Evaluation of Arrival Sequencing at Arlanda Airport

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Evaluation of Arrival Sequencing at Arlanda Airport

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- Analysis of studies focused on the topic
- Proposal to improve the current situation

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Prague .... June 12, 2019

Abstract

This work presents an analysis of arrival sequencing at Stockholm Arlanda airport. The sequencing of arrivals is very important part of air traffic control management and assures safe space and time distancing of arriving aircraft. In this work we use historical flight data from Opensky Network database. The historical flight data contains the information about all the arrivals of the year 2018. The aim of this work is to propose the key performance indicators (KPIs) for evaluation of the arrival sequencing at Stockholm Arlanda airport. The three KPIs we are considering in this work are the minimum time to final, spacing deviation and sequence pressure. We choose data subsets of different size representing different traffic situations. We visualize the results and summarize them in tables which assures better clarity for the comparison of the same KPIs for different data subsets. In addition, we demonstrate how the proposed KPIs can be used for evaluation of optimization results from related study. We conclude that the proposed KPIs are very useful for analysis of the arrival aircraft sequencing and help to uncover inefficiencies within the terminal manoeuvring area (TMA).

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

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Abbreviations

Abbreviation	Explanation
ATM	Air Traffic Management
AVG	Average
KPI	Key Performance Indicator
SMART	Specific, Measurable, Achievable, Realistic and Timely
STD	Standard Deviation
TMA	Terminal Manoeuvring Area

Glossary

Term	Explanation
90^{th} quantile width	Maximum width of 90% confidence interval
Final point	The common landing point
Minimum time to final	Minimum time from a grid cell to the final point
Time in final	The time aircraft landed at the final point
Time to final	The time aircraft has fly to get to the final point

1. Introduction

Air traffic management (ATM) is one of the very important parts of transportation by air, it assures smooth traffic flow in each airspace sector, its safety, regularity, and efficiency using different management methods to assure these requirements in a regular airspace sector and around an airport. Air traffic management could be considered as a connection of three specific activities. These activities are air traffic control, air traffic flow management, and aeronautical information services. In this project, we are going to refer to air traffic control part of air traffic management, which represents a process of keeping aircraft separated in the sky mainly during landing and take-off.

Air traffic management around an airport requires more actions taken by air traffic controllers which is why there is another group of air traffic controllers for each airport which takes care of air traffic control in the terminal manoeuvring area (TMA). TMA is a part of airspace close to an airport that manages arriving and leaving aircraft. The focus of air traffic control in the TMA is the spatial and temporal separation of an aircraft for precluding any traffic collisions between aircraft.

Arrival sequencing is one of many parts of air traffic control in the terminal manoeuvring area. The efficient distribution of arrivals and take - offs could help with fuel consumption, congestion of the airport, and more. Sequencing and spacing are important for the airport to manage smooth traffic flow around the airport.

This chapter presents problem formulation and research questions for this study. Furthermore, the purpose and the research questions are also presented here.

1.1. Problem description

There are many different approaches for sequencing of arrivals used by airports, this thesis aims to develop new key performance indicators (KPIs) for evaluation of sequencing and to evaluate sequencing strategy used by the Arlanda airport in Stockholm. Key performance indicators (KPIs) are metrics for measurement of efficiency, quality, or economy and are usually used for organization management. Among number of KPIs developed, the ones we are interested in were proposed by Eurocontrol in [1] which we will fine-tune for evaluation in Stockholm Arlanda airport, test their applicability and validate on example of Stockholm Arlanda airport arrivals in the year 2018 using historical flight data.

1.1.1. The aim of the thesis

This thesis aims to evaluate sequencing strategy used at Stockholm Arlanda airport and propose new key performance indicators for this evaluation. The main purpose of evaluation of sequencing at Stockholm Arlanda airport is to have a clear overview and insight of the air traffic control operations taken by the Arlanda airport on arrivals. This could help in future adjustment of routes or operating methods to reach maximisation of runway utilisation.

1.2. Research questions

- How does Stockholm Arlanda airport manage sequencing for their arrival aircraft?
- Which KPIs are suitable for Arlanda airport and what do they evaluate?
- How the KPIs proposed could help with capturing problematic events?

1.3. Delimitations

The study is limited to data driven analysis and KPIs development to assure efficient evaluation of arrival sequencing at Stockholm Arlanda airport.

2. Background

In this section, we present an overview of the related work. In addition, we give the background information about the KPIs and describe the data source used in this work.

2.1. Related work

Various authors considered the evaluation of arrival sequencing at airports using KPIs. However, evaluation of arrival sequencing can differ for different airports and their air traffic control system. In [2] the authors developed a novel approach for understanding and characterizing the sequence of arrivals on the airport which relies on an analysis of spacing evolution over time between aircraft and inspecting aspects such as convergence, speed, and monotony. The motivation to develop and study new approach was to develop a method which would be able to characterize different operating methods, route structures, and environment among airports. The authors extended the methodology in [1] with an analysis of spacing and pressure for four European airports where each of them represents a different type of operation. The main focus in this paper was on additional time for each arriving aircraft, the spacing deviation for a pair of aircraft, and sequence pressure for a sequence of aircraft. In [3] a research group designed optimization framework for computing aircraft arrival routes to guarantee temporal separation of all aircraft arriving at TMA incorporating realistic continuous descent operation speed profiles. In this paper, the authors made an experimental study based at Stockholm Arlanda airport, where the authors applied their framework to a real-world instance. In [4] the authors 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. Research and development of terminal spacing tools have been ongoing for several years. Older tools focused on increasing runway throughput using complex models of controller behaviour. For example, in [13] 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. In history, detailed studies had been made for assessing the impact of new concepts in relation to sequencing [5], [6], [7]. Different dimensions were considered such as flight efficiency like distance and time flown, human factors such as workload, radio communications, and instructions and effectiveness such as achieved spacing in final using simulation data. In [7] 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 late versus early sequencing actions. Regarding aircraft spacing during arrivals, various analyses have been performed in the context of airborne spacing when studying different algorithms of the flight crews [8], [9], [10], [11], [12]. Most of the studies involved the relation between spacing accuracy, which is basically the control error, and a number of speed changes, which is control effort, as well as the reactionary effect. In all these cases, the authors considered that both aircraft in the aircraft pair followed known paths.

2.2. Key Performance Indicators

Key performance indicators (KPIs) are metrics for measurement of efficiency, quality, or economy and are usually used for organization management. These indicators should fulfil requirements of the SMART analytical technique. The SMART abbreviation stands for Specific, Measurable, Achievable, Realistic, and Time Specific, the SMART analysis is a technique for proposing goals in project management and planning [6]. The first essential step in developing efficient KPI is to verbally express the measure and to set the goal and purpose. Understanding of the purpose of the indicator allows to determine the source. In this work, the data source is the Opensky Network database. The next attribute which needs to be fulfilled in order to achieve efficient KPI is the frequency. Frequency explains how often we are going to report on the indicator. When planning of KPI is done, the KPI itself needs to be built. Some of the KPIs are single metric or measure and some need some more complex formula. When the KPI is built, the test rounds with test data are made to evaluate whether the results are correct. The last step in creating KPI is to present it which is usually done using understandable visuals such as graphs and charts. A good and efficient KPI can be assessed by the general characteristics of KPIs. The first characteristic is the relevance of the indicator to the topic and to the users. Another characteristic is the clearness of definition which should be achieved in order to ensure consistent collection and fair comparison. Vague definitions could lead to misinterpretation and confusion. The KPI should also be easy to understand for all users and stakeholders. KPIs should be comparable on a consistent basis both between organizations and over time. The KPI results and calculations and accuracy of the information need to be verifiable. Other characteristics of good KPI are allowance of innovation, statistical validity, and cost effectiveness.

2.3. Opensky Network Data

In this master thesis project, the data was collected by Opensky network database which keeps unfiltered raw data and makes it accessible for academic and institutional purposes. Opensky network is a non-profit association based in Switzerland which aims to improve the security, reliability, and efficiency of the air space usage by providing open access of real-world air traffic control data to the public. The data collection is formed with multitude of sensors connected to the Internet by volunteers, industrial supporters, and academic or governmental organizations. All the data is collected in a historical database and is believed to be the largest air traffic surveillance dataset of its kind and is primarily used by researchers. The technologies used by Opensky Network are the Automatic Dependent Surveillance-Broadcast (ADS-B) and Mode-S, both technologies provide aircraft information over publicly accessible 1090 MHz radio frequency channel [7].

2.4. Arrival sequencing

Arrival sequencing is part of air traffic control in the terminal manoeuvring area. The efficient distribution of arrivals and take - offs could help to reduce fuel consumption, congestion of the airport, and more. For aircraft sequencing, the required final spacing needs to be determined. The minimum allowable time separation of arriving aircraft is 1.5 minutes in heavy traffic and 2 minutes in normal operations. In each arrival sequence the separation or spacing of aircraft is needed. The separation of aircraft is a process of keeping an aircraft outside a minimum distance from another aircraft to reduce risk of collision and for preventing secondary factors such as wake turbulence. The aircraft separation is done by rules, known as separation minimum, applied by the air traffic controllers. The spacing of aircraft could be secured by the controller’s commands. The action to delay aircraft in order to prevent collision with preceding aircraft could be on lateral, thus path stretching, or longitudinal, thus speed reduction, dimensions. The action on lateral dimension is basically path stretching. The path stretching could be done in the form of circle, which represents a holding pattern and holds aircraft in desired elevation in designated part of the TMA waiting for approaching or by simple path extension in the form of additional turning which assures small delay.

3. Methodology

In this section, the methods and procedures are presented. First of all, we present the basics for data driven analysis and KPIs terms. Then, we describe the process of working with data. Next, data cleaning is followed by data filtering. Then, we describe KPIs chosen for this project and its calculations.

3.1. Data driven analysis

Data driven means that progress in an activity or approach is compelled by data rather than intuition or personal experience and the strategic decisions are made by data analysis and interpretation. Data driven approach is an organization and examination of data with the goal of better and more correct results.

Data analysis is a process of inspecting and examining data in order to find useful information, informing the conclusion or to support decision- making process and is a widely used approach for optimization by various fields such as science or social science. Data analytics are converting raw data into information useful for decision making or for optimization. Data is usually collected and analysed to help with answering questions, testing hypotheses, or disprove theories.

Usual parts of data driven analysis are the implementation of data requirements that are needed to determine which data needs to be collected. The next part is the data collection, data can be collected in various ways, usually from a number of sources. The third part is data cleaning which is needed for getting rid of errors or unwanted data. The last step is data analysis itself which contains calculations among data and its visualization if needed.

3.2. Data preparation

Data preparation consists of data cleaning and data filtration procedures which are inconceivable parts of work with raw data. Well-prepared data is a very important criterion for achieving suitable and efficient results from data analysis.

3.2.1. Data cleaning

Data cleaning is an essential part of work with data that assures getting rid of all errors that might be present at collected raw data. Cleaning of data is the process of detecting and removing or correcting inaccurate or invalid records from the dataset. The errors and inaccurate records in the raw dataset could be caused by flaws in transmission or by entry errors. Analysing of such a not cleaned dataset would cause a lot of errors in analysis and could spoil the results of an analysis.

For this project, we took historical data collected by the Opensky network during the year 2018 from Stockholm Arlanda airport. The raw data from Opensky Network was provided by the master thesis supervisor. We used Python programming language and Spyder scientific environment for the analysis. The dataset contains information on all aircraft arrivals during the year 2018. The data contains a number of various errors probably caused by flaws in the transmission of data or its processing. The data is collected on the ground using sensors, which capture the ADB-S signal transmitted by transponders located at aircraft. The technology is not reliable, and some data is lost which causes errors in our dataset.

For better understanding the errors found in our dataset, we need to introduce the dataset itself first. Our chosen dataset contains, as has been already said, data from all arrivals to Stockholm Arlanda airport during the year 2018. The data represents the aircraft positions recorded every one second which can be used for reconstruction of the 4D flight trajectory. The information contains ID of the flight, its callsign, icao24 24-bit aircraft identifier, type of aircraft, and the origin destination of the flight. For each flight, there are multiple rows in the dataset which contains information about its position in time. Expect above mentioned information, the dataset also includes information about the date the flight ended, current date, current time and timestamp, current longitude and latitude coordination, and current barometric altitude. An example piece of the Opensky Network dataset can be seen in Appendix 1. The list of fields of the initial dataset is shown in Table 1 below. Thanks to these attributes of data we are able to analyse the differences of aircraft sequencing management at Stockholm Arlanda airport.

Table 1 - List of fields of the dataset

Field	Description
flightID	Unique flight identifier
sequence	Aircraft sequence number
endDate	The date the flight landed
callsign	Unique airline identifier of specific flight
icao24	Unique 24-bit aircraft identifier
date	The date of the initial flight
time	The time of the initial flight
timestamp	date and time in UNIX format
lat	Latitude
lon	Longitude
baroAltitude	Barometric altitude
aircraftType	ICAO aircraft code
origin	ICAO code for origin airport

We select the piece of data related to arrivals within the terminal manoeuvring area for Stockholm Arlanda airport. The errors found in the dataset are records that never landed or missed the final point. Other errors found were records which footprint did not start by descending but by taking off and continued with a few hours' time gap with landing, these errors caused a lot of inconsistencies in our computation of minimum time to final which will be presented below. Data with errors included records of flights were landing normally but then suddenly their barometric altitude lifted a bit again and the flights started descending once more, usually with multiple hours' time gap. In this dataset, the go-around flight records would be treated as errors as well, since the flights never landed on the airport. We delete the erroneous records from the dataset which didn't have any sign of landing in final point and the ones landed with information, that does not belong to the actual aircraft trajectories, we split the records and kept only the accurate part of the information for that given flight ID records.

3.2.2. Data filtering

Data filtration is usually a second step after the data cleaning. Data filtering is a process of choosing a smaller part of a dataset called data subset and using this data subset for visualisation and analysis. The data filtration is usually temporal when a data subset is used for analysis but the whole dataset is kept. Filtering data could help with the calculation of the results for particular groups of interest, analysis of the results for a particular period of time, or for training and validation of statistical models. Data filtration requires the specification of common key how exactly the data is filtered. Filtering is also done to remove unnecessary information.

In this work, the data filtration was made mainly with the reason to compare KPIs for different dates and time groups based on historical data. The first criterion we used for data filtration was to take only the data subset of data in which longitude and latitude coordinate is within the terminal manoeuvring area polygon given by simplified coordinates of four entry points. These four entry points are presented in Table 2 below.

Table 2 - Entry points for Arlanda airport TMA

Nr.	Name	Latitude	Longitude	Direction
1	ELTOK	59.5861	16.6503	West
2	HMR	60. 2794	18.3917	North
3	Xilan	59.6594	19.0761	East
4	Nilug	58.8158	17.8847	South

The second criterion used for data filtration was a specific date and time chose from the dataset. For example, we have looked at the busiest and the least busy days during the year 2018, for the day with a large number of delays and for an average day in terms of traffic load. For each chosen date we used various smaller data subset to make analysis from for example the least busy hour, the busiest hour, night-time operations, and day-time operations. These data subsets presented we used for further analysis. The flights in a specific hours or specific time intervals were filtered out using the time the aircraft entered the TMA. In other words, even if the flight landed a few minutes outside the specific time interval, the data is still taken because the flight entered the area during the time interval.

3.3. Flight trajectory

The flight trajectory is a very important description for every single flight. The data describing the trajectory could help us better understand air traffic management at Stockholm Arlanda airport. Flight trajectory is in our dataset given by longitude and latitude coordinates and barometric altitude in time.

For visualization of flight trajectories, we used longitude and latitude coordinates for each flight which we standardized to fit 11 x 15 grid with side size 6 nautical miles. Only the parts of flights that are in the TMA of Stockholm Arlanda airport are presented in flight trajectory visualization. The limits on x and y axis represent the entry points presented before in standardized form.

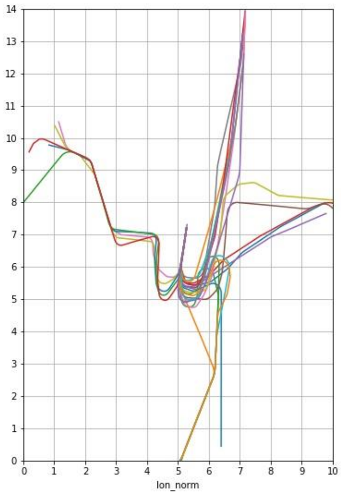


Figure 1 - Flight trajectory plot, example

Visualisation of flight trajectories for some random example can be seen above in Figure 1. Visualization of these coordinates gives us a clear view of flight paths of the chosen data subset. In this work, we visualize flight trajectories for every data subset to have an overview of what was going on. For example, some errors in data could be detected by visualization of flight trajectories or flights which arrived on different runways.

3.4. Suggested key performance indicators

In this section, the proposed and suggested key performance indicators are presented. The definition of each key performance indicator together with description of how they are calculated is demonstrated in the following subsections.

3.4.1. Minimum time to final

One of the KPIs used in this work is the minimum time to final trajectory. Minimum time to final trajectory is a trajectory in given airspace which takes the least time to get from point A to point B. In this work, the minimum time trajectory will be calculated from each point in the airspace to the final point. The final point in this example is considered the common point where most of the aircraft ends its flight (runway). For the calculation of minimum time trajectory, we need to declare another variable called minimum time to final. Minimum time to final is the minimum time it takes to aircraft to get from point A to point B. In other words, the minimum time to final is the time flown by aircraft among the minimum time trajectory [1].

In this master thesis project, we calculate the minimum time to final for each cell in a predefined grid laid over a TMA of Stockholm Arlanda airport. The predefined grid has 11 x 15 cell granularity dimensions to assure integrity with previous research and provides the grid edge length about 6 nautical miles [3]. Figure 2 shows an example of minimum time to final table.

As a first step to calculate the minimum time to final can be considered standardisation of longitude and latitude coordinates. Standardization of data is basically the conversion of data to a different scale. The standardisation is needed to fit data into 11 x 15 grid dimensions. Standardisation of the coordinates is made by taking longitude or latitude values and consider the smallest and the largest values of this range, which are for the X axis [0,10] and [0,15] for the Y axis. Then the remaining values are labelled respectively by their position in range to the new edge values. Once we have the data standardized it is possible to plot the flight trajectories into the grid.

Index	X	Y	min_time
0	1	3	735
1	1	4	673
2	1	5	532
3	1	6	620
4	1	7	513
5	1	8	460
6	1	9	518
7	1	10	509
8	1	11	440
9	1	14	853
10	2	2	593
11	2	3	525
12	2	4	628
13	2	5	591
14	2	6	426
15	2	7	437
16	2	8	438
17	2	9	374
18	2	10	448
19	2	11	380
20	2	12	694
21	2	13	819

Figure 2 - Minimum time to final table, example

When we look at the grid with plotted flight trajectories, we can see that not every cell is filled. Because of this, we are going to have the minimum time to final only for the cells through which at least one trajectory has passed. The calculation of the minimum time to final for each cell continues with searching through the dataset and finding the smallest time to final for each cell. In our algorithm, we use basic Boolean rules to decide which cell the current standardized coordinate belongs to. For example, x, y coordinates higher than or equal to zero but smaller than 1 belong to the cell [1,1].

The minimum time to final for each row in our data subset can be calculated easily. For each flight, we take the last record, which indicates that the aircraft landed, and use the timestamp from this record for the minimum time to final calculation. From now on, the timestamp taken from the last record will be referred to as time in final for that given aircraft. For each row in the dataset for a given flight segment we deducted the current row timestamp from the time in final. The result is the number of seconds to the final point. This calculation is presented in the formula below.

$$Time\ to\ final = Time\ in\ final - Current\ timestamp$$

Once the Boolean rules are set, we can start searching for the minimum time to final for each cell. This process consists of iterating over rows in our data subset and looking only for columns with x, y coordinates, and with time to final and making a new table with minimum time to final. The process is presented in the form of pseudocode below.

```
START:      This program computes the minimum time to final for each cell of the grid and
            creates a new table of the minimum time to final

INPUT:      Time to final, x, y IN data subset

COMPUTE:    FOR each row in data subset

                Compute time to final
                Assign time to final to the cell of the grid
            ENDFOR

DETERMINE:  IF x, y combination exists in new table

                Compare the minimum time to final
                IF value from data subset < value from new table

                    Rewrite value in new table
                ELSE
                    Pass
            ELSE
                Add x, y, time to final to new table

OUTPUT:     New table with the minimum time to final for each cell
```

Figures 3 and 4 illustrate the distribution of the minimum time to final in the form of heatmap and contour plot respectively.

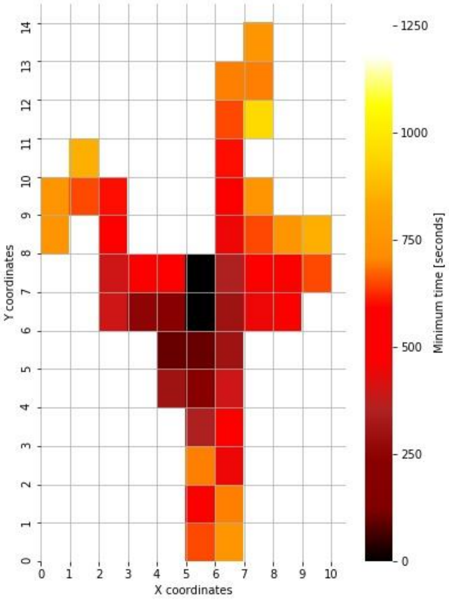


Figure 3 - Minimum time to final visualization, heatmap

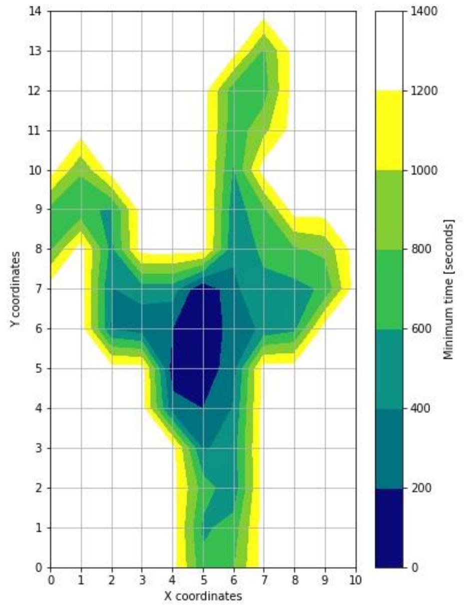


Figure 4 -Minimum time to final visualization, contour plot

In [1] the values assume non-congested conditions and define the minimum time to final as the flying time of the trajectory with the minimum time to final among all the trajectories of the same flow passing through this point. The values further explain that in practise, the values discretise the area in the form of a map of cells, each containing the minimum time to final from this cell to the final approach fix. The minimum time to final is computed for each cell similarly to [1]. On the contrary, in our work, we compute the minimum time to final for every data subset separately which assures higher accuracy of results, which provides the reference trajectories with the minimum time to final in the actual current conditions. The idea is to reflect the current situation better and capture the inefficiencies in the real situation.

3.4.2. Spacing deviation

The spacing of an arriving aircraft pair is defined as the difference between their respective minimum time to final at time t [1]. A spacing deviation is one of the KPIs used for this project and represents the inter aircraft spacing control error. Spacing deviation calculation reflects the information about control error which is the accuracy of spacing around the airport.

For spacing deviation calculation, we consider each aircraft pair and assign a unique identifier to it. A spacing deviation is also the difference between the minimum time to final for arriving aircraft pair, the only difference is, that spacing deviation examines the difference of the position of these two aircraft at the same time to final. The spacing deviation is calculated for a pair of aircraft tagged as the leader and the trailer. The leader aircraft is the aircraft that arrives at the final point first and the trailer aircraft is the aircraft that arrives second. For presenting the formula for spacing deviation calculation, we need to understand one more variable which is called time separation. Time separation for an aircraft pair is the time difference of time in final of each aircraft in the pair [1]. The formula for spacing deviation calculation can be seen below, where s is the time separation for a given aircraft pair. With this formula, the spacing deviation is calculated at all times during aircraft landing.

$$Spacing\ deviation\ (t) = minimum\ time\big(trailer(t)\big) - minimum\ time(leader(t-s))$$

From the formula is clear, that the spacing deviation is calculated over time, which means that we discretize the timeline with a stable number n of steps which differs from the data subset. The aim is to calculate as many values as is possible for that given data subset, which differs and that is why the n variable is calculated for each subset and represents the flight in the whole data subset with the least number of records to assure calculation consistency. Since the time the trailer landed is more important, the exact timestamps taken are the actual timestamps of trailer aircraft. For the consistency of calculation, random sample of fixed length (n) of these is taken. To assure reproducibility of calculation we set seed for a random function. Since each flight has a different number of records (rows) in the data subset, we use the random sample of a given size to assure the accuracy of statistics of results. The size of the random sample of timestamps is different for each data subset because we always take as the size the number of records of flight with the least records.

We demonstrate an example of the spacing deviation results in Figure 5. The spacing deviation plot illustrates the results of the calculation from 900 seconds to final to the landing and the y-axis limits are set for every data subset from -600 to 600 seconds deviation. We illustrate the description of the statistics of results such a 90% confidence interval and median curves in the Figure. These descriptions are calculated for different intervals of time to final to assure a better fit for the data. Blue curves represent 90% confidence interval borders and the black curve represents the median. The statistics is also calculated for each data subset and one special value which clearly indicates delays is included. The value is 90th quantile width which informs about the width of the 90% confidence interval in its widest point.

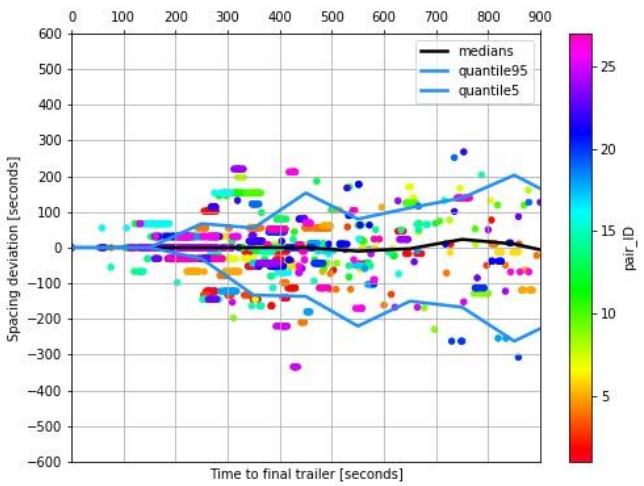


Figure 5 - Spacing deviation visualization, example

3.4.3. Sequence pressure

The sequence pressure is calculated for a sequence of landing aircraft and is an indicator for measuring the aircraft density in the sequence and measures the pressure of arriving aircraft at different time horizons. The sequence pressure consists of the number of aircraft sharing the same minimum time to final in a given time window [1] . The observation of sequence pressure reflects the information about the type of metering used by Arlanda airport and sequencing close to the airport. Sequence pressure calculation brings also information about aircraft density of arrivals among specific time periods.

For the calculation of sequence pressure, we took inspiration mainly from [1]. The sequence pressure calculation depends on calculating how many aircraft are sharing the same minimum time to final. This calculation is made for every single flight in multiple time steps. For each flight we took the time period it is present in the TMA, which is defined by the time the flight entered the imaginary polygon border end the time the aircraft landed. We divide this time period with 90 seconds granularity and get several timestamps for that given flight. We are going to calculate the sequence pressure in these timestamps.

For each timestamp taken for the calculation, we examine whether any other aircraft were present in the TMA within the given time window. In this work, we seek to find an efficient evaluation of spacing and that is why we examine three different window sizes. These lengths are 90 seconds, 120 seconds, and 240 seconds. During the analysis of results, we are going to test the sensitivity of the results to the change in this parameter. When an aircraft is present in the TMA within chosen time window from the reference aircraft, we take its latitude and longitude values and calculate the minimum time to final and compare it with minimum time to final assigned to the corresponding cell. Sequence pressure is the total number of aircraft sharing the same minimum time to final.

Figure 6 illustrates an example of sequence pressure results from 900 seconds to final to landing. The y-axis limits are set from 0 to 6 for every data subset to assure consistency in the results. The black curve stands for the median and the blue curves are the borders for 90% confidence interval. In every moment there should be at least value of one which represents the aircraft which was the calculation made for.

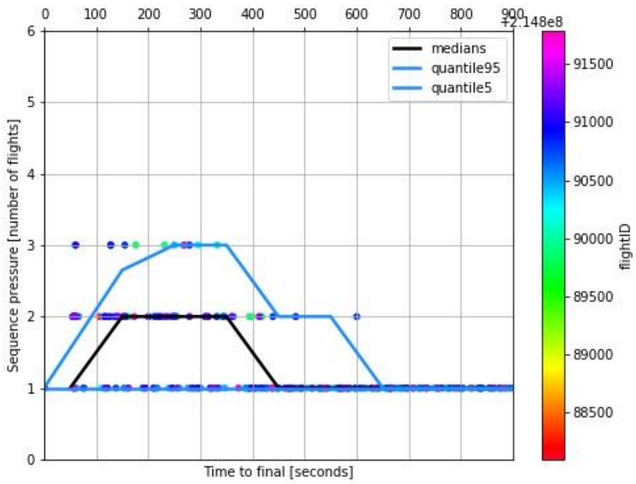


Figure 6 - Sequence pressure visualization, example

4. Data analysis

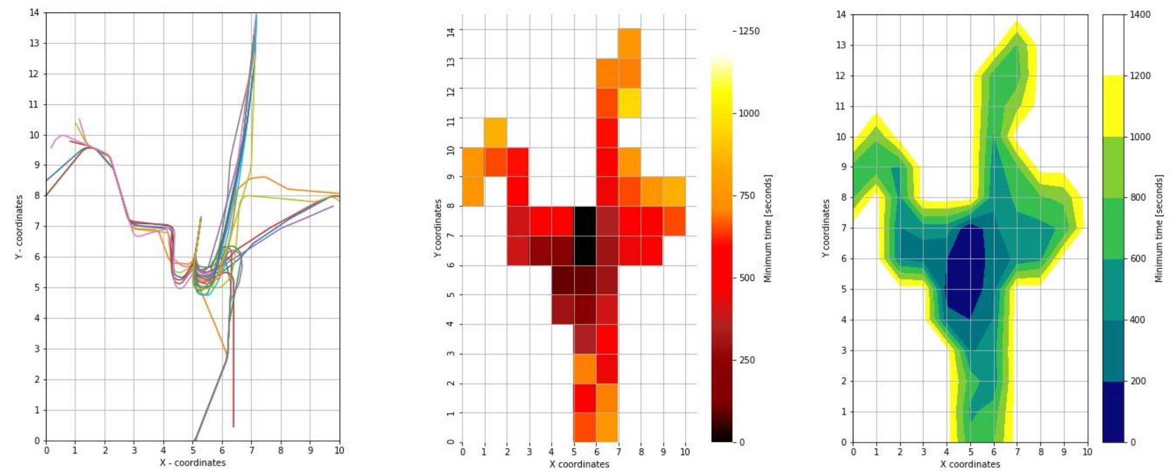
In this section, the results for the KPI calculations will be analysed. For the analysis, we chose data subsets from the dataset which is usually one specific hour on one specific day or a few more hours on the same day. We choose the busiest day of the year, the least busy day, the day which we know had a lot of delays, average density day, and a few more. For each of these days, we computed the KPIs for the least busy hour, the busiest hour, day-time operations, and night-time operations. We calculated the traffic density based on the number of flights arrived during the day. The average is roughly 283 flights per day and the median is 291 flights per day.

4.1. High traffic day

The first data subset we chose to analyse is the 12th of April 2018. On the 12th of April 2018, the number of flights arriving at Stockholm Arlanda airport was 352 which is high above the average. This day is one of the busiest days during the year 2018.

4.1.1. The busiest hour

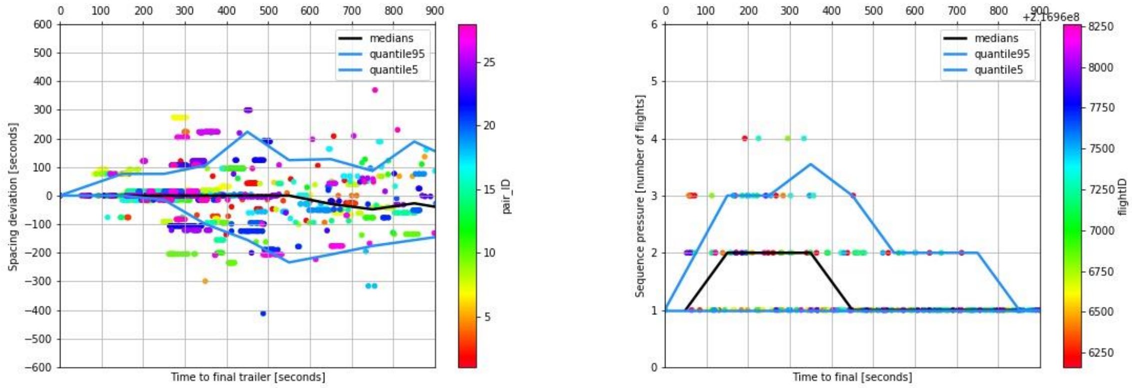
The busiest hour of the 12th of April was between 5:00 and 6:00 in the morning. During this hour 30 flights entered the TMA of Stockholm Arlanda airport. Figure 7a illustrates all the trajectories of the aircraft arrived at TMA during this hour. The flight trajectory plot clearly shows that all flights landed at the same runway from the four different directions. There are no visible holding patterns of aircraft in this Figure which could mean that the traffic flow was quite smooth during this hour. Figures 7b and 7c show the minimum time to final for each cell used. Figure 7c is the contour plot and Figure 7b is a heatmap. The heatmap and the contour plot both indicate the smooth traffic flow and gradual descending with no sudden delays or holds of aircraft.



a) *b)* *c)*

Figure 7 – April 12th, 5:00 – 6:00, (total 29 aircraft), min = 0s, max = 932s, avg = 508s, std = 228s a) Flight trajectories, b) Heatmap c) Contour plot

In Figure 8a below the spacing deviation is shown. The blue curves represent a 90% confidence interval and the black curve illustrates the median values. Both of these were calculated over multiple intervals of time to final to assure a tighter fit to the data. The median values are mostly around zero which is a sign of a balanced traffic flow. Larger dispersion of values is visible around 500 seconds to final of the trailer which then calms down and decreases towards zero around 300 seconds to final.



a) *b)*

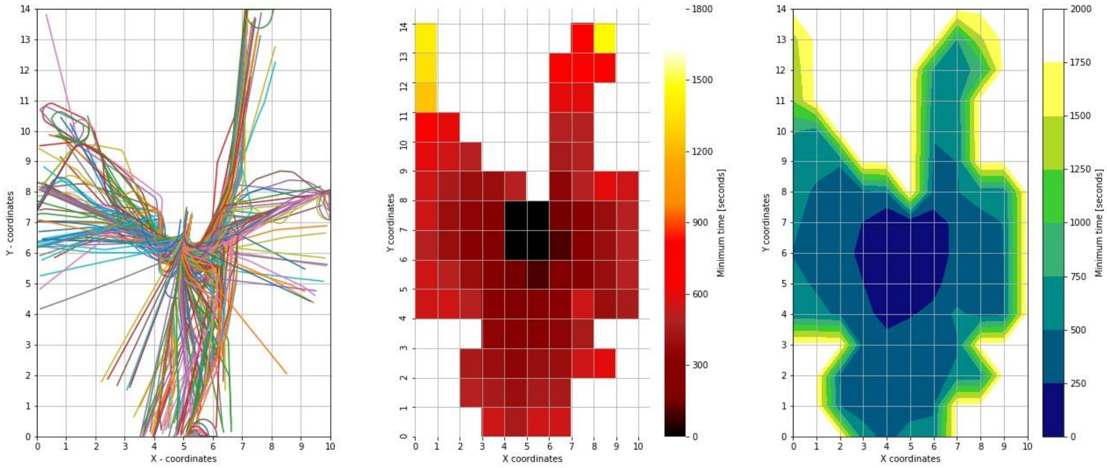
Figure 8 – April 12th, 5:00 – 6:00, (total 29 aircraft), a) Spacing deviation, min = -412, max = 369s, avg = 0.15, std = 81.32, 90th quantile width = 378, b) Sequence pressure, window size = 120s, min = 1, max = 4, avg = 1.43, std = 0.7

Figure 8b shows the sequence pressure calculation for the 120 seconds time window. The highest pressure was with three aircraft sharing the same minimum time to final at the same moment and the lowest pressure is, as expected, only one aircraft sharing the same minimum time to final at the moment. High sequence pressure values indicate high density, but the indicators presented before are not showing any significant delays or holds. The situation with higher traffic density is managed well in this example.

4.1.2. Day- time operations

In this project, we are also going to compare day- time and night-time operations in Stockholm Arlanda airport. Day time operations are calculated for the time interval between 6:00 in the morning and 24:00 which is midnight. This calculation covers 18 hours in total. During this time interval, 305 aircraft landed at the Stockholm Arlanda airport.

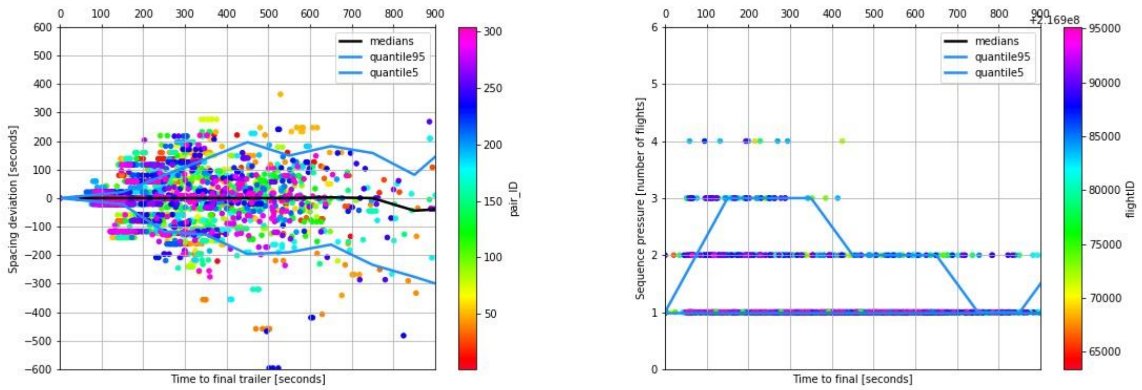
Flight trajectories for day-time operations on the 12th of April are illustrated in Figure 9a. We can see that all flights landed on the same runway. Some holding patterns and path extensions can also be seen mainly in the form of circles. In Figures 9b and 9c we can see the minimum time to final visualization in the form of contour plot and heatmap respectively. The maximum value of the minimum time to final is 1451 which means that the traffic flow wasn't as busy as other days and that the flight management had to put path extensions into flight trajectories of some of the flights. On the contrary, from both the heatmap and the contour plot can be seen that such a high value of the minimum time to final is only on the western entry point which gives us an idea that the western part of TMA was the busiest part. Higher value of the minimum time to final can also be seen on the paths from the northern entry point, but from the flight trajectory plot we can assume, that this is only one exceptional flight.



a) *b)* *c)*

Figure 9 – April 12th, 6:00 – 0:00, (total 305 aircraft), min = 0s, max = 1451s, avg = 463s, std = 258s, a) Flight, b) Heatmap, c) Contour plot

In Figure 10a the spacing deviation for day-time operations is shown, the spacing deviation plot for day-time operations of the 12th of April has a reasonable shape. The median curve is only with little exceptions very close to zero and confidence interval curves also have a very nice shape. The dispersion of spacing deviation values gets close to zero with approximately 100 seconds deviation at 300 seconds to final. Around 50 seconds to final until zero seconds to final shows zero deviation.



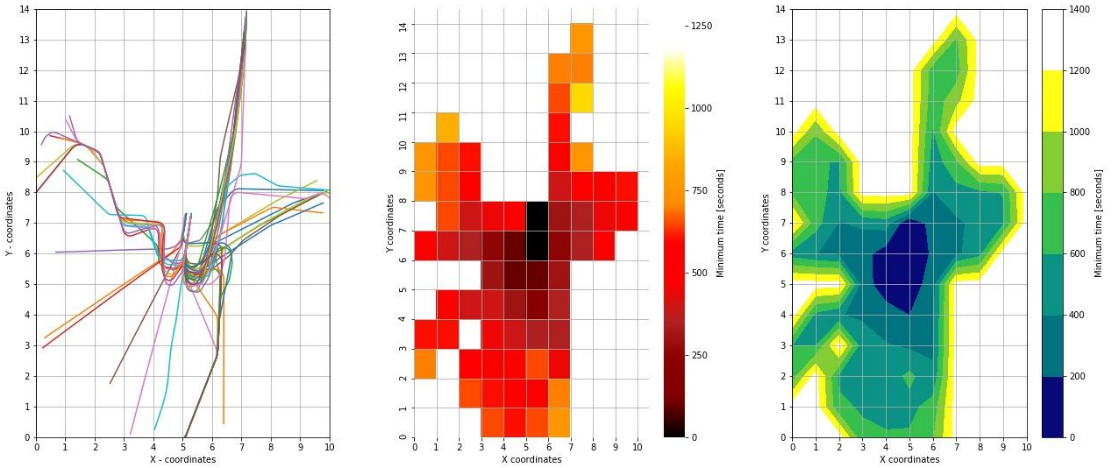
a) *b)*

Figure 10 – April 12th, 6:00 – 0:00, (total 305 aircraft, a) Spacing deviation, min = -596s, max = 364s, avg = 0.17, std = 81.94, 90th quantile width = 392, b) Sequence pressure, window size = 120s, min = 1, max = 4, avg = 1.22, std = 0.51

In Figure 10b the sequence pressure is calculated with 120 seconds time window. The maximum value for this calculation is four but the confidence interval curves go up only to three which indicates the sequence pressure of four occurrence as an outlier.

4.1.3. Night-time operations

Night-time operations are operations made during the night. The time interval we use starts at 0:00 midnight and lasts until 6:00 in the morning and covers six hours of the flight operations made at Stockholm Arlanda airport. Figure 11a shows the flight trajectories observed in this time interval, only 47 flights arrived at Arlanda airport during these six hours. The figure demonstrates that all the flights landed at the same runway and no significant flight extensions were used.

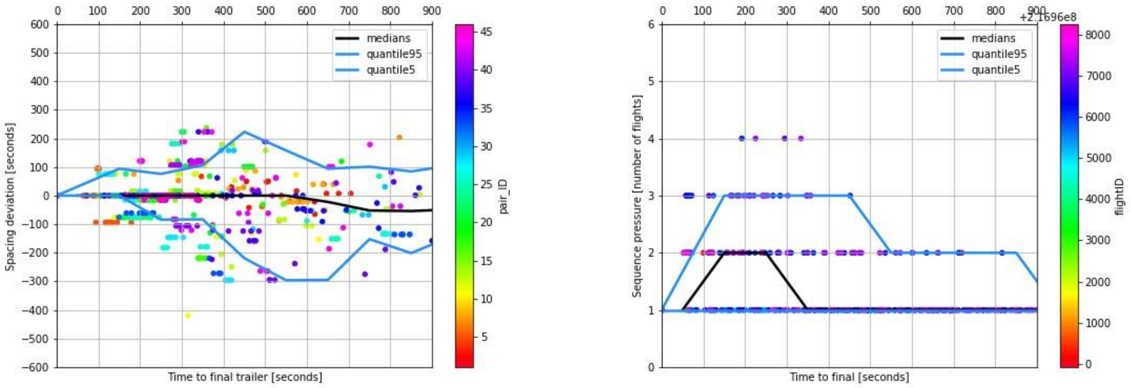


a) b) c)

Figure 11 – April 12th, 0:00 – 6:00, (total 47 aircraft), min = 0s, max = 932s, avg = 491s, std = 198s, a) Flight trajectories, b) Heatmap, c) Contour plot

Figures 11b and 11c illustrate the minimum time to final visualisation. The maximum values of the minimum time to final reaches approximately 1000 seconds which is a common maximum value in the comparison with other data subsets. The minimum time to final visualization shows gradual approaching the final point of the aircraft.

In Figure 12a we can see the spacing deviation calculated for night-time operations. The spacing deviation has very small dispersion, maximum of 454 seconds if we consider the confidence interval curves. Higher 90th quantile width can be seen around 500 seconds to final and then it halves around 300 seconds to the final. This phenomenon reflects the fact that the traffic flow was very low during the night. In Figure 12b the sequence pressure for 120 seconds time window is calculated. The sequence pressure plot has low values, where the median reaches a pressure of three only for approximately 100 seconds which indicates calm traffic conditions at night. The four occurrences of the sequence pressure of four aircraft indicate outlier values and thus are not significant for the analysis.



a) *b)*

Figure 12 – April 12th, 0:00 – 6:00, (total 47 aircraft) - a) Spacing deviation, min = -419s, max = 237s, avg = 13.25, std = 81.26, 90th quantile width = 454, b) Sequence pressure, window size = 120s, min = 1, max = 4, avg = 1.36, std = 0.65

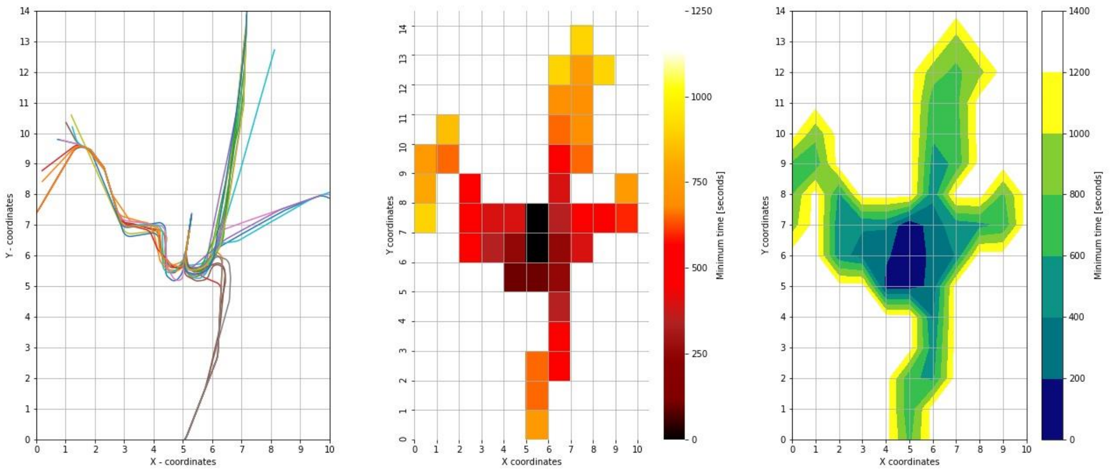
4.2. The busiest day of the year 2018

According to our calculations, the busiest day of the year 2018 on Stockholm Arlanda airport is the 16th of May where a total of 361 aircraft landed at the Arlanda airport. We noticed in the dataset that the total number of landings per day around three hundred is not very exceptional, but May 16th is the absolute peak for the year 2018.

4.2.1. The busiest hour

The busiest hour observed during the 16th of May was between 5:00 and 6:00 in the morning when a total of 32 aircraft landed at the Stockholm Arlanda airport.

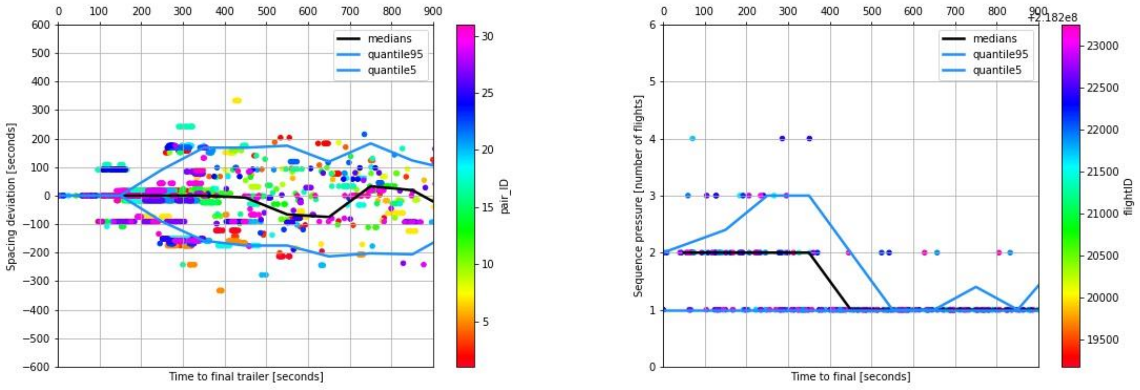
Figure 13a shows the flight trajectories from the busiest hour of the busiest day of the year. The flight trajectories are well organized and follow a clear pattern. Figures 13b and 13c below shows the minimum time to final visualisation in the form of heatmap and contour plot respectivelly. Both of these Figures show smooth traffic flow with low minimum time to final values and the traffic flow from each entry point seems to be well distributed. Higher values of the minimum time to final can be seen from the northern and the western entry point and lower values from the eastern and southern entry point.



a) *b)* *c)*

Figure 13 – May 16th, 5:00 – 6:00, (total 32 aircraft),), min = 0s, max = 924s, avg = 532s, std = 245s - a) Flight trajectories, b) Heatmap, c) Contour plot

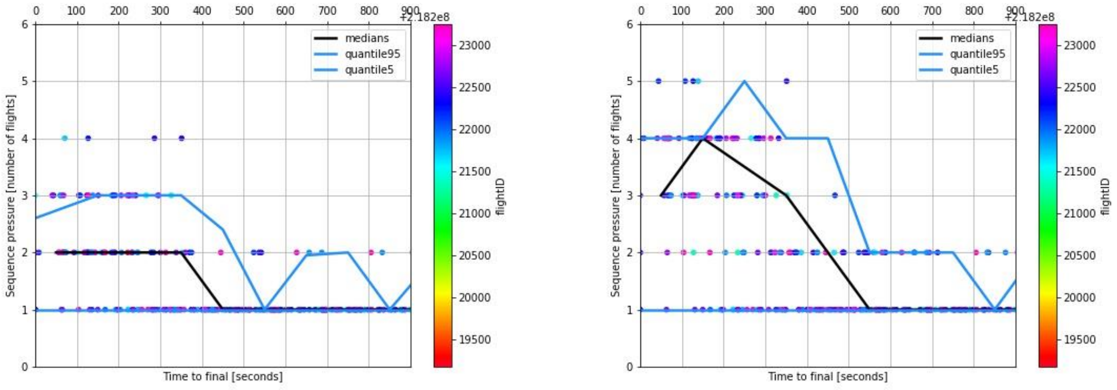
In Figure 14a the spacing deviation is shown. The spacing deviation also does not show any wide dispersion of values which indicates quite smooth traffic flow. The highest values are around 500 seconds to final and decreasing towards zero seconds to final until zero deviation. We can observe unexpected deflection of the median curve around 650 seconds to final which calms down and gets back to zero at around 450 seconds to final.



a) *b)*

Figure 14 – May 16th, 5:00 – 6:00, (total 32 aircraft) - a) Spacing deviation, min = -333s, max = 333s, avg = 9.82, std = 85.6, 90th quantile width = 385.35, b) Sequence pressure, window size = 90s, min = 1, max = 4, avg = 1.34, std = 0.6

In this work, we used multiple window widths for sequence pressure calculation. In most of the cases, the sequence pressure computed with 120- second window size is shown. We use the busiest hour of the busiest day data subset to apply the sensitivity analysis and demonstrate the difference caused by the different window sizes. The sequence pressure is calculated with window sizes 90, 120, and 240 seconds respectively. We present the sequence pressure calculated with 90 seconds time window in Figure 14b. Maximum pressure reaches four aircraft sharing the same minimum time to final, but the confidence interval reaches only the value of three. Figure 15a shows the sequence pressure calculation with 120 seconds time window. The maximum value, and also confidence interval reach four aircraft sharing the same minimum time to final. Lastly, Figure 15b illustrates sequence pressure calculation as well but with the window of 240 seconds. The maximum value reaches five aircraft, which is exceptionally high in comparison with the sequence pressure calculated for 90, or 120 second window sizes.



a)

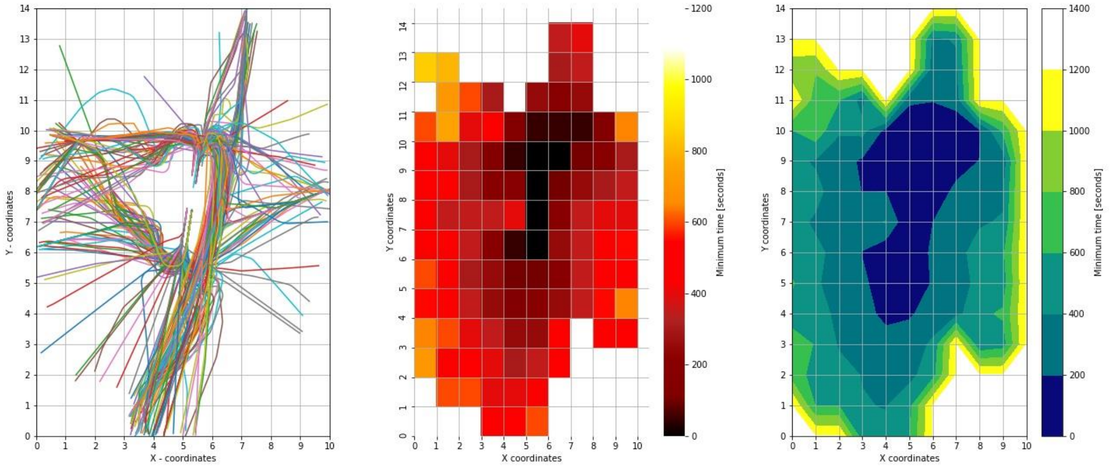
b)

Figure 15 – May 16th, 5:00 – 6:00, (total 32 aircraft) - a) Sequence pressure, window size = 120s, min = 1, max = 4, avg = 1.42, std = 0. 7, b) Sequence pressure, window size = 240s, min = 1, max = 5, avg = 1.89, std = 1.18

With the demonstration of results above, we proved that the window size in sequence pressure calculation has a major impact on the results and final evaluation. While the results of window sizes 90 and 120 seconds are very similar, the 240- second window size is too large and gives too high values for the sequence pressure. However, the window size of 90 seconds could be too strict and cause a negative error. The similarity between 90- and 120-seconds time window can be cause by the fact, that the minimum allowable time separation on the runway is 1,5 minutes, thus 90 seconds, in high traffic and the desired value is 2 minutes, thus 120 seconds, in normal operation. After these findings, we evaluate the conditions at Stockholm Arlanda airport mainly with 120- second window size.

4.2.2. Day-time operations

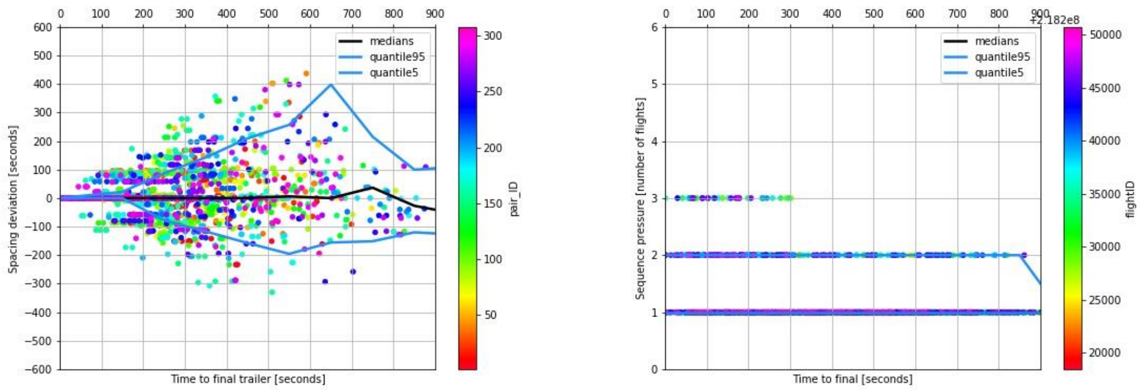
During day-time operations altogether 309 flights arrived at Stockholm Arlanda airport. In Figure 16a, the flight trajectories from this data subset can be seen, the fact that two runways were used during this time interval is clearly visible as well. Also, no significant holding patterns as circles are present, but little path extensions in the form of curves are visible. Figures 16b and 16c are the minimum time to final visualization. The minimum time to final visualization is very informative for this example since the flights took a lot of different flight paths. The larger field with zero value of the minimum time to final is given by the fact that two runways were used. The maximum value of 853 seconds which is the minimum time to final for edge cells is quite small in comparison with some days which experienced congestions.



a) b) c)

Figure 16 – May 16th, 6:00 – 0:00, (total 309 aircraft), min = 0s, max = 853s, avg = 358s, std = 190s - a) Flight trajectories b) Heatmap, c) Contour plot

The spacing deviation calculation is shown in Figure 17a. Spacing deviation has a very large dispersion and the average value is almost two times higher than during day-time operations on the 12th of April which could point out high traffic flow and high sequence pressure on the runway. Also, high dispersion as this could be caused by control errors. The dispersion of values is quite high around 600 seconds to final, but the dispersion is decreasing towards zero seconds to final. The spacing deviation stabilized quite quickly in comparison with other data subsets since zero deviation is observed from approximately 150 seconds to final. Figure 17b shows sequence pressure calculated with 120 seconds time window. In contrast to spacing deviation, sequence pressure with 120 seconds time window points out on calm traffic with no high pressure on the runway which can be caused by the fact that two different runways were used during this time interval.

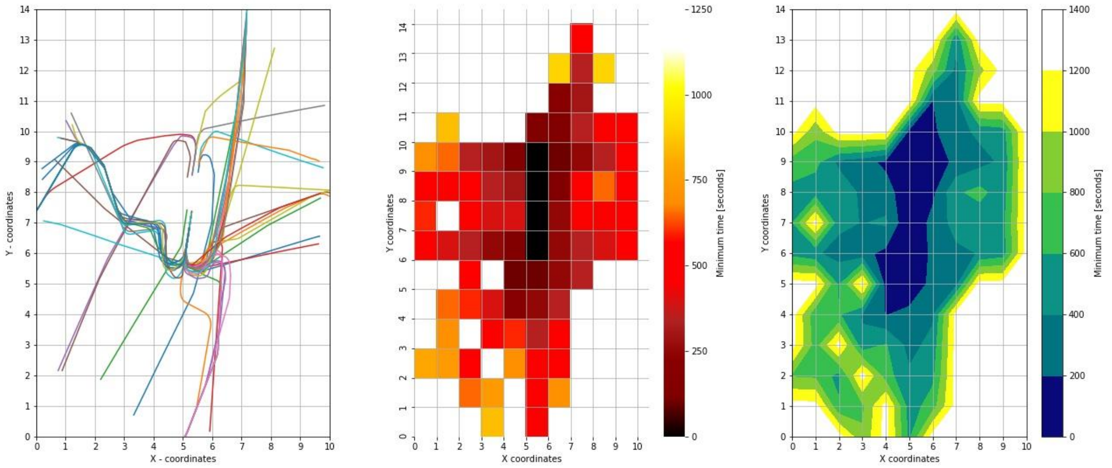


a) b)

Figure 17 – May 16th, 6:00 – 0:00, (total 309 aircraft) - a) Spacing deviation, min = -330s, max = 437s, avg = 8.61, std = 79.76, 90th quantile width = 553.59 b) Sequence pressure, window size = 120s, min = 1, max = 3, avg = 1.21, std = 0.45

4.2.3. Night-time operations

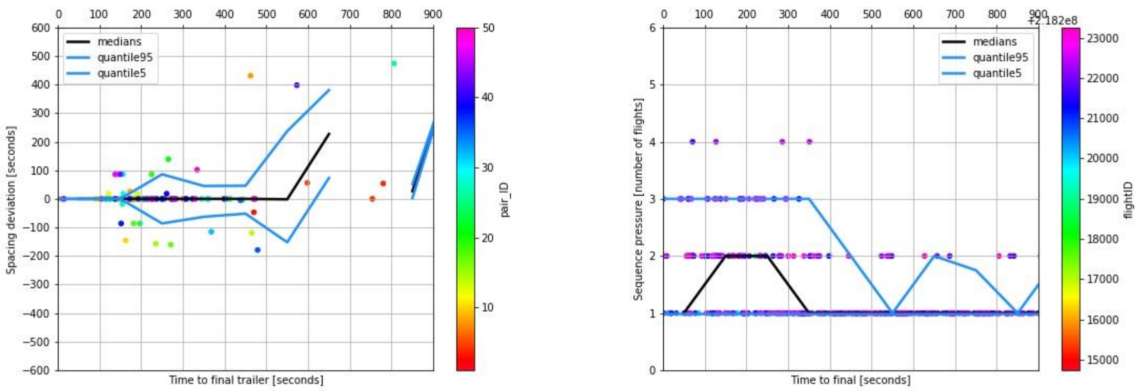
Night-time operations are operations from 0:00 midnight and 6:00 in the morning. The total amount of flights landed on the Stockholm Arlanda airport is 51. In Figure 18a, where flight trajectories are shown, the fact that two runways were used is clearly visible. Figures 18b and 18c illustrate the minimum time to final visualisation and do not indicate any delays or holdings of aircraft. What is interesting is the fact that the maximum value of the minimum time to final is for night-time operations higher than for the day-time operations even if fewer aircraft landed.



a) b) c)

Figure 18 – May 16th, 0:00 – 6:00, (total 51 aircraft), min = 0s, max = 924s, avg = 425s, std = 219s - a) Flight trajectories, b) Heatmap, c) Contour plot

Spacing deviation in Figure 19a does not show median and quantile values between 850 and 650 seconds to final which could be caused with no data for this plot. In Figure 19b we demonstrate the sequence pressure calculation with 120 seconds time window. The sequence pressure plot has the maximum value of four aircraft which is quite high for such a smooth spacing deviation. Because the sequence pressure of four is a high value for night-time operations and represents outliers, we are going to investigate this situation further.



a) b)

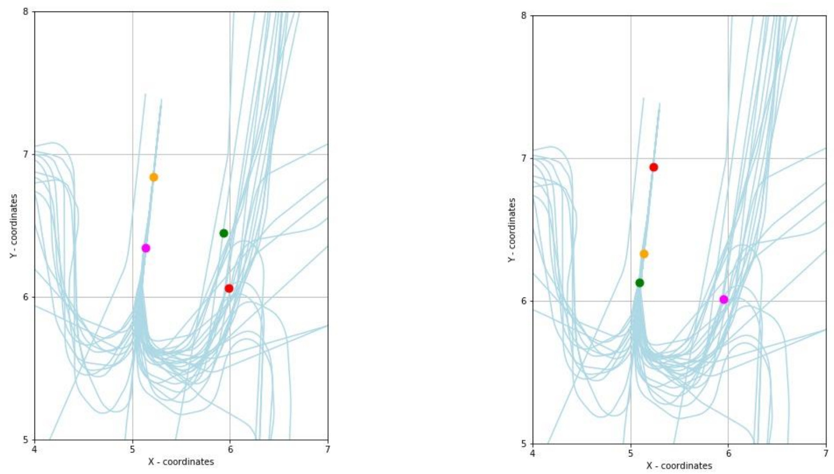
Figure 19 – May 16th, 0:00 – 6:00, (total 51 aircraft)- a) Spacing deviation, min = -179s, max = 474s, avg = 8.89, std = 88.99, 90th quantile width = 389.05, b) Sequence pressure, window size = 120s, min = 1, max = 4, avg = 1.33, std = 0.62

4.2.3.1. *Investigation of an outlier in sequence pressure results*

Since the sequence pressure plot in Figure 19b illustrates sequence pressure for night-time operations, the sequence pressure value of four aircraft is unexpectedly high. Such a high sequence pressure indicates a potential separation problem during this time interval. Totally, the sequence pressure of four occurred four times. Next, we investigate these situations.

Figure 20a illustrates how we calculated the sequence pressure for aircraft with flight ID 218221716 in the time window between 5:19:02 and 5:21:02. The orange dot stands for aircraft with flight ID 218221716, the red one for 218221369, the green one for 218221611, and the magenta for 218221954. We observe that all four aircraft were located within one grid cell during a time window of 120 seconds.

Similarly, Figure 20b illustrates the situation for aircraft with flight ID 218222252 which happened in a time window between 5:54:57 and 5:56:57 in the morning. The orange dot illustrates aircraft with flight ID 218222252, the red dot illustrates 218222739, the green one 218222252, and the magenta 218222443. The aircraft represented by magenta dot could be considered as non-problematic since turning with a safety radius and thus path extension is needed. The red aircraft is already landed, but the locations for the orange and green aircraft indicate a potential separation problem.



a) b)

Figure 20 - May 16th, 0:00 – 6:00, (total 51 aircraft) – a) Sequence pressure for 218221716 (time 5:20:02), b) Sequence pressure for 218222252 (time 5:55:57)

Both figures below show a high value of sequence pressure calculation for aircraft with flight ID 218222443 with a difference in the timestamp. Figure 21a occurred in the time window between 5:54:34 and 5:56:34 in the morning. The orange dot in the figure illustrates aircraft with flight ID 218222443, the red dot illustrates 218222252, the green one 218222739, and magenta 218222170. The red and the magenta aircraft are very close to each other which represents a potential separation problem. Figure 21b shows the situation calculated for the time window between 5:56:04 and 5:58:04. The orange dot in Figure 21b illustrates aircraft with flight ID 218222443, the red dot illustrates 218222170, the green one 218222873, and magenta 218223219. In conclusion, all the four cases where aircraft share the same grid cell within a small time window of 120 seconds, and with the cell side size of 6 nautical miles, it may indicate a separation problem, leading to a safety violation.

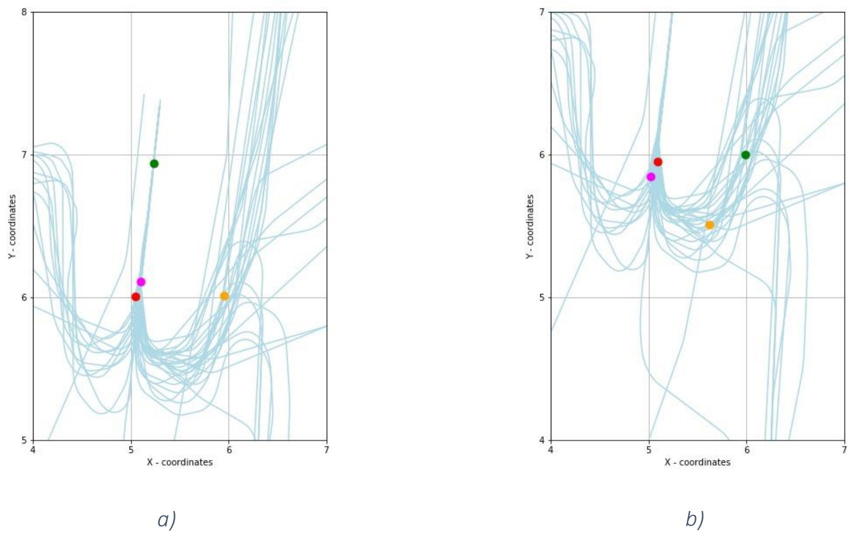


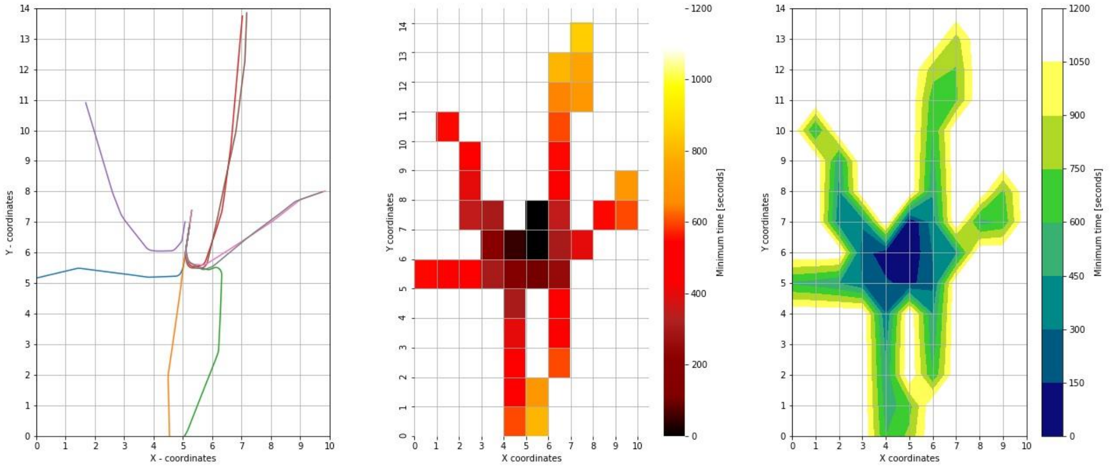
Figure 21 - May 16th, 0:00 – 6:00, (total 51 aircraft) – a) Sequence pressure for 218222443 (time 5:55:34), b) Sequence pressure for 218222443 (time 5:57:04)

4.3. The least busy day of the year 2018

The least busy day of the year 2018 was on December 29th where only 73 aircraft landed at Stockholm Arlanda airport. In comparison with the busiest day of the year 2018 when 352 aircraft landed it is almost five times lower value.

4.3.1. The busiest hour

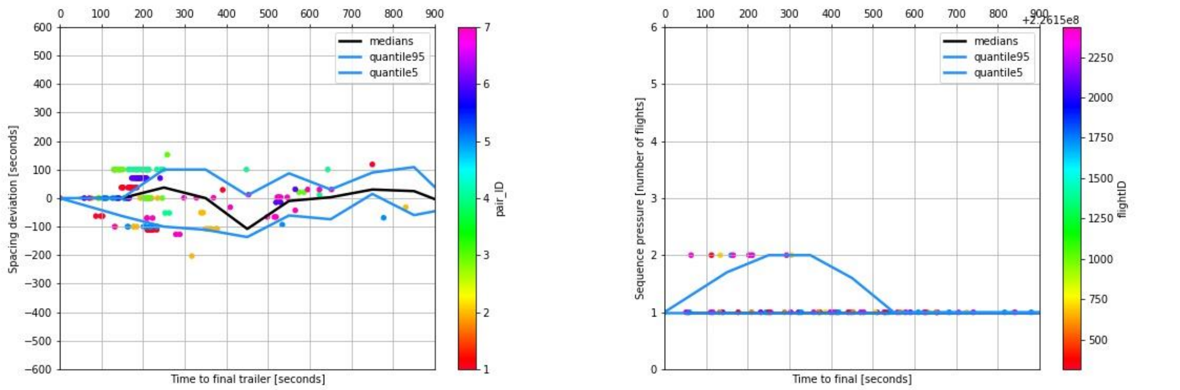
During the day December 29th there was more than one hour with maximum flights per hour. These hours are between 7:00 and 8:00, 11:00 – 12:00 and 17:00 – 18:00. We demonstrate the 11:00 – 12:00 time interval since the results are the most informative. Only eight flights arrived at Arlanda airport during this time. Figure 22a illustrates the flight trajectories for this data subset. Figures 22b and 22c show the minimum time to final visualization. The values of minimum time to final are the smallest from this analysis. The values of the minimum time to final are gradually decreasing from the entry points towards the cell with the final point. Higher values of the minimum time to final can be seen from the southern and the northern entry point. Unexpectedly, the minimum time to final values for the eastern entry point are also higher even though the flight trajectory is shorter. The minimum time values from the western and north-western direction are lower.



a) *b)* *c)*

Figure 22 – December 29th, 11:00 – 12:00, (total 8 aircraft), min = 0s, max = 836s, avg = 456s, std = 215s, a) Flight trajectories, b) Heatmap, c) Contour plot

The spacing deviation is demonstrated in Figure 23a, the spacing deviation for this data subset has very low dispersion. The minimum and the maximum values are close to 200 seconds which is one of the smallest deviations from the analysis. The values of the minimum and maximum deviation are usually between 300 and 400 seconds for other data subsets. We present the sequence pressure illustration in Figure 23b. The maximum sequence pressure reaches two as well as the quantile and median curves. Such small values point up low traffic density in this data subset.

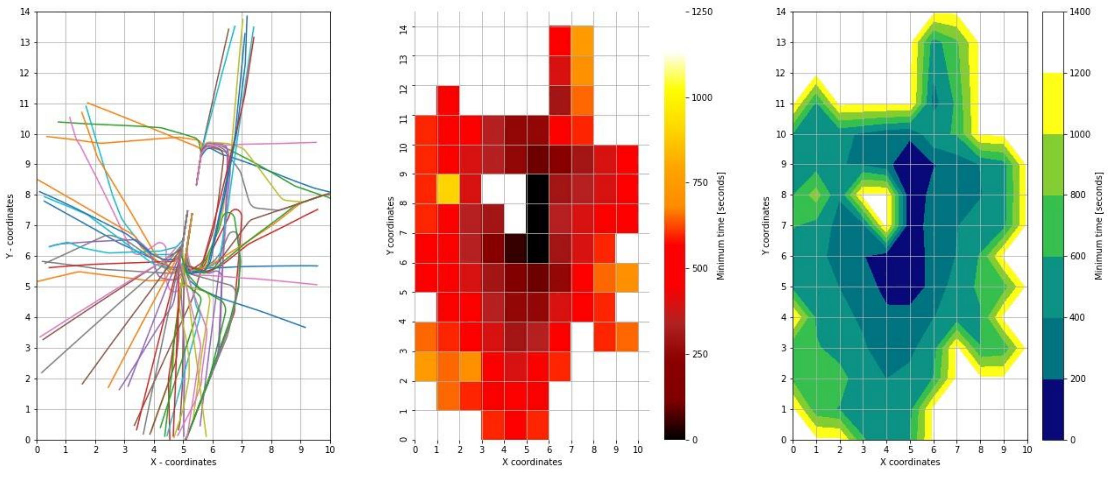


a) *b)*

Figure 23 – December 29th, 11:00 – 12:00, (total 8 aircraft) - a) Spacing deviation, min = -203s, max = 152s, avg = 0.62, std = 73.18, 90th quantile width = 211, b) Sequence pressure, window size = 120s, min = 1, max = 2, avg = 1.15, std = 0.36

4.3.2. Day-time operations

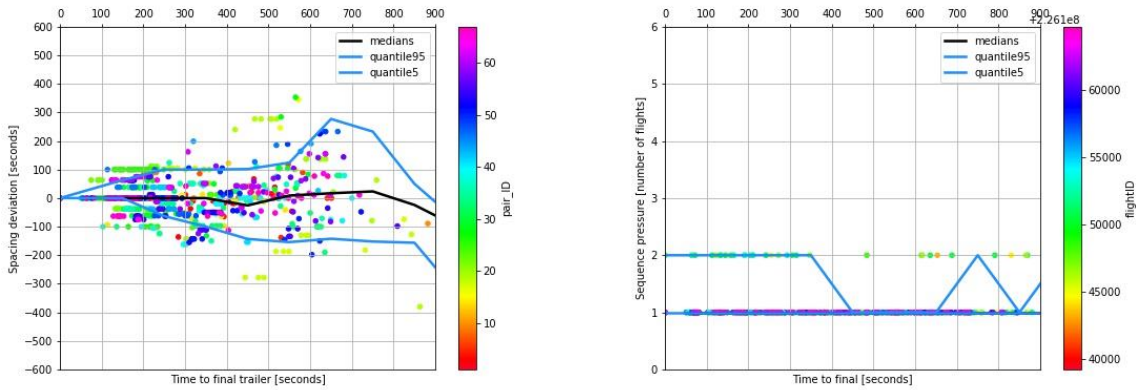
During day-time operations for the 29th of December, only 68 aircraft landed at the Stockholm Arlanda airport. The number of flights in this day-time data subset is the smallest one over our analysis. Flight trajectories are presented in Figure 24a. Aircraft landed during this data subset on two different runways which could cause low sequence pressure on the runway. A number of various directions and flight trajectories were taken during this data subset which is uncommon. The fact that only a few aircraft arrived could cause different flight trajectories since the air space was less dense and less traffic control was needed. Figures 24b and 24c shows minimum time to finals to final. The values of the minimum time to final are decreasing gradually towards the cell containing the final point.



a) b) c)

Figure 24 – December 29th, 6:00 – 0:00, (total 68 aircraft), min = 0s, max = 882s, avg = 444s, std = 178s - a) Flight trajectories, b) Heatmap, c) Contour plot

We show the spacing deviation in Figure 25a. Higher dispersion of spacing deviation values can be seen around 700 seconds to final, then it narrows quickly. Around 500 seconds to final there is only half the dispersion, from approximately 150 seconds to final 90% confidence interval stays around zero deviation. Figure 25b shows the sequence pressure with time window 120 seconds for this data subset. The maximum value reaches the sequence pressure of two, but the median value stays at one. Such a low sequence pressure can be caused by the usage of two runways as we anticipated above.

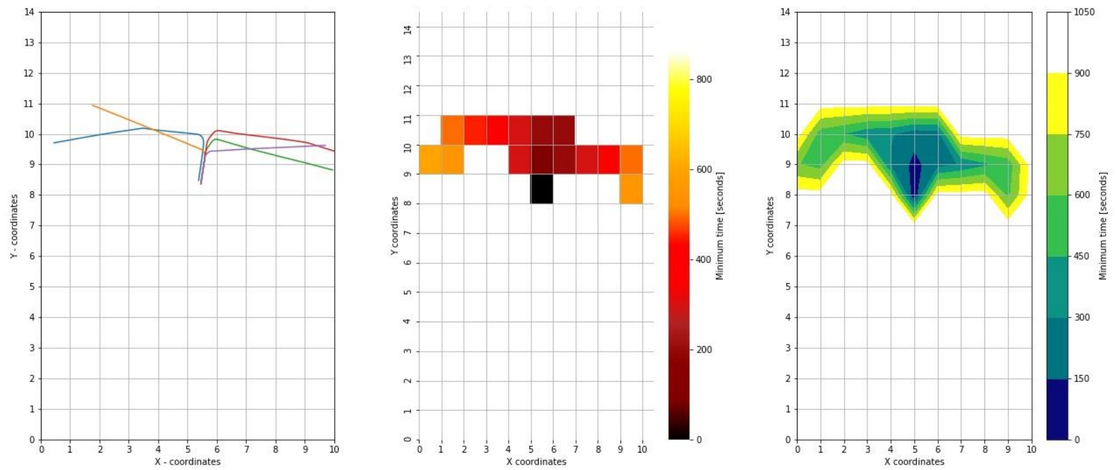


a) b)

Figure 25 – December 29th, 6:00 – 0:00, (total 68 aircraft) - a) Spacing deviation, min = -380s, max = 353s, avg = 3.29, std = 69.37, 90th quantile width = 419.2, b) Sequence pressure, window size = 120s, min = 1, max = 2, avg = 1.07, std = 0.25

4.3.3. Night-time operations

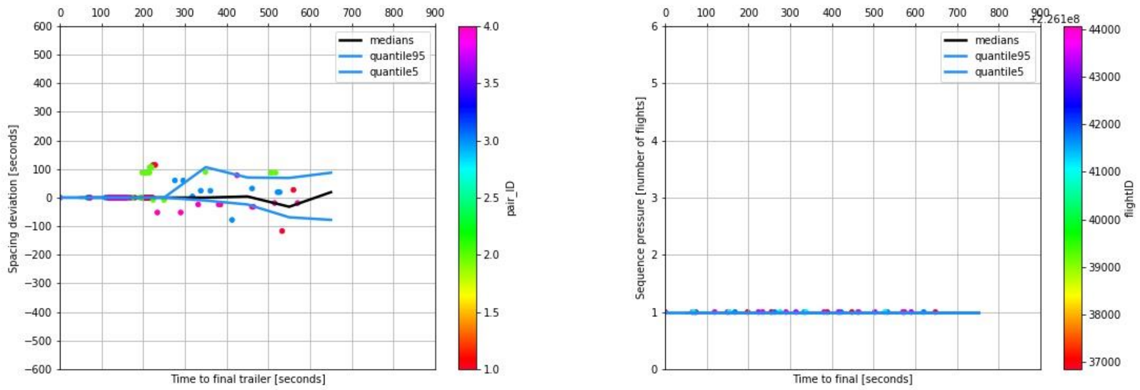
Night-time operations on the 29th of December served only to five arriving aircraft. We present flight trajectories from these flights in Figure 26a. Figures 26b and 26c illustrate minimum time to final for these flights. This data subset is very poor in records, but still gives important information about the spacing techniques at Stockholm Arlanda airport. The maximum value of minimum time to final, 610 seconds, is the smallest value in this whole analysis. From the flight, trajectory plot is clear that aircraft flew straight to the runway without any path extensions.



a) *b)* *c)*

Figure 26 – December 29th, 0:00 – 6:00, (total 5 aircraft), min = 0s, max = 610s, avg = 349s, std = 175s - a) Flight trajectories, b) Heatmap, c) Contour plot

We present spacing deviation in Figure 27a; the spacing deviation plot starts approximately around 650 seconds to final which is not an error. The later start of calculation is caused by the fact that the maximum value of the minimum time to final is 610 seconds and no records for a higher minimum time to final are present. This fact points up to a very low traffic density during night-time operations on December 29th. The 90th quantile width is also very low for this data subset. The sequence pressure is shown in Figure 27b, the maximum value of the sequence pressure is pressure of one aircraft for the runway. This fact indicates low traffic density as well.



a) *b)*

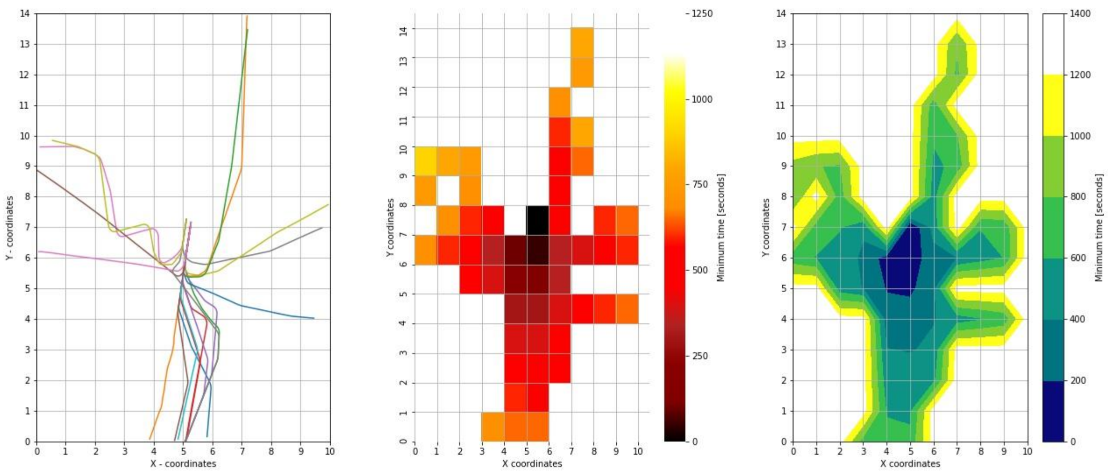
Figure 27 – December 29th, 0:00 – 6:00, (total 5 aircraft) - a) Spacing deviation, min = -117s, max = 114s, avg = 12.64, std = 37.79, 90th quantile width = 164.8, b) Sequence pressure, window size = 120s, min = 1, max = 1, avg = 1, std = 0

4.4. Day with heavy delays

For further analysis, we include also the day with heavy delays from the year 2018. The day with heavy delays is February 26th when only 217 aircraft in total arrived at Stockholm Arlanda airport, but heavy delays were observed.

4.4.1. The busiest hour

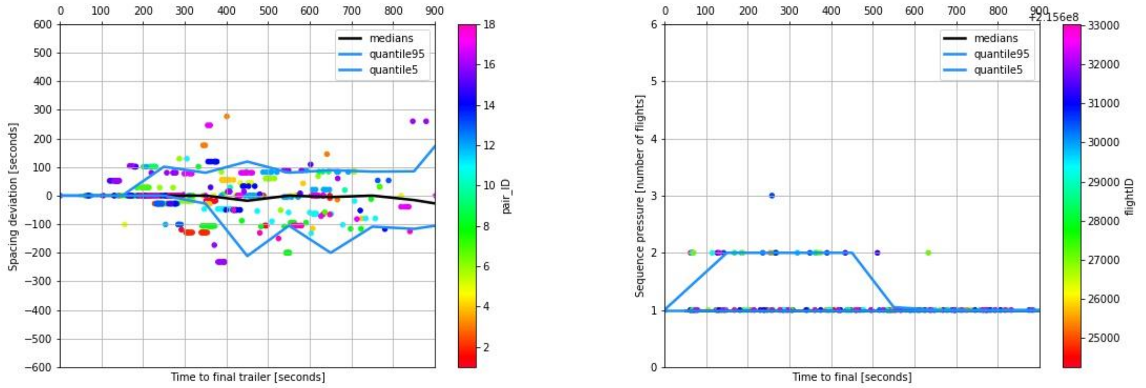
Most aircraft landed at Stockholm Arlanda airport on February 26th between 20:00 and 21:00 which is an uncommon time to observe the busiest hour in comparison with other data subsets. Most of the other data subsets presented in this project had the busiest hour in the morning. The fact that the busiest hour is such late could be caused by heavy delays earlier that day which lessen the capacity of an airport and calming of the situation with higher capacity. In Figure 28a flight trajectories are shown, a total of 19 aircraft landed at Arlanda airport during this hour. Flight trajectory plot does not indicate any significant path extensions which prove our hypothesis. Figures 28b and 28c are heatmap and contour plot for the minimum time to final from each cell. These figures do not indicate high values which indicate no congestion. Higher values of the minimum time to final are seen at the western entry point.



a) b) c)

Figure 28 – February 26th, 20:00 – 21:00, (total 19 aircraft), min = 0s, max = 924s, avg = 521s, std = 201s - a) Flight trajectories, b) Heatmap, c) Contour plot

Figure 29a demonstrates the spacing deviation for this data subset. The spacing deviation is quite narrow for this example and does not indicates problems in air traffic control. Figure 29b illustrates the sequence pressure with the time window of 120 seconds. The maximum value of sequence pressure reaches two aircraft which is very low pressure on the runway.

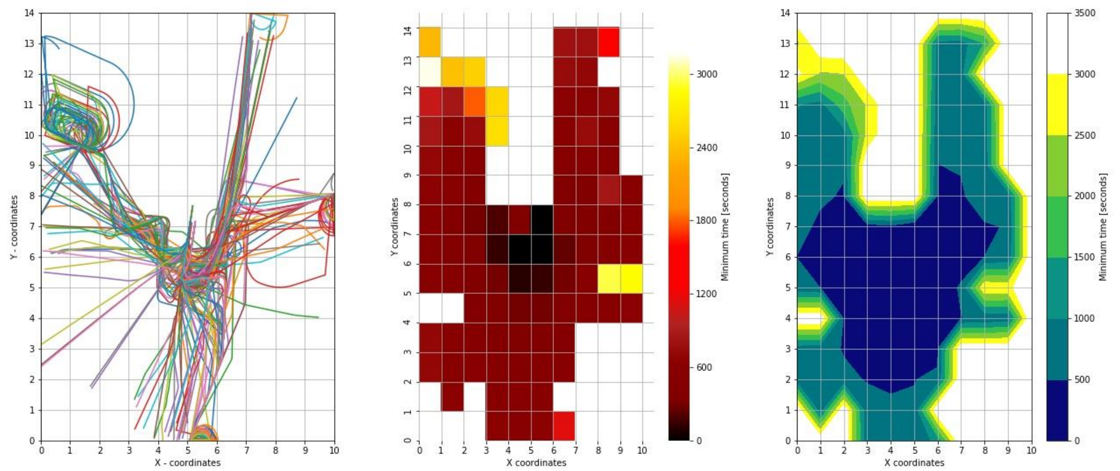


a) b)

Figure 29 – February 26th, 20:00 – 21:00, (total 19 aircraft) - a) Spacing deviation, min = -232s, max = 277s, avg = -4.91, std = 67.2, 90th quantile width = 330.35, b) Sequence pressure, window size = 120s, min = 1, max = 3, avg = 1.16, std = 0.38

4.4.2. Day-time operations

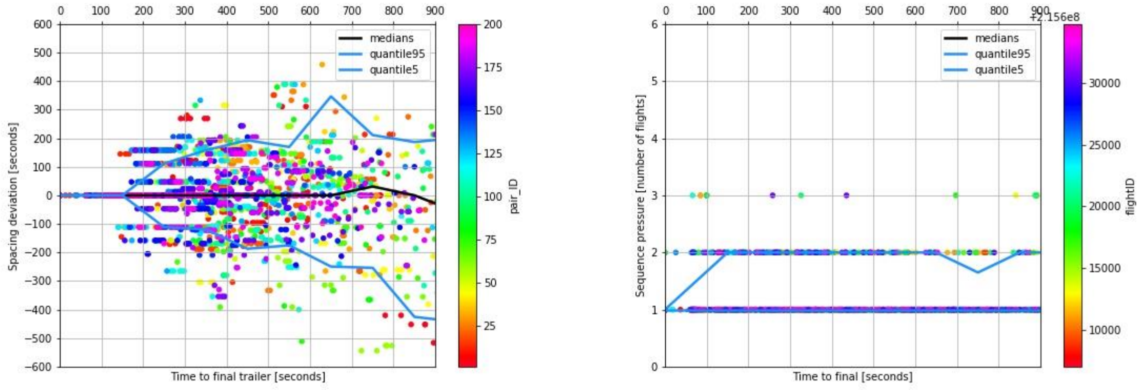
During day-time operations on February 29th a total of 201 aircraft landed at Stockholm Arlanda airport. Figure 30a illustrates flight trajectories, a lot of path extensions in the form of rounds and curves can be seen in this figure. These path extensions could cause very heavy delays during the day. Figures 30b and 30c shows the minimum time to final with the maximum value of 3142 seconds. The maximum value of 3142 seconds for the minimum time to final is an exceptionally high value which is almost three times higher than the usual maximum value of the minimum time to final which is around 1000 seconds to final. Also, the standard deviation for the minimum time to final is exceptionally high with value 650 seconds. Such a high value of standard deviation points out to high differences of total times flown for different flights.



a) b) c)

Figure 30 – February 26th, 6:00 – 0:00, (total 201 aircraft), min = 0s, max = 3142s, avg = 718s, std = 650s - a) Flight trajectories, b) Heatmap, c) Contour plot

Figure 31a demonstrates spacing deviation for day-time operations on the 26th of February. Spacing deviation has a high dispersion of values, but 90% confidence interval curves indicate that most of the high deviation values are outliers. The higher spacing deviation occurs around 750 seconds to final when at around 500 seconds to final the value halves. In Figure 31b sequence pressure is shown. The maximum value of sequence pressure reaches three which is a very low value for such a high traffic density.

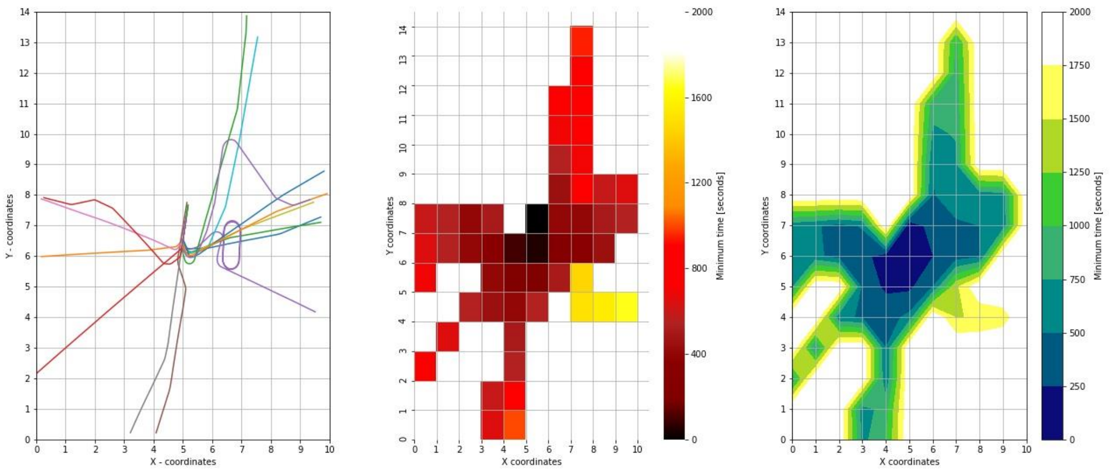


a) b)

Figure 31 – February 26th, 6:00 – 0:00, (total 201 aircraft) - a) Spacing deviation, min = -544s, max = 458s, avg = 1.21, std = 109.89, 90th quantile width = 612.05, b) Sequence pressure, window size = 120s, min = 1, max = 3, avg = 1.13, std = 0.36

4.4.3. Night-time operations

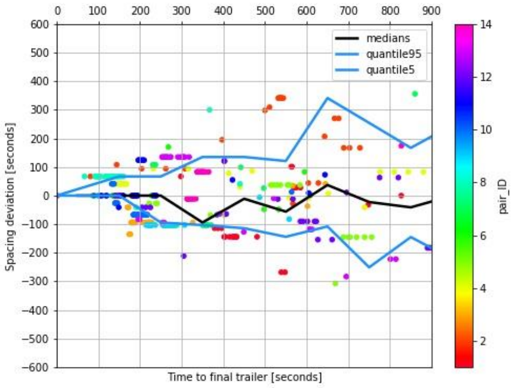
During night-time operations on February 26th a total of 15 aircraft arrived at Stockholm Arlanda airport. In Figure 32a the flight trajectories for night-time operations are illustrated. Minor holds of flights can be seen in the figure which is unusual for night-time operations and probably is a result of severe weather conditions. Figures 32b and 32c illustrate the heatmap and contour plot respectively for the minimum time to final. The violet trajectory with path extension in the form of a circle in Figure 32a causes a high value of the minimum time to final for the corresponding cells, which can be seen on both heatmap and contour plot.



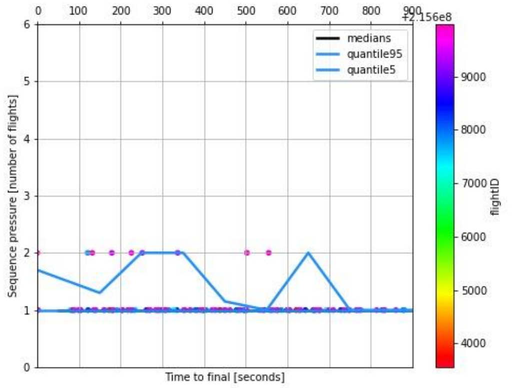
a) b) c)

Figure 32 - February 26th, 00:00 – 06:00, (total 15 aircraft) - min = 0s, max = 1636s, avg = 615s, std = 342s - a) Flight trajectories, b) Heatmap, c) Contour plot

Figure 33a demonstrates the spacing deviation for this data subset. The wider spread of confidence interval curves can be seen around 650 seconds to final. The spread almost halves at approximately 550 seconds to final. Figure 33b shows sequence pressure for night-time operations. The maximum sequence pressure for this data subset is two aircraft which is expected value for the night-time operations.



a)

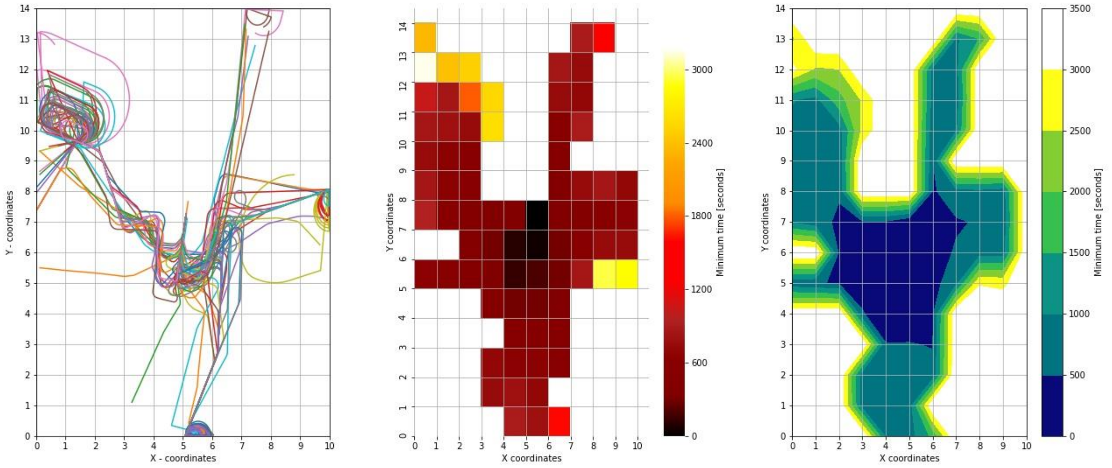


b)

Figure 33- February 26th, 00:00 – 06:00, (total 15 aircraft) - a) Spacing deviation, min = -307s, max = 356s, avg = 0.61, std = 112.06, 90th quantile width = 505 b) Sequence pressure, window size = 120s, min = 1, max = 2, avg = 1.07, std = 0.25

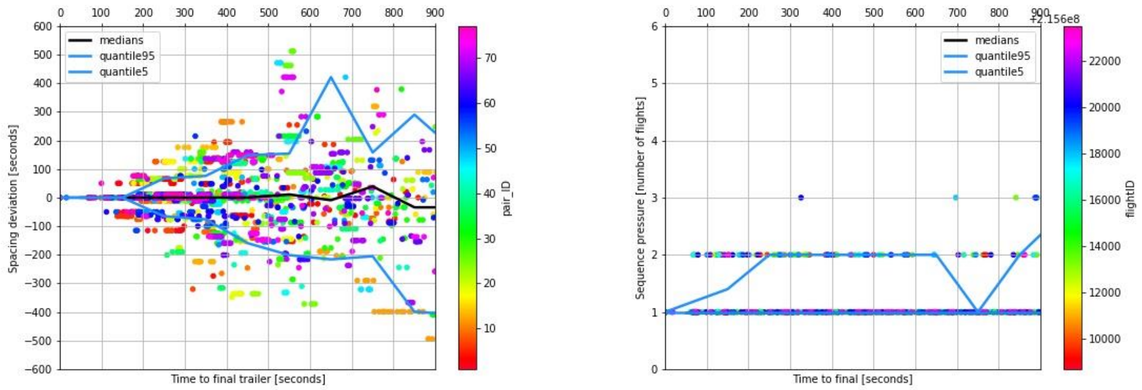
4.4.4. The period with heavy delays

For further analysis, we consider also the period when the heavy delays happened during the day of the 26th of February. According to our research, the period with heavy delays had a gradual start from 10:00 in the morning and last until 16:00 in the afternoon. The heaviest delays happened between 12:00 and 15:00 in the afternoon. For analysis of this period, we extracted data subset which starts at 10:00 in the morning and ends at 16:00 in the afternoon. During this period 80 aircraft arrived at Stockholm Arlanda airport. In Figure 34a, flight trajectories are illustrated. In the flight trajectory plot, multiple holding patterns were observed in both forms, extended curves, and circles. Figures 34b and 34c demonstrate minimum time to final visualization in the form of heatmap and contour plot respectively. Large values of minimum time to finals to final can be seen from multiple cells which are caused by the heavy delays during this time interval. In the heatmap is clearly seen, that the highest values of minimum time to final can be seen from the south-west direction and also from the east.



a) b) c)

Figure 34 - February 26th, 10:00 – 16:00, (total 80 aircraft) - min = 0s, max = 3142s, avg = 847s, std = 702s - a) Flight trajectories, b) Heatmap, c) Contour plot



a) b)

Figure 35 - February 26th, 10:00 – 16:00, (total 80 aircraft) - a) Spacing deviation, min = -494s, max = 512s, avg = 0.26, std = 117.0, 90th quantile width = 689 b) Sequence pressure, window size = 120s, min = 1, max = 3, avg = 1.14, std = 0.38

Figure 35a illustrates the spacing deviation for this data subset. The spacing deviation values have very large spread, with 90th quantile width 689 which is an exceptionally high value for a quantile width in comparison with other data subsets included in this project. The dispersion of values is getting smaller around approximately 550 seconds to final and getting to zero in approximately 150 seconds to final. Figure 35b demonstrates sequence pressure for this period with heavy delays. Surprisingly, the sequence pressure close to the runway is not very high with the maximum value of three aircraft and the maximum confidence interval of two aircraft. From Figure 32a with flight trajectories can be seen that the path extensions of flights are maintained close to entry points to the TMA which could cause that traffic close to the runway is already calmed by it. Another explanation of such a low sequence pressure close to the runway could be that a total amount of 80 aircraft arriving during six hours of operations is less than average observed in other data subsets included in this project. And thus, it could be controlled very well with high precision.

4.4.5. The most delayed hour of the day

For further investigation and for a good overview on what exactly was going on during the period with heavy delays, we detected the most delayed hour of the day. The most delayed hour of the day happened between 13:00 and 14:00 in the afternoon on February 26th. During this hour a total of 17 aircraft landed at Stockholm Arlanda airport. Figure 36a shows the flight trajectories, where massive holding patterns and path extensions can be seen. Figures 36b and 36c illustrate the minimum time visualization in the form of heatmap and contour plot respectively. High values of minimum time to final are observed. The most delayed directions are north-west and east.

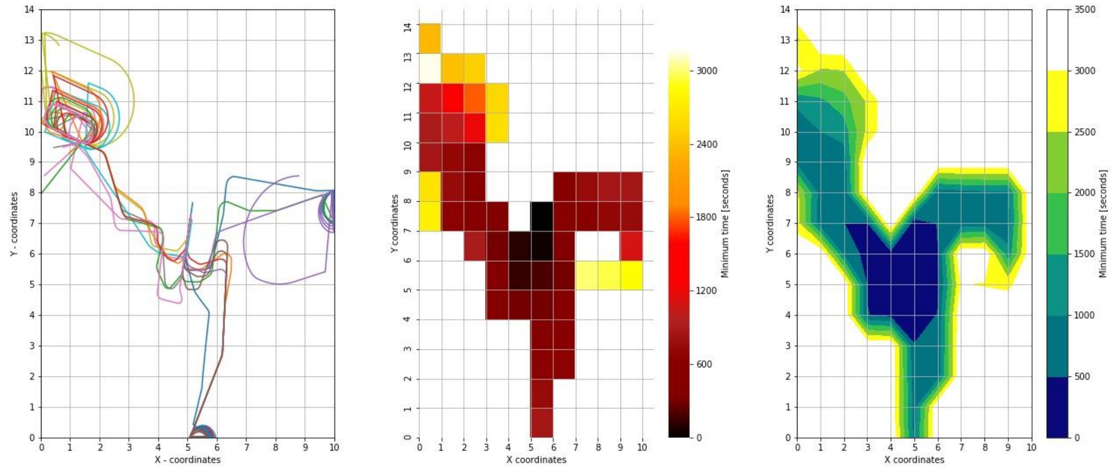


Figure 36 - February 26th, 13:00 – 14:00, (total 17 aircraft) - min = 0s, max = 3142s, avg = 1062s, std = 902s - a) Flight trajectories, b) Heatmap, c) Contour plot

In Figure 37a spacing deviation for this data subset is illustrated. The shape of spacing deviation is a lot spoiled by the high values of minimum time to final. On the contrary, the sequence pressure shown on Figure 37b represents very low sequence pressure on the runway. The low sequence pressure indicates, that despite such heavy delays, the air traffic control effort assured smooth traffic conditions. Also, the fact that the queuing of aircraft and their holding were done close to the entry points assures good separation of aircraft in the TMA closer to the runway.

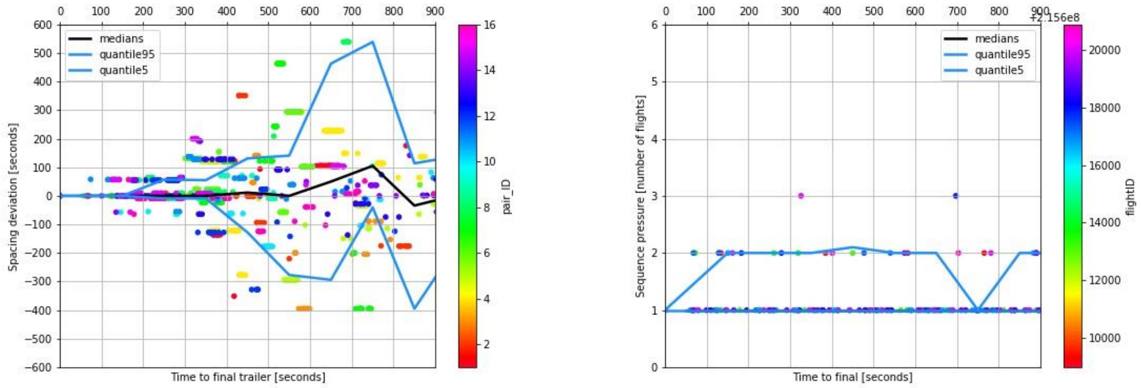


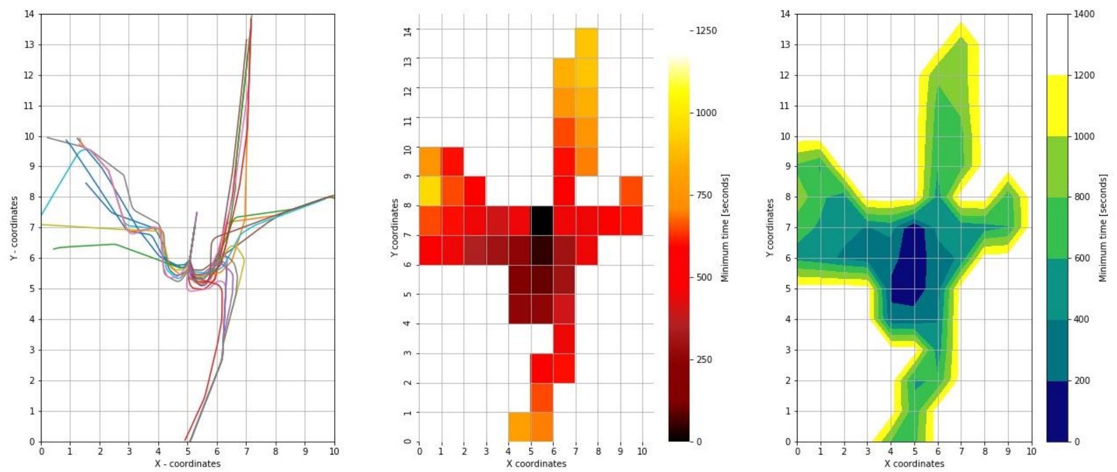
Figure 37 - February 26th, 13:00 – 14:00, (total 17 aircraft) - a) Spacing deviation, min = -395s, max = 539s, avg = 22.47, std = 135.74, 90^{th} quantile width = 757 b) Sequence pressure, window size = 120s, min = 1, max = 3, avg = 1.17, std = 0.41

4.5. Average day of the year 2018

We consider also the day of the year 2018 with an average density of aircraft to assure quality comparison and evaluation of results. The average density of aircraft during the year 2018 is 283 aircraft per day. The closest to average is the day January 29th when 282 aircraft landed at Stockholm Arlanda airport.

4.5.1. The busiest hour

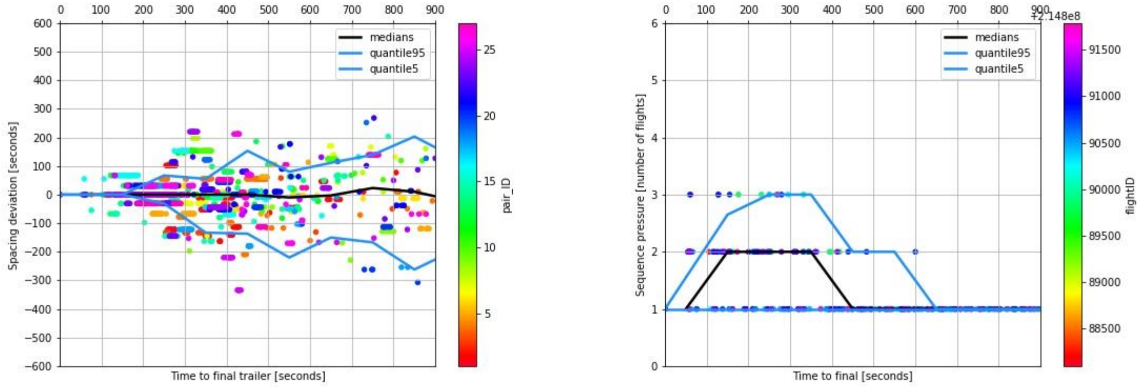
The busiest hour of the day January 29th was between 6:00 and 7:00 in the morning. In total 28 aircraft landed at Arlanda airport during this time. In Figure 38a flight trajectories are demonstrated. Traffic flow looks calm and well controlled. The flight trajectories of aircraft follow a clear pattern which signs well controlled traffic flow. No significant path extensions are visible. Figures 38b and 38c illustrate minimum time to final visualisation. The values of the minimum time to final decreases gradually towards the final point.



a) b) c)

Figure 38 – January 29th, 6:00 – 7:00, (total 28 aircraft), min = 0s, max = 939s, avg = 520s, std = 225s, - a) Flight trajectories, b) Heatmap, c) Contour plot

Figure 39a shows the spacing deviation for this data subset. Figure 39b illustrates the sequence pressure plot. The maximum value of sequence pressure is four aircraft sharing minimum time to final. The sequence pressure of four occurred only once in the whole data subset which suggests that the sequence pressure of four is not a significant value. The quantile curves reach only to maximum sequence pressure of three which is a more reasonable value for such calm traffic conditions. The median curve reaches only to the sequence pressure of two aircraft to runway.

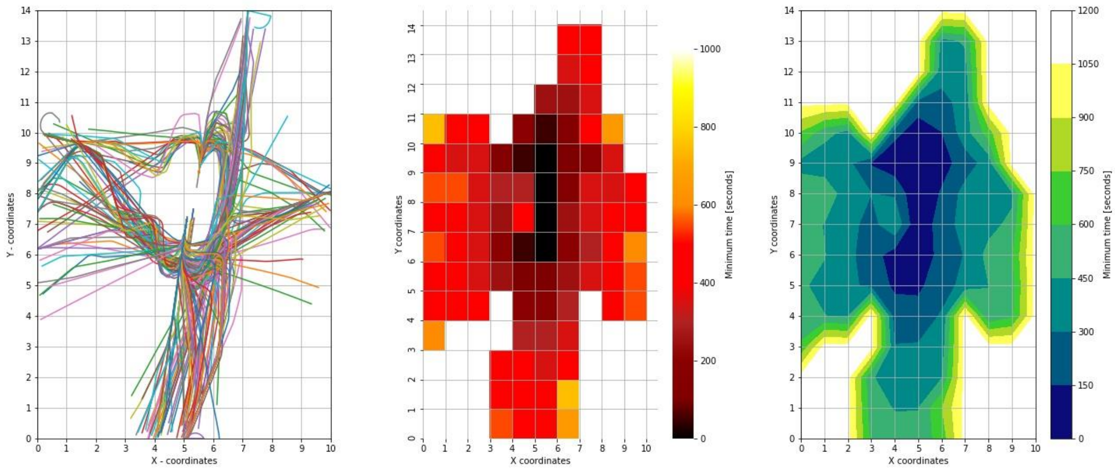


a) *b)*

Figure 39 – January 29th, 6:00 – 7:00, (total 28 aircraft) - a) Spacing deviation- min = -334s, max = 268s, avg = 3.02, std = 71.89, 90th quantile width = 465, b) Sequence pressure- window size = 120s, min = 1, max = 3, avg = 1.34, std = 0.57

4.5.2. Day-time operations

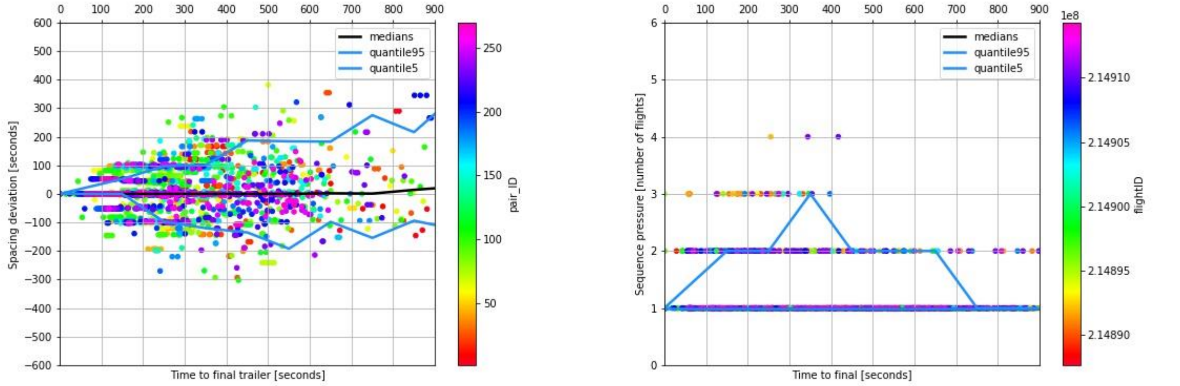
During day-time operations in Stockholm Arlanda airport on 29th of January 271 aircraft landed at the airport. In Figure 40a flight trajectories are illustrated. Two runways were used which is seen from the figure. Figures 40b and 40c illustrate the minimum time to final. The highest value is 885 seconds to final which points out to pretty calm traffic conditions and no significant path extensions.



a) *b)* *c)*

Figure 40 – January 29th, 6:00 – 0:00, (total 271 aircraft), min = 0s, max = 743s, avg = 358s, std = 167s - a) Flight trajectories, b) Heatmap, c) Contour plot

Figure 41a shows the spacing deviation for this data subset. Figure 41b illustrated sequence pressure. The maximum value of sequence pressure is four aircraft, but a 90% confidence interval reaches only three which make the pressure of four aircraft outlier. The median curve stays at the sequence pressure of one aircraft for runway which can be caused by using two runways. Using two runways the traffic demand on the runway is distributed. Because of the high values of sequence pressure, sequence pressure of three aircraft, happened very close to the runway, less than 100 seconds to final, we will investigate this situation further.



a) b)

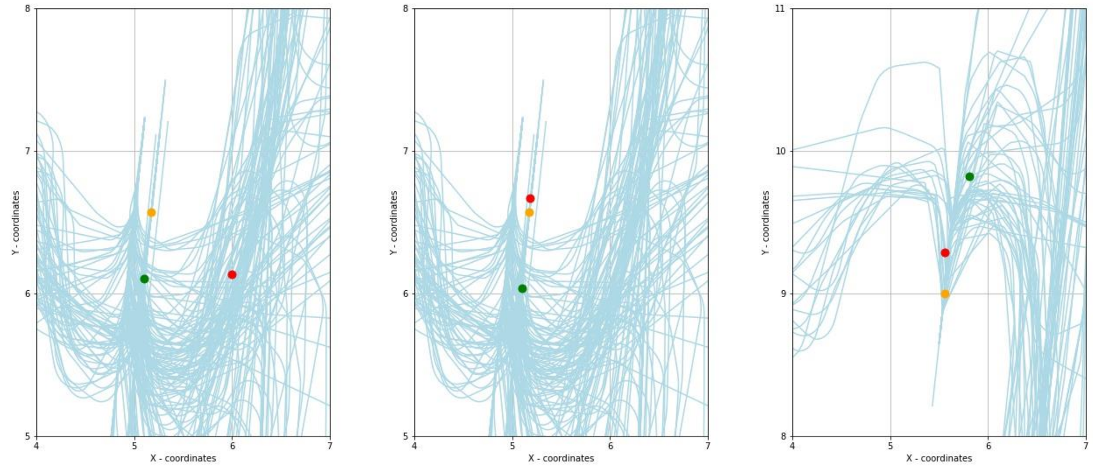
Figure 41 – January 29th, 6:00 – 0:00, (total 271 aircraft) - a) Spacing deviation- min = -302s, max = 382s, avg = 5.67, std = 74.51, 90th quantile width = 429.55, b) Sequence pressure, window size = 120s, min = 1, max = 4, avg = 1.19, std = 0.44

4.5.2.1. Investigation of high sequence pressure close to the runway

The sequence pressure of three aircraft close to the runway could represent potential aircraft separation problem. The sequence pressure of three aircraft occurred three times between 100 and 0 seconds to final. Figures 42a, 42b, and 42c illustrate all of these three situations. In Figure 42a, the high value of sequence pressure happened for aircraft with flight ID 214891029 in a time window between 07:01:18 and 7:04:18. The orange coloured dot illustrates aircraft 214891029, red one illustrates 214890864 and the green one illustrates 214891089. Since two parallel runways were used, one of the possible explanations for the situation could be that the orange and the green aircraft used different runways. Also, the red aircraft had to turn which requires a secure radius and thus extended its path. The figures below illustrate potential separation problems in the arrival spacing at Stockholm Arlanda airport.

Figure 42b illustrates the situation which occurred for aircraft with flight ID 214891738 in a time window between 7:20:45 and 7:22:45. The orange dot stands for aircraft with flight ID 214891738, red for 214890801, and green for 214890801. Since both orange and red aircraft are on the runway and from the data, we know that they share the same altitude, we can assume that both are already landed which would not represent a problem.

Figure 42c shows the situation for the aircraft with flight ID 214895732 in a time window between 9:31:46 and 9:33:46. The orange dot illustrates 214895732, the red one 214895525, and the green one 214895414. The aircraft illustrated by the orange dot is already landed on the runway while the green and red aircraft are approaching and thus indicates potential separation problem.

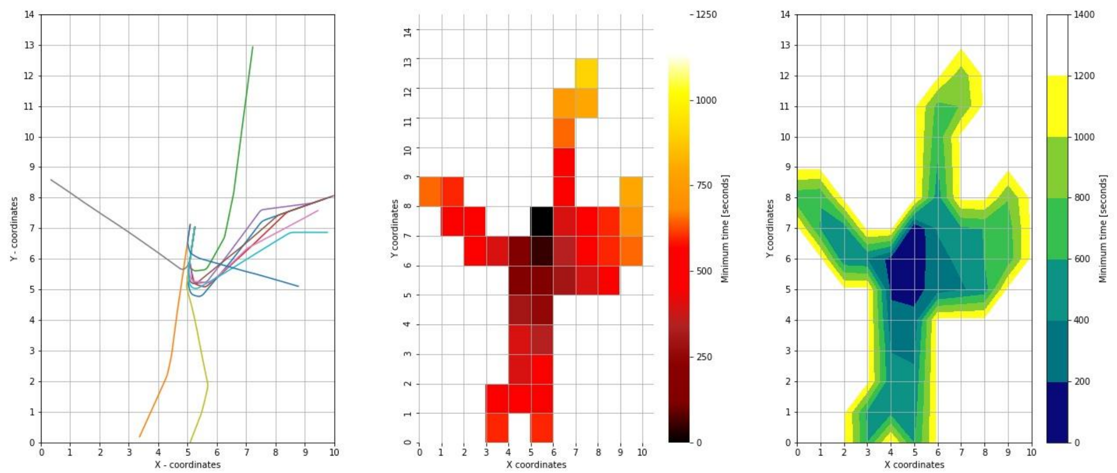


a) *b)* *c)*

Figure 42 – January 29th, 6:00 – 0:00, (total 271 aircraft) – a) Sequence pressure for 214891029 (time 7:02:18), b) Sequence pressure for 214891029 (time 7:21:45). c) Sequence pressure for 214895732 (time 9:32:46)

4.5.3. Night-time operations

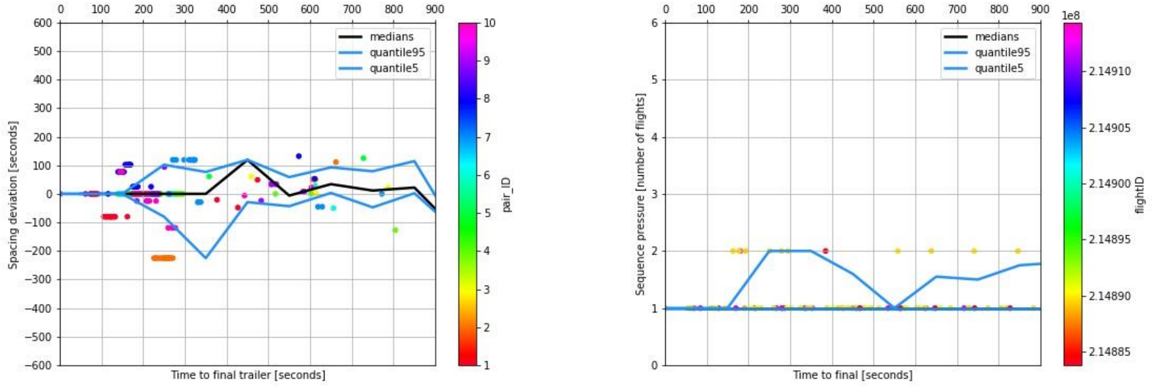
During night-time operations a total of 11 aircraft landed at Stockholm Arlanda airport. The flight trajectory plot is shown in Figure 43a. Only one runway was used, and no significant path extensions are seen. Figures 43b and 43c demonstrate minimum time to final visualisation. Higher values of the minimum time to final can be seen for the northern and eastern entry point and lower for the southern and western entry point.



a) *b)* *c)*

Figure 43 – January 29th, 0:00 – 6:00, (total 11 aircraft), min = 0s, max = 883s, avg = 472s, std = 205s - a) Flight trajectories, b) Heatmap, c) Contour plot

In Figure 44a spacing deviation can be seen. Spacing deviation for this data subset is very narrow and indicates very calm traffic during night-time operations on January 29th. Sequence pressure is illustrated in Figure 44b. The maximum value of sequence the pressure reaches pressure of 2 but quantile nor median curves reach such value.



a) *b)*

Figure 44 – January 29th, 0:00 – 6:00, (total 11 aircraft - a) Spacing deviation- min = -225s, max = 132s, avg = 7.39, std = 78.02, 90th quantile width = 301.75, b) Sequence pressure- window size = 120s, min = 1, max = 2, avg = 1.13, std = 0.34

5. Discussions

In this chapter, the results will be discussed. For a better view of the results, we summarize all the resulting statistics in tables. First, we present the minimum time to final results in Table 3 below, where abbreviations *Avg* means average, *Std* standard deviation, and *Aircraft* column stands for the number of aircraft which arrived at Stockholm Arlanda airport during the given time interval. The first observation is that there is low correlation between the number of flights arriving to the airport and the maximum value of minimum time to final. For example, for the busiest day of the year, 16th of May, during day-time operations 309 aircraft arrived but the maximum value of minimum time to final is only 853 seconds and during the day with heavy delays, the 26th of February, day-time operations operated only 201 arriving aircraft but the maximum value of minimum time to final was 3142 seconds. In this example, the number of arriving aircraft for the 26th of February day-time data subset is approximately less by a third of the number of arriving aircraft for the 16th of May day-time data subset. Although the number of arriving aircraft is lower, the maximum value of minimum time to final for the 26th of February is more than three times higher which indicates heavy delays. Maximum values of minimum time to final are close to 1000 seconds for most of the data subsets with the only exception for the day with heavy delays data subset. Average values of minimum time to final stays around 500 seconds with an exception for the day with heavy delays data subsets. In comparison with maximum value, where the value increased more than three times for this data subset, the average values are calmer since the values for the 26th of February data subset risen only about approximately half. Standard deviation values for the minimum time to final follow the same pattern but the values for the day with heavy delays are again exceptionally high since the values are almost three times higher than the standard deviation values for other data subsets.

Table 3 - Statistics for minimum time to final

Day	Date	Data subset	Time	Aircraft	Min [s]	Max [s]	Avg [s]	Std [s]
High traffic	12th of April	The busiest hour	5:00 – 6:00	29	0	932	508	228
		Day-time	6:00 – 0:00	305	0	1451	463	258
		Night-time	0:00 – 6:00	47	0	932	491	198
The busiest	16th of May	The busiest hour	5:00 – 6:00	32	0	924	532	245
		Day-time	6:00 – 0:00	309	0	853	358	190
		Night-time	0:00 – 6:00	51	0	924	425	219
The least busy	29th of December	The busiest hour	11:00 – 12:00	8	0	836	456	215
		Day-time	6:00 – 0:00	68	0	882	444	178
		Night-time	0:00 – 6:00	5	0	610	349	175
Heavy delays	26th of February	The busiest hour	20:00 – 21:00	19	0	924	521	201
		Day-time	6:00 – 0:00	201	0	3142	718	650
		Night-time	0:00 – 6:00	15	0	1636	615	342
		Delayed period	10:00 – 16:00	80	0	3142	847	702
		Most delayed hour	13:00 – 14:00	17	0	3142	1062	902
Average	29th of January	The busiest hour	6:00 – 7:00	28	0	939	520	225
		Day-time	6:00 – 0:00	271	0	743	358	167
		Night-time	0:00 – 6:00	11	0	883	472	205

We present statistics for spacing deviation for all data subsets in Table 4 below. Instead of comparing minimum and maximum values of the spacing deviation, we use the 90th quantile width variable which indicates the maximum spread of values in the calculation within the 90th confidence interval curves. The values of a 90th quantile width variable are usually between 300 to 500. The data subset for February 26th indicates an exceptional value of 90th quantile width only for the period with heavy delays data subset which is almost three times higher than the rest of the values. The average values of spacing deviation are between 0 seconds and 15 seconds. Smaller average values indicated well controlled air traffic in the terminal manoeuvring area. Higher values could indicate worse controlling of air traffic or lack of aircraft to utilize spacing techniques for arriving aircraft. Since the higher values of average usually appear for night-time operations, the reason is most likely a lower number of arriving aircraft. Standard deviation values for spacing deviation are between 70 and 80 seconds. The only exceptional values are for the day with heavy delays.

Table 4 - Statistics for spacing deviation

Day	Date	Data subset	Time	Min [s]	Max [s]	Avg [s]	Std [s]	90th quantile width
High traffic	12th of April	The busiest hour	5:00 – 6:00	-412	369	0.15	81.32	378
		Day-time	6:00 – 0:00	-596	364	0.17	81.94	392
		Night-time	0:00 – 6:00	-419	237	13.25	81.26	454
The busiest	16th of May	The busiest hour	5:00 – 6:00	-333	333	9.82	85.6	385.35
		Day-time	6:00 – 0:00	-330	437	8.61	79.76	553.59
		Night-time	0:00 – 6:00	-179	474	8.89	88.99	389.05
The least busy	29th of December	The busiest hour	11:00 – 12:00	-203	152	0.62	73.18	211
		Day-time	6:00 – 0:00	-380	353	3.29	69.37	419.2
		Night-time	0:00 – 6:00	-117	114	12.64	37.79	164.8
Heavy delays	26th of February	The busiest hour	20:00 – 21:00	-232	277	4.91	67.2	330.35
		Day-time	6:00 – 0:00	-544	458	1.21	109.89	612.05
		Night-time	0:00 – 6:00	-307	356	0.61	112.06	505
		Delayed period	10:00 – 16:00	-645	512	6.3	128.12	935
		Most delayed hour	13:00 – 14:00	-395	539	22.47	135.74	757
Average	29th of January	The busiest hour	6:00 – 7:00	-334	268	3.02	71.89	465
		Day-time	6:00 – 0:00	-302	382	5.67	74.51	429.55
		Night-time	0:00 – 6:00	-225	132	7.39	78.02	301.75

Lastly, Table 5 below shows the statistics for sequence pressure calculation among all data subsets in our analysis. We chose window size 120 seconds to compare the results for different datasets. For comparison between the different window sizes, we present the sequence pressure results for window sizes of 90, and 240 seconds for the busiest day, 16th of May, for data subset of the busiest hour. From the values can be seen that window sizes of 120 and 90 seconds do not differ much, but a significant difference can be seen for the window size of 240 seconds. The similarity between the results for window sizes of 90 and 120 seconds can be explained by the fact that the minimum allowable time separation on the runway is 1,5 minutes, thus 90 seconds, in high traffic and the desired value is 2 minutes, thus 120 seconds, in normal operation. The maximum value of sequence pressure is 5 for the 240 seconds window size and 4 for 90, and 120 seconds. A large difference can also be seen in the standard deviation since window sizes of 90- and 120-seconds values are around 0.7, value for a window size of 240 seconds is almost twice as much. Overall the maximum values of sequence pressure in the table culminates around three to four aircraft sharing the same minimum time to final with the only exception for the least busy day, the 29th of December, data subset. The maximum sequence pressure on the runway is two aircraft for the 29th of December. Average values stay around 1.3 aircraft with no exceptional peaks. Standard deviation values for sequence pressure are below one for all data subsets with the exception of the large window size for the 16th of May where the value is over one. From the data can be seen, that higher sequence pressure values happen closer to the runway, which illustrates the fact the traffic becomes denser closer to the final point.

Table 5 – Statistics for sequence pressure

Day	Date	Data subset	Time	Window size [s]	Min [s]	Max [s]	Avg [s]	Std [s]
High traffic	12th of April	The busiest hour	5:00 – 6:00	120	1	4	1.43	0.7
		Day-time	6:00 – 0:00	120	1	4	1.22	0.51
		Night-time	0:00 – 6:00	120	1	4	1.36	0.65
The busiest	16th of May	The busiest hour	5:00 – 6:00	90	1	4	1.34	0.6
		The busiest hour	5:00 – 6:00	120	1	4	1.42	0.7
		The busiest hour	5:00 – 6:00	240	1	5	1.89	1.18
		Day-time	6:00 – 0:00	120	1	3	1.21	0.45
		Night-time	0:00 – 6:00	120	1	4	1.33	0.62
The least busy	29th of December	The busiest hour	11:00 – 12:00	120	1	2	1.15	0.36
		Day-time	6:00 – 0:00	120	1	2	1.07	0.25
		Night-time	0:00 – 6:00	120	1	1	1.0	0
Heavy delays	26th of February	The busiest hour	20:00 – 21:00	120	1	3	1.16	0.38
		Day-time	6:00 – 0:00	120	1	3	1.13	0.36
		Night-time	0:00 – 6:00	120	1	2	1.07	0.25
		Delayed period	10:00 – 16:00	120	1	3	1.15	0.38
		Most delayed hour	13:00 – 14:00	120	1	3	1.17	0.41
Average	29th of January	The busiest hour	6:00 – 7:00	120	1	3	1.34	0.57
		Day-time	6:00 – 0:00	120	1	4	1.19	0.44
		Night-time	0:00 – 6:00	120	1	2	1.13	0.34

For further analysis and discussions, we present tables for comparison of few selected data subsets. First, the comparison of the busiest day of the year and the least busy day of the year follows. For this comparison we chose the busiest hour data subset for both days. Table 6 below shows the comparison of statistics for these two data subsets. Even though the comparison is between the busiest day and the least busy day, the values for minimum time to final and spacing deviation are very similar. This fact indicates well-managed traffic flow with higher density during the busiest day of the year. Since there are no significant differences between the classic statistics, the 90^{th} quantile width indicator captures the difference between different traffic densities. The 90^{th} quantile width indicator is almost twice higher for the busiest day of the year which points on the higher traffic density during this data subset. The difference between the sequence pressure statistics can be seen mostly on the maximum value of the sequence pressure. But from previous investigation we know, that the sequence pressure of four is an outlier for this data subset. The average value and standard deviation values do not differ much.

Table 6- Comparison of the busiest day and the least busy day

	Statistics	The busiest day	The least busy day
	Time period	5:00 – 6:00	11:00 – 12:00
	Number of flights	29	8
Minimum 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

For the next comparison we present the differences between day-time and night-time operations. For this comparison we chose the day-time and night-time operations for the same day to assure consistency of data. The day chosen is the least busy day since the differences are most visible for this data subset. In Table 7 below the statistics for both are illustrated. The maximum value of minimum time to final is very small for night-time operations but the values do not differ much between these two data subsets. The 90^{th} quantile width for the day- time operations are almost three times higher than the value for night-time operations which indicates higher traffic density during the day. Both of the data subsets have very low sequence pressure values.

Table 7 - Comparison of day- time and night-time operations

Statistics		Day-time operations	Night-time operations
Time period		6:00 - 24:00	6:00 - 0:00
Number of flights		68	5
Minimum 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

The last comparison we present is the comparison of different data subsets from the day with heavy delays, February 26th. The different data subsets are the most delayed hour, the period with heavy delays and day-time operations all containing the most delayed hour of the day. This comparison shows that the scope for the same trajectories results in different key performance indicator values, because the baseline to which we compare our delays is different. In Table 8 below the statistics for all these data subsets is shown. The maximum value of the minimum time to final is the same for all of these data subsets. The same maximum value is given by the most delayed flight, which is present in each of these subsets.

The average value of the minimum time to final KPI tends to decrease with the increase of the subset size, which captures more flights with smaller delays, and they result in lower values of the minimum time to final. The standard deviation of the minimum time to final KPI shows the same trend. The standard deviation and 90th quantile width indicators of the spacing deviation KPI follow the same trend as well. The sequence pressure statistics are quite similar for each of these subsets which is caused by the fact that traffic density did not change significantly during the period of observation and the same sequencing operations are applied.

Table 8 - Comparison of different data subsets during the day with heavy delays

Statistics		The most delayed hour	Period with heavy delays	Day-time operations
Time period		13:00 – 14:00	10:00 – 16:00	6:00 – 24:00
Number of flights		17	80	201
Minimum time to final	Minimum	0	0	0
	Maximum	3142	3142	3142
	Average	1062	847	718
	Standard dev.	902	702	650
Spacing deviation	Minimum	-395	-494	-544
	Maximum	539	512	458
	Average	22.47	0.26	1.21
	Standard dev.	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 dev.	0.41	0.38	0.36

6. Example application of the KPIs for evaluation of the optimization results

In the related work part of this report, we presented [3] where the authors designed an optimization framework for arrival routes with experimental study at Stockholm Arlanda airport. Using the data provided by the authors, we calculated the KPIs presented in this report to evaluate the experimental study at Stockholm Arlanda airport. During this evaluation, we are going to compare the results for optimized routes given by the research group against real practices.

6.1. Data collection

Historical arrival data from Stockholm Arlanda airport was used for this experiment. The source for this dataset is Opensky Network [14]. The dataset used consists of records for the arrivals between 30th of September and the 7th of October of the year 2017. This specific data sample from 2017 is used instead of the whole dataset of the year 2017 because of the chosen date for the experiment, the 3rd of October, and with the aim of shortening the computational time.

6.2. Data filtration and data selection

Minor data filtration processes were applied to this dataset. We filtrate only the parts of the flight records which were in the TMA of Stockholm Arlanda airport, which is given by entry points presented in Table 1 above on page 5. Another data filtration we used was to detect erroneous records such as flights which do not arrive at the TMA from outside or the ones which missed the final point.

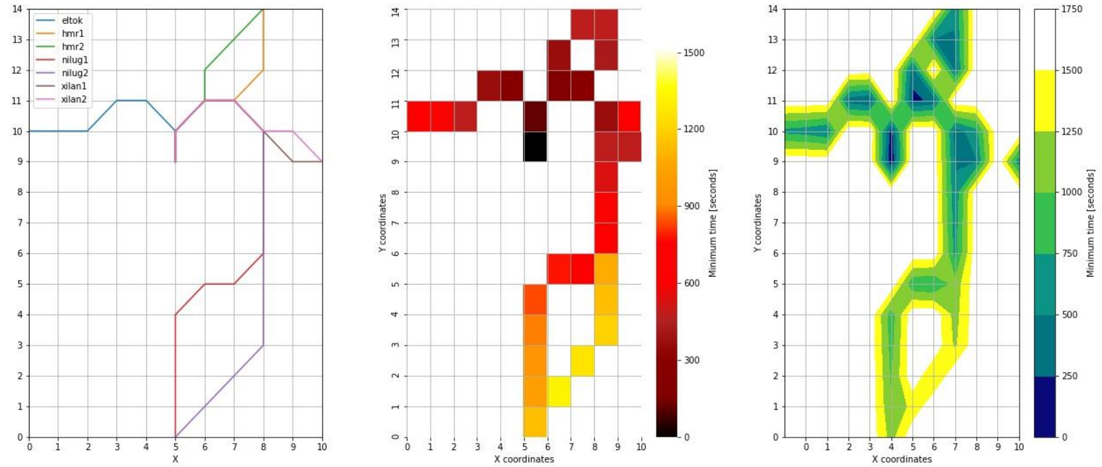
From the whole dataset, we selected only the records which represent the arrivals during the 3rd of October between 15:00 and 16:00 in the afternoon. The data was selected according to aircraft arrival times to the terminal manoeuvring area. This data selection rule assures that whole parts of each flight entering the TMA between 15:00 and 16:00 are taken into the analysis regardless of its time in final.

6.3. KPIs calculation

For this practical experiment, the similar KPIs calculation method was used for the analysis for the year 2018. Further, we compare the resulting KPIs for the optimized routes and real practices for the same date and time (October 3rd, 2017, 15:00 – 16:00)

6.3.1. Optimized routes

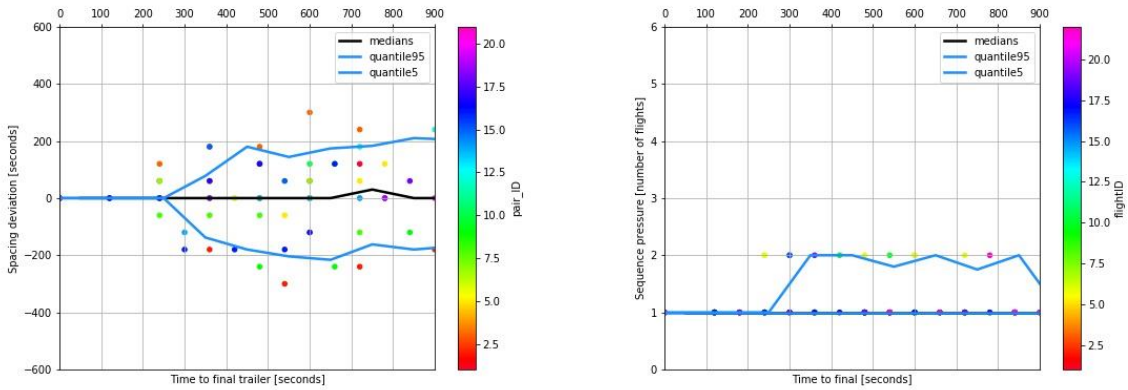
The optimized routes were designed from each of the entry points of Stockholm Arlanda airport which are presented in Table 1 on page 5. The simulated optimized routes developed in [3] are illustrated in Figure 45a below. In Figure 45b the heatmap for simulated optimized routes is demonstrated and Figure 45c shows contour plot. Both heatmap and contour plot illustrate gradual lessening of minimum time to final towards the final point. Such graduality indicates smooth arrival on each of the routes with no holds. The highest values of minimum time to final are close to the southern entry point which is the furthest from the runway. The highest values from west and east entry points are similar since the runway is approximately in the middle between them. The closest entry point to the runway, the northern entry point, also shows the lowest minimum time to finals to final from the beginning.



a) b) c)

Figure 45 – Simulated optimized routes (22 aircraft), min = 0s, max = 1320s, avg = 644s, std = 341s - a) Flight trajectories, b) Heatmap, c) Contour plot

Figure 46a below illustrates spacing deviation for the simulated optimized routes. The spacing deviation has wider spread until 300 seconds to final and then reaches zero at approximately 250 seconds to final which is sooner than most of the data subsets from 2018 analysis. The median curve stays close to zero deviation which indicates good control over arriving aircraft pairs. Sequence pressure can be seen in Figure 46b. The maximum value of sequence pressure for the simulated optimized routes reaches two which is very low pressure to the runway and indicates a very smooth and well controlled traffic flow. Around approximately 250 seconds to final the sequence pressure reaches only pressure of one aircraft to the runway which corresponds to zero spacing deviation of aircraft pairs in Figure 46a around the same time to final.

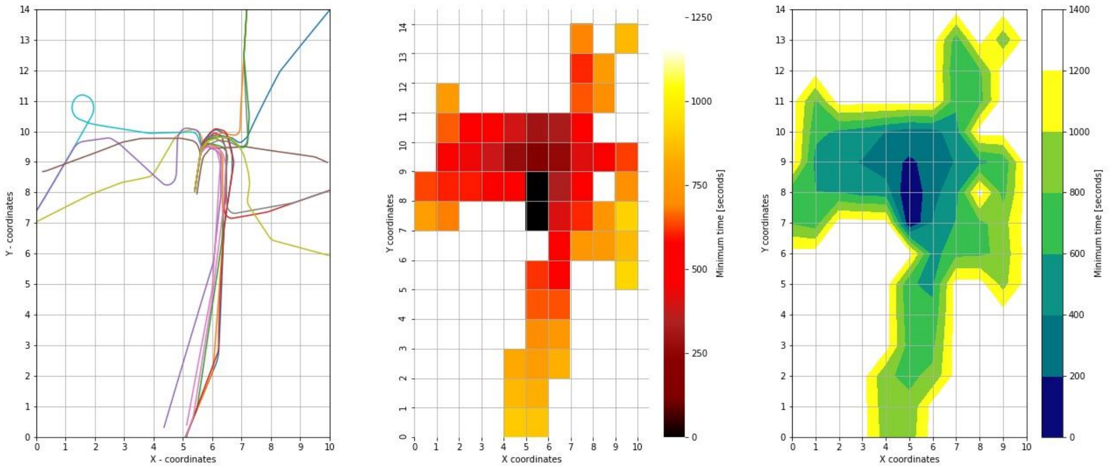


a) b)

Figure 46 - Simulated optimized routes (22 aircraft) – a) Spacing deviation, min = -300s, max = 300s, avg = 6.74s, std = 109.46s, 90th quantile width = 390, b) Sequence pressure, window size = 120s, min = 1, max = 2, avg = 1.05, std = 0.21

6.3.2. Real practices

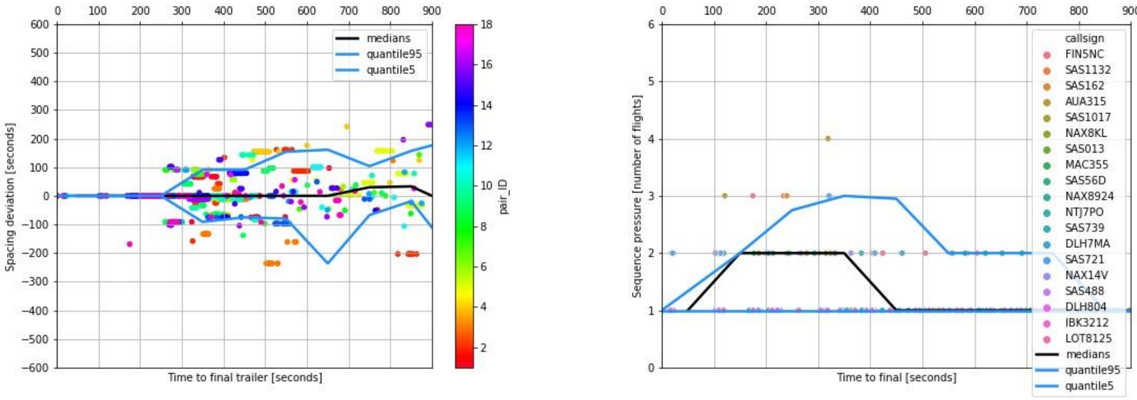
For the experimental study, the date 3rd of October 2017 was chosen because it was one of the busiest days of the year 2017 with 432 aircraft arrivals. Only one hour from this day is analysed and it is between 15:00 and 16:00 in the afternoon. Figure 47a illustrates the flight trajectories used with aircraft arriving at Stockholm Arlanda airport. The flight trajectories indicate an only a small number of path extensions and only one hold using a circle. The flight trajectories from the southern and the northern entry point almost follow the optimized routes but the flight trajectories from eastern and western entry points have larger spread and do not follow the same pattern. Figures 47b and 47c demonstrate minimum time to final visualization using heatmap and contour plot respectively. A gradual decrease of minimum time to finals to final indicates smooth traffic conditions with no significant problems but in comparison to the optimized routes, we see that more grid cells are covered by the flights, which indicates higher complexity from the control point of view.



a) b) c)

Figure 47 – 3rd of October 2017 (total of 19 aircraft), min = 0s, max = 1273s, avg = 998s, std = 360s, a) Flight trajectories, b) Heatmap, c) Contour plot

Figure 48a shows the spacing deviation for this data subset. The higher spread can be seen around 650 seconds to final and then the spacing deviation smooths out to both sides of this peak. Closer to zero seconds to final, the spacing deviation decreases at around 450 seconds to final and then reaches zero spacing deviation at approximately 250 seconds to final. The shape of the spacing deviation figure together with statistics is similar to the optimized routes spacing deviation plot in Figure 48a. Figure 48b demonstrates sequence pressure calculation for the 3rd of October. The confidence interval curve reaches the maximum sequence pressure of three aircraft and the median curve reaches only the sequence pressure of two aircraft. Only one occurrence of the sequence pressure of four aircraft indicates a clear outlier. Because 19 aircraft per one hour is at the average, the outlier sequence pressure of four is unexpected. We are going to investigate this occurrence in more details.



a) *b)*

Figure 48 - 3rd of October 2017 (total of 19 aircraft) – a) Spacing deviation, min = -236s, max = 249s, avg = 6.74s, std = 64.72s, 90th quantile width = 390, b) Sequence pressure, window size = 120s, min = 1, max = 4, avg = 1.33, std = 0.55

6.3.2.1. Investigation of an outlier in sequence pressure results

On the 3rd of October 15:00 – 16:00 data subset an extremely high sequence pressure outlier was found. Because of such unexpected value, we are going to investigate this occurrence further. For further investigation, we searched in the data which are the four aircraft sharing similar minimum time to final and the reference timestamp. The reference timestamp was 1507043756 which is in translation October 3rd and time 15:15:56. The shared minimum time to final is 169 seconds and is given for the cell with coordinates [6,10]. In Table 9 below the corresponding aircraft callsigns and timestamps can be seen together with x, y coordinates in the grid, longitude and latitude coordinates, and altitude.

Table 9 - Sequence pressure of four outlier, corresponding aircraft information

Aircraft	Timestamp	X	Y	Latitude	Longitude	Altitude
SAS162	1507043756	5.55446	9.92894	59.8583	17.9977	914
AUA315	1507043812	5.97906	9.9959	59.8608	18.1007	914
SAS1132	1507043696	5.77047	9.73955	59.834	18.0501	914
FINSNC	1507043708	5.57507	9.11875	59.7691	18.0021	914

This information about the four aircraft indicates, that these aircraft are very close to each other with only a few seconds difference in the estimated minimum time to final, which may create a problem in air traffic control. We visualized this situation on our flight trajectories plot where we plotted positions of these aircraft in the specified time above the flight trajectory plot adjusted for better vision. The aircraft positions are shown in coloured dots in Figure 49. Table 10 the corresponding colours to each aircraft.

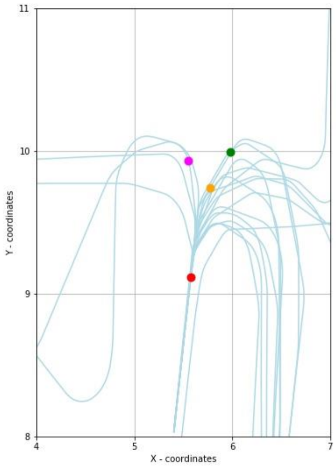


Figure 49 – Outlier investigation, aircraft positions

Table 10 – Aircraft callsigns with corresponding colours

Aircraft	Colour
SAS162	Magenta
AUA315	Green
SAS1132	Orange
FINSNC	Red

The fact that all these four aircraft are in the same cell within the same 120 seconds time window indicates that there was a potential separation problem during the given time interval (between 15:14:56 and 15:16:52). This demonstrates how the sequence pressure KPI makes it easy to capture such problematic events and may be used for investigation of air traffic inefficiencies within the terminal manoeuvring area.

For a good overview we also present table with comparison of statistics of the simulated optimized routes data subset and real operation data subset. Table 11 below shows the statistics for both of these data subsets. The statistics values are very similar but the maximum value of minimum time to final is higher for the optimized routes, which is surprising. On the contrary, the average value of the minimum time to final KPI is much lower for the optimized routes data subsets which indicates that even the maximum value is higher, the values are lower overall. The statistics for spacing deviation show the same average and 90^{th} quantile width value for both of these data subsets. On the contrary the values of the sequence pressure differ much more with the maximum value of sequence pressure of 4 for the real operation data subset. This confirms that optimization framework targeting automated safe separation reached its goal.

Table 11 - Comparison of the simulated optimized routes and the real operation data subsets

Statistics		Optimized routes	Real operations
Number of flights		22	19
Minimum time to final	Minimum	0	0
	Maximum	1320	1273
	Average	644	998
	Standard dev.	341	360
Spacing deviation	Minimum	-300	-236
	Maximum	300	249
	Average	6.74	6.74
	Standard dev.	109.46	64.72
	90th quantile width	390	390
Sequence pressure	Time window	120	120
	Minimum	1	1
	Maximum	2	4
	Average	1.05	1.33
	Standard dev.	0.21	0.55

7. Conclusions and future work

In this work, we presented a set of KPIs and demonstrate their application on example of Stockholm Arlanda airport using the historical flight data provided by Opensky Network [15]. The main inspiration was taken from [1] where the authors introduced the first ideas for these new KPIs and evaluated arrival spacing and sequencing at four European airports. We elaborate on the calculation and develop the KPIs further in order to make them applicable for the purpose of detailed evaluation of Stockholm Arlanda airport arrival performance.

We consider the arrivals to Stockholm Arlanda airport in 2018. From the corresponding dataset we choose only the records, which correspond to flight arrivals in the TMA of Stockholm Arlanda airport. For the analysis we took multiple data subsets from the whole dataset. We analysed data subsets for the days with different air traffic intensity: the busiest day of the year, the least busy day, the average, high traffic day and the day with heavy delays. For each of these data subsets we calculated the KPIs for different time intervals which are day-time operations period (6:00 – 0:00), night-time operations (0:00 – 6:00), the busiest hour and the period with heavy delays for the data subset of the day with heavy delays. These time intervals were chosen to enable comparison of arrival sequencing in different traffic conditions at Stockholm Arlanda airport. Analysis of the extreme values of the sequence pressure KPI led to the discovery of the potential spacing violation problems in the vicinity of the runway. We visualized these potentially problematic situations but without information from air traffic controllers, who worked in that particular situations, we cannot make any final conclusions.

We presented visualisation of KPI results for each data subset in the analysis. The flight trajectory plots illustrate the paths used and demonstrate path extensions and holds of aircraft. The heatmaps and the contour plots of minimum time to final help to illustrate the current traffic situation and nicely visualize the problematic regions. The spacing deviation plots demonstrate the inter aircraft spacing error over the last 900 seconds of flying time. The sequence pressure plots illustrate the sequence pressure on the runway for the last 900 seconds of flying time. In the sequence pressure plots can be clearly seen, that higher sequence pressure values occur closer to the runway, which nicely reflects the fact the traffic becomes denser closer to the final point. The plots of aircraft position investigation caused by high sequence pressure values illustrate the aircraft positions at a given 120 seconds time window. The aircraft position plots show problematic situations for further analysis.

We summarized all the results from the analysis in tables which assures better clarity for the comparison of the same KPIs for different data subsets. Analysis of statistics of the spacing deviation demonstrates that this KPI clearly reflects the situations with highly congested traffic and delays on arrivals. The main statistical indicator for this is the 90th quantile width, which is defined as the maximum width of the 90% confidence interval in the given data subset calculation and clearly indicates traffic delays and congestion. The statistics of minimum time to final KPI also help to differentiate between congested and non-congested conditions at air traffic, which could be used for assessment of the level of congestion in future analysis and evaluations. The analysis of statistics for the sequence pressure KPI demonstrates the efficiency of aircraft arrival spacing used and could be used as an indicator for potential aircraft separation problems. The spacing deviation and the sequence pressure KPIs are based on the definition of the minimum time to final and help to evaluate how the current 4D positions of the aircraft pairs differ in the situations of different traffic intensity. Also, we presented comparisons of different data subsets on selected examples.

In the end, we demonstrated the application of the proposed KPIs to the evaluation of the optimization results. The optimization was implemented using historical data from Stockholm Arlanda airport during the year 2017. We evaluate the optimization results implemented and presented in [3]. The simulation results and real practice historical data were provided for this analysis. We demonstrated how the use of the sequence pressure performance indicator makes it easier to capture such problematic events.

To summarize, the research questions we identified in the introduction section of this thesis were answered as follows. The answer for the first question: "How does Stockholm Arlanda airport manages sequencing for their arrival aircraft" can be clearly read from the Data analysis and discussion parts. In the majority of cases, the traffic flow was well-managed during the year 2018 and provided smooth arrivals of aircraft. Even on high traffic days or on the day with heavy delays the resulting sequence pressure on the runway was low which indicates well-managed incoming flow. In the flight trajectory figure of the day with heavy delays can be seen that holdings of aircraft and its queuing is managed close to the entry points which assures separation of approaching aircraft close to the runway. The second research question: "Which KPIs are suitable for Arlanda airport and what do they evaluate?" has also clear answer. All the considered key performance indicators are suitable for Arlanda airport are Minimum time to final, Spacing deviation and Sequence pressure. All of them together evaluate overall arrival spacing operations on Arlanda airport and are able to capture problematic situations. The KPIs proposed can differentiate between congested and non-congested traffic or detect traffic density of incoming aircraft. The last question: "How the KPIs proposed could help with capturing problematic events?" is pointing out to the future work. The KPIs proposed could help with capturing potential problematic events and led to their further investigation. One of the problematic events which can be detected by the sequence pressure is potential spacing problem and thus, safety violation.

In conclusion, the presented KPIs can be used to evaluate the arrival sequencing situation and to capture potential problematic situations. The KPIs developed help to uncover observable effects with information about controller's spacing activity. The methodology we presented in this work can be applied to the analysis of the arrival sequencing at any other airport without extensive changes in the code. The KPIs can be used for the evaluation of air traffic management operations in arrivals and for investigation of air traffic inefficiencies in the terminal manoeuvring area. This thesis contributes to the future optimization of arrival management and spacing evolution at Arlanda airport. This work can support adjustment of routes or operating methods, to easily reach maximisation of runway utilisation or any other desired characteristics of the airport operation on arrivals. The potential future work could include the application of these KPIs presented to the evaluation of operations and for long-term arrival spacing planning.

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Appendix 1: Example piece of the data

flights - DataFrame

Index	flightID	sequence	endDate	callsign	icao24	date	time	timestamp	lat	lon	baroAltitude	aircraftType	origin
0	214172272	1652	180101	TOM691	406c6d	180101	134333	1514814213	59.6474	19.5985	5791	B788	VVPQ
1	214172272	1653	180101	TOM691	406c6d	180101	134407	1514814247	59.6501	19.4916	5486	B788	VVPQ
2	214172272	1654	180101	TOM691	406c6d	180101	134432	1514814272	59.652	19.4171	5181	B788	VVPQ
3	214172272	1655	180101	TOM691	406c6d	180101	134532	1514814332	59.6557	19.2428	4876	B788	VVPQ
4	214172272	1656	180101	TOM691	406c6d	180101	134602	1514814362	59.6574	19.1581	4572	B788	VVPQ
5	214172272	1657	180101	TOM691	406c6d	180101	134613	1514814373	59.658	19.128	4572	B788	VVPQ
6	214172272	1658	180101	TOM691	406c6d	180101	134618	1514814378	59.658	19.1134	4572	B788	VVPQ
7	214172272	1659	180101	TOM691	406c6d	180101	134623	1514814383	59.6578	19.1	4572	B788	VVPQ
8	214172272	1660	180101	TOM691	406c6d	180101	134628	1514814388	59.6573	19.0856	4572	B788	VVPQ
9	214172272	1661	180101	TOM691	406c6d	180101	134634	1514814394	59.6564	19.0701	4572	B788	VVPQ
10	214172272	1662	180101	TOM691	406c6d	180101	134638	1514814398	59.6555	19.0589	4572	B788	VVPQ
11	214172272	1663	180101	TOM691	406c6d	180101	134645	1514814405	59.6538	19.0401	4572	B788	VVPQ
12	214172272	1664	180101	TOM691	406c6d	180101	134651	1514814411	59.6518	19.0237	4572	B788	VVPQ
13	214172272	1665	180101	TOM691	406c6d	180101	134658	1514814418	59.6492	19.0052	3962	B788	VVPQ
14	214172272	1666	180101	TOM691	406c6d	180101	134744	1514814464	59.632	18.886	3962	B788	VVPQ
15	214172272	1667	180101	TOM691	406c6d	180101	134838	1514814518	59.612	18.7474	3657	B788	VVPQ
16	214172272	1668	180101	TOM691	406c6d	180101	134924	1514814564	59.5952	18.6317	3352	B788	VVPQ
17	214172272	1669	180101	TOM691	406c6d	180101	135015	1514814615	59.5766	18.5052	3048	B788	VVPQ
18	214172272	1670	180101	TOM691	406c6d	180101	135026	1514814626	59.5727	18.4783	3048	B788	VVPQ
19	214172272	1671	180101	TOM691	406c6d	180101	135029	1514814629	59.5718	18.4709	3048	B788	VVPQ
20	214172272	1672	180101	TOM691	406c6d	180101	135031	1514814631	59.5714	18.4672	3048	B788	VVPQ
21	214172272	1673	180101	TOM691	406c6d	180101	135032	1514814632	59.5711	18.4639	3048	B788	VVPQ
22	214172272	1674	180101	TOM691	406c6d	180101	135033	1514814633	59.571	18.4614	3048	B788	VVPQ
23	214172272	1675	180101	TOM691	406c6d	180101	135034	1514814634	59.5709	18.4591	3048	B788	VVPQ
24	214172272	1676	180101	TOM691	406c6d	180101	135035	1514814635	59.5707	18.4567	3048	B788	VVPQ
25	214172272	1677	180101	TOM691	406c6d	180101	135036	1514814636	59.5707	18.4541	3048	B788	VVPQ
26	214172272	1678	180101	TOM691	406c6d	180101	135037	1514814637	59.5706	18.4515	3048	B788	VVPQ
27	214172272	1679	180101	TOM691	406c6d	180101	135038	1514814638	59.5706	18.4488	3048	B788	VVPQ
28	214172272	1680	180101	TOM691	406c6d	180101	135039	1514814639	59.5707	18.4465	3048	B788	VVPQ
29	214172272	1681	180101	TOM691	406c6d	180101	135040	1514814640	59.5707	18.4442	3048	B788	VVPQ
30	214172272	1682	180101	TOM691	406c6d	180101	135041	1514814641	59.5708	18.4412	3048	B788	VVPQ

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