fuel consumption is evaluated for terminal areas with a Terminal Inefficiency metric based on the variation in terminal area fuel consumed across flights, reported by a major U.S. airline. Furthermore, in [10] and [11], fuel savings of the Continuous Descent Operations (CDO) with respect to conventional procedures are analyzed. The works report the reduction in fuel consumption of around 25-40% when flying CDOs.
Arrival flight efficiency at Stockholm-Arlanda airport in 2019 and 2020 was analysed in [1], [2] and [12]. In this paper, we extend and complement the methodology presented in these works, performing the cluster-wise performance assessment of the arrival operations.

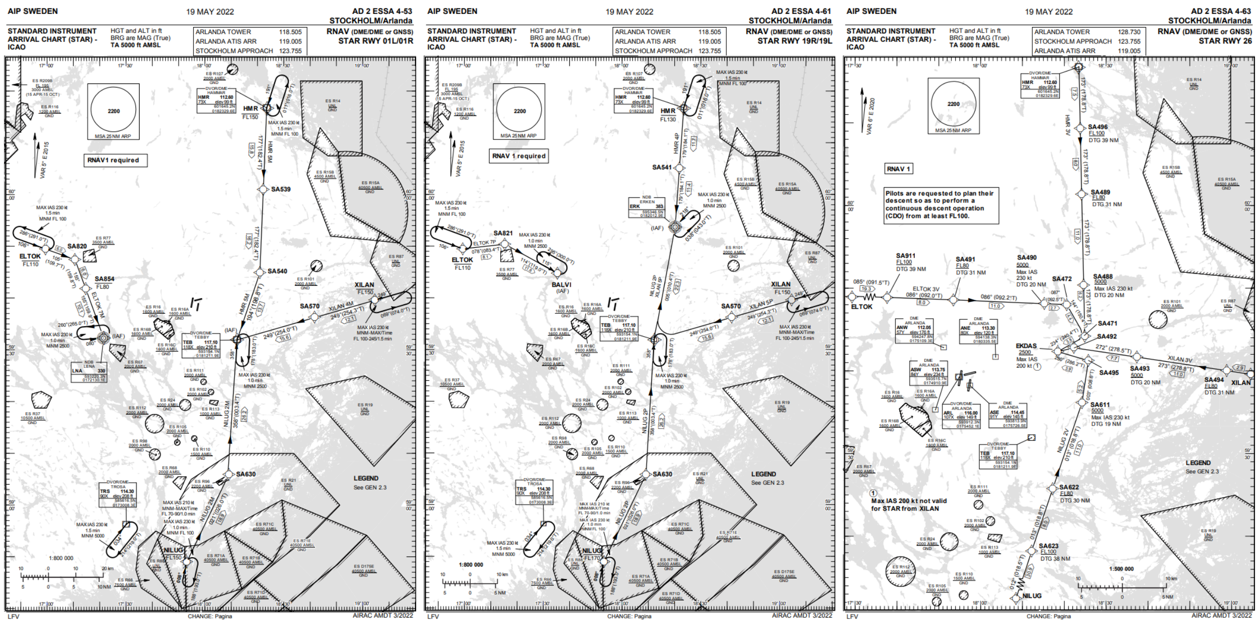
3. Airport

For the analysis, we choose the Stockholm-Arlanda (ESSA) airport, with about 230.000 yearly movements. Arlanda airport is situated below the airspace of Stockholm TMA, to which arriving aircraft enter via one out of four entry points. Arlanda is a multiple-runway airport, operating with a parallel pair of runways and an intersecting single runway. The airport has open STARs (Standard Arrival Routes) for all runways and closed STARs for the runways 01L, 19R and 26. The closed STARs bring the aircraft all the way from TMA entry point to the final approach, while the open STARs end at an initial approach fix (IAF), from which an air traffic controller (ATCO) vectors the aircraft to the final approach. Published STARs for runway 01L/01R, 19L/19R and 26 are shown in Figure 1. .

4. Datasets

4.1 Flight Trajectories

For the flight trajectories, we rely on the historical database of the OpenSky Network [14], [15], which provides an open-source data in a form of aircraft state vectors for every second of the trajectories. 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. The applicability of this type of data for performance assessment purposes is justified in [16].



(a) (b) (c)

Figure 1 – Published open STARs for runway 01L/01R (a), 19L/19R (b) and closed STARs for runway 26 (c), at Stockholm-Arlanda airport. Open STARs for runway 26 are similar to those of runway 01L/19R and 01R/19L (Source: Swedish AIP [13]).

A cleaning and filtering was however required to remove any incomplete or erroneous records and non-typical flights. This includes removing fluctuations in latitude, longitude or altitudes, smoothing of altitude inconsistencies with Gaussian filter, removing incomplete or too damaged trajectories, removing flights such as: go-arounds, not landing on the runway, departure and arrival at the same airport (mostly helicopters), most non-commercial. The resulting dataset contains only complete aircraft trajectories from the terminal area entry until landing, representing the normal operations.
The analysis in this paper is based on data for arriving aircraft in the year 2019. In total, 137.000 ADS-B transponder-equipped aircraft arrived to Arlanda during 2019, of which 26432 aircraft landed on runway 01R, 31621 on 19L and 43584 on 26, which corresponds to the three most utilized runways subject to investigation in this work. For characterization of the horizontal, vertical and fuel performance, we consider only the busiest month in 2019 (October), as explained in Section 6.1. The corresponding total number of arrivals for October 2019 was 8948, of which 3086 landed on runway 01R, 2168 on 19L and 2317 on 26.

4.2 Weather

The source of historical weather data in this paper is ERA5 reanalysis dataset [17] provided via the C3S Data Store in form of NetCDF files with $0.25°$ granularity and temporal granularity of one hour. The data is used for evaluation of weather impact on flight efficiency as well as for creating CDO profiles and for fuel consumption calculation.

5. Methodology

5.1 Clusters

In order to investigate the efficiency separately for different arrival flows, we cluster the arriving aircraft into 6 different clusters. The analysis in this paper is performed for the three most busy runways for aircraft arrivals to Stockholm-Arlanda airport: runways 01R, 19L and 26. For the three selected runways, we cluster the trajectories using the methodology proposed in [5], also applied in [18], [19]. Then a user-preferred route tree is constructed as defined in [20]. We identify the start of the reference trajectory as the point on the TMA border as the closest to each cluster centroid. The reference trajectory goes directly to a 2 NM straight segment before interception of the instrument landing system (ILS) glide slope, at the published final approach point (FAP) altitude, which is 4000 ft for runway

01R and 2500 ft for runway 19L and 26. The resulting clusters for runways 01R, 19L and 26 are illustrated in Figure 2.

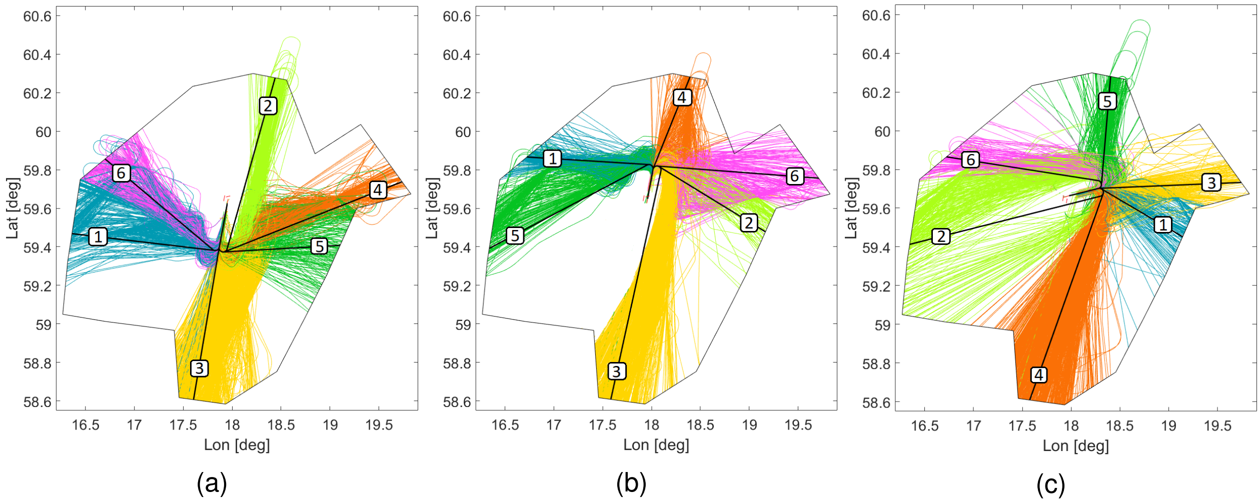


Figure 2 – Arrival aircraft trajectories inside Stockholm TMA in October 2019, for runways 01R (a), 19L (b) and 26 (c), colored by cluster, and the corresponding reference trajectories shown in black.

5.2 CDO Profiles

We calculate CDO trajectories for all arrivals to TMA, using the given entry conditions obtained from the Opensky Network database, with the goal to use them as a reference for calculation of the fuel-related PIs. We model the performance of the CDO descent profiles using Base of Aircraft Data (BADA) v4.2 [21] and consider an idle thrust descent without using speedbrakes, utilizing the BADA idle rating model. We calculate the engine idle thrust and drag at every timestamp and feed it into the Total Energy Model (Equation 1), using a speed profile designed according to the speed schedule formulas provided in BADA, which we convert to true airspeed (TAS). From the TEM, we obtain the vertical speed (dh/dt) at every timestamp. By calculating the vertical speed along the trajectory, we obtain the full vertical profile of the reference CDOs.
For the aircraft mass, we consider 90% of the maximum landing weight for each aircraft type, specified in BADA.

$$(Th - D) \cdot V_{TAS} = m \cdot g_0 \cdot \frac{dh}{dt} + m \cdot V_{TAS} \cdot \frac{dV_{TAS}}{dt} \quad (1)$$

Here, Th is the thrust force, D is the drag force, V_{TAS} is the true airspeed, m is the aircraft mass and g_0 is the gravitational acceleration.
We use the weather data source described in Section 4.2, to obtain historical data on temperature and wind at different altitudes and positions, which we use to imitate the prevailing atmospheric conditions and for conversion between ground speed (GS) to TAS.
For each flight, we create two different CDOs, called Reference Trajectory 1 (RT1) and Reference Trajectory 2 (RT2). The two trajectories only differ in the lateral distance, with RT1 following the same horizontal trajectory as the real flight, and RT2 following the horizontal trajectory of the reference trajectory explained in Section 5.1. Thus, in most cases, RT2 will have a shorter horizontal trajectory than RT1, and since the horizontal trajectory of RT1 is identical to that of the real flight, it will also include any path extension (e.g. vectoring, holding patterns) performed by the aircraft, but still continuously descending.
Figure 3 shows the horizontal and vertical trajectories for an example flight for RT1 and RT2. As can be seen, the vertical profile is almost identical for RT1 and RT2, the only difference being that RT1 spends more time in TMA and thus, crosses the TMA border at a higher altitude.
When calculating the vertical reference trajectories, we assume an unrestricted descent, hence, we do not respect any altitude restrictions that may apply in the TMA. However, we do not allow our

vertical reference trajectories to cross the TMA border at a higher altitude than the cruise altitude for the flight, thus, we may have an initial level flight segment for flights that have a low cruise altitude.

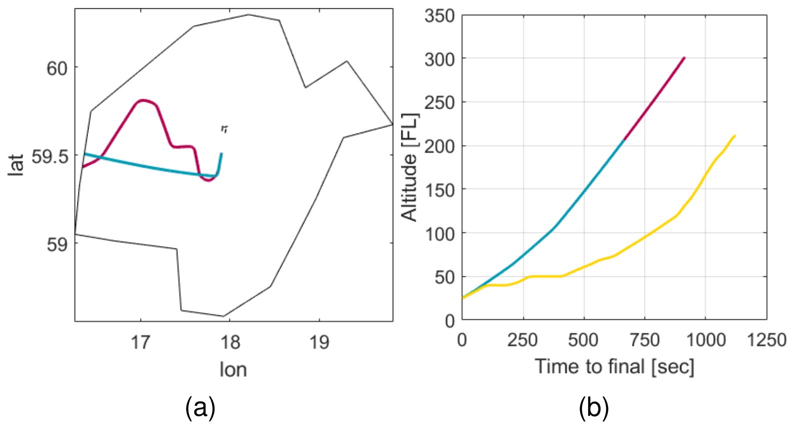


Figure 3 – Example of horizontal (left) and vertical trajectories (right) for RT1 (red), RT2 (blue) and real flight (yellow), for an arrival in Stockholm TMA. Note that the horizontal trajectory of the real flight coincides with the one for RT1 (red).

5.3 Performance Indicators

5.3.1 Horizontal Flight Efficiency

The horizontal flight efficiency is assessed through the horizontal deviation from a reference trajectory, denoted as Additional Distance. As a reference trajectory, we use the direct route created for each cluster as described in Section 5.1. We express Additional Distance in percentage to the corresponding reference trajectory distance.

5.3.2 Vertical Flight Efficiency

The vertical flight efficiency is assessed through the Vertical Deviation from a Reference Profile, and complemented by the Time Flown Level. CDOs enable the execution of a flight profile optimized to the operating capability of the aircraft, resulting in optimal continuous engine-idle descents (without using speedbreaks). Vertical inefficiencies during the descent phase result from the inability of flights to follow CDOs. When the aircraft levels at intermediate altitudes before landing, the descent is considered to be vertically inefficient.

The Time Flown Level is calculated using the technique proposed by EUROCONTROL in [22] with small changes. We identify the point of the trajectory in which the aircraft enters the TMA and use it as a starting point for the calculations (instead of the Top of Descent (ToD), which may lie outside of TMA). A level segment is detected when the aircraft is flying with the vertical speed below the certain threshold. We use the value of 300 feet per minute for this threshold, the minimum time duration of the level flight is considered 30 seconds, and these 30 seconds are subtracted from each level duration as suggested in [22]. We do not consider as level the flight under 1000 feet, corresponding to the final approach. We calculate Time Flown Level in percentage to the total time spent in TMA.

For the Vertical Deviation, we use the reference CDO profile calculated using the methodology explained in Section 5.2. We use the obtained RT1 vertical reference trajectory to calculate the Vertical Deviation from the Reference Profile metric as a function of time to final, and the area under the curve measured in ft·minutes constitutes our metric. Note that using RT2 as a reference trajectory would result in almost identical result as with RT1 as the only difference in the reference trajectories is their length, and different ground speed due to wind variations at different locations in TMA.

5.3.3 Fuel Efficiency

We calculate the fuel consumption according to the formula provided in the BADA manual (Equation 2).

$$F = \delta \cdot \theta^{\frac{1}{2}} \cdot m \cdot g_0 \cdot a_0 \cdot L_{HV}^{-1} \cdot C_F \tag{2}$$

Here, δ is the pressure ratio, θ is the temperature ratio, m is the reference mass, g_0 is the gravitational acceleration, a_0 is the speed of sound at sea level, L_{HV}^{-1} is the fuel lower heating value and C_F is the fuel coefficient. For the reference CDOs, we use the idle thrust fuel coefficient. For the actual trajectories, we use the TEM as a reference for calculating the thrust, obtaining the temperature and wind conditions at different pressure altitudes from historical weather data described in Section 4.2 . Then we use the thrust to obtain the thrust coefficient. To ensure the calculated thrust stays within the feasible limits, we use BADA formulas for calculating the thrust at the maximum climb rating and idle rating, which bound the calculated thrust from below and above.
Next, we calculate the fuel coefficient from the thrust coefficient and input it to the formula for the fuel flow calculation in Equation 2. We do not take into account the effects of deploying flaps at lower speeds, which will generate more drag and increase the fuel consumption.

5.4 Impact Factors

In this work, we examine the influence of several impact factors, such as traffic intensity and different weather conditions on the arrival flight performance within TMA.

5.4.1 Traffic Intensity

We analyze flight efficiency during the descent and consider the number of arriving aircraft. The normalized number of arrivals per hour is used as a measure of traffic intensity. We calculate the Traffic Impact Factor (TIF) proposed in [2], [23], by discretizing the traffic intensity into 10 bins.

5.4.2 Weather Conditions

To quantify the impact of weather, we consider the following 24 weather metrics: u- and v- components of the 10 m and 100 m wind, wind gust, convective available potential energy (CAPE), convective precipitation, K index, convective snowfall, convective snowfall rate water equivalent, large scale snowfall, large scale snowfall rate water equivalent, snowfall, total column cloud ice water, total column cloud liquid water, total column rain water, total column snow water, total column water, total precipitation, low cloud cover, medium cloud cover, high cloud cover, total cloud cover, cloud base height. We use WIF, developed in [2], as a unified weather condition metric. In this work, we perform Principal Component Analysis (PCA) and take the principal components as WIF contributing factors. To avoid negative correlation between the initial features and negative weights in the principal components we substitute u and v components of wind by calculated wind speed, perform a unity-based normalization (scaling to [0,1]) of the cloud base height (cbh) term and substitute it by $1 - cbh$. After performing PCA we use the following algorithm. First, we normalize all principal component to fit into the range from 0 to 1. Then we sum them up and group the resulting numeric values into 10 bins, discretizing the results to obtain the unified WIF score.

6. Results

In this section we present the results of the performance evaluation for the arrival flows to runways 01R, 19L and 26 at Stockholm-Arlanda airport. We calculate the additional distance, time on levels, vertical deviation and additional fuel burn for all arrivals in October 2019, which was the busiest month in 2019. The calculation of the reference CDOs and fuel consumption are computationally expensive tasks. Additional distance and time on levels can be calculated reasonably quickly for the whole year, but as it relates to the additional fuel burn, we chose to use the same dataset for our investigation. In the analysis of the impact of weather and traffic intensity, we use the data for the whole year of 2019.

6.1 Horizontal Flight Efficiency

Figure 4 shows the horizontal flight efficiency expressed in additional distance compared to the corresponding direct reference trajectory, for the three runways per cluster. Negative values of this PI correspond to the efficient flights with the actual point of entry to the TMA closer to the runway than the location of the cluster centroid, from where the reference trajectory starts.

Table 1 – Average vertical deviation from the corresponding reference CDO, expressed as ft·minutes.

cluster	01R	19L	26
1	30700	22200	25000
2	31600	27000	23900
3	20700	24100	26000
4	33100	23600	30000
5	31800	24200	26300
6	33600	24800	20700

6.2 Vertical Flight Efficiency

Figure 5 shows the percentage of time on levels for Arlanda airport arrivals. In Figure 6 we present the vertical efficiency analysis in terms of vertical deviation from a reference CDO for the last 10 minutes of flight before the final approach segment, for each runway and cluster at Arlanda. Table 1 contains the corresponding values of the vertical deviation calculated in ft·minutes.

6.3 Fuel Efficiency

Additional fuel burn for the actual arrivals to Arlanda, compared to RT1 and RT2 is shown per cluster and per runway in Figure 7.

6.4 Impact of Weather and Traffic Intensity on TMA Performance

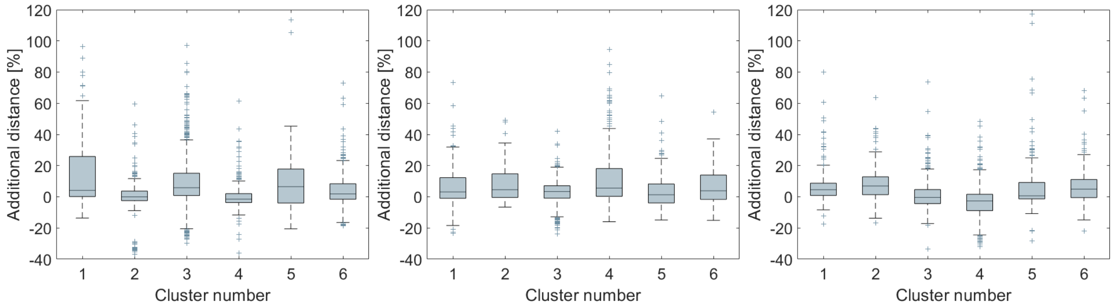
To analyse the impact of different weather factors on horizontal and vertical flight efficiency in TMA, we regress the medians of the Additional Distance and the Time Flown Level onto WIF, per cluster for each of the three runways. Next, to analyse the impact of traffic intensity on the arrival performance, we regress the medians of the same performance metrics onto TIF, per cluster for individual runways. Tables 2, 3 present the resulting R^2.

Table 2 – R^2 for the Regressions of Additional Distance Medians (in %) onto the TIF and WIF by clusters, for 3 runways.

cluster	TIF			WIF		
	$O1R$	$19L$	26	$O1R$	$19L$	26
1	0.87	0.91	0.74	0.16	0.01	0.03
2	0.71	0.73	0.48	0.5	0.2	0.54
3	0.91	0.84	0.79	0.04	0.7	0.34
4	0.65	0.78	0.88	0.32	0.08	0.1
5	0.95	0.2	0.89	0.33	0.2	0.01
6	0.68	0.89	0.79	0.43	0.36	0.79

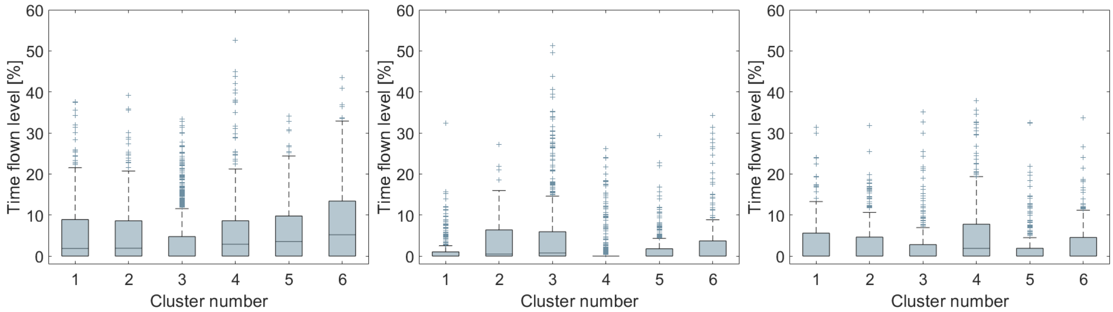
Table 3 – R^2 for the Regressions of Time Flown Level Medians (in %) onto the TIF and WIF by clusters, for 3 runways.

cluster	TIF			WIF		
	$O1R$	$19L$	26	$O1R$	$19L$	26
1	0.9	0.08	0.58	0.65	0.32	0.0
2	0.03	0.0	0.08	0.24	0.1	0.36
3	0.57	0.23	0.42	0.24	0.52	0.34
4	0.17	0.85	0.71	0.61	0.3	0.36
5	0.53	0.02	0.0	0.11	0.22	0.06
6	0.28	0.2	0.0	0.27	0.37	0.02



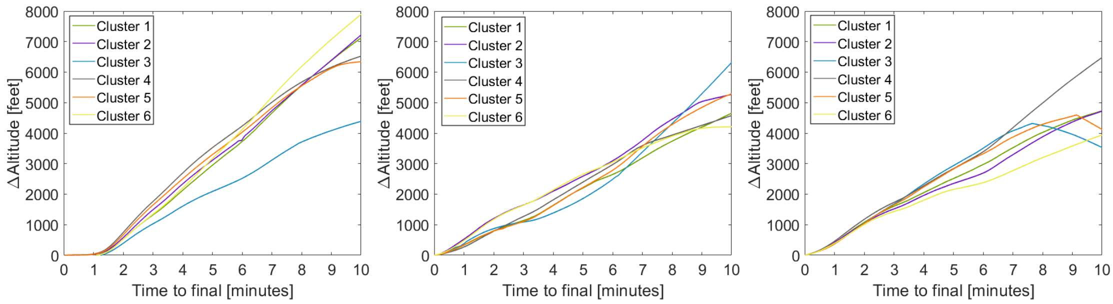
(a) (b) (c)

Figure 4 – Additional distance per cluster for Stockholm-Arlanda airport arrivals in October 2019, for runway 01R (a), 19L (b) and 26 (c).



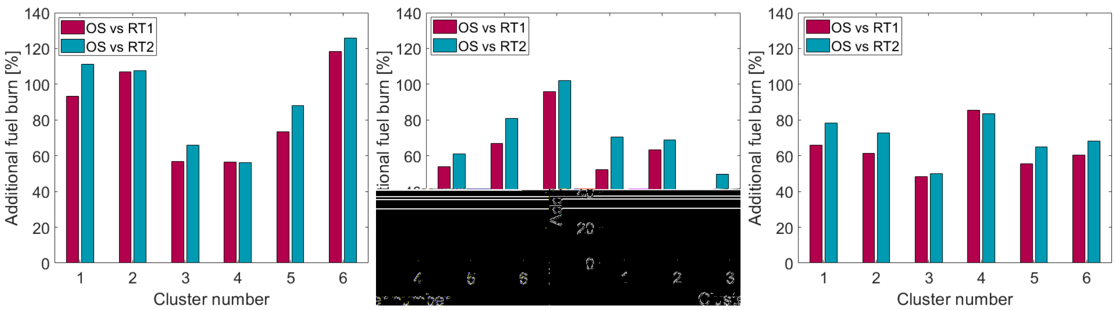
(a) (b) (c)

Figure 5 – Time flown level for Stockholm-Arlanda airport arrivals in October 2019, for runway 01R (a), 19L (b) and 26 (c).



(a) (b) (c)

Figure 6 – Average vertical deviation per cluster for Stockholm-Arlanda airport arrivals in October 2019, compared to RT1, for runway 01R (a), 19L (b) and 26 (c).



(a) (b) (c)

Figure 7 – Average additional fuel burn per cluster for Stockholm-Arlanda airport arrivals in October 2019, compared to RT1 and RT2, for runway 01R (a), 19L (b) and 26 (c).

6.5 Discussions

Analyzing the horizontal, vertical and fuel efficiency, we observe that the overall performance in TMA is noticeably lower when runway 01R is used for landings (with the medians of additional distance ranging between 0 and 6.5%, time flown level - 0 to 5.2% and additional fuel burn (RT2 considered) of 55.7 to 125.2%.

Studying the results of the additional fuel burn (Figure 7), calculated in comparison to RT1, we observe how much extra fuel is spent due to vertical inefficiency (RT1 is the ideal reference trajectory with the same horizontal track as the actual one). And from the additional fuel burn calculated in comparison to RT2, we can see how much extra fuel is spent due to both horizontal and vertical inefficiency (RT2 reference trajectory corresponds to the ideal descent with the shortest route from the point of TMA entry to the final approach).

The additional fuel burn for clusters 2 and 4 corresponding to runway 01R (Figure 7 (a)), is close to identical when comparing RT1 to RT2, which is confirmed by the low additional distance characterizing horizontal efficiency (Figure 4 (a)). The additional fuel burn for clusters 2 and 4 is mainly due to vertical inefficiency, as observed in Figures 5 (a) and 6 (a). Additional fuel burn for cluster 1 shows a significant difference between additional fuel burn when comparing RT1 and RT2, which is explained by the relatively high additional distance obtained for this cluster. The vertical deviation for runway 01R (Figure 6 (a)) is close to zero for all clusters for the last minute to final, which is explained by fact that the calculations where performed down to 2500 ft, while the FAP altitude for 01R is at 4000 ft, compared to 19L and 26, where the FAP altitude is at 2500 ft. A FAP altitude at 4000 feet ensures a constant decent from that point, which is what we observe in the figure.

For runway 19L (Figure 7 (b)), we observe a better fuel efficiency in general, compared to that for runway 01R (with the medians of additional distance ranging between 1.3 and 5.6%, time flown level - 0 to 0.8% and additional fuel burn (RT2 considered) - 41.8 to 107.7%). In more detail, we can see that cluster 4 shows a relatively low additional fuel burn when RT1 is considered, explained by the relatively low time flown level and vertical deviation from CDO (Figures 5 (b) and 6 (b)). The significant difference when RT1 and RT2 performance is compared can be explained by the additional distance (Figure 4 (b)). Cluster 5 shows a low difference between RT1 and RT2 performance, which is also visible when studying the additional distance PI. For cluster 5, the difference between RT1 and RT2 fuel efficiency is relatively low, which is in line with the low additional distance, observed in Figure 4 (b). Hence, the fuel inefficiency in this cluster results from the vertical inefficiency mostly, as shown in Figures 5 (b) and 6 (b).

The results uncover the best overall TMA performance when runway 26 is in use (with the medians of additional distance ranging between 0 and 6.9%, time flown level - 0 to 1.9% and additional fuel burn (RT2 considered) - 37.0 to 81.8%). When studying the additional distance for clusters 3 and 4 (Figure 4 (c)), we can see that it is low or negative, supported by similar additional fuel burn for RT1 and RT2 for these clusters (Figure 7 (c)). However, the values of the additional fuel burn for cluster 4 are higher than for cluster 3 (RT1 considered), which is accompanied by higher values of the time flown level and vertical deviation from CDO (Figures 5 (c) and 6 (c)). In addition, we observe sharp decrease in the vertical deviation of clusters 3 and 5 at 7 or 8 minutes to final (Figure 6 (c)), which can be explained by the relatively short distance in TMA for these clusters.

The degraded overall TMA performance when runway 01R/19L is in use, can be explained by the fact that it is the preferred runway during the selected peak traffic hours. Runway 26, on the other hand, is used more frequently during the day, but does not experience the same level of traffic intensity.

High impact of traffic intensity factor on the horizontal efficiency is observed for all runways and all clusters, with several exceptions: runway 26 cluster 2, runway 19L cluster 5 and runway 01R clusters 4 and 6 (Tables 2, 3), where the median values of the corresponding PI (additional distance) are quite low. On the contrary, traffic intensity does not demonstrate noticeable impact on vertical efficiency expressed in time flown level, but again with several exceptions: runway 01R cluster 1 and runway 19L cluster 4. The impact or weather factor on the chosen PIs is noticeably lower than the impact or traffic intensity, and demonstrates only moderate correlation for selected clusters: with additional distance for runway 01R cluster 2, runway 26 clusters 2 and 6; and with time flown level for runway 01R clusters 1 and 4 and runway 19L cluster 3.

The results of the arrival performance analysis as well the analysis of the impact factors on the TMA performance, are subject to further discussions with operational specialists.

7. Conclusions and Future Work

In this paper, we have clustered the arriving traffic to Stockholm-Arlanda airport and presented a per-flow analysis of the TMA performance. We provided a fuel efficiency assessment for a busy month in 2019 and concluded that, for the three most-used runways, the cluster-wise additional distance ranges from 0 to 6.9%, the time flown level from 0 to 5.2%, the vertical deviation from 20700 to 33600 ft·minutes and the additional fuel burn from 37.0 to 125.2%. Further performance analysis shows that the overall TMA performance, in October 2019 was the best when runway 26 was used, followed by 19L and 01R. The impact of traffic intensity and weather are also taken into consideration. We uncovered that traffic intensity has significant impact on the horizontal efficiency for most of the runways and clusters, which confirms our previous findings.

In future work we plan to continue investigations of the fuel efficiency in TMA, which is a proxy to aviation's impact on the environment.

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9. Copyright Statement

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