Stockholm TMA capacity - A study of the landing rate and its effects on arrival outcome

Axel Rydin

2013-12-18
Stockholm TMA capacity - A study of the landing rate and its effects on arrival outcome

Examensarbete utfört i Logistik vid Tekniska högskolan vid Linköpings universitet

Axel Rydin

Handledare Valentin Polishchuk
Examinator Tobias Andersson Granberg

Norrköping 2013-12-18
Upphovsrätt

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Abstract

Stockholm TMA handles traffic to Sweden’s two biggest airports movement wise: Stockholm Arlanda and Stockholm Bromma. The airports are located in close proximity to each other, meaning traffic in and out of the airports is likely to conflict, depending on the runway configurations. Stockholm TMA capacity will depend on how complex the traffic is, especially in the arrival sector (sector East), as well as weather, wind and other capacity factors.

The thesis focuses on arriving traffic to Stockholm Arlanda. The number of arrivals for any given hour is restricted by a landing rate. The landing rate is set depending on a number of factors. For a high landing rate to be set, Stockholm Arlanda will need to be in traffic peak, utilizing one of the runway configurations used for hours of high traffic intensity.

By collecting data for each traffic peak, my work presented in this thesis consists of following up the landing rate. Looking at arrival counts for hours with different landing rates has provided an image of how the rate affects arrival outcome. Also, the main contributors when setting the landing rate have been analyzed. Main data sources used are Eurocontrol radar data, runway reports and a form developed specifically for the work on this thesis.

During the data collection period the arrival outcome has been found to be generally lower than the landing rates, as the traffic demand at Stockholm Arlanda has not been full for whole hours during traffic peaks. At times when demand has existed, the arrival outcome has generally been in line with the landing rate. When looking at shorter time periods within a traffic peak, the landing rate restricts the arrival flow on most weekday mornings.

Landing rates have been set according to procedures stated in the manual of operations for ATCC Stockholm. Using an excel table called Ratetest; the effects to the landing rate of wind, runway and distance on final conditions at Stockholm Arlanda are calculated. The output of Ratetest has been found to restrict the landing rate consistently, as the landing rate was only set higher than the Ratetest output at one time during the data collection period.

At times when the conditions were such that a high landing rate was possible, the landing rate value was restricted not only by Ratetest output, but by traffic analysis as well. In my work, one of the conclusions drawn is that a max rate of 42 arrivals per hour was more likely to occur with a favorable runway configuration in terms of traffic complexity. A combination of runway 19L for landing at Stockholm Arlanda and runway 12 at Bromma gave the highest landing rates.
Foreword

In this concise foreword I would like to take the time to thank all the people at ATCC Stockholm who have helped me with my thesis. It has been incredible as an ATC student to take part of your work and be so warmly and kindly invited to your work environment. I have been able to make study visits at a regular basis and sit in and listen, thus learning a lot; not only usable in the thesis but also in my upcoming internship at the ATCC. I feel privileged to have been given the opportunity to study a subject that will - in time - be closely related to my own line of work.

A couple of persons deserve a special thank you. Mayte Åqvist and Jens Andersson for keeping their door open whenever I was in need for specific information, practical things or just somebody to discuss with. Thank you to all the TS-Ts that have not only kept up with me hanging around their work area, but also been kind enough to fill out my data collection forms. Niklas Rooslien deserves a special mention here as he introduced me to Stockholm TMA in early October.

I have been met with nothing but respect and welcoming words during my time at ATCC Stockholm. To the people there who take their time to read this thesis, I hope you will do it keeping in mind that I am after all new to the subject, but the fact that you all shared your knowledge with me made able to write this thesis. For that I am very thankful.

Axel Rydin

Malmö 13/1-2014
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List of acronyms

ACC - Area Control Centre
ANS - Air Navigation Services
ANSP - Air Navigation Services Provider
ATA - Actual Time of Arrival
ATC – Air Traffic Control
ATCC - Air Traffic Control Centre
ATCO – Air Traffic Controller
ATM – Air Traffic Management
CFMU – Central Flow Management Unit
CTOT – Calculated Take-Off Time
ESSA - Stockholm Arlanda (ICAO Airport Code)
ESSB - Stockholm Bromma (ICAO Airport Code)
ETA - Estimated Time of Arrival
FAB – Functional Airspace Block
GP – Glide Path
IAF - Initial Approach Fix
IAP – Instrument Approach Procedure
ICAO – International Civil Aviation Organization
ILS – Instrument Landing System
LOC - Localizer
MDI - Minimum Departure Interval
NUAC - Nordic Unified Air Traffic Control
RWY – Runway
SID – Standard Instrument Departure
STAR – Standard Terminal Arrival Route
STCA – Short-Term Conflict Alert
TMA - Terminal Control Area
TST - Tactical Supervisor Terminal
TSA - Tactical Supervisor Area
TWR – Tower
VHF – Very High Frequency
List of definitions

**ANS**
Air Navigation Services - This term includes air traffic management (ATM), communications, navigation and surveillance systems (CNS), meteorological services for air navigation (MET), search and rescue (SAR) and aeronautical information services (AIS). These services are provided to air traffic during all phases of operations (approach, aerodrome and en-route) [1].

**AMAN**
Arrival Manager – A sequencing aid to help control the traffic flow into a TMA by giving ACC sectors times over feeder fixes, to ensure a steady, efficient and optimized flow of traffic [19].

**ATA**
Actual Time of Arrival – The time at which an aircraft arrives, updated shortly before arrival regardless of flight planned ETA.

**ATC Clearance**
“Authorization for an aircraft to proceed under conditions specified by an air traffic control unit.” [1]

**CTOT**
Calculated Take-off Time – The time window given to an aircraft that has been assigned a departure slot. The CTOT needs to be matched with -5/+10 minutes for an aircraft to be given take-off clearance. The purpose of the CTOT is to prevent delay in the air due to airspace and/or aerodrome capacity. [1]

**En-route**
All phases of flight between departure aerodrome and destination aerodrome succeeding departure and preceding arrival. [1]

**ETA**
Estimated Time of Arrival – The time at which an aircraft is estimated to arrive at its destination. [1]

**Final**
Short for “final approach” and commonly used by ATC. An aircraft on “short final” is an aircraft establish on the ILS closing in on the runway threshold. A long/short final is not determined in terms of exact distance in NM from runway threshold. Generally, aircraft on short final approach have started reducing to their final approach speed, whilst an aircraft on long final still has at least 10 NM to go. [1]

**Flight Rules**
The flight rules determine if the pilots navigate by keeping visual contact with terrain (Visual Flight Rules, or VFR), or navigate using aircraft instruments, utilizing navigational aids (Instrument Flight Rules, or IFR) [19].

**IAF**
Initial Approach Fix - Normally the point where the SID ends, radar vectoring past that point is standard at many airports. [1]

**ILS**
Instrument Landing System – The ILS is the most commonly used landing instrument, providing the aircraft with vertical and horizontal navigational guidance to runway threshold. It consists of two main parts: the LOC (Localizer) for horizontal guidance, and the GP (Glide path) for vertical guidance. Aircraft are often turned onto the ILS by radar.
vectoring and shall be established on the LOC approximately 2 NM before meeting the GP. [1]

Landing Rate
The rate at which aircraft land during an hour of the day at a specific aerodrome. [28]

MDI
Minimum Departure Interval – The minimum time interval required between successive departures on the same SID [20]. Used as a measure to limit the number of movements in the TMA. [28]

Movement
The definition for an aircraft in a specific airspace or at an airport, regardless of phase of flight. Any arrival, departure or aircraft en-route represents one movement. It is commonly used in aviation as a capacity measurement. [1]

Radar vectoring
“Provision of navigational guidance to aircraft in the form of specific headings, based on the use of radar.” [1] Using radar vectoring, ATC can instruct aircraft to turn.

Released
A term used to describe when aircraft that have been/are about to be transferred to the next controller can be given instructions and clearances, even though the aircraft has not entered the new sector. For example, aircraft descending toward an aerodrome in the next sector are usually released for further descent before entering the new sector. [1]

Peak
The highest traffic volumes during a day. [28]

Planner
Short for Planner Controller. Planners are used in an ACC environment where sectors are manned by two controllers: one executive and one planner. The responsibilities of the planner involves solving conflicts outside the own area of responsibility, before the conflicting traffic enter own sector, as well as coordinating direct routes with adjacent sectors. [1]

Precision Approach
An approach procedure utilizing both horizontal and vertical guidance. The most commonly used precision approach is the ILS approach. [1]

SID
Standard Instrument Departure – A designated IFR departure route linking the aerodrome to a point or route where the en-route phase commences. [21]

STAR
Standard Terminal Arrival Route – A designated IFR arrival route that links an en-route point, like a feeder fix, with a point where an approach procedure is commenced. [22]

STCA
Short-Term Conflict Alert – A safety system built into the COOPANS system, alarming controllers if aircraft are predicted to get too close. The alarm is time-based and triggered whenever the system detects a potential conflict within 60-120 seconds. Most alarms are false as STCA does not know whether aircraft will stop their climb/descend before separation expires. [41]
Wake Turbulence

The turbulence created by whirls of air originating from aircraft wing tips. Larger aircraft means more wake turbulence. Succeeding aircraft needs to take caution and ATC needs to apply extra separation between the larger preceding aircraft and succeeding aircraft. [8]
1 Introduction

LFV is the major ANSP (Air Navigation Services Provider) in Sweden, employing 1,300 people to operate ANS (Air Navigation Services). Through the collaborative effort NUAC, LFV and the Danish equivalent Naviair run the three ATCCs (Air Traffic Control Centres) in Sweden and Denmark; controlling all en-route traffic in the DK-SE FAB (Functional Airspace Block), as well as the TMAs (Terminal Control Area) in adjunction to the major airports in both countries. LFV also run a majority of the Swedish control towers, including Arlanda, Bromma, Landvetter and Malmö Airport. [40]

Stockholm TMA is operated from ATCC Stockholm, located in close vicinity to Stockholm Arlanda airport. It is by far the most occupied TMA in Sweden with up to just over 1000 movements per day.

In Stockholm TMA traffic is handled to Sweden’s two biggest airports movement wise: Arlanda and Bromma. Having two major airports in close vicinity to each other creates complex scenarios, ultimately affecting capacity. With the future expansion of Stockholm Bromma[18] and a forecasted steady increase of TMA traffic in the years to come [26], traffic counts and traffic complexity is likely to continue to increase.

1.1 Problem definition

The maximum capacity of Stockholm Arlanda and Stockholm Bromma in terms of movements per hour is defined in an agreement between LFV and the airports [38]. Agreement capacity numbers are what the airports and Stockholm TMA are considered able to handle during one hour, constrained by a maximum amount of arrivals and departures. For instance, the maximum amount of arrivals at Stockholm Arlanda is 42 per hour.

Stockholm TMA capacity is not constant, but varies depending on a number of factors. What has been agreed between LFV and the airports is a maximum, not an average number. Factors affecting capacity is among others weather, runway configuration and restrictions due to environmental standards. As the smoothness of traffic flow to Arlanda and Bromma is dependent on TMA capacity, the number of arrivals and departures at the aerodromes is in direct relation to how much traffic the TMA can handle.

At any given time there is a landing rate in place for Stockholm Arlanda, restricting the flow of traffic into the TMA by defining how many ESSA arrivals the TMA can handle per hour. The selection of a feasible landing rate is arbitrary to some extent, as it is a prediction of how many aircraft that will be able to land during an hour under given conditions. As of today, LFV do not have follow-up procedures to determine how a set landing rate pans out in terms of actual arrivals per hour, meaning capacity cannot be accurately measured. The landing rate and the process behind setting it is described thoroughly in chapter 3.6.

1.2 Objective

The thesis objective is to investigate and follow up how TMA capacity is affected during different operating conditions, focusing on the application of landing rates for Arlanda:

- To describe the process of setting landing rates and its effects on the arrival flow into Stockholm TMA.
- By following up how the actual number of landing aircraft reflects the set rate, provide the client with statistic groundwork to help optimizing TMA capacity.
• By investigating how landing rates are set during certain conditions, determine landing rate contributors and which LFV account for.
• To follow up if LFV is delivering capacity numbers in accordance with maximum numbers in the airport-ANSP agreement.

1.3 Delimitations
As landing rates are not set for Stockholm Bromma, landing rate follow-up is solely for Arlanda. Bromma traffic will not be excluded from capacity analysis, but is regarded as a complexity factor affecting TMA capacity. The difference from Arlanda traffic is that Arlanda arrivals are analyzed per landing in comparison to the current landing rate, whilst Bromma arrivals are not.

The ANSP-airport agreement between LFV and Stockholm Arlanda defines capacity figures for night time traffic as well as day time traffic. As no data is collected during the night, the thesis does not cover night time capacity figures.

This report focuses on arrivals and no data collection has been made to follow up departure counts. The number of departures per hour is not directly connected to TMA efficiency, but is more dependent on tower operations and given conditions at the airports, unless the departure flow in Stockholm TMA needs to be restricted in form of an MDI or other measures.

1.4 Methodology
Main data sources are live observations at ATCC Stockholm, recent reports reviewing the TMA capacity and data collection through comparing landing rates with landing counts. In order to get a bird’s eye view of the system – from landing rate set to aircraft landed, from ACC to tower – a lot of the reference material originates from field work.

A form has been developed to gather data from the TS-Ts (Tactical Supervisors-Terminal, chapter 3.3.2) at ATCC, who set the landing rates for Arlanda and observe the traffic flow through the TMA. An English version of this form has been included in this proposal as an appendix (Appendix I). The form was distributed to the TS-Ts at Stockholm TMA in week 41, by having a file in the TS-T position with forms to fill in whenever a landing rate is set or changed. Form data was collected between October 8th and November 20th and focuses on hours with peak traffic, as that is when landing rates are likely to affect the flow of traffic into the TMA. The landing rate form is Arlanda exclusive, as landing rates are not set for Stockholm Bromma as of today.

To analyze landing rate outcome, there was a need for the actual arrival count data to be extracted. This data is available from the TS-T position, where Flight Lists can be printed including all traffic in Stockholm TMA during hours of choice. The lists can be filtered to only include Arlanda arrivals, with an ATA (Actual Time of Arrival) for each flight, updated on short final approach. By analyzing flight list data for hours where landing rate forms have been filled in it is possible to draw conclusions of landing rate outcome.

An in depth description of methods used, data constraints and methodology discussion is found in Chapter 5.
2 Theoretical frame of reference
The theoretical frame of references is meant to provide all necessary background theory to be able to understand the thesis. The basics of ATC; focusing mainly on sequencing, separation standards and approach control, are covered in short in this chapter.

2.1 ATM
ATM (Air Traffic Management) is all about safety. Making sure aircraft are guided in a safe and expeditious way whilst on the ground and in the air is what ATM all boils down to. The procedures and resources that are used to facilitate that are the components of ATM; including ASM (Airspace Management), ATFCM (Air Traffic Flow and Capacity Management) and ATC (Air Traffic Control Service) [2].

In recent years, it has become increasingly important to manage air traffic in the most fuel efficient and optimized way as possible. With aircraft being built to use fuel more efficiently, aircraft operators relying on fuel efficient cost indexes when planning flight profiles and cheaper tickets for the masses, there is an increasing pressure on ATM stakeholders to live up to expectations on their end. With new initiatives like SES (Single European Sky), where the European airspace is meant to be harmonized into larger FABs [3] rather than be constrained by national borders, the optimization process of ATM seem to have only just begun.

2.1.1 ASM
ASM is used for planning the use for a specific airspace. An airspace is designed with lateral and vertical borders and can be classified into different airspace classes, depending on navigational aids in the vicinity, what kind of traffic that uses the airspace, the need for ATC and many other factors[5].

Looking at Stockholm TMA as an example, it is an airspace designed to facilitate approach control, mainly to arriving and departing traffic, in the vicinity of airports in the Stockholm area. The airspace design of another TMA in Sweden would look widely different, as capacity needs vary.

2.1.2 ATFCM
The main purpose of ATFCM is to optimize traffic flows according to ATC capacity in sectors, while enabling airlines to operate air traffic safely and efficiently [4]. ATFCM is divided into three phases, based on time before the day of operations; the strategic, pre-tactical and tactical phases. The strategic phase takes place about a year before the flight, where predictions of capacity needed at the ATCCs around Europe, as well as an early plan for routing is developed [4]. From the start of the strategic phase to the end of the tactical phase, ATFCM aims at keeping delays at a minimum, smoothening the flow of air traffic during all days of operation. Delays are however an inevitable part of aviation, and there will be days when sectors are too crowded capacity wise.

If traffic trends indicate a peak in a sector that exceeds ATC capacity, a regulation can be sent to the CFMU in Brussels, restricting the amount of traffic in a specific airspace by delaying aircraft on the ground, before departure. The advantages of keeping an aircraft with inevitable en-route delay on the ground are to be found in fuel consumption as well as keeping adjacent sectors from exceeding capacity limits. In case of the need for an ATFCM regulation, concerned aircraft will be allocated slot times to smoothen out traffic entering the capacity limited sector. A CTOT is given to the aircraft, which must be matched within a time frame of -5/+10 minutes, meaning the aircraft has to take off within that time, or be delegated a new CTOT [11].
The need for ATFCM regulations in Sweden is most commonly associated with snowfall, where the runway capacity at an airport is impaired due to the need for snow sweeping. Other weather phenomena like predicted thunderstorm activity or fog can be the source of a traffic regulation.

2.1.3 ATC

ATC is a service provided to prevent collision between aircraft, both in air and on the ground (where applicable), while maintaining an expeditious and orderly flow of traffic [1]. It is a service where safety is always prioritized above everything else, with high demands from operators on the level of service and overall efficiency.

ATC relies on an extensive set of rules and regulations. Aircraft must remain separated at all times and there can never be any uncertainty as to which rule of separation that is applied at any moment. In basic terms, an aircraft shall be separated from other aircraft from the point where it leaves the gate and enters the area of responsibility for an ATCO (the maneuvering area) at the departure aerodrome, until it has taxied to its gate at the destination aerodrome [1]. This can be achieved in many ways. At the airport, the TWR ATCO can use visual separation to maintain separation to other aircraft by keeping visual contact with the aircraft and potential conflicting aircraft. When leaving the vicinity of the aerodrome, the aircraft is transferred to controllers that use radar separation instead, where separation is maintained by monitoring vertical, horizontal and lateral distance to other aircraft and adjacent sector borders using radar information [1].

All available separations to an ATCO are clearly stated in the Operations Manual used in that specific sector or aerodrome, which originate from the basic rules stated in ICAO Annexes and Documents. In Sweden, the standard radar separation between aircraft is 5NM and/or 1000ft, below FL (flight level) 410 (41,000 feet). The radar separation used in TMAs is commonly 3NM, as is the case in Stockholm TMA. Read more about separation standards in chapter 2.3.

Tools available to an ATCO to provide safe and efficient ATC is instructing aircraft to climb, descend, adjust vertical speed, adjust speed and turning the aircraft using radar vectoring or clearing the aircraft to another point [1]. The sheer amount of available clearances and instructions that are at the ATCOs disposable makes it impossible to cover here, but above mentioned clearances and instructions are in general terms what an ATCO uses. Almost all instructions and clearances are given by voice communication using VHF radio frequencies. In the ATCO training process, quite an extensive part of training covers being able to deliver clearances by voice communication in a clear, understandable way. Good English skills (the main language of aviation and the standard language used on ATC frequencies around the world) is a prerequisite for starting ATCO training.

2.2 Separation standards

Separation between aircraft can be distance-based; using lateral, horizontal and/or vertical separation. It can also be time-based, most commonly used following departures and in environments without radar coverage. The provision of ATC, a prerequisite for separation between aircraft, is dependent on the airspace class and flight rules used (Chapter 2.2).

2.2.1 Vertical separation

The minimum vertical separation between aircraft shall be 1000ft below FL290 (29,000ft) and 2000ft at and above this level [1]. However, in RVSM (Reduced Vertical Separation Minima) airspace, aircraft that are RVSM approved can be separated by 1000ft up to and including FL410 (41,000ft). Most aircraft are RVSM approved these days, with the exception of some RVSM exempted military
jets. Europe has had RVSM airspace up and running since January 2002 [6]. On rare occasions, RVSM airspace can be cancelled due to significantly bad weather and severe turbulence. [31]

Figure 1: RVSM Cruising levels [1]

In an ACC environment, cruising levels are allocated in relation to direction of flight. In RVSM airspace, odd levels up to and including FL410 are used by eastbound flights, while even levels are used by westbound flights (Figure 1).

2.2.2 Horizontal separation

Unless otherwise prescribed by the NSA (National Supervisory Authority), the horizontal radar separation minimum shall be 5.0 NM. In an approach environment, this is reduced to 3.0 NM, down to 2.5 NM between succeeding aircraft on the same final approach track within 10 NM from the runway end. There are a number of different criteria that need to be fulfilled for the 2.5 NM separation on final approach to be applied. For example, the runway braking action needs to be reported as “good” and the average runway occupancy time for aircraft using the runway may not exceed 50 seconds [1].

2.2.3 Lateral separation

There are plenty of lateral separations that will not be covered in this report, as they are most commonly used in settings where radar coverage is poor and procedural separations are needed to positively establish that aircraft are separated without using radar. In area and approach control, it is however required to keep a separation of 2.5 NM to the sector boundaries, or half of the radar separation if greater than 5 NM [1]. This is done to make sure that aircraft within own sector do not come too close to aircraft in adjacent sectors, where there is no guarantee that all traffic is known to own sector controllers.

2.2.4 Wake turbulence separation

Extra separation is applied following large aircraft with a high maximum take-off weight. This is due to the phenomena called “wake vortices”. Whenever aircraft aerofoils produces lift, following the difference in pressure between wing surfaces, air follows the wing to the wingtip and creates vortices. These vortices are stronger the heavier the aircraft is, hence wake turbulence separation is applied to avoid aircraft following a large aircraft to be affected by wake turbulence [8].

Aircraft are divided into four different categories, the fourth being introduced recently when the Airbus 380 (the world’s largest commercial jet) was developed (Table 1).
Table 1: WTC [8]

<table>
<thead>
<tr>
<th>WTC (Wake Turbulence Category)</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light (L)</td>
<td>0 – 7,000kg</td>
</tr>
<tr>
<td>Medium (M)</td>
<td>7,001 – 135,999kg</td>
</tr>
<tr>
<td>Heavy (H)</td>
<td>136,000kg +</td>
</tr>
<tr>
<td>Super Heavy (J)</td>
<td>Airbus 380-800 (~560,000kg)</td>
</tr>
</tbody>
</table>

Wake turbulence separation can be either time-based following departure or distance-based (Table 2, table 3). The wake vortices move in a downward spiral to less than 1000ft below the aircraft, so aircraft that are vertically separated are not subject to extra wake turbulence separation.

Table 2: Wake Turbulence radar separation [9]

<table>
<thead>
<tr>
<th>Aircraft Category</th>
<th>Preceding aircraft</th>
<th>Succeeding aircraft</th>
<th>Wake turbulence radar separation minima</th>
</tr>
</thead>
<tbody>
<tr>
<td>Super Heavy (J)</td>
<td>H</td>
<td></td>
<td>6.0 NM</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td></td>
<td>7.0 NM</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td></td>
<td>8.0 NM</td>
</tr>
<tr>
<td>Heavy (H)</td>
<td>H</td>
<td></td>
<td>4.0 NM</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td></td>
<td>5.0 NM</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td></td>
<td>6.0 NM</td>
</tr>
<tr>
<td>Medium (M)</td>
<td>L</td>
<td></td>
<td>5.0 NM</td>
</tr>
</tbody>
</table>

Following departure, the separation between a category Heavy aircraft and a Medium/Light aircraft shall be 2 minutes if using the same runway intersection and 3 minutes if the succeeding aircraft takes off from an intermediate runway intersection[1]:

Table 3: Wake turbulence time-based separation following departure [9]

<table>
<thead>
<tr>
<th>Aircraft Category</th>
<th>Preceding aircraft</th>
<th>Succeeding aircraft</th>
<th>Runway intersection</th>
<th>Wake turbulence time separation minima</th>
</tr>
</thead>
<tbody>
<tr>
<td>Super Heavy (J)</td>
<td>H</td>
<td>M/L</td>
<td>Same/intermediate</td>
<td>2 min</td>
</tr>
<tr>
<td></td>
<td>M/L</td>
<td></td>
<td>Same</td>
<td>3 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Intermediate</td>
<td>4 min</td>
</tr>
<tr>
<td>Heavy (H)</td>
<td>M/L</td>
<td></td>
<td>Same</td>
<td>2 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Intermediate</td>
<td>3 min</td>
</tr>
<tr>
<td>Medium (M)</td>
<td>L</td>
<td></td>
<td>Same</td>
<td>2 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Intermediate</td>
<td>3 min</td>
</tr>
</tbody>
</table>
2.3 Sequencing

Aerodromes are the main bottlenecks in the ATC system [32]. If all aircraft were to land at a busy runway at their time of preference, the congestion would lead to hazardous situations. A runway can only handle one movement at a time, meaning the flow of traffic into the aerodrome needs to be organized in such a way that aerodrome control can cope. This is done by applying the rules of separation, commonly 2.5 NM between arrivals within a 10 NM final, described in chapter 2.3.2. For the aircraft to be ordered in such a way, sequencing techniques need to be applied further out from the aerodrome to ease the burden on the TMA. Much in the same way that aircraft cannot arrive at the same time to a runway, the TMA can only handle a certain amount of traffic as well, like any sector in ATC. The flow of traffic into a TMA usually follows a limited number of entry paths, commonly known as STARs (Chapter 2.5.1), leading past the TMA entry points. These points are called feeder fixes and can be viewed as points that the main flow of traffic passes, feeding the TMA arrival sector with traffic.

To ensure a steady, separated flow of traffic into the feeder fixes, the TMA adjacent ACC sectors apply sequencing techniques to arrange the traffic in a specific order. By speed control, descending traffic to decrease true air speed, radar vectoring and instructions to pass feeder fixes at certain times, traffic can be sequenced in such a way that it can be safely and expeditiously handled by the approach controllers after passing feeder fixes.

Inside the TMA, approach control continues sequencing between aircraft that pass different feeder fixes, creating a final order that the aircraft will use the runway in. There are usually a number of feeder fixes meaning approach control need to create a pattern to join the different entry flows into one (Figure 2).

![Figure 2: Example of entry flows joining into one for RWY26 at ESSA. Red arrows lead to the end of the STARs, where radar vectoring is commenced at the latest (red dotted lines). Blue lines indicate SIDs. [12]](image-url)
2.3.1 Sequencing aids
As ACC sectors usually sequence all traffic past one feeder fix, that is one of many feeder fixes inside the TMA, busy airports need some sort of system to ensure that the flow of traffic does not exceed the TMA maximum capacity. For instance, picture a TMA with four feeder fixes. If aircraft continuously arrive with 5 NM gaps (standard radar separation) to the individual feeder fixes while there is only one arrival runway in use with 2.5 NM spacing, for every four aircraft the TMA will need to apply a 5 NM delay.

While gaps between aircraft can be manually ordered by approach control, as is the case in ATC training, it is not a workload efficient method. Most busy TMAs worldwide use some sort of sequencing aid to avoid this, commonly known as an AMAN (Arrival Manager).

The AMAN systems enable sequencing so that aircraft can be sequenced to one feeder fix in relation to the other feeder fixes. It opts to optimize the traffic sequence by arranging the aircraft order over feeder fixes in relation to proposed order on the aerodrome runway. This is done by allotting aircraft arrival times over feeder fixes, delaying aircraft when needed. Instead of having ACC sectors sequencing independently of other TMA adjacent ACC sectors, the allotted arrival times take all traffic flows into the TMA into account [23].

![AMAN functionality](image)

Figure 3: AMAN functionality [23]. Three aircraft are predicted to land at the same time (14:10), where spacing requirements are applied, producing a landing sequence as the output.

2.4 Approach control
Approach control (APP) takes place in the vicinity of one or more aerodrome(s); following departure when an aircraft is handed over by aerodrome control and preceding arrival before an aircraft is handed over to aerodrome control [1]. Approach control in a major TMA is usually split up according to those two branches; with an arrival and a departure sector, where the airspace is designed to allow handling of most arrivals, including the inbound turns onto the ILS, in the arrival sector.
2.4.1 SIDs and STARs

The path of aircraft in and out of the TMA are called SIDs (Standard Instrument Departure) & STARs (Standard Terminal Arrival Route). They are designed to safely and efficiently get traffic in and out of the TMA. In busy environments the SID and STAR system eases the workload on controllers, as paths are designed to minimize conflicts between arriving and departing traffic [10][12].

Figure 4: Example of SID and STAR network for runway 01R/01L at ESSA [13].

Not all aircraft follow a SID after departure. Aircraft can be assigned alternate departure clearances, such as a heading and a lower altitude than the SID uses. It is common to use alternate departure clearances for slower traffic, to create diverging tracks between aircraft quickly, thus enabling a smoother and more efficient departure flow. Otherwise the faster traffic, that might be flight planed in the same general direction as the slower traffic, would have to wait behind.
The SIDs and STARs are named after points located on the respective flight paths, along with a version number and runway designator.

Table 4: SID and STAR examples [13].

<table>
<thead>
<tr>
<th>Name</th>
<th>Waypoint</th>
<th>SID/STAR</th>
<th>For RWY…</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELTOK6M</td>
<td>ELTOK</td>
<td>STAR</td>
<td>01R (Arlanda)</td>
</tr>
<tr>
<td>DKR4E</td>
<td>DKR</td>
<td>SID</td>
<td>19L (Arlanda)</td>
</tr>
</tbody>
</table>

2.4.2 Approach procedures

There are multiple approach procedures, most of which are IAPs (Instrument Approach Procedures) that utilizes aircraft instruments, in correspondence with ground instruments and navigational aids, to guide aircraft onto the runway. IAPs can be divided into two categories: precision approaches and non-precision approaches [1].

Precision approaches use both horizontal and vertical guidance while non-precision approaches only provide horizontal guidance [33]. An example of a precision approach is the most common IAP: the ILS approach. When weather and other conditions permit, aircraft may land with visual contact with the runway and surrounding terrain [1]. This is called a visual approach and is considered to be an environmental friendly approach as pilots may shorten the downwind and final, thus lowering fuel consumption. However, at many major airports today, the visual approach may only be used sparsely or not at all, due to the fact that pilots are given free choice on pathing; making noise abatement over certain sensitive areas in the aerodrome vicinity a tricky task.

The ILS approach is a precision approach and is definitely the most common approach procedure used today [34]. It utilizes two main instrument components: the LOC (Localizer) for horizontal guidance and the GP (Glide Path) for vertical guidance, both of which are located by the runway. The ILS can be viewed as something like a cone (Figure 5), extending from the runway threshold out to a distance of at least 20 NM (the LOC stretching even further than that). As long as the aircraft is inside the cone, it receives the signal from the ILS and will be able to establish on the LOC and GP.

![ILS Plan View](image)

**Figure 5: ILS in plan and profile view [37]**

When radar vectoring an aircraft for an ILS approach, the aircraft should intercept the ILS LOC at an angle not greater than 30 degrees from the ILS track. The aircraft shall be on that heading for at least 1 NM before establishing on the LOC, and be in level flight, established on the LOC, at least 2 NM before meeting the GP[1]. It is important to establish on the LOC before meeting the GP, as catching
the GP from above is a stressful situation for pilots, and has been the cause of incidents in the past [14].

Figure 6: Radar vectoring for an ILS approach. The line is how the ILS is displayed on a radar screen. The square with a tail of dots is a radar echo of an aircraft. The final heading at which the ILS is intercepted shall be maintained for at least 1 NM according to ICAO regulations.

2.4.3 Approach segments
The approach phase is divided into five different segments (Figure 7).

1. Arrival segment – The arrival segment, or “feeder route” is the route taken from the en-route feeder fix to the IAF. It usually follows a STAR and ends at the IAF. [1]

2. Initial approach segment – Starting off at the IAF, the initial approach segment commences after the completion of the STAR and is often associated with radar vectoring until established on the ILS (Chapter 2.5.4). This segment ends at the IF (intermediate fix). [1]

3. Intermediate approach segment – The segment between the IF and FAF (Final Approach Fix). While in the intermediate approach segment, pilots are to make final speed adjustments and pre-landing checks. [1]

4. Final approach segment – The final approach segment commences at the FAF where the aircraft usually meets the ILS GP, meaning the aircraft will start receiving vertical guidance all the way
down to the runway threshold. The angle at which the aircraft descends from the FAF to the runway threshold is usually around 3 degrees, meaning a standard FAF is about 6 NM out from the threshold if aircraft are to intersect with the GP at 2,500ft. The final approach segment ends at the MAP (Missed Approach Point). [1]

5. Missed approach segment – When an aircraft is to land, requirements to land need to be met before reaching the decision height. If requirements are not met, the aircraft cannot land and will need to initiate the missed approach segment to go around for another approach. The landing requirements depend on the ILS category (Category I-IIIC) determined by how the ILS is equipped and if aircraft are, in their turn, equipped to make use of the different ILS categories. The best ILS category that can be used in practically 0 visibility is the “ILS CAT IIIIC”, mostly found at major airports. [1]
Stockholm TMA

Stockholm TMA is roughly the airspace surrounding Stockholm Arlanda and Stockholm Bromma, with the air above Västerås airport in the west, Uppsala in the north, Nynäshamn to the south and extending out in the Baltic Sea in the east. It is divided into three sectors; East, West and South and can be manned with up to seven controllers at the same time.

The following chapter will go into detail on the TMA; describing the geography, working positions, traffic flows and working methods. To understand how arriving and departing traffic to the Stockholm airports is handled, one must first dig deeper into the conditions, rules and methods that constitute the basis for Stockholm TMA operations.

3.1 Geography

Stockholm Arlanda is located due north of Stockholm, around 35km from the city center, about half way to Uppsala. The airport’s closest neighbor is Stockholm outer suburb Märsta, due southwest of runway 01L/19R. The airport’s proximity to the outer suburbs of Stockholm affects the operations at the airport due to its environmental licensing [36]. For instance, the license permits use of two out of three runways simultaneously – meaning the airport never operates at full runway capacity – and regulates the use of different runways during the night due to noise abatement standards.

Stockholm Bromma is much closer to the city, only about 8km from the city center in the western parts of Stockholm inner suburb Bromma. The airport is closed from 10 pm to 7 am on weekdays due to noise abatement, as arriving and departing traffic need to fly over densely populated areas.
3.2 Sectors

Stockholm TMA is divided into three sectors: E (East), W (West) and S (South), with boundaries between the three, and adjacent sectors, drawn to allow for an efficient traffic flow of departing and arriving traffic to Stockholm Arlanda and Stockholm Bromma.

![Diagram of Stockholm TMA sectors]

Figure 9: Stockholm TMA sectors [13]

3.2.1 Sector E

Sector E is the main arrival sector in Stockholm TMA, located east of the dividing sector boundary between RWY 01L/01R (or 19R/19L), as shown in Figure 9. The main traffic flows into sector E will look differently depending on the runway configuration, but the working method during traffic peaks has the same principles regardless of the runways in use. Arriving aircraft will follow the STARs inbound the IAFs TBY and ERK and be radar vectored from any given point along the STAR, at the latest by the IAF, to the arrival runway in use (Chapter 3.4) [13].
Sector East’s vertical limits are displayed on Figure 9, with a roof of FL195 (sector 6 above), extending all the way down to GND (Ground), except for in the south where sector S has the airspace between FL65 and GND to vector aircraft in and out of Stockholm Bromma [13].

![Figure 10: Sector E [36]](image)

3.2.2 Sector W

Sector W is the main departure sector in Stockholm TMA. The vertical limits of sector W are more complicated than the ones in sector E, as sector W is connected to both sector Västerås and sector Uppsala, controlled by respective aerodrome control. Sector W controllers do not vector aircraft all the way in to either of those aerodromes, as they provide approach control services themselves [36].

The departure flow, or SID network, existent in sector W looks differently depending on the departure runway in use, meaning areas of conflict will move with the runway configuration. As RWY 30 is in use at Stockholm Bromma, the departures from ESSB will enter sector W and may conflict with
ESSA departures. While the main focus in sector E is the arriving traffic, sector W handles mainly departures [36].

Figure 11: Sector W [36]

3.2.3 Sector S
Sector S is the main sector controlling traffic to and from Stockholm Bromma. As ESSB and ESSA are so close to each other, the need for coordination between sector S and sector E/W is big, especially with certain runway configurations. The vertical limits of sector S is GND up to either sector E or W when on top, or FL105 with sector 2 above [36].
3.3 Working positions

There are several working positions in Stockholm TMA, each with its own purpose and responsibilities, the latter being strictly documented in the Operations Manual [36]. Positions can be opened and closed in relation to the current traffic situation. During night time operations there is only one position open at a time, while it is possible to have up to seven open simultaneously. There are no exact rules of when to open up a new position, or close one down. The TS-T monitors traffic load numbers, MAESTRO data and other factors, and can actively decide whether to open up a position or not. The opening and closing of working positions is based a lot on working experience.

- **WS (Watch Supervisor)**: The WS is not a working position in the TMA, but has the general responsibility of the operations room at ATCC Stockholm. The WS has responsibility over staffing during watch hours, ATFCM and administrative work. In case of an emergency, the WS assists and spreads information accordingly [36].
• **TS-T (Tactical Supervisor Terminal):** The TS-T position is not operative in the same sense as other TMA working positions. There is no voice communications with pilots, but the TS-T covers a more administrative and flow management filling function, much like the WS: TS-T sets the landing rate for Stockholm Arlanda, using Ratetest and taking the current and imminent traffic pattern into account, as well as other circumstances affecting the rate at which arrivals are predicted to be able to land. After the landing rate has been set, TS-T makes inputs into the sequencing aid MAESTRO (Chapter 5) [36].

The TS-T is responsible for various other system inputs, as the runway configuration, current open working positions and which areas that are STCA exempted\(^1\), the latter depending on the runway in use [36].

• **APP-C:** APP-C is the planner position (Chapter 1.6) for the arrival sector in Stockholm TMA, coordinating the flow of traffic in and out of the TMA when required. The silent agreements between Stockholm TMA and adjacent sectors dictates what needs coordination and what does not. For example, traffic deviating from STAR needs to be coordinated with APP-C, which is likely when there is thunderstorm activity in the vicinity of TMA entry points. When a runway change is needed or required due to environmental restrictions, APP-C coordinates the last departure and last arrival with ESSA tower [36].

• **ARR-E:** ARR-E (Arrival East) is the sector responsible controller for TMA sector E (East). If the DIR-E position is closed, ARR-E is responsible for approach control, by clearing traffic in accordance with their approach procedure onto final approach at ESSA. ARR-E delivers traffic to the DIR-E from sector E, on a suitable heading with the standard altitude of 5,000ft. There is no exact boundaries of the responsibility division between ARR-E & DIR-E; the positions are seamless [36].

• **DIR-E:** The DIR-E (Director East) operates close to the final, making the last inbound turns onto the ILS for the runway in use. Only arriving traffic is handled, with the objective to distance aircraft on final in an optimized way, while always staying within separation limits. Speed control is used extensively to ensure that minimum separation is upheld at all times. As aircraft cannot be speed controlled past 4 NM final, it may sometimes be needed to coordinate with ESSA tower for them to claim the separation responsibility. This is possible when visibility is such that aerodrome controllers can separate aircraft on short final visually. Aircraft that are transferred to the DIR-E are released for further descent, turns towards the final and speed control. The DIR-E position opens when there are many simultaneous arrivals to ESSA, and/or when traffic complexity in sector East demands it [36].

• **ARR-W:** ARR-W (Arrival West) is the sector responsible controller for TMA sector W (West). If the DEP-W position is closed, ARR-W is responsible for all west, north and southbound departures as well as arrivals inbound ELTOK (feeder fix in sector W). ARR-W and DEP-W operate within the same sector but on different frequencies. Aircraft that conflict with arrivals are usually on the ARR-W frequency [36].

---

\(^1\) STCA exemption exists to ensure the STCA alarm is not triggered close to the final, as the alarm would go off too frequently. The zone in which STCA is exempted depends entirely on the runway configuration.
- **DEP-W**: DEP-W (Departure West) is responsible for ATC for by ARR-W delegated aircraft within sector W; the majority of ESSA departures and aircraft that conflict with the departure flow [36].

- **APP-S**: APP-S (Approach South) is the sector responsible controller for TMA sector S (South). If the DIR-S position is closed, APP-S is responsible for approach control, by clearing traffic in accordance with their approach procedure onto final approach at ESSB [36].

- **DIR-S**: The DIR-S (Director South) has the same responsibilities as DIR-E, but for Stockholm Bromma instead of Stockholm Arlanda. The amount of simultaneous arrivals to ESSB is lower, but as the conditions in sector S are different, it is not uncommon for DIR-S to be open.

- **DEP-E**: DEP-E (Departure East) will be available to open during hours when the amount of eastbound ESSA departures creates complex traffic scenarios, easing ARR-E workload. ARR-E and DEP-E will operate in the same sector, but on different frequencies [36].

### 3.4 Traffic flow patterns

The traffic flow in and out of Stockholm TMA will vary depending on the runway configuration for ESSA and ESSB. As the runway configuration determines conflict areas, how much space there is for radar vectoring, flight level restrictions at feeder fixes etc., it is the number one determining factor for traffic patterns inside the TMA. In turn, the traffic flow will affect controller workload and overall capacity. This chapter aims at describing the traffic patterns at Stockholm Arlanda, in relation to Stockholm Bromma, with the use of different runway configurations. Focus will be placed on the peak operation runway configurations: 01R/01L and 19L/19R.

#### 3.4.1 Runway 01R/01L

The 01R/01L runway configuration is used when winds are northerly, with runway 01R for landing and 01L for departure. Using the left runway for departure enables using sector E as the main arrival sector, as aircraft that are north-, south- or westbound do not affect sector E, leaving as much space as possible for radar vectoring arrivals.

This runway configuration is a bit special for arrivals, as the final – extending to the south as the runway faces north – conflicts with ESSB RWY 30 departures. ESSA arrivals will establish on the localizer at 4,000ft instead of the standard 2,500ft; which means that aircraft will meet the GP (Chapter 2.5.3) a lot further out from the runway threshold when established on the LOC. ESSB departures climb to 3,000ft; below ESSA arrivals, and will not be able to climb further until clear of ESSA traffic.

The longer finals for RWY 01R and the increased traffic complexity with conflicting ESSB RWY 30 departures led to an amendment in the Operations Manual for Stockholm TMA:

> “When RWY 01R/01L or 01L/08 are in use, landing rate should be 38”

The newly updated Operations Manual however changed this to “…landing rate should not be higher than 40” while the work on this thesis was in progress.

---

2 The DEP-E position is not yet in place, but will be implemented in the near future after successful simulation[16].
3.4.2 Runway 19L/19R

With southerly winds the 19L/19R runway configuration is used. Following the same concept as for RWY 01R/01L, runway 19R is used for departures to keep the main departure flow in sector W. Low speed departures will departure on a heading and are, if eastbound, radar vectored below the southern arrival flow until free and able to climb further.

The eastern and southern arrival flow meet the northern around where the arrows point (Figure 13), by IAF “ERK” (Figure 15) where the STARs end. In high traffic intensity, the ARR-E has the option to radar vector aircraft from the vicinity of ERK down on a southbound heading, before turning aircraft on a downwind and handing over traffic to the DIR-E. The flight paths for aircraft from the north will then resemble an “S”, which is why that methodology is called an “S-curve”. The same pattern can of course be found for RWY 01R/01L as well, as can be seen in Figure 13 with arrivals from the south.

This runway configuration creates less complex scenarios including ESSB, but traffic to ESSB from the north when RWY 30 is in use will meet the ESSA arrival flow to RWY 19L.

Figure 13: Runway 01R/01L. Red arrows indicate the arrival flow (STARs), blue arrows indicate the departure flow (SIDs) [12].
3.4.3 Runway configuration at ESSB

The runway used at ESSB will also have an impact on TMA traffic flow patterns. With RWY 30 in use, arrivals to Bromma from the north and east will pass through sector E, adding to traffic complexity as the traffic occasionally conflicts with ESSA movements (Figure 15). Traffic on STAR “HMR 6Y” and XILAN 5Y” cover quite some distance in nautical miles in sector E airspace. While there is also two STARs to ESSB with RWY 12 in use passing through sector E, aircraft from the north are often given shortcuts through sector W to avoid the detour through sector E [28], affecting the arrival flow to ESSA less. This is just an example of why runway 12 is perceived to provide a little less complex scenarios for sector E than runway 30.
Figure 30: Bromma traffic pattern (RWY 30).
3.5 Feeder fixes

Stockholm TMA has four main feeder fixes: HMR to the north, XILAN to the east, NILUG to the south and ELTOK to the west (Figure 15). Traffic to ESSB from the south passes TRS, meaning the ESSA and ESSB arrival flows are separated.

Figure 15: TMA feeder fixes. The red arrows indicate the direction of the traffic flow after passing fixes. The orange arrow indicates ESSB traffic [36, with own edits].

All traffic inbound TMA feeder fixes are restricted to be below a certain FL, depending on the arrival runway, to ensure traffic will be around the same altitude when approaching the IAF (Table 6).

Table 5: Level restrictions for TMA feeder fixes. Cleared flight level, with the level restriction within the parenthesis [36].

<table>
<thead>
<tr>
<th>ESSA arrivals</th>
<th>HMR</th>
<th>XILAN</th>
<th>NILUG</th>
<th>ELTOK</th>
</tr>
</thead>
<tbody>
<tr>
<td>RWY 01L/R</td>
<td>FL 100 (190)</td>
<td>FL 120 (150)</td>
<td>FL 110 (150)</td>
<td>FL 110 (110)</td>
</tr>
<tr>
<td>RWY 19 L/R</td>
<td>FL 100 (150)</td>
<td>FL 120 (150)</td>
<td>FL 110 (190)</td>
<td>FL 110 (110)</td>
</tr>
<tr>
<td>RWY 26</td>
<td>FL 100 (150)</td>
<td>FL 120 (120)</td>
<td>FL 110 (190)</td>
<td>FL 110 (150)</td>
</tr>
<tr>
<td>RWY 08</td>
<td>FL 100 (190)</td>
<td>FL 120 (190)</td>
<td>FL 110 (190)</td>
<td>FL 110 (110)</td>
</tr>
</tbody>
</table>
3.6 Landing rate

Landing rates in Stockholm TMA are applicable for ESSA, but not for ESSB. The MAESTRO (chapter 4.2) functionalities are currently being tested for future implementation for ESSB as well. The process for setting a landing rate for ESSA is described in the Operations Manual, according to the following steps [24]:

1. Apply a buffer of +0.5 NM to the minimum separation on final approach into Ratetest (chapter 4.1)
2. Add the wind component (to Ratetest).
3. Analyze the weather situation
4. As a complement, analyze the flight list data (examples of influential factors are non-ESSA arrivals and predicted traffic complexity)
5. Set the landing rate.

As a redundancy to Ratetest, the table below is used as a general guideline of what rate to set with different distances on final approach:

Table 6: Rate by final distances [36].

<table>
<thead>
<tr>
<th>Minimum distance on final</th>
<th>2,5</th>
<th>3</th>
<th>3,5</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate</td>
<td>40-42</td>
<td>36-39</td>
<td>33-35</td>
<td>30-32</td>
<td>27</td>
<td>24</td>
<td>22</td>
<td>19</td>
</tr>
</tbody>
</table>

---

3 The flight list data that the report refers to is the same as the entry count data in Chapter 5 – Data collection.
4 Technical Tools

4.1 Ratetest

Ratetest is a table programmed in Excel to provide the TS-T with a basis for setting the landing rate. It is programmed to account for wind and runway configuration, as well as minimum distance on final. The format still used today was developed year 1999, and is an in-house solution made by LFV. When entering wind values and minimum distance used on final, with a 0.5NM buffer above minima separation, the model computes a landing rate [27]. As the normal separation during peak hours is 2.5NM between aircraft, given that conditions for that are met, the standard distance used when computing the peak landing rate is 3NM (Figure 16-17).

The software is merely a tool to help the TS-T set a feasible landing rate, but is considered to still fulfill its purpose [29]. The distance buffer of 0.5NM comes in handy to ensure the DIR-E has a sufficient buffer for vectoring onto final by tightening the sequence.

![Ratetest Table](image)

**Figure 16**: Image of Ratetest. In the marked areas in the picture; "Bana" is Runway, "Markvind" is surface wind, "Vind 1.5ft" is the wind at 1,500 feet and "avstånd" is the minimum distance on final, plus a buffer of 0.5NM.

When Ratetest was implemented as a tool for setting the landing rate, many more of the parameters in the table were used than today. Inputs were made according to how many aircraft of different wake turbulence categories that were flight planned to enter the TMA, it was possible to changes to the “Max in TMA” cell according to restrictions of how many aircraft that could occupy sector E (Chapter 3.2.1) at any given time, and one could get an image of the capacity loss due to different inputs in the “S:A KAP. Förlust” cell [27]. The wake turbulence function in Ratetest is now

Axel Rydin
Stockholm TMA Capacity
axery746@student.liu.se

1.1
redundant, as MAESTRO automatically creates gaps between aircraft of different wake turbulence categories, no matter the rate (Chapter 4.2).

Today, Ratetest is used to calculate the theoretical amount of arrivals that can land during one hour, taking a buffer of 0.5NM into account, during given wind, runway and minimum final on distance conditions. Those three parameters make out the input and will, when combined, give an output in form of arrivals per hour to Stockholm Arlanda (Figure 17).

**Figure 17:** Input and output in Ratetest as it is used today. In this example, the combined runway, wind and distance inputs gives a theoretical arrival count of 38.17 aircraft per hour.

Take note that the “Rate” window is not used today, the TS-T looks directly at the output and uses that as a factor for determining the landing rate [28].
4.2 MAESTRO

“MAESTRO” is the sequencing tool used in Swedish and Danish airspace, integrated into COOPANS and developed by French ATC system developer Egis-Avia. It is the most commonly used sequencing aid in the world [15]. The main functions of MAESTRO are the AMAN and DMAN (Departure Management) functions, where AMAN’s purpose is to optimize the landing sequence at a specific aerodrome.

The AMAN function provides an arrival sequence to the TMA, displayed to all affected controllers in Approach and adjacent En-route sectors. This enables controllers to handle arriving traffic in an efficient way, determining delay for arriving aircraft in relation to the current landing rate input into MAESTRO. The system evens out workload between en-route and approach controllers, as the arrival flow into the TMA is restricted by the delay figures for concerned aircraft; a direct result of the landing rate input into the system.

In Stockholm TMA, Maestro is used for determining sequence and time over feeder fixes [23]. There is no operational use of Maestro after the feeder fix for the controllers operating the ARR-E and DIR-E positions, but the by Maestro proposed runway sequence can be used as a guideline if preferred. This means that the sequence inside Stockholm TMA is fully determined by controllers manning the sector and may differ from what Maestro bases the time over arrival fix from.

MAESTRO is an optimization tool that relies on a number of inputs into the system, to produce an arrival sequence over TMA feeder fixes as the output. One of the inputs made on several occasions during a day is the landing rate. The time for an aircraft over a given feeder fix will be directly reliant on the set rate, as the maximum number of aircraft sequenced into the TMA over any given hour is the same as the landing rate (if not manually overridden by the APP-C). The ACC sectors are given a margin of +/- 2 minutes to match the time given by MAESTRO for any aircraft, but may sequence aircraft no tighter than 5 NM apart (constant or increasing), according to standard separation (Chapter 2.3.2). The time buffer allows ACC controllers to deviate slightly from MAESTRO feeder fix times, as it is a challenging and capacity demanding task to match the times exactly. Given that the demand is equal to or greater than the landing rate, this means that there is no guarantee for the entry flow to be equal to the landing rate.

In basic terms, MAESTRO calculates feeder fix times by dividing an hour with the landing rate, giving a number of seconds between arrivals on final approach. The surface wind component is then taken into account, which combined with wind at FL100 produces a calculated distance between arrivals. Depending on the wind component, a set value of 90 seconds between arrivals could mean vastly different distances between aircraft, especially when aircraft are facing strong headwind on final approach [29]. The concept is similar to the one used in Ratetest (Chapter 5.1), with the main difference that the landing rate is an input in MAESTRO and an output in Ratetest.

4.2.1 Effects on arrival outcome

As the operational importance of the set landing rate is the input of it into MAESTRO, the MAESTRO system plays an important part in the actual outcome of arrivals per hour. The traffic flow into the TMA is regulated by MAESTRO output, but can be manually changed by APP-C by coordinating with ACC sectors. If a landing rate of 40 is used, the times over feeder fixes are arranged by MAESTRO to let the same number of aircraft per hour into the TMA.
4.2.2 Wake turbulence functionalities

Maestro has a built-in constraint to take wake turbulence separation into account. If a landing rate of 40 is put into the Maestro, but the 40 aircraft in sequence to land within a particular hour has a number of Heavy aircraft in it, Maestro will force extra separation to be built into the sequence, resulting in an actual landing rate lower than 40 [29]. The functionality was explained in detail in an OI (Operative Information) message (Appendix sent out while this thesis is a work in progress.)

The only aircraft types exempted from the MAESTRO wake turbulence functionality are the B757 (Heavy when preceding other traffic, Medium when trailing [8]), A380 (treated as Heavy in MAESTRO, but should be Super Heavy) and the T402. Stockholm Arlanda only gets the occasional B757 out of the three types. [31]
5 Data collection

During the period October 9th – November 20th, data was collected through the TS-T position with the purpose of following up how set landing rates turn out in terms of arrivals per hour at Stockholm Arlanda. To avoid having to be on the spot for every traffic peak during the data collection period, a form (Appendix I) was created for the TS-Ts to fill in for every peak. The form was a necessary tool to understand why a certain landing rate was set and how conditions at the airport were during the time when that specific peak rate was in place.

For every day in the data collection time period where a filled-out form or runway report exists, data was extracted directly from the “Network Manager” EUROCONTROL database using the date and times from the form and/or runway reports (Chapter 5.2-5.3). The data used comes in three different forms:

- **Traffic Load: ESSA Arrival Count**
  The most important part of the arrival count data is the actual landing time of any given aircraft on the list. By counting aircraft within a certain time frame using the actual times of arrival (ATA), it is possible to draw first conclusions of landing rate outcome. The ATA is updated on short final approach, shortly before the runway threshold.

  ![Figure 18: Traffic Load: ESSA Arrival Count. Columns to the far left and far right include the ATA (same data) for every aircraft. Aircraft are represented by a call-sign (column 2), aircraft type (column 3), departure and destination aerodrome (column 4-5).](image)

  The column showing aircraft types (by ICAO aircraft type designator [30]) does not include information on aircraft wake turbulence category. This has been noted manually in the data, as it is significant information for data analysis.

- **Traffic Load: TMA Entry Count**
  The entry count data show all movements in the TMA that affect sector E during a certain time frame. This data has been used to follow up how many aircraft that enter the TMA, that can be put in relation to landing rate. The data shows arrivals sorted by entry times into Stockholm TMA. The actual time of arrival from the arrival count data is viewable in this data as well, but aircraft are not sorted by it.

  ![Figure 19: Traffic Load: TMA Entry Count. Aircraft are sorted by the TMA entry time (column 1). The ATA is shown as well, in the far right column.](image)
Entry count data has not been collected for all of the dates during the time period. It has been used as support data to analyze peak periods with a relatively high demand, to investigate whether the difference between landing rate outcome and traffic demand can be related

- Traffic demand: ESSA Arrivals
This data contains the flight planned arrival time for each aircraft arriving at Stockholm Arlanda during a certain time frame. It is used as an overview of traffic demand during peak hours. If the amount of aircraft during a specific time frame exceeds the landing rate, the demand is probable to be higher than what the TMA can handle capacity wise; with ACC delay as a possible outcome. It is important to note that the arrival time in the TDD is from flight planned data, updated shortly after take-off, meaning the actual arrival time may differ from that for a number of reasons.

<table>
<thead>
<tr>
<th>05:10X</th>
<th>ED31490</th>
<th>E737</th>
<th>ESSA</th>
<th>E</th>
<th>350</th>
<th>04:36</th>
<th>04:35X</th>
<th>N</th>
<th>I</th>
<th>1</th>
<th>04:33</th>
<th>05:10X</th>
</tr>
</thead>
<tbody>
<tr>
<td>05:12X</td>
<td>E01100X</td>
<td>E577</td>
<td>ESSA</td>
<td>E</td>
<td>100</td>
<td>04:36</td>
<td>04:35X</td>
<td>N</td>
<td>I</td>
<td>0</td>
<td>04:28</td>
<td>05:12X</td>
</tr>
<tr>
<td>05:22X</td>
<td>L11101X</td>
<td>E170</td>
<td>ESSA</td>
<td>E</td>
<td>300</td>
<td>04:34</td>
<td>04:35X</td>
<td>f</td>
<td>I</td>
<td>1</td>
<td>05:17</td>
<td>05:22X</td>
</tr>
<tr>
<td>05:28X</td>
<td>E03204X</td>
<td>E736</td>
<td>ESSA</td>
<td>E</td>
<td>320</td>
<td>04:46</td>
<td>04:45X</td>
<td>N</td>
<td>I</td>
<td>1</td>
<td>04:44</td>
<td>05:28X</td>
</tr>
<tr>
<td>05:30X</td>
<td>W7880X</td>
<td>E754</td>
<td>ESSA</td>
<td>E</td>
<td>450</td>
<td>04:46</td>
<td>04:45X</td>
<td>N</td>
<td>I</td>
<td>1</td>
<td>04:49</td>
<td>05:30X</td>
</tr>
<tr>
<td>05:32X</td>
<td>E50409X</td>
<td>E577</td>
<td>ESSA</td>
<td>E</td>
<td>360</td>
<td>04:36</td>
<td>04:35X</td>
<td>t</td>
<td>I</td>
<td>1</td>
<td>04:32</td>
<td>05:32X</td>
</tr>
<tr>
<td>05:38X</td>
<td>E53173X</td>
<td>E738</td>
<td>ESSA</td>
<td>E</td>
<td>370</td>
<td>04:53</td>
<td>04:50X</td>
<td>N</td>
<td>I</td>
<td>1</td>
<td>04:58</td>
<td>05:38X</td>
</tr>
<tr>
<td>05:48X</td>
<td>E32140X</td>
<td>E736</td>
<td>ESSA</td>
<td>E</td>
<td>370</td>
<td>04:34</td>
<td>04:35X</td>
<td>f</td>
<td>I</td>
<td>1</td>
<td>04:43</td>
<td>05:48X</td>
</tr>
<tr>
<td>06:10X</td>
<td>A14207X</td>
<td>E321</td>
<td>ESSA</td>
<td>E</td>
<td>370</td>
<td>04:46</td>
<td>04:45X</td>
<td>t</td>
<td>I</td>
<td>1</td>
<td>04:46</td>
<td>05:30X</td>
</tr>
<tr>
<td>06:12X</td>
<td>E53138X</td>
<td>E736</td>
<td>ESSA</td>
<td>E</td>
<td>370</td>
<td>04:36</td>
<td>04:35X</td>
<td>N</td>
<td>I</td>
<td>1</td>
<td>04:58</td>
<td>05:31X</td>
</tr>
</tbody>
</table>

Figure 20: Traffic demand: ESSA Arrivals. Columns to the far left and right show the ETA (same data).

5.1 Data delimitations
All data is collected by hand and is not available digitally. Data processing is therefore a time consuming task, which means that the statistical material cannot be too extensive. All data is in paper format and it is not possible to filter it any further than the options given in EUROCONTROL “Network Manager” before printing it.

The arrival count data landing times accuracy is on a per minute-basis, rounded up to the nearest whole minute. This means that sometimes aircraft land on the same time in the data. As numbers are rounded up, the maximum time based distance between two aircraft with the same time is 59 seconds. The minimum separation on final is 2.5NM, so it is possible for two aircraft to come as close as 59 seconds without coming too close. When weather permits, Arlanda tower can assume responsibility for the separation by visual means, negating the need for the radar separation of 2.5NM.

The entry times in the entry count data are based on the time when an aircraft enters the TMA. As it can occur that aircraft enter by other means than over feeder fixes (for example by direct routing to IAF before reaching feeder fix), it is not certain that the amount of aircraft entering the TMA will be the same as the landing rate, given that the demand for that exists. It is possible that the entry count and landing rate do not match, as a set landing rate is no guarantee that the exact amount will be fed from ACC sectors during an hour, even though the demand exists. As ACC controllers have a +/- 2 minute buffer for the time in MAESTRO, there may be deviations from the landing rate. Therefore, entry count data was not used extensively, but was used as a mean for TMA efficiency analysis.

Traffic demand data is based on flight planned arrival times. If the actual landing times in the arrival count data differ from traffic demand data times, there are a number of things that could have caused the delay. The delay could have emerged during the early stages of the flight, during en-route or in

4 Note: seconds mentioned do not relate to a time-based separation, but rather explains why two aircraft in the data can arrive at the same minute.
holding over feeder fix. As the data does not show where the delay, if any, emerged, the data cannot be used to determine TMA capacity caused delays.

5.2 Form
To gain further understanding of reasons behind the landing rates set in Stockholm TMA, a form was developed where the TS-T could fill in the rate on a daily basis, along with other useful information to analyze rate outcome. The form (Appendix I) used was created for that purpose, and the TS-Ts in Stockholm TMA had the opportunity to give feedback on a draft before distribution in the TS-T position. The following elements were regarded important:

- Rate: The landing rate set during a specific time frame
- Runway configuration: Runways in use at ESSA & ESSB, which affects what rate can be set and, in conjunction with the wind component, determines the time between arrivals on final.
- Ratetest: Rate suggested by the Ratetest formula.
- Factors to the set rate: On what basis is the landing rate set, other than the Ratetest suggestion?
- Significant weather: If any weather affects the traffic flow in the TMA during the hours of the rate.
- Other actions taken: Refers to MDI, ATFCM regulations, arrival gaps and other actions that reduce the traffic flow into the TMA.

The main purpose of the form was to answer the following questions, which then created a basis for looking at the different types of data from the “Network Manager” (Chapter 5.1):

- What is the landing rate?
- Why is a certain landing rate set?
- What are the conditions at the time for the rate?

For peak periods with a lack of a completed form, archived reports on runway configuration and rate during which time were used instead (Chapter 5.2.2).

5.2.1 Form turnout
The form usage is considered fairly high, with an average of almost one form filled out per day. As there are two main peak periods during any given day (7-8 local time in the morning, and 15-17 in the afternoon), forms were filled out a little less than 50% of the time.

The TS-Ts were instructed to fill in a form for every peak period. At times when the rate changed during peak hours, they had the opportunity to enter the new rate (and reasons behind it) in the far right column of the form.

5.2.2 Shift report runways (runway report)
For dates when rate forms have not been filled out, it was possible to get hold of rate data for most dates during the data collection period. This was done by copying the archived runway reports, where runway configuration, Ratetest output and actual landing rate (referred to as the “MAESTRO Rate”) are listed. The main data from ACD, ECD and TDD lists were printed for these dates as well, giving a minimum output of rate outcome without knowledge of factors behind the set rate.
Table 7: Shift Report Runways example from October 15th Stockholm TMA.

Shift Report Runways
2013-10-15

<table>
<thead>
<tr>
<th>Time</th>
<th>Wind component (Unused)</th>
<th>RWY ESSA</th>
<th>RWY ESSB</th>
<th>Distance final</th>
<th>Ratetest output</th>
<th>Maestro Rate</th>
<th>Outcome (Unused)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>00.00</td>
<td>26/19L</td>
<td>30</td>
<td></td>
<td></td>
<td>42</td>
<td>41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>05.00</td>
<td>19L/19R</td>
<td>30</td>
<td>2.5</td>
<td></td>
<td>42</td>
<td>41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>06.35</td>
<td>26/19R</td>
<td>30</td>
<td>3</td>
<td>37,43</td>
<td>38</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.30</td>
<td>26/19R</td>
<td>30</td>
<td>3</td>
<td>37,43</td>
<td>38</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.35</td>
<td>01R/01L</td>
<td>30</td>
<td>2.5</td>
<td>44</td>
<td>40</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18.30</td>
<td>26/01L</td>
<td>30</td>
<td>5</td>
<td>27</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19.16</td>
<td>01L/08</td>
<td>30</td>
<td>2.5</td>
<td>41</td>
<td>40</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.2.3 Shift Reports
For every ATC shift at ATCC Stockholm, the TS-T, WS and TS-A (Tactical Supervisor-Area) fill in shift reports where information regarding a shift is compiled into one document. The shift report can contain information on conditions that might have affected the landing rate for a specific day, but rarely states the landing rate explicitly. Because of this, the information in the shift reports have not been extensively used for this thesis, but can sometimes provide useful hints on what the traffic situation under a given landing rate was like.

5.3 Data usage
Data described in Chapter 5.1-5.2 is used to follow up the outcome of arrivals, the actual landing count, put in relation to the current landing rate, as well as looking at landing rate contributors. Firstly, the form, runway report (and shift reports) are used to provide an image of the conditions for a specific peak period, according to the questions in chapter 5.2.1. Secondly, the raw data with the arrival outcome for certain peak periods is extracted from the arrival count data. This data provides actual numbers (traffic counts) for the given time frame. Thirdly, the outcome is put in relation to traffic demand for further analysis. All of the data is then compiled into one excel table (Appendix II: table of results) to make analysis easier.

Chapter 5.3.1 further explains the data usage process.
5.3.1 Data usage example: 2013-10-08
To exemplify the process, the first date of the data collection period (October 8th) has been chosen as a sample instance.

This date has a completed form, which means the runway report is not included as it contains the same information. The rate was 41, with a Ratetest output of 43 for the peak period, with runway 19L/19R in use at Stockholm Arlanda and runway 30 at Stockholm Bromma (Figure 21).

![Completed form, 2013-10-08](image)

The information from the form is then used when looking at the arrival count data from the "Traffic Load: ESSA Arrival Count" lists.

The arrival count data is then printed out and arrivals are counted to find the outcome for the hour, and half hour, with the most traffic during the specific peak period. In this case, this hour occurs between 05:12 and 06:11 (UTC) with a total of 37 arrivals, 2 of which are classified as wake turbulence category Heavy. The half hour is not necessarily within the time frame of the hourly outcome, but in this case it is; with a number of 21 arrivals (1 of which is Heavy) (Figure 22).
Figure 22: Arrival count data, time 04:40-05:58 (next hour on the next page, not displayed here).

The outcome is then compared to the demand in the traffic demand data (Traffic Demand: ESSA Arrivals list). The hour does not necessarily need to match in time, as the ETAs in the traffic demand data are estimates made prior to any sequencing or en-route delays inbound ESSA. Instead, the hour with the maximum number of estimated arrivals is used as an estimate of traffic demand.

In this case, the demand during the first peak period of October 8th is 38 arrivals, one of which is of wake turbulence category Heavy, for one hour. The half hour period contains 23 aircraft, also with one Heavy (Figure 23).
Figure 23: Traffic demand data for 2013-10-08. There are 23 arrivals within the 30 minute interval in the picture, one of which is Heavy (SAS946, ETA 05:18).

Lastly, all of the information gathered from the form and the data for this date is input into an excel file (Appendix II), used as means for result compilation and analysis (covered in Chapter 6).
6 Results & Analysis from data collection

This chapter aims at presenting results from the time frame of the data collection period (October 8th – November 20th) in a comprehensible way. Using an excel table (Appendix II: Table of Results), the statistics from the data have been analyzed to try and answer the following main questions, that originate from the thesis objectives (Chapter 1.2):

- What set of factors determine the landing rate during different conditions?
- How does the arrival count (outcome) compare to the landing rate?

Furthermore, any trends in statistics that might be interesting to look at are presented here as well.

6.1 Result reading guidelines

The Table of Results (Appendix II) is divided into several columns that need explanation before reading.

<table>
<thead>
<tr>
<th>Date</th>
<th>Day</th>
<th>Rate</th>
<th>Ratenet</th>
<th>Out(1h)+H</th>
<th>Out(30)+H</th>
<th>Dem(1h)+H</th>
<th>Dem(30)+H</th>
<th>RWY ESSA</th>
<th>RWY ESSB</th>
<th>Kommentarer</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013-10-08</td>
<td>Am</td>
<td>41</td>
<td>41</td>
<td>39</td>
<td>22</td>
<td>39</td>
<td>24</td>
<td>19R</td>
<td>30</td>
<td>Outcome Rate</td>
</tr>
<tr>
<td>2013-10-08</td>
<td>Pm</td>
<td>41</td>
<td>41,56</td>
<td>38</td>
<td>20</td>
<td>0</td>
<td>0</td>
<td>19R</td>
<td>30</td>
<td>Outcome Rate</td>
</tr>
<tr>
<td>2013-10-09</td>
<td>Pm2</td>
<td>39</td>
<td>39,5</td>
<td>35</td>
<td>20</td>
<td>0</td>
<td>0</td>
<td>01R/01L</td>
<td>30</td>
<td>Outcome Rate</td>
</tr>
<tr>
<td>2013-10-10</td>
<td>Pm1</td>
<td>40</td>
<td>40,7</td>
<td>20</td>
<td>20</td>
<td>0</td>
<td>0</td>
<td>01R/01L</td>
<td>20</td>
<td>Outcome Rate</td>
</tr>
<tr>
<td>2013-10-10</td>
<td>Am</td>
<td>35</td>
<td>35,5</td>
<td>38</td>
<td>21</td>
<td>35</td>
<td>24</td>
<td>19R</td>
<td>30</td>
<td>Outcome Rate</td>
</tr>
<tr>
<td>2013-10-10</td>
<td>Pm</td>
<td>40</td>
<td>40,5</td>
<td>37</td>
<td>20</td>
<td>0</td>
<td>0</td>
<td>01R/01L</td>
<td>30</td>
<td>Outcome Rate</td>
</tr>
<tr>
<td>2013-10-10</td>
<td>Pm1</td>
<td>39</td>
<td>39,8</td>
<td>35</td>
<td>17</td>
<td>0</td>
<td>0</td>
<td>01R/01L</td>
<td>22</td>
<td>Outcome Rate</td>
</tr>
</tbody>
</table>

Figure 24: Table of Results (Appendix II)

Date and Day

Some dates are missing in the table, as neither the form, form supplement or shift reports could provide any information on Rate or Ratenet. Other than that, all dates between October 8th and November 20th are covered in the first column. Most dates have two entries, as there is both a morning and an afternoon peak in the data.

Rate

This column shows the current landing rate, extracted from form or runway report data (Chapter 5.2).

Ratenet

The ratetest output (Chapter 4.1) is shown here, extracted from form or runway report data.

Out(1h)+H

This column shows the outcome of the most traffic intense hour during a peak. A very important thing to note is that every aircraft of wake turbulence category “Heavy” are counted twice. This is due to the fact that the distance on final is usually double between a Heavy and a Medium aircraft (Chapter 2.3.3-2.3.4), and the MAESTRO will provide extra separation after a Heavy aircraft (Chapter 5.1). The demand columns are treated in exactly the same way. The number of Heavy aircraft per hour during the peak ranges from 0-4. The outcome and how many heavy aircraft included in that count are hidden columns H-I, meaning “Out(1h)+H” is the sum of column H+I. Data originates from the arrival count data (Chapter 5).

Out(30)+H

Using the same principle as the column explained above, this is the outcome for 30 minutes. The decision to include a 30 minute column was made as full hours of full demand are fairly uncommon in Stockholm TMA, but half hours are easier to find. This way, it is easier to see for which dates that the...
landing rate actually restricts the flow of traffic into the TMA, as a cell in this column multiplied by two creates an artificial hour, comparable with the landing rate as well. Data originates from the arrival count data (Chapter 5).

Dem(1h)+H
Showing the flight planned hour of maximum intensity during an hour of the peak. Originates from traffic demand data (Chapter 5), which has only been extracted for dates where the outcome comes close to the landing rate (which is the reason why most rows read “0”). Hidden columns K-L show how many Heavy aircraft that have been counted twice.

Dem(30)+H
Using the same principle as above, but for a 30 minute period instead. Hidden columns N-O show how many Heavy aircraft that have been counted twice.

RWY ESSA
Shows the runway configuration at Stockholm Arlanda during the peak, as provided in the form, form supplement and/or shift reports.

RWY ESSB
Shows the runway configuration at Stockholm Bromma during the peak, as provided in the form, form supplement and/or shift reports.

6.2 Landing rate contributors
At all times except one; when Ratetest gives an output lower than 41, the landing rate is set accordingly, rounded down to the closest figure. Ratetest output lower than 41 is most common when there is strong headwind on final approach, as aircraft speeds will decrease substantially, giving a distance in seconds between aircraft that is greater than in normal conditions. Another scenario when the Ratetest output is usually fairly low, is when the minimum distance between aircraft on final is increased by request from ESSA tower (as seen in Figure 25: row 65), where the distance between aircraft is minimum 6NM due to poor weather conditions).

For all peak periods in the data collection time period, the Ratetest output serves as a roof for how high the landing rate is set. Only once the landing rate exceeds the Ratetest output.

Ratetest is evidentially relied heavily upon when its output gives a relatively low arrival count per hour due to wind conditions or increased minimum distances on final (Figure 25). The theoretical arrival count that Ratetest gives is, with the 0.5NM buffer between aircraft, probably believed to give sector East (ARR-E and DIR-E in particular) sufficient cover to handle the incoming traffic in a safe and efficient manner during such conditions of decreased capacity.
Looking instead at the peak period when Ratetest output equals to or exceeds 41, the table paints a more complex picture (Figure 26). The systematical setting of the landing rate in accordance with Ratetest output no longer appears to exist. In other words, a number of factors apart from the wind condition and minimum distance on final are included into the mix.

Firstly, at any time the runway configuration at ESSA is 01R/01L, the rate is set to 40. This is done in accordance with the addition to the Manual of Operations as of November 8th:

"With runway 01R/01L and 01L/08 in use at Arlanda, the landing rate should not exceed 40" [24]
What is noticeable is that before November 8\textsuperscript{th}, the text read

\textit{“…the landing rate should not exceed 38”}.

Seemingly, the recommendation in the newer addition was followed before there even was a new addition.

As the landing rate never exceeds 40 with runway 01R/01L in use during the data collection period, the more interesting data cells for result analysis can be found when runway 19L/19R is in use instead.

The maximum rate set in Stockholm TMA is 42 (Appendix II and Table 7), which is also in accordance with the airport-ANSP agreement [38]. What the rate is set to between numbers 40-42, given that Ratetest allows it, cannot be explained solely by entries into the Manual of Operations or Ratetest output values. An example of this is the 8\textsuperscript{th} of October (Figure 19 and Appendix II), where a rate of 42 is theoretically possible. However, the form data suggest that 41 is set due to \textit{“2 arrivals ESSB, 2 departures ESSB”} [25], meaning the runway configuration at ESSB will also contribute to landing rates, as the complexity in sector E increases with the number of ESSB movements.

The above suggests that landing rates would be higher with ESSB runway 12 in use, over runway 30, after other landing rate contributors have been taken into account (Ratetest output, ESSA runways, as mentioned above). That is also the case. Out the 13 times when it has been possible with a rate of 42, it has been set to such five times. Out of the three times it has been a possibility with a rate of 42 with runway 12 at ESSB, it has been set to 42 three out of three times (Figure 27). Take note that runway 30 is more common than runway 12 at ESSB during this time of year due to wind conditions.

<table>
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<th>Rate</th>
<th>Ratetest</th>
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<th>Out(30)+H</th>
<th>Dem(1h)+H</th>
<th>Dem(30)+H</th>
<th>RWY ESSA</th>
<th>RWY ESSB</th>
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<tr>
<td>2013-11-14</td>
<td>Thu am</td>
<td>42</td>
<td>44,17</td>
<td>37</td>
<td>20</td>
<td>0</td>
<td>0</td>
<td>0/19/19R</td>
<td>12</td>
</tr>
<tr>
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<td>Wed pm</td>
<td>42</td>
<td>42,5</td>
<td>30</td>
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<td>0</td>
<td>0</td>
<td>0/19/19R</td>
<td>30</td>
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<tr>
<td>2013-11-14</td>
<td>Thu pm</td>
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<td>42,5</td>
<td>36</td>
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<td>0</td>
<td>0/19/19R</td>
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<td>42</td>
<td>42</td>
<td>33</td>
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<td>42,67</td>
<td>38</td>
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<td>23</td>
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</tr>
<tr>
<td>2013-10-18</td>
<td>Fri pm</td>
<td>40</td>
<td>43</td>
<td>36</td>
<td>22</td>
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<td>0/19/19R</td>
<td>30</td>
</tr>
<tr>
<td>2013-11-15</td>
<td>Fri am</td>
<td>40</td>
<td>42,5</td>
<td>26</td>
<td>16</td>
<td>0</td>
<td>0</td>
<td>0/19/19R</td>
<td>30</td>
</tr>
</tbody>
</table>

Figure 27: Ratetest 42 or greater, Runway 19L/19R at ESSA (Rate 42 conditions).

The complexity factor that the traffic not landing at ESSA comprises in sector E is considered to be the main landing rate contributor, beside Ratetest output and the ESSA runway configuration (which in turn affects the scope of the complexity factor). It is suggested in the data, and is supported by the landing rate process (Chapter 3.6, bullet 4).
6.3 Landing rate outcome

Previously in this thesis it has been established that the landing rate has a direct impact on the arrival count – the outcome, even at times when the outcome is lower than the landing rate. The results from the data collection points at a majority of peak periods having lower outcome than the landing rate. In most cases this is due to demand for that particular period also being lower than the landing rate.

To constrain the amount of data, demand counts shown in the traffic demand data have only been extracted for peak periods when the outcome is equal, or comes close to, the landing rate.

It is important to note that even if outcome does not come close to the landing rate, there might be smaller periods than full hours that are full with traffic, hence directly affected by the landing rate. That is the sole reason for the 30 minute periods in the Table of Results (Appendix II) to be included.

Figure 28: Sorted by outcome (30 min), for peak period when the total outcome (1hr) does not come close to the landing rate.

The 30 minute outcome figures indicate that outcome is affected by the landing rate at most of the peak periods (Figure 28), even though one might have to look at smaller time frames than one hour to find such patterns. For example, the 6th of November has a fairly low outcome during the afternoon with an outcome of 30 during a rate of 42.

Looking at full hours of outcome in relation to the landing rate, on 19 occasions out of the 47 in total, outcome comes close, or is equal to, the landing rate. For an outcome to be defined as “close to” the landing rate, it needs to be within 3 aircraft from the rate. Only two of these 19 occasions are afternoons, and none happen on Fridays (Figure 29).

There are of course days when outcome is lower than the landing rate, even when demand exists. As this is not a trend in the data, it is hard point at specific reasons as to why. The data, especially when looking at demand, is delimited as described in chapter 5.1, which could be a contributor. It is also possible that conditions have changed a bit since setting the rate. Finally, the landing rate can never be more than an estimation of a number of aircraft that are able to arrive within an hour. Real traffic scenarios are far more complex and unpredictable than what can be described in statistics like this.
### Figure 29: Afternoons and fridays filtered out.

<table>
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<th>Date</th>
<th>Day</th>
<th>Rate</th>
<th>Rate test</th>
<th>Out(2h)+H</th>
<th>Out(30)+H</th>
<th>Dem(1h)+H</th>
<th>Dem(30)+H</th>
<th>RWY ESSA</th>
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<td>24</td>
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<td>39</td>
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<td>20</td>
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<td></td>
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<td>41</td>
<td>42</td>
<td>41</td>
<td>22</td>
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<td>23</td>
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<td></td>
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<td>39</td>
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<td>Outcome ~ Rate</td>
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</table>
7 Conclusions & Discussion
During the time frame of October 8th through November 20th, the arrival outcome was in most cases lower than the landing rate, even when giving arrivals of WTC Heavy extra weight to compensate for the lower AMAN rate. This is mainly due to demand for the period being lower than the landing rate. However, that does not mean that the landing rate does not restrict the arrival outcome, as the demand during shorter time spans than one hour are often found to be in line with the landing rate, especially during morning peaks Monday through Thursday.

When demand allows it, outcome is generally in line with the landing rate. Why a small number of dates deviate from this cannot be established in this thesis. Looking at specific days and not trends is not applicable, as individual traffic scenarios are impossible to analyze using only numbers and statistics.

Regarding what landing rate contributors that can be considered as LFVs, as one of the objectives for this thesis inclines an investigation of, it depends on the perspective of the viewer. Ratetest is a fairly basic software that is developed by LFV. The formula behind the calculations are set in stone theoretically regarding wind conditions (as the wind component is based on exact math). The wind calculations in Ratetest and how they will affect aircraft speeds on final can never be an exact reflection of the live conditions though, as wind changes constantly in direction and speed.

It is clear that Ratetest is widely used to determine the landing rate, but apart from common the wind component calculations, it is unclear exactly using which formulas Ratetest calculates a given landing rate. To use a table extensively when the formulas behind it are not known to the user is of course not an optimal situation. While the table clearly still serves its purpose, it could definitely be clearer to the user.

Different TS-Ts will make different decisions when setting the landing rate, even while conditions are fairly equal on paper, as setting the landing rate is arbitrary to an extent, and a decision making process based on experience and work methods. That does not mean the process described in the Manual of Operations is not being followed, but rather that whenever Ratetest output is fairly high, there will be different interpretations of traffic analysis. The methodology used in this thesis will never be able to provide an as thorough analysis on the traffic, but will only be able to provide the numbers. A point for discussion could very well be if landing rates should be set more consequently in relation to current conditions in the TMA, or if it should remain an individual decision based on own analysis. Perhaps the process should be made even more individual, where the buffer in Ratetest is not applied.

One can debate whether the landing rate is mainly a tool for optimizing the usage of the final approach and airport runway by as many aircraft as possible, or a safety net to protect sector E from getting too busy with traffic. This thesis argues that both are important, but that protecting sector E and ensuring a safe flow of traffic must be prioritized over said optimization. What is important to understand is that both are equally affected by the landing rate. If the landing rate is continuously followed up, taking outcome as well as workload into account, efficiency can possibly be improved. Traffic complexity is however hard to count in numbers. Two hour long scenarios with the same amount of arrivals to ESSA and ESSB, as well as other traffic in sector E, may look similar on paper but not in reality. Creating definite landing rate methods (for example always setting a rate of 42 when all conditions are met) should therefore be considered with caution.
The results gathered however indicate that conditions for setting a rate of 42 arrivals per hour is fairly common, but the rate is rarely set that high. It is more likely to see a rate of 42 with runway 12 in use at Bromma. As it is desirable to set the landing rate as high as possible, without affecting workload (and in extension: safety), ESSB traffic patterns with RWY 12 and 30 respectively could be examined from a ESSA rate perspective. How to be able to increase the landing rate while maintaining workload at a good level is a topic for further discussion. An example of this could very well be the future DEP-E working position, or other measures that increase overall TMA capacity.
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[40] LFV 2013, URL: http://www.lfv.se

**Personal Communication**
[27] Lise-Lotte Sverkersson (NUAC/LFV), 2013-11-21
[28] Niklas Rooslien (NUAC/LFV), 2013-10-08
[29] Peter Berglund (NUAC/LFV), October 2013
[41] Eivind Martinsen (LFV/EPN), May 2013
## Appendix I: TST Form

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<th>(New rate):</th>
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<td>(Time for new rate):</td>
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<tr>
<td>Runway configuration:</td>
<td>(Reason new rate):</td>
</tr>
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<td>Ratetest:</td>
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</tr>
<tr>
<td>Factors to the set rate:</td>
<td></td>
</tr>
<tr>
<td>Significant weather:</td>
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</tr>
<tr>
<td>Other actions taken (MDI, Runway inspection, Departure gap, Regulation, etc.):</td>
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## Appendix II: Table of Results

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<th>Out(30)+H</th>
<th>Dem(1h)+H</th>
<th>Dem(30)+H</th>
<th>RWY ESSA</th>
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