

CRANFIELD UNIVERSITY

SOFIA RYDELL

ARRIVAL AND DEPARTURE MANAGER COOPERATION FOR
REDUCING AIRBORNE HOLDING TIMES AT DESTINATION
AIRPORTS

SCHOOL OF ENGINEERING
Master of Science by Research

MSc
Academic Year: 2010 – 2011

Supervisor: Dr. David Zammit-Mangion
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ABSTRACT

This thesis addresses the possibility of using a delay-on-ground concept in which flights with less than 1 hour flying time (often referred to as pop-up flights) absorb their arrival sequencing delay at the departure gate by being issued their Arrival Manager (AMAN)-scheduled time as a Required Time of Arrival (RTA) that is inserted into the Flight Management System (FMS). Due to their short duration these flights are currently often inserted into the AMAN sequence shortly before Terminal Manoeuvring Area (TMA) entry and thereby often need to absorb their arrival sequencing delay in the inefficient manner of airborne holding or vectoring close to the arrival airport. The literature review examines current operational procedures of AMANs and Departure Managers (DMANs), the current FMS RTA function and live trials in which the delay-on-ground concept was tested in real operations. A case study airport in Europe that has potential to benefit from the concept is identified. The performance of the delay-on-ground concept for the case study airport is then assessed by performing 180 fast-time Monte Carlo simulation runs. For each run the arrival flow to the case study airport and the departure flows from two medium-sized airports from which the pop-up flights originate are simulated. Each run represents an operational day and variations in departure/arrivals time is put into the timetables to simulate the variation in actual departure/arrival times resulting from operational factors normally encountered in day-to-day operations. An algorithm is written in Matlab to simulate an AMAN-DMAN cooperation in which pop-up flights are locked to the required departure times to meet their RTAs. It is shown that a significant reduction in airborne delay time and fuel consumption can be achieved at the case study airport by using the concept. It is also shown that it is possible to ensure that the pop-up flights depart at the required times to meet their RTAs without negatively affecting the departure sequences.

Keywords: Air Traffic Management (ATM), Arrival Manager (AMAN), Departure Manager (DMAN), Required Time of Arrival (RTA).

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LIST OF SHORT NOTATIONS

4DT	Four Dimensional Trajectory
ACC	Area Control Centre
A-CDM	Airport Collaborative Decision Making
ADS-B	Automatic Dependent Surveillance-Broadcast
AIP	Aeronautical Information Publication
AMAN	Arrival Manager
ANSP	Air Navigation Service Provider
AOC	Airline Operations Centre
ATC	Air Traffic Control
ATCC	Air Traffic Control Centre
ATM	Air Traffic Management
BADA	Base of Aircraft Data
CAS	Calibrated Airspeed
CDU	Control Display Unit
CFMU	Central Flow Management Unit
DMAN	Departure Manager
ETA	Estimated Time of Arrival
FL	Flight Level
FMS	Flight Management System

GDP	Gross Domestic Product
GPF	Global Parameters File
GPS	Global Positioning System
I4D	Initial Four Dimensional
IAF	Initial Approach Fix
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
KIAS	Knots Indicated Airspeed
NextGen	Next Generation Air Transportation System
NUP2+	North European Automatic Dependent Surveillance-Broadcast Network Update Programme Phase 2+
OAG	Official Airline Guide
OPF	Operations Performance File
PTF	Performance Table File
RBT	Reference Business Trajectory
RTA	Required Time of Arrival
SBT	Shared Business Trajectory
SESAR	Single European Sky ATM Research
SID	Standard Instrument Departure
SMAN	Surface Manager

STAR	Standard Terminal Arrival Route
SWIM	System Wide Information Management
TMA	Terminal Manoeuvring Area
TOBT	Target Off-block Time
TTOT	Target Take-off Time

LIST OF AIRPORT IATA CODES

AES	Aalesund
ARN	Stockholm-Arlanda
BGO	Bergen
CPH	Copenhagen-Kastrup
HAU	Haugesund
KRS	Kristiansand
KSU	Kristiansund
MOL	Molde
SVG	Stavanger
TRD	Trondheim

1 INTRODUCTION

1.1 General introduction and motivation for change

Aviation provides society with enormous benefits in terms of people's mobility for business and tourism purposes. Figure 1-1 shows the impact on European Gross Domestic Product (GDP) of aviation in 2004. Without considering the catalytic effects: this amounts to 222 billion Euros in 2004 (about 1.5% of the total European GDP). Forecasts indicate that in 2020 this figure will be 470 Billion Euros. In order to enable this, the Air Traffic Management (ATM) system needs to accommodate the expected increase in air traffic. It has been estimated that if airports cannot meet the future demand, there will be a loss of approximately 50 Billion Euros in potential added value annually in Europe in 2020 [1].

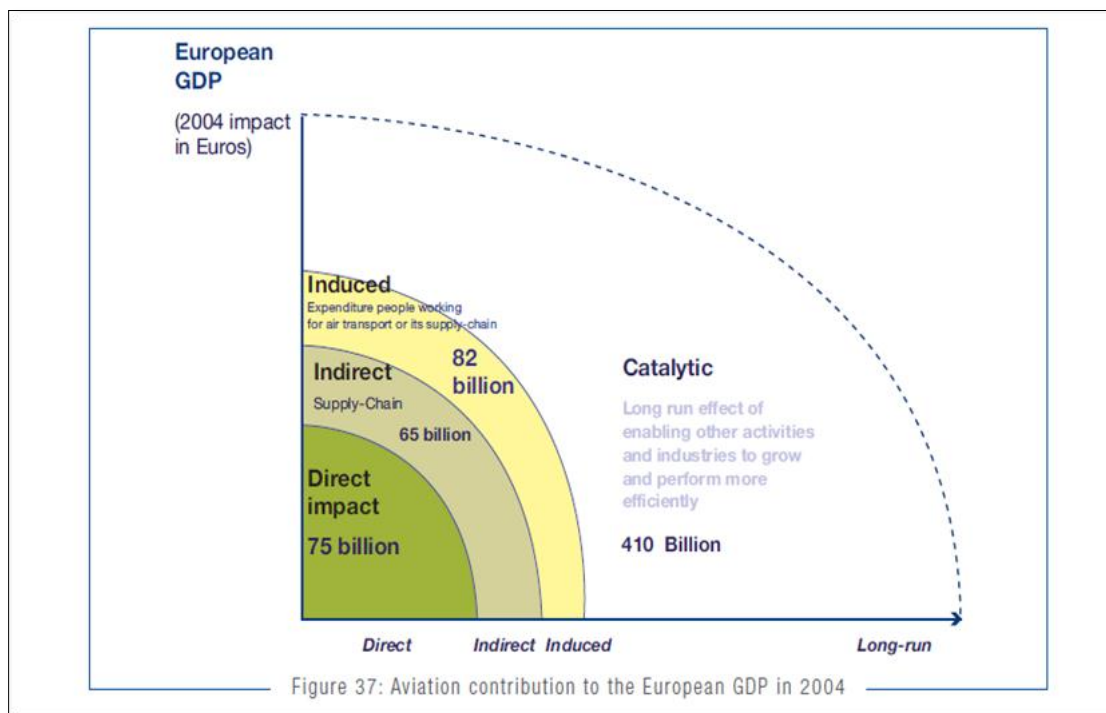


Figure 1-1: Aviation contribution to the European GDP in 2004 [1, p. 106].

Forecasts indicate that air traffic will double or even triple in the next 15-20 years [2]. However, there are two major factors possibly preventing this growth: environmental

impact, both in terms of noise exposure and greenhouse gas emissions, and the inability of the current ATM system to provide the capacity [3]. Figure 1-2 demonstrates the future capacity gap where new solutions need to be found to meet expected demand [4].

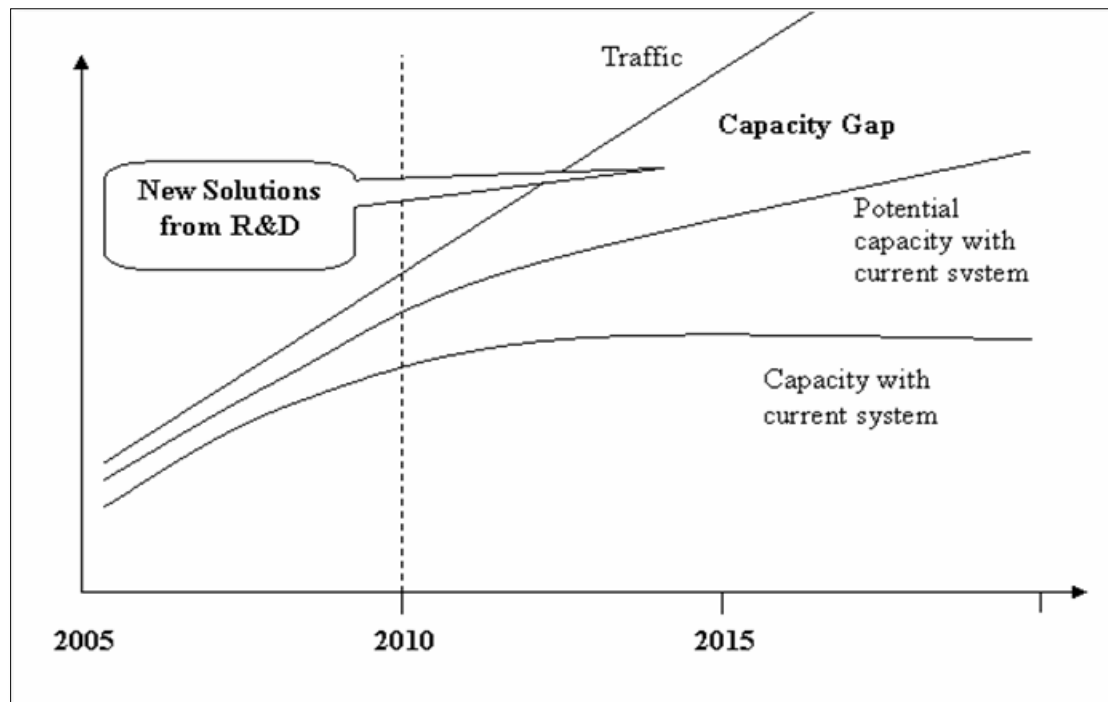


Figure 1-2: Predicted evolution of European capacity of the ATM system according to SESAR [4, p. 91].

The biggest capacity issues will be experienced in Terminal Manoeuvring Areas (TMAs) and airports in the future and if no changes are made in how surface management, departure management and arrival management is handled this will be the most restricting factor limiting the growth of air traffic [1].

To deal with the problems facing the ATM industry, all aviation stakeholder in Europe have come together to create and commit to following the Single European Sky ATM Research (SESAR) Master Plan [1]. This plan will be used to coordinate all ATM research and development in Europe in the future [1, 5]. Initiatives with similar goals as the SESAR project are in place in other parts of the world, such as the USA's Next Generation Air Transportation System (NextGen) [1].

SESAR aims to transform the current ATM system to one that can provide increased capacity and safety, reduce the environmental impact of the industry, and do so in a cost-effective manner. In order to achieve this, SESAR recognizes that the current tactical ATM system, where low altitude queuing is used extensively, needs to be replaced by enhanced predictability, with more efficient queue management in and out of airports. The queue management process will ensure the optimum use of TMAs and airports and minimize holding both in the air and on the ground [1, 5]. This will be aided by utilizing aircraft on-board functionalities together with more automation on ground [1].

The foundation for the SESAR Concept of Operations is a trajectory based ATM system. This system will replace the current “first-come-first-served” system by a much more predictable system where airspace users’ intentions are known early on through their Four Dimensional Trajectories (4DTs). The 4DT will specify the latitude, longitude, altitude and time at waypoints along the flight path and represent how the airspace user wants to fly from departure gate to arrival gate. This trajectory will be referred to as the Shared Business Trajectory (SBT) and will be made available a certain time before departure. During a negotiation process, changes may be made to the SBT taking into account the overall demand and capacity of the ATM system; this will result in the Reference Business Trajectory (RBT). The time dimension in the RBT will sometimes be specified as a contract in the form of a Required Time of Arrival (RTA) on one or more waypoints along the flight path. The aircraft agrees to fly to the RTA using its Flight Management System (FMS) RTA function [6]. The RTA function is available in many modern airliners and enables an aircraft to meet a time set to a waypoint in its trajectory with high accuracy [7, 8, 9]. The RBT is the agreed trajectory that the aircraft will fly and the Air Navigation Service Provider (ANSP) facilitate. A clearance to execute the trajectory will be given progressively as the flight is executed [6].

The trajectory based system envisioned in the SESAR Concept of Operations will extend to include the airports. During the turnaround phase (between landing and take-off) the flight trajectory is in an idle state in all except for the time dimension so that the impact of the time dimension on the later part of the flight can be monitored. This will

provide input to Departure Manager (DMAN) and Arrival Manager (AMAN) tools so that the runway usage can be planned early on [6].

To enable this trajectory based ATM system information needs to be shared between all stakeholders through a more efficient mean than what is available today. The concept of System Wide Information Management (SWIM) will be developed during SESAR and will be the “intranet of the ATM system” where all relevant information can be shared between all relevant stakeholders. The information will include trajectories, surveillance data, aeronautical information and meteorological information [6].

To achieve the paradigm shift to a full trajectory managed ATM environment the SESAR Concept of Operations has been structured into three Concept Storyboard Steps progressively leading to the full SESAR Concept of Operations. Step 1 - Time Based Operations - will make better use of current technology and communication between air and ground systems and will progressively be available from 2013. In Step 2 - Trajectory Based Operations - aircraft will plan, share and execute their user-preferred 4DT. To achieve this step new technology and new standards for sharing of trajectories will need to be developed; this is expected to be progressively available from 2017 and forward. In Step 3 - Performance Based Operations - SWIM will be implemented to facilitate the sharing of all necessary information between stakeholders, this will progressively be available from 2020 [6, 10].

This work focuses on the benefits that can be seen during Step 1 - Time Based Operations. In Step 1 there will be no negotiation of complete RBTs before take-off, the focus will be on improved and synchronised arrival and departure management. In Step 1 Initial Four Dimensional (I4D) operations will be introduced. This will be limited to the aircraft communicating their 4DT to an AMAN when they approach the airport, and be assigned a single RTA to a point during descent if needed. Flights departing from an airport in the close vicinity of their arrival airport (so called pop-up flights) will be assigned a slot in the AMAN queue before take-off by communicating, not their full 4DT, but their expected arrival time at destination airport.

One of the goals in the SESAR Concept Storyboard Step 1 is to implement AMAN and DMAN tools at European airports where they are not already in operation to enable

them to handle the increasing traffic 1. These tools are Air Traffic Control (ATC) support tools that automatically set a sequence optimized for capacity to arrival and departure runways as early as possible, enabling delay to be absorbed in the most efficient manner [11, 12]. An AMAN has as one of its main goals, the reduction of airborne holding close to TMAs and achieves this through speed reduction en-route as its preferred choice of method. These tools can be of benefit at medium to large airports and particularly during peak hours [11]. Also envisioned in Step 1 is for AMANs and DMANs at different airports to cooperate [1]. A possible way to use this cooperation would be to allow more AMAN delay to be taken at the departure airport for short-haul flights.

As part of Time Based Operations, an increasing number of flights will, over the coming years, use its FMS RTA function to meet a time set to a point in descent to provide the AMAN with increased predictability and aid it in its queue management [1]. The on-board FMS RTA function will enable aircraft to take their delay en-route by slowing down or, alternatively, delaying departure at the departure airport. The latter is particularly appropriate for short-haul flights [7].

The FMS RTA function has existed since the early 1990s but operational usage to date has been fairly limited [8]. It has been recognized that the ATM system needs to start taking advantage of modern on-board functionalities, RTA being one of them. Arrival management has been identified as one area where currently available technology, such as the FMS RTA function, could be used to make operations more efficient [9].

It has been found that a promising early application of RTAs in arrival management is to issue them to so called pop-up flights, i.e.: flights with a flying time of around 1 hour or less. In current operations these flights are not taken into account in the AMAN's calculations until they are picked up by radar, often shortly before TMA entry. Consequently these flights will need to take any airborne delay at low altitudes, particularly in peak traffic hours [11, 7, 9]. If these flights can enter the AMAN sequence when still at departure airport, an important step will be taken towards more efficient arrival management [7]. The Cassis project, part of the Eurocontrol TMA2010+ project, has proposed and evaluated a delay-on-ground concept in which

pop-up flights enter the AMAN sequence before takeoff by being issued with an RTA set to TMA entry [7, 9].

Over the last 10 years several research projects have investigated the performance and limitations of the current FMS RTA function. It has been found that high RTA accuracy¹ can be expected when the RTA is assigned early in the descent down to around FL100² (altitude at which the TMA entry point is typically crossed). It has also been shown that a speed and altitude constraint can be met together with the RTA at TMA entry with high accuracy. As the RTA function was originally developed for the en-route part of flight certain limitations on the performance of the current RTA function when assigned late in the descent has been recorded and these are described in section 2.3.1. It is expected that with future enhancements to the RTA function it will be possible to achieve high RTA accuracy far down in the descent as well [7, 8, 9, 13, 14, 15, 16].

During 2008 and 2009 a limited number of trial flights testing the delay-on-ground concept were performed in the Cassis project. These flights originated from departure airports with little traffic, enabling the integration of the flights into the AMAN sequence without AMAN-DMAN cooperation. That is, the amount of traffic at the departure airport was low enough for the controllers to, without the support of a DMAN, ensure that the pop-up flights departed at the required times to meet an RTA at TMA entry point. It was shown that it was possible for these flights to absorb their AMAN delay on the departure airport and achieve high RTA accuracy at a TMA entry point. Airborne holding, that would otherwise have been necessary, was therefore avoided on arrival at the TMA [7, 9]. In the future, when AMAN-DMAN cooperation will be available, it should be possible to extend the delay-on-ground concept to include pop-up flights that depart from larger airports as well.

The fuel savings that could be achieved if the delay-on-ground concept was to be used in daily operations is quantified in this work. This has not previously been done and is

¹ RTA accuracy is the difference between the actual time of arrival and the required time of arrival in seconds.

² Each Flight Level (FL) represents 100 feet, i.e. FL100 = 10,000 feet (1 foot = 0.3048 metre).

considered useful by the industry [7], and will hopefully motivate the airlines and the Air Navigation Service Providers (ANSPs) to adopt the concept.

1.2 Research aims and objectives

This work has evaluated the delay-on-ground concept for one case study airport. First, a literature review has been conducted covering current operational procedures of AMANs and DMANs, the current FMS RTA function and live trials in which the delay-on-ground concept examined in this work was tested in real operations. A case study airport in Europe that has potential to benefit from the concept has been identified. The delay-on-ground concept and the associated AMAN-DMAN cooperation have been simulated for the case study airport. The fuel savings potential at the case study airport has been quantified. The possible implications on the departure sequences of ensuring that pop-up flights depart on the required times to meet an RTA at the arrival airport has been measured. The aim of this research has not been to propose a solution on how to achieve the AMAN-DMAN cooperation required for the delay-on-ground concept, but it has been to measure the benefits in terms of reduced fuel consumption in approach and possible effects on the departure sequences due to the delay-on-ground concept.

1.3 Research methodology

A suitable case study airport has been identified by studying AMAN equipage and the nature of the arriving traffic to airports in Europe. A large set of fast-time Monte Carlo simulation runs have been performed to assess the performance of the delay-on-ground concept for a case study airport. Each run represented an operational day and variations in departure/arrival times were put into the actual timetables to simulate the variations in departure/arrival times from day-to-day due to operational reasons. For each run the arrival flow to the case study airport was simulated. The departure flows from two medium-sized airports from which the pop-up flights originate were also simulated. A runway model [17] setting departure and arrival sequences with the required separation between flights was used to simulate the departure/arrival flows. An algorithm was written in Matlab to simulate the AMAN-DMAN cooperation. The output of the simulations has, together with the Base of Aircraft Data (BADA) files [18], enabled a

fuel savings analysis and shown how the departure sequences will be affected by pop-up flights being locked to departure times to meet their RTAs.

2 LITERATURE REVIEW

2.1 Arrival Manager (AMAN)

2.1.1 Introduction

Over the course of the last ten years an increasing number of airports in Europe have started using AMANs [11]. In 2010, 13 of the 25 busiest European airports (in terms of number of arrivals) were using an AMAN [19].

An AMAN is a ground-based ATC support tool that automatically sets an arrival sequence with the required wake vortex separation between flights in order to optimize runway capacity. The sequence can be set to points such as metering fixes (for example TMA entry point and an Initial Approach Fix (IAF)) and/or the runway threshold. An AMAN is particularly useful at busy airports during peak traffic periods, as it helps to utilize available capacity in a more efficient way. Although many AMANs provide a sequence for the runway to facilitate optimization according to wake vortex criteria, this time is often used to calculate a corresponding time at which the aircraft need to be over a particular metering fix. One of the main goals of using an AMAN is to minimize circular holding and low level vectoring. This is achieved by setting a sequence with the required separation between flights as early as possible. The delay that needs to be imposed on flights is then known far in advance and can be absorbed in the most efficient manner. This is usually a linear delay, i.e. introduced through a speed reduction en-route [11].

2.1.2 AMAN inputs

An AMAN needs the following inputs: flight plan data, radar data, aircraft performance data, wake vortex category for different aircraft types, airspace constraints (such as speed restrictions in TMAs) and wind predictions. Using this input, the trajectory predictor and sequencer element of the AMAN perform the necessary calculations to produce an optimized sequence as well as the required delay times to impose on flights as described below [11].

2.1.3 Trajectory predictor element

The trajectory predictor produces a predicted trajectory including estimated times over particular metering points and/or the runway for each flight. These times are unconstrained, that is, they are the times the aircraft would meet if there were no other traffic to take into account (AMAN demand times) [11].

2.1.4 Sequencer element

The sequencer element performs the sequencing and separation activity of the AMAN. The sequence is set using basically a ‘first come, first served’ basis, but also takes other factors into account. These factors include grouping of flights according to wake vortex category to minimize the overall delay and fairness in how delay is imposed on individual flights. This results in the AMAN-scheduled sequence with constrained times (AMAN-scheduled times). A comparison between unconstrained and constrained times gives the required delay (AMAN delay) that needs to be imposed on each flight [11].

2.1.5 AMAN outputs

The outputs of an AMAN are an optimised sequence and estimated times for flights to be at the metering point/runway and the delay (AMAN delay/arrival sequencing delay) required for individual flights to meet these times. The controller then needs to decide on and forward the necessary instructions to the individual flights, which may include speed reduction, to achieve the AMAN-scheduled times [11].

2.1.6 AMAN horizon

The AMAN horizon is defined as the time and geographical distance before the metering fix at which an aircraft is first detected by the AMAN. In current operations, this time value varies between 5 and 45 minutes. The reason for this large variation is that different TMAs are surrounded by different ACC (Area Control Centre) sector geometry and ANSP borders [20]. The greater the AMAN horizon, the more efficient the AMAN can be in optimizing the sequence and imposing linear delay, as opposed to inefficient vectoring or orbital holding. However, in current operations, pop-up flights often cause late changes to the sequence, as described below [11].

2.1.7 The problem of pop-up flights in AMANs

The aim of the AMAN is to set a stable arrival sequence as early as possible to increase predictability and provide as much time as possible for the required delay to be absorbed by the aircraft in an as efficient way as possible. However, a problem that AMANs face is that of pop-up flights showing up at a late stage in the planning, causing disturbances to the sequence. These pop-up flights originate from airports in the close vicinity (approximately within a 200 nautical mile³ radius or 1 hour flying time) of the AMAN-equipped airport. Because of their short duration, these flights “popup” into the AMAN sequence at a late stage, usually when they are picked up by radar. If the sequence is either full or ‘frozen’ when a pop-up flight is detected by the AMAN, the flight can incur significant delay. The sequence is defined as ‘frozen’ when all aircraft have been assigned a place in the sequence [11, 7]. At Stockholm-Arlanda airport, the sequence is considered as ‘frozen’ 16 minutes before TMA entry [20].

If the pop-up flights could be inserted into the AMAN sequence before takeoff it would result in an extended and more stable AMAN horizon [11, 7]. Some AMAN-equipped airports currently insert the pop-up flights into the arrival sequence before takeoff. This is done by reserving an AMAN time slot and keeping the aircraft on the ground until it fits the slot. However, once the aircraft is airborne, the AMAN may detect that the aircraft will not be able to meet the assigned time slot and will therefore have to re-sequence other traffic and/or delay the pop-up flight to the first available slot [11].

A concept that is promising in terms of providing a solution to the pop-up flight problem is to assign the AMAN-scheduled time as an RTA to pop-up flights that are equipped with the RTA function before takeoff. If these flights can be introduced into the AMAN sequence when they are still at the departure airport and meet the RTA to a metering fix (or runway) with high accuracy, the arrival sequence can be made more stable earlier on. The FMS RTA function will guarantee that the aircraft can meet a slot that is assigned to it already before takeoff [11].

The option of giving the AMAN-scheduled times to aircraft as time clearances in the form of RTAs that are inserted into aircraft’s FMS was investigated in the Cassis

³ 1 nautical mile = 1852 metres.

project. This was done both for pop-up flights that were still on ground at departure airport (delay-on-ground trials) and other flights when airborne. The Cassis project consisted of two subprojects; Cassis 1 and Cassis 2. Cassis 1 consisted of three trial weeks that took place during 20008. Cassis 2 consisted of two trial weeks that took place during 2009. See sections 2.3.3 to 2.3.8 for presentation and discussion of the results from the Cassis project [7, 9, 16].

2.2 Departure Manager (DMAN)

A DMAN is a ground-based ATC support tool that automatically sets a departure sequence with the required separation between flights at a departure runway. The required separation is calculated taking into account wake vortex categories of different aircraft types and Standard Instrument Departure (SID) usage. A DMAN needs accurate information on when flights are expected to be ready to push-back from gate (Target Off-block Times (TOBTs)). This information can be provided either by the airline company or the ground handler and needs to be given as early as possible for the DMAN to be effective in setting an optimized sequence of departing flights. Using this information together with predictions of taxi times to the runway from the different gates, a demand timetable is built for the runway. Using this demand timetable, the DMAN calculates an optimized sequence of flights respecting separation minima. The resulting sequence contains the DMAN-scheduled times with any necessary delay (DMAN delay/departure sequencing delay) imposed on flights. DMAN delay/departure sequencing delay is the delay that is required to maintain the minimum separation between departing flights. This delay is obviously the highest in peak traffic hours, when a large amount of aircraft are demanding the runway at the same time. The predictability of takeoff times that a DMAN provides can be used to absorb the DMAN delay for departing flights in a more efficient way by keeping them at gate for longer instead of in queues at the departure end of the runway. This is of course particularly useful for busy airports in peak traffic periods [21].

To have information on accurate TOBTs as early as possible is crucial for a DMAN to set a departure sequence early on [21]. Today, an accurate TOBT may not be known with sufficient accuracy until the flight actually requests push-back from gate.

Increasing the DMAN horizon and having a departure sequence set earlier on is a prerequisite to enable AMAN-DMAN cooperation. During the SESAR project it is expected that Airport Collaborative Decision Making (A-CDM)⁴ processes will be improved so that knowledge of flights' readiness will be available earlier enabling valid departure sequences to be set earlier on [22].

2.3 The Flight Management System (FMS) Required Time of Arrival (RTA) function

2.3.1 Explanation of the function

Today, many modern aircraft types are equipped with the FMS RTA function. This function has existed in some aircraft since the early 1990's. Still, operational usage has been fairly limited to date [8]. Due to the realization that RTA usage can contribute to making flight operations more efficient, live flight trials and simulations have been performed in a number of projects in order to evaluate the performance and limitations of the current FMS RTA function [7, 8, 9, 14, 15, 16, 23, 24]. The RTA function and results from some of the projects evaluating the function are presented in this chapter.

The RTA function utilizes a feedback control system adjusting speed to meet a specific time-of-arrival over a certain waypoint in an aircraft's trajectory [13]. In non-RTA operations, the aircraft speed is decided by a set cost index having been manually inserted by the flight crew. This cost index reflects whether fuel economy or time is the more important factor affecting the speed for the particular flight. However, if an RTA has been entered into the FMS the RTA algorithm has authority to change the cost index to either speed up or slow down the aircraft, subject to its performance limits, to meet the RTA. An FMS can display an RTA window for a particular future waypoint, that is the earliest and latest possible arrival time (time-control authority) that the aircraft can meet by speeding up or slowing down. If the RTA is entered when the aircraft is still on ground, the FMS will display the recommended takeoff time to meet the RTA with the cost index that has been selected as well as the takeoff window giving the entire range

⁴ A-CDM is a term that is used to denote the process of sharing information about the turn-round process of flights at airports as early as possible between all stakeholders in order to increase predictability and operational efficiency.

of departure times (corresponding to different cost indices) that will ensure that the RTA is met [14].

The time-of-arrival over a certain fixed point over the ground is the result not only of the aircraft speed but also of the wind that the aircraft will fly through up until that point. An RTA-capable FMS predicts the 4DT of the aircraft with the associated Estimated Time of Arrival (ETA) at waypoints along its path. If winds that differ from those entered into the FMS and used in its calculation of the reference trajectory are encountered, the ETA over waypoints will change. The closed-loop functionality with respect to time of the RTA function will command speed changes to still meet the time set for the RTA point [15]. These speed changes are commanded when the ETA does not correspond to the RTA by a certain tolerance. The purpose of the tolerance is to create a deadband in order to minimize continuous thrust resetting. On some aircraft types this tolerance can be set by the flight crew and usually decreases as the aircraft approaches its RTA waypoint [8]. That way, unnecessary speed changes are avoided when the aircraft is far from the RTA waypoint but still gives the FMS the ability to meet the RTA [14].

Both live trials and simulations have shown that as the aircraft progresses along its trajectory and detects winds that are different from those used in its prediction of the RTA, the algorithm performs very well in its ability to command speed changes and can still achieve very high RTA accuracy [8, 15, 16]. Figure 2-1 demonstrates the closed-loop functionality with respect to time of the FMS RTA function. The figure shows how the RTA function responds to disturbances, such as unpredicted winds, to still meet the time set for a certain waypoint in its trajectory [13].

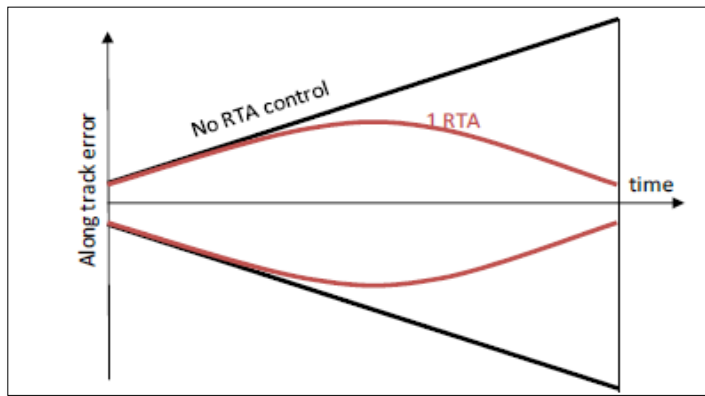


Figure 2-1: Development of trajectory error with and without RTA control [13, p. 2-3]

The ability of the current FMS RTA function to command speed changes in the later part of descent is limited, mainly due to the restricted speed envelope of the aircraft. Due to the reduction in time-control authority in this part of flight, most of the RTA algorithm's ability to recover from incorrect winds is lost. Data from one of the RTA trial flights that took place in 2001 shows how time-control authority is reduced during descent and that almost no time-control authority remains after the aircraft has passed FL100. This effect is shown in Figure 2-2 [14].

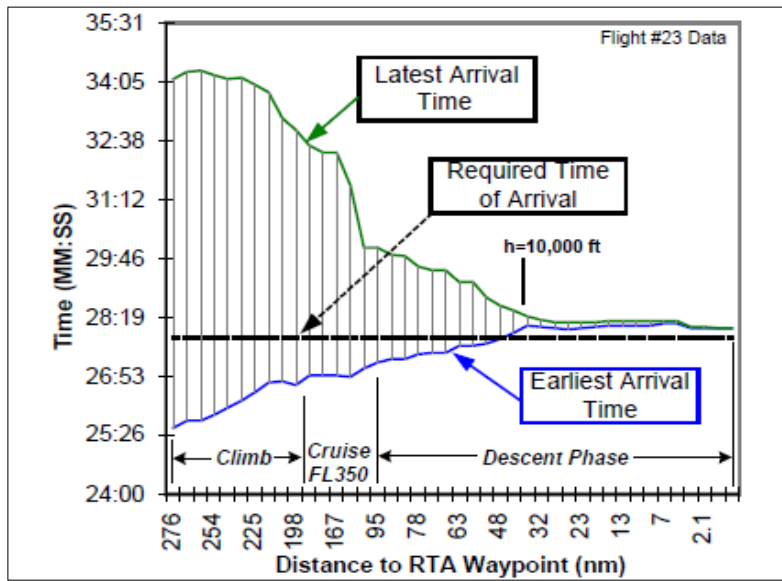


Figure 2-2: Time-control authority for one of the 2001 RTA trial flights [14, p. 7]⁵

Besides the constraint of the reduced time-control authority, there also tends to be large differences between reported and actual winds at the different flight levels during descent [14]. Current FMSs can accept manual insertion of predicted wind at three or five flight levels during descent, depending on the FMS type, besides what the wind is at ground level. The wind level estimate at different flight levels is then linearly interpolated between these points. This creates a wind profile used by the FMS in its trajectory prediction, but this profile can still vary significantly from that actually encountered. This adds to the difficulty of having an RTA set to a point in the later part of the descent [8]. Examining data collected during two of the RTA trial flights reveals how large the wind variations can be between the different flight levels in descent and how much the predicted wind profile used in the FMS calculations can differ from the actual winds as shown in Figure 2-3 and Figure 2-4 [14, 15].

⁵ NM = Nautical Mile

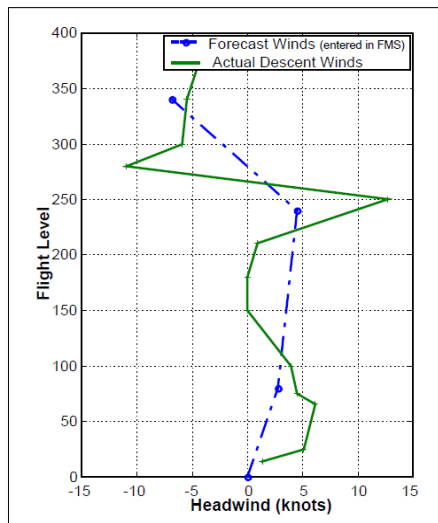


Figure 2-3: Actual and predicted descent winds for one of the 2001 trial flights [14, p. 7]

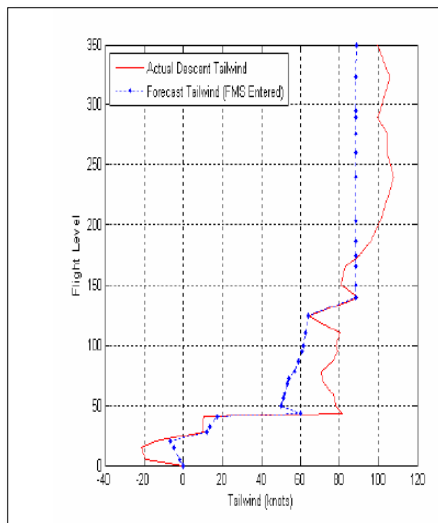


Figure 2-4: Actual and predicted descent winds for one of the NUP2+ trial flights [15 p. 9]

2.3.2 Current aircraft RTA equipage

A recent Eurocontrol study has detailed the aircraft types that currently have RTA capability, shown in Table 2-1. Based on this equipage information the same study estimated the percentage of Instrument Flight Rules (IFR) flights in Europe that have RTA capability, as shown in Table 2-2 [8].

Table 2-1: Aircraft types with RTA equipage [8]

FMS	Aircraft type	RTA tolerance (seconds)	Flight phase with RTA capability
General Electric Aviation Systems	B737 Classic/Next Generation	6	Climb, Cruise, Descent
Thales-General Electric Aviation Systems	A320, A330, A340	30	Climb, Cruise, Descent
Honeywell Pegasus	A320, A330, A340, B757, B767, MD90	30	Cruise
Honeywell	B777, B747-400, MD11	30	Cruise

Table 2-2: Percentage of RTA-equipped IFR flights in Europe [8]

RTA tolerance (seconds)	GPS time⁶	Flight phase with RTA capability	Flights in Europe (%)
+30	No	Cruise	40
+30	Yes	Cruise	28
+6	No	Climb, Cruise, Descent	21
+6	Yes	Climb, Cruise, Descent	11

2.3.3 Observed RTA accuracy

Table 2-3 presents the RTA accuracy that was experienced in a number of projects evaluating the RTA capability, with the RTA set to different points in descent. All of these projects, except for the Eurocontrol real-time simulations, were performed through live trials with operational flights. The Cassis project is by far the project that has performed the most operational trials with several hundred RTA flights performed into

⁶ Global Positioning System (GPS) time is a requirement for synchronisation between ground-based tools and airborne tools and is expected to be required even for initial RTA operations.

Stockholm-Arlanda airport. The Cassis results should therefore be seen as the most relevant statistically. In Table 2-3 only Cassis flights that were given an RTA when already airborne are included. The results from the delay-on-ground trials are presented in section 2.3.4 [7, 8, 9, 14, 15, 16, 23, 24].

In some of the flights the assigned RTA corresponded to the FMS ETA, whilst in others it differed by up to 6 minutes [7, 8, 9, 14, 15, 16, 23, 24]. Generally, the Cassis trials showed that RTA accuracy was higher, the closer the RTA was to the ETA [7, 9].

During the Eurocontrol simulations some flights had the FMS programmed with winds that were an exact match with actual encountered winds, and some had a wind error between the FMS and actual winds [8]. As described above, when the aircraft encounters winds that are different from the winds used in the FMS calculations of the reference trajectory the FMS commands speed changes to attempt to still meet the RTA [15]. However, below FL100 the ability of the FMS to command speed changes in the presence of incorrect winds is reduced [14].

In the North European Automatic Dependent Surveillance-Broadcast Network Update Programme Phase 2+ (NUP2+) project some flights were provided with descent wind forecasts from the AVTECH Aventus NowCast tool rather than the traditional wind forecasts from Airline Operations Centre (AOC). The forecasts supplied by AOC can be fairly irregularly updated and are not tailored for individual flights. The AVTECH Aventus NowCast tool takes an individual aircraft's 4DT into account and supplies winds that are the most relevant for the aircraft's trajectory. The tool uses winds recently downlinked by other aircraft as well as winds forecasted by the MET office [24]. As the winds can rapidly change between the different flight levels during descent and due to the reduced FMS time-control authority during descent it is crucial to uplink the winds that are the most relevant to the individual flight and as recently updated as possible to achieve high RTA accuracy in this part of flight [8, 14, 15].

Referring to Table 2-3 it can generally be said that the RTA accuracy was higher for points higher up in the descent. This is expected as most of the time control authority is lost in the later part of the descent and winds change rapidly between the different flights levels in the descent as described above. However, high mean RTA accuracy was

seen for all flights, even when the RTA was set as far down in the descent as the runway threshold [7, 8, 9, 14, 15, 16, 23, 24].

Table 2-3: Summary of RTA accuracy for a number of RTA trials [7, 8, 9, 14, 15, 16, 23, 24]

Project	2001 trials	2001 trials	NUP2+ (2007), without wind tool	NUP2+ (2007), with wind tool	Eurocontrol simulations (2007)	Eurocontrol simulations (2007)	Eurocontrol simulations (2007)	Cassis 1 (2008)	Cassis 1 (2008)	Cassis 1 (2008)	Cassis 1 (2008)	Cassis 2 (2009)	Cassis 2 (2009)
RTA point	Top-of-STAR ⁷	Runway	Runway	Runway	Point at FL100	Point at FL 050	Point at FL045	TMA EP ⁸	TMA EP	IAF ⁹	Runway	TMA EP	TMA EP
Aircraft type	B737	B737	B737	B737	A320/B737 Simulator	A320/B737 Simulator	A320/B737 Simulator	B737	A330	B737	B737	B737	A330/A321
Number of flights	33 ¹⁰	33	5	8	6	4	11	154	6	32 ¹¹	32	137	21
Max. abs. error (seconds)	7	21	43	12	20	39	79	100	30	x ¹²	x	60	30
Abs. mean (seconds)	4.8	12.7	24	7.9	9.7	27.5	17.6	13.5	11.7	4	14.7	8	11
Standard deviation (seconds)	2.7	7.3	16.4	3.8	10.9	15.3	25	21.8	13.7	3.9	9.4	13.6	14

⁷ STAR = Standard Terminal Arrival Route, altitude = FL060 – FL180 for all 2001 trials.

⁸ TMA EP = TMA Entry Point, altitude = FL100 – FL330 for all Cassis trials.

⁹ IAF = Initial Approach Fix, altitude approximately FL050 for all Cassis trials.

¹⁰ For all 2001 trial flights.

¹¹ For all Cassis 1 IAF and runway trial flights.

¹² Information not available.

2.3.4 Delay-on-ground trials

In the Cassis project, in addition to giving RTAs to aircraft that were already airborne, the delay-on-ground concept was evaluated by issuing RTAs set at TMA entry to 43 pop-up flights when still at departure airport. These pop-up flights originated from Sundsvall airport in Sweden approximately 200 nautical miles from Stockholm-Arlanda airport requiring a flying time of about 30-35 minutes to Stockholm TMA entry. The pop-up flight trials were performed with Boeing 737 aircraft only [7, 9].

2.3.4.1 Procedure for the delay-on-ground trials

In some Cassis delay-on-ground trials the delay was absorbed at the departure gate and in some trials the delay was absorbed close to the gate after push-back from gate. If the delay was absorbed after push-back a small amount of fuel was consumed during the delay absorption, whereas if the delay was absorbed at the gate an additional benefit was that the engines had not been started yet and there was no fuel consumption during the delay absorption. The following procedure was set up to enable the delay-on-ground trials to be performed: [7]

1. When the aircraft requests taxi from gate, the Sundsvall tower makes a phone call to Stockholm Air Traffic Control Centre (ATCC) with estimated takeoff time.
2. The flight is entered into the AMAN sequence by Stockholm ATCC; the RTA (AMAN-scheduled time) is communicated over a phone call between Stockholm ATCC and the Sundsvall tower. The Sundsvall tower then assigns the RTA to the aircraft.
3. The flight crew enters the STAR and the RTA into the FMS. This gives the pilots the RTA recommended takeoff time and the RTA takeoff window containing the range of takeoff times that would allow the aircraft to meet the RTA.
4. Any AMAN delay is absorbed close to the gate or at the gate before takeoff.
5. The aircraft takes off according to the takeoff time advised by the FMS.

2.3.4.2 RTA accuracy for the delay-on-ground flights

Table 2-4 shows the RTA accuracy that was experienced in the Cassis delay-on-ground trials.

Table 2-4: RTA accuracy for the Cassis delay-on-ground flights [7, 9]

	Cassis 1 delay-on-ground flights	Cassis 2 delay-on-ground flights
Number of flight trials	18	24
Maximum delay assigned (minutes)	x ¹³	7
Average delay assigned (minutes)	x	1
Mean absolute RTA accuracy (seconds)	27.9	4.8
Standard deviation (seconds)	38.3	8
Percentage outside of 30 seconds (%)	37	0
Percentage outside of 60 seconds (%)	21	0

2.3.4.3 Comments on results for the delay-on-ground trials

For the delay-on-ground trials 37% of flights missed their assigned RTA by more than 30 seconds during Cassis 1 [9]. This high number of missed RTAs was probably because of a number of issues experienced in Cassis 1 that were due to the pilots' and controllers' inexperience with working with the concept. These problems were solved in Cassis 2 and promising results were observed, with 100% of flights meeting their assigned RTA at TMA entry point within +/-30 seconds. Before the trials the Cassis project established that a +/-30 second allowance for metering of traffic to a TMA entry point was suitable. These results are therefore seen as very positive. In Cassis 2 there were four cases where aircraft had to absorb an arrival sequencing delay of over 3 minutes. On these occasions the aircraft successfully absorbed this delay at the departure airport and consequently did not have to be put in holding when arriving at Stockholm TMA [7].

¹³ Information not available.

2.3.4.4 The need for a new communication network

During the Cassis trials the required information (i.e. the delay/weather situation in Stockholm-Arlanda, estimated takeoff time, RTA and STAR) was communicated with phone calls between Sundsvall tower and Stockholm ATCC and normal voice radio communication between Sundsvall tower and the trial aircraft. This amount of communication and coordination with phone calls and voice radio communication will not be acceptable for daily operations. A completely new network for communication/information exchange is required for the delay-on-ground concept to come into daily operations. This network should give all actors (AOCs, departure airport tower and ATCC handling the AMAN) easy access to the AMAN sequence and possibility to share information regarding when pop-up flights are ready for takeoff and what the delay situation is at the arrival airport. All communication with the flight crew should occur over datalink [7, 9].

2.3.5 Speed and altitude constraint with RTA

To ensure an ordered flow of traffic most TMAs have a speed restriction of 250 Knots Indicated Airspeed (KIAS) below FL100 [11]. Most of the RTA live flights trials performed during Cassis did not have a speed restriction. Air traffic controllers expressed that the unpredictability that this led to would be unacceptable in daily operations and that the RTA flights that were given a speed restriction together with the RTA were easier to handle [7, 9]. Of the 80 RTA flights that were given a speed restriction 85% managed to meet this speed within 10 knots and 95% within 20 knots [7]. The Cassis project has recommended that a speed and/or altitude constraint should be set for the RTA point to give ATC predictability [7, 9].

To evaluate the FMS's capability to meet an RTA together with a speed and altitude constraint at TMA entry Boeing 737 real-time simulations were performed in Cassis in addition to the live flight trials [16]. The simulations consisted of seven flights: six RTA flights and one reference flight that did not have an RTA. Four of the RTA flights were intentionally flown with a wind error in the FMS of either a 15 knots headwind ('+15 kt error' in graphs, flights number 2 and 8) or tailwind ('-15 kt error' in graphs, flights number 3 and 9). The purpose was to observe the speed changes occurring when aircraft

try to meet an RTA in the presence of unpredicted winds. The simulations were performed by AVTECH Sweden AB in their AASES Simulator. Individual RTA flights were combined to create virtual in-trial pairs to represent a possible traffic scenario of aircraft approaching a TMA and thereby assess possible in-trial separation issues between flights individually self-managing towards an RTA.

All RTA flights were given an altitude constraint to be at TMA entry either ‘at or below FL 150’ or ‘at FL080’. Furthermore, these flights were given a speed constraint at TMA entry of ‘at or below 230 knots’. The speed constraint is representative of what is in use in high traffic in current operations at Stockholm-Arlanda airport, where aircraft are asked to keep at 230 or 250 KIAS when entering the TMA, depending on the amount of delay. All the simulated flights met their altitude constraint and either met their speed constraint or missed it by a few knots at the most. How the speed changed during the descent for the flights is presented in Figure 2-5 and Figure 2-6 below.

Figure 2-5 shows how the speed changed for the three simulated flights having an altitude constraint of ‘at or below FL150’ as well as for the reference flight.

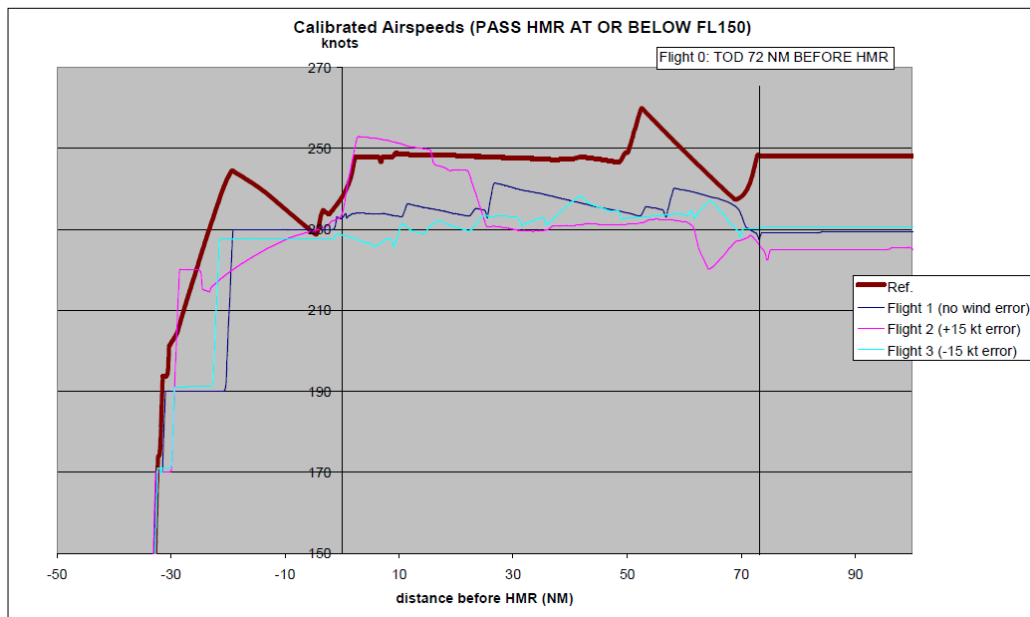


Figure 2-5: Speed profiles for flights with altitude restriction at or below FL150 [16, p. 21]¹⁴

The speed profile for the reference flight was a typical profile with constant Calibrated Airspeed (CAS) just below 250 knots for the majority of the descent up until approximately 5,000 feet, where speed was decreased.

Flight number 1, having no wind error, only made smaller speed corrections during the descent and passed the TMA entry point only 3 knots above the speed constraint. After passing the RTA point the flight maintained a constant speed at 230 KIAS until reaching the deceleration point at approximately 5,000 feet.

Flight number 2 encountered a 15 knots headwind that had not been accounted for and therefore increased speed to be able to meet the RTA constraint. The aircraft still managed to slow down and reach a speed only 3 knots above the speed constraint at TMA entry. The speed reduction continued after passing the TMA entry point.

Flight number 3 had to compensate for a tailwind of 15 knots. The aircraft kept reducing its speed during the descent in order to meet the RTA. The aircraft managed to

¹⁴ HMR = TMA entry point, TOD = Top-of-Descent.

meet the speed constraint and passed the TMA entry point at a speed of 228 knots. The speed was kept constant after the RTA point until reaching the deceleration point at approximately 5,000 feet.

The speed profiles for the flights with a ‘at FL080’ altitude restriction as well as for the reference flight are shown in Figure 2-6.

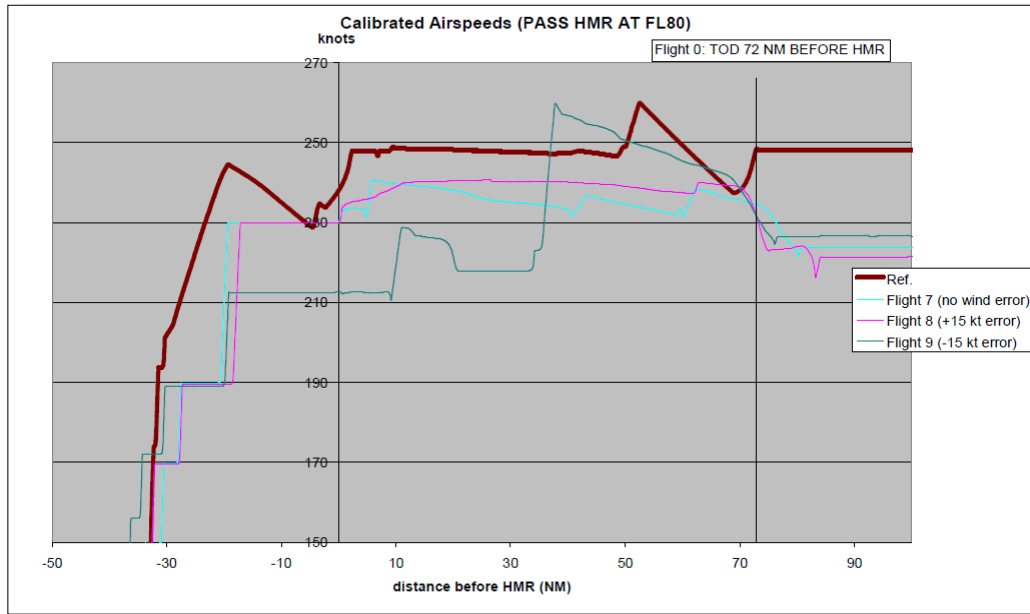


Figure 2-6: Speed profiles for flights with altitude restriction at FL080 [16, p. 22]¹⁵

For flight number 7 the winds entered in the FMS were correct. The flight maintained a close to constant speed from top-of-descent to TMA entry and met the speed constraint. The speed was subsequently kept constant until the declaration point at approximately 5,000 feet was reached.

Flight number 8 had a positive wind error, i.e. it had to deal with a headwind that was 15 knots stronger than anticipated. Because of this the speed at the beginning of the descent was too low. Speed was increased to account for this and was later reduced to meet the speed constraint at TMA entry. The speed constraint was met at exactly 230

¹⁵ In the simulations, flights that were numbered 4, 5 and 6 were planned to be simulated but never were.

knots. After the RTA point the speed was maintained until deceleration at approximately 5,000 feet.

Flight number 9 encountered a tailwind 15 knots stronger than it had accounted for. It therefore had a speed that was too high at the beginning of the descent, which was corrected for by slowing down. At TMA entry the speed was 212 knots, so well below the 230 knots limit. After TMA entry the speed was kept constant until the deceleration point at 5,000 feet.

All RTA flights except for one met their RTA within a ± 30 second accuracy. This flight met the RTA with an accuracy of 32 seconds.

2.3.6 In-trail separation between RTA flights

In order to evaluate the development of in-trail separation, separate RTA flights from the Cassis real-time simulations have been combined in suitable pairs. Only flights with the same altitude and speed constraint at TMA entry were combined, as this is what is likely to occur in real operations. This created 18 virtual pairs of aircraft flying with an RTA.

The numbering of the six flights simulated are different on the graphs presenting in-trail separation than the graphs presenting altitude and speed profiles. Flights number 7, 8 and 9 are referred to as flights number 4, 5 and 6 in the in-trail separation graphs. In the in-trail separation evaluation graph a positive wind error is presented as “head” and a negative wind error is presented as “tail”. When there was no wind error this is represented as “none” in the graph.

All the pairs were separated by 120 seconds at cruise level (cruise level was the same for a given pair) at the point at which the RTA was assigned. The cost index and weight were also the same at the start of the simulation. From this it was possible to examine how pair-wise in-trial separation developed after cruise having had realistic en-route spacing at the start of the simulations.

The most interesting in-trail pairs are presented in Figure 2-7. These pairs are the ones having the smallest separation or the largest speed difference at the RTA point of the 18 simulated flights.

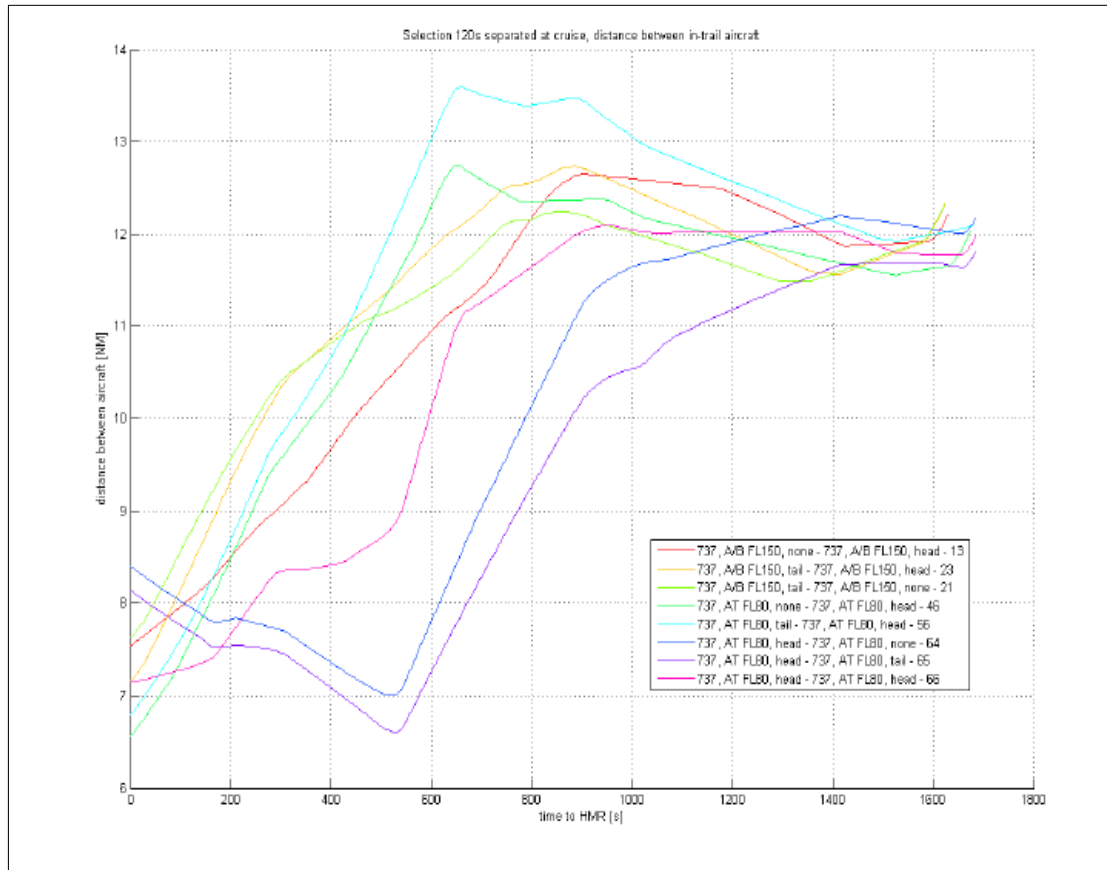


Figure 2-7: Development of in-trail separation for Boeing 737 simulations [16, p. 50]¹⁶

The right side of the figure shows the start of the simulations where aircraft are still at cruise level separated by 120 seconds (approximately 12 nautical miles). The coloured lines represent the different flight combinations and specify the conditions for the flights. The trailing aircraft in the pair is presented first.

To better enable an evaluation of the in-trail separation by an air traffic controller the two pairs representing the smallest separation and the highest speed difference were

¹⁶ A/B = Above.

presented on a radar screen for visualization of how the scenario developed. For the pair with the highest speed difference the lead aircraft passes the TMA entry point at FL078 at 220 KIAS, at the same time the trailing aircraft is at FL099 at 250 KIAS. The separation at that point is 7.2 nautical miles. The plots of how the in-trail separation of the pairs develops and what the scenario would look like on the radar screen has been shown to an en-route controller from the Swedish ANSP Luftfartsverket. The controller gave the following feedback:

1. All the pairs have sufficient separation over TMA entry.
2. The controller expressed it would be comfortable to work with the situation represented on the radar screen and it was not perceived as a stressful situation.
3. Air traffic controllers would like to have aircraft enter the TMA with similar speeds. In these simulations ground speed varied up to 40 knots between aircraft. The controller still felt that in the simulated scenario both the separation and speed differences at TMA entry would have been acceptable if the needed communication and coordination is performed between the ACC controlling the flights before TMA entry and the controller in the TMA.
4. In the case of the pair where the separation is the smallest over TMA entry the controller would have asked what speeds the aircraft have to be able to feel in charge of the situation.

From these simulations it can be concluded that the scenarios that were simulated did not cause situations that would have been unacceptable for ATC. However, a larger number of simulations/trials with a mix of aircraft types and with a larger set of varying conditions are needed to enable any definite conclusions. More controller feedback will also be required.

2.3.7 Pilot feedback

Pilots taking part in the Cassis RTA flights were asked to give their perception of working with the FMS RTA function. The RTA function is today provided as an ancillary function and it takes several keystrokes on the FMS Control Display Unit

(CDU) to access it. Most pilots have never performed a flight with the RTA function engaged [8]. Despite this and the fact that only minimal briefing was given to pilots before the flight trials encouraging results were seen and both pilots and controllers learned quickly how to work with the concept. Pilots commented that they appreciated getting inbound clearance when still on ground (in delay-on-ground flights) and earlier than in current operations for all other RTA flights and being able to be part of managing delays rather than being instructed to use vectors or go into holding [7, 9].

After a pilot had performed a Cassis trial s/he was asked to answer some questions about the experience. Most pilots had a positive view on working with an RTA and found that their workload was the same or only slightly higher compared to normal operations. All the answers to these questions that were recorded can be viewed in Appendix A [7, 9].

2.3.8 Controller feedback

The air traffic controllers participating in Cassis were also asked to give their view on RTA operations. The RTA concept presents a completely new working method for the controllers. Controllers are traditionally used to working with physical distance and speed when visualizing the traffic situation and how it will develop [7, 9]. However, because the Maestro AMAN has been in use at Stockholm-Arlanda airport since 2005 [11], controllers were used to working with time to a certain extent [7, 9]. After the trials controllers reported that they found it easy to get use to the concept and that they learnt quickly [7, 9].

2.4 Literature review summary

Live flight trials have shown that it is possible to issue pop-up flights with an RTA set to a TMA entry point and that way insert them into the AMAN sequence already when at departure airport. The trials have also shown that the RTAs can be met with high accuracy and as a consequence it is possible to avoid airborne holding at the arrival airport [7, 9]. Live trials and real-time simulations have indicated that using RTAs operationally and thereby letting flights self-manage with respect to speed to meet an RTA is acceptable to ATC. In the trials and simulations it was possible to provide ATC

with the needed predictability by issuing altitude and/or speed constraints together with the RTA [7, 9, 16]. During real-time simulations the ability of the FMS to meet all the three constraints of time (RTA), altitude and speed set at a TMA entry point was evaluated. It was shown that it was possible to meet all three constraints with high accuracy. During the same real-time simulations, the in-trail separation was evaluated between pairs of aircraft controlling to RTAs. It was found that the separation never became so low that it would have caused concern to ATC [16].

The literature review has revealed that certain limitations exist to how well the current FMS RTA capability performs in adjusting speed in the later part of descent (below approximately FL100). This is due to the limitations in the available speed envelope in this part of flight. To be able to set RTAs to this part of flight it is therefore crucial to have accurate wind predictions in the FMS. Future enhancement in the ability of the FMS to accept descent wind predictions together with more accurate ways of predicting descent winds, such as using the AVTECH Aventus NowCast tool, should enable operations where RTAs are set to the later part of descent [8, 14, 15, 24]. However, considering the current FMS RTA capability the TMA entry point (which is typically passed at or before FL100) appears to be suitable to set the RTA to for an initial implementation. A likely and desirable future extension is to set the RTA to further down in the descent.

Pilots and air traffic controllers that have been involved with RTA live trials have predominantly reported a positive view on working with the concept [7, 9].

The Cassis project has found that the information that needs to be exchanged between the ATCC handling the AMAN, departure towers, AOC and pilots to enable the delay-on-ground concept to be performed cannot be exchanged efficiently with current communication means. A completely new network needs to be developed particularly for the purpose of enabling easy exchange of the required information before the delay-on-ground concept can come into daily operations [7, 9].

3 THE CASE STUDY AIRPORT

3.1 Identification of the case study airport

A study has been carried out to examine at which European airports the delay-on-ground concept could bring benefits. The sources used have been Flightstats.com [25]¹⁷ and the ‘AMAN Status Review 2009’ [11]. At first, airports that fitted the following criteria were selected for further consideration:

1. Traffic flow of approximately 400-800 movements per day.
2. AMAN-equipped.

Criterion 1 was selected to capture airports that are not too busy (and thereby too complex) to suit a short-term implementation, but that still have peak hours where the delay-on-ground concept could be of benefit. The selection resulted in eleven European airports being examined further in terms of the nature of the arriving traffic. Flightstats.com was used to examine the traffic at a typical weekday at the eleven airports. The following criteria needed to be met for an airport to be a potential case study airport:

3. A large number of arriving pop-up flights, with many of these arriving from airports that have a relatively low number of movements per day (less than 150 movements per day).
4. Pop-up flights typically being scheduled to be flown by an RTA-equipped aircraft.

The reason for looking for an airport with many pop-up flights arriving from airports that have a relatively low number of daily movements was to find a case study airport that can benefit from the concept in the short term (without AMAN-DMAN cooperation required) as well as in the long term.

¹⁷ Flightstats.com provides information on flights that are scheduled to arrive to and depart from airports worldwide. It integrates information from several different sources, for example; airlines, airports, Official Airline Guide (OAG) schedules and Automatic Dependent Surveillance-Broadcast (ADS-B).

The airport that was found to be the most suitable and therefore chosen as the case study airport was Oslo-Gardermoen airport.

3.2 Further examination of the case study airport

A timetable of scheduled arrivals into Oslo-Gardermoen airport on a typical weekday has been obtained using Flightstats.com. This timetable included scheduled arrival time at gate, departure airport, typical flight duration, aircraft type, airline company and movements per day of departure airports where pop-up flights originate. To find out which of these flights are RTA-equipped information on which aircraft types are RTA-equipped has been used [8]. It has then been assumed that all aircraft that are of an RTA-equipped type have the RTA function. It has been found that RTA-equipped pop-up flights arriving into Oslo-Gardermoen airport originate from ten different departure airports as described in Table 3-1. The International Air Transport Association (IATA) codes for the airports are specified within the parenthesis.

Table 3-1: Departure airports where RTA-equipped pop-up flights originate and their daily number of aircraft movements [25]

Departure airport	Aircraft movements on a typical day
1. Kristiansund (KSU)	18
2. Molde (MOL)	18
3. Haugesund (HAU)	24
4. Alesund (AES)	36
5. Kristiansand (KRS)	46
6. Trondheim (TRD)	147
7. Stavanger (SVG)	174
8. Bergen (BGO)	244
9. Stockholm-Arlanda (ARN)	602
10. Copenhagen-Kastrup (CPH)	647

From the information in this table it is believed that pop-up flights originating from airports 1-5 can, relatively easy, be issued with an RTA, and thereby inserted into the AMAN sequence when still at departure airport without AMAN-DMAN cooperation. For airports 1-5 it is assumed that as the number of movements is so low the controllers are able to, without the support of a DMAN, ensure that the pop-up flights depart at the

required times to meet their RTAs. When AMAN-DMAN cooperation will be required is when the departure airport has so many movements that it is common for there to be a queue to use the runway in peak hours. It will then be required to have a DMAN that can automatically communicate with the AMAN at destination airport and reserve departure times for the pop-up flights to meet their RTAs. Considering the number of movements for airports 6-8 it is likely that AMAN-DMAN cooperation will be required for these airports to be included in the delay-on-ground concept. For airports 9-10 to be included in the delay-on-ground concept AMAN-DMAN cooperation will definitely be required.

The total number of arrivals and pop-up flight arrivals into Oslo-Gardermoen for each hour of the day is specified in section 4.7.

4 SIMULATION OF THE DELAY-ON-GROUND CONCEPT FOR THE CASE STUDY AIRPORT

4.1 Introduction

A large set of fast-time Monte Carlo simulation runs (180 in total) have been performed to assess the performance of the delay-on-ground concept explored in this work for Oslo-Gardermoen airport. In the simulations, with each run representing an operational day, all flights departing from the airports listed in Table 3-1 took their AMAN delay at the departure gate. Not all of these departure flows were simulated. The departure flows from Stockholm-Arlanda and Copenhagen-Kastrup were simulated and the implications on the departure sequences of locking the pop-up flights to certain times/time spans were measured. To simulate the other departure flows was irrelevant for the study. For each run the arrival flow to Oslo-Gardermoen airport was also simulated. Variations in departure/arrival times was put into the actual timetables to simulate the variations in departure/arrival times from day-to-day due to operational reasons; this is explained further in section 4.4. The AMAN delay experienced by the pop-up flights was measured for each run to get an understanding of the amount of airborne delay that would be saved by using the delay-on-ground concept. For pop-up flights arriving to Oslo-Gardermoen from Stockholm-Arlanda and Copenhagen-Kastrup airports an AMAN-DMAN cooperation was simulated (from now on referred to only as Oslo, Stockholm and Copenhagen airports). In this AMAN-DMAN cooperation the AMAN at Oslo airport and DMANs at Stockholm and Copenhagen airports were simulated to automatically communicate to ensure that the pop-up flights depart at/during the required times/time spans to meet their RTA (slot in the AMAN queue). This cooperation is explained in section 4.2. The implication of locking pop-up flights to certain times/time spans on the departure sequences at Stockholm and Copenhagen airports was then measured. As already mentioned, it was likely that AMAN-DMAN cooperation would be required for pop-up flights departing from airports 6, 7 and 8 to be integrated into the AMAN sequence before takeoff. However, in this work this was not simulated. It was desired to have a case study in which the AMAN and DMAN constraints of only a few airports were integrated to keep the required algorithm

complexity and workload at a level that could be managed within the framework of a Master of Science by Research. With this in mind it was considered suitable to choose the departure airports that are guaranteed to require AMAN-DMAN cooperation.

It should be emphasized that even departure airports that do not require AMAN-DMAN cooperation to be included in the delay-on-ground concept need to have a certain information flow and coordination with the arrival airport. This will be required to be similar to what occurred in the Cassis live trials, as explained in section 2.3.4.1. As discussed in the literature review the Cassis project concluded that a new communication network will need to be found to handle this information flow and coordination efficiently. In the simulations such a communication network allowing real time information exchange has been assumed. AMAN-DMAN cooperation will be required when the departure airport has so many movements that it is common for there to be a queue to use the runway in the peak hours. It will then be required to have a DMAN that can automatically communicate with the AMAN at destination airport and reserve departure times/time spans for the pop-up flights to meet their RTAs. In the simulations it was assumed that for the airports with a lower number of movements the controllers will be able to sequence and delay movements without the support of a DMAN and still ensure that the pop-up flights depart at the required times/time spans. It has also been assumed that this can be achieved without having any significant implication on other departing traffic. In conclusion, therefore, at departure airports with a low number of movements a certain level of cooperation will be required between the arrival and departure airports. However, this cooperation will not include AMAN and DMAN systems automatically communicating their constraints (what is referred to as AMAN-DMAN cooperation in this work). In this work the focus is on those departure airports that require AMAN-DMAN cooperation to be included in the delay-on-ground concept.

In the simulated scenarios all pop-up flights departing from Stockholm and Copenhagen airports and flying to Oslo, Stockholm and Copenhagen airports took their AMAN delay on ground. That is, not only pop-up flights departing for Oslo airport but also flights flying the Copenhagen - Stockholm and Stockholm - Copenhagen routes. The decision to include these pop-up flights as delay-on-ground flights in the simulations

was taken as it seems likely that in a possible future scenario of connecting the AMAN and DMAN constraints of three airports it will be desired to allow all pop-up flights to take their delay on ground. As it was not only desired to measure the airborne delay that can be avoided with the proposed delay-on-ground concept but also to measure the effect the concept has on departure sequencing of the non pop-up flights it was considered important to simulate the locking of all pop-up flights that are likely to in a future scenario be locked to a time/time span in the DMANs. The method used in locking pop-up flights to exact departure times is described in section 4.5.

In the main set of runs the pop-up flights were locked to their exact RTA recommended takeoff times on the departure runways. In a smaller set of runs the pop-up flights were locked to a time in their RTA takeoff window (i.e. the actual departure time was allowed to vary within this time window), to compare the implications for the departure sequences when pop-up flights were locked to an exact departure time and when they were locked to a time within their RTA takeoff window. The realistic scenario is that pop-up flights departing from medium to large airports will be locked to a time within their RTA takeoff window to maintain certain flexibility. The RTA recommended takeoff time corresponds to the airline selected cost index, whereas the RTA takeoff window corresponds to the entire range of possible cost index settings with current predicted winds [14]. Thus, no matter where a pop-up flight departs in its RTA takeoff window it is as likely to meet its RTA, as long as the winds have been predicted correctly. The difference is that if a pop-up flight is locked to a time within the RTA takeoff window, rather than the exact RTA recommended takeoff time, the airline may not get to fly with its preferred cost index setting. Therefore, if pop-up flights are locked to a time within their RTA takeoff window the aim should be for the pop-up flights to be able to depart at the beginning of the window to have a low cost index with low fuel consumption. The RTA takeoff window for a 1 hour flight is 6 minutes long [26]. The flights included in the simulations performed in this work have a duration of slightly less than 1 hour, but their RTA takeoff window has been approximated as 6 minutes long.

In the simulations it was necessary to simulate not only the arrival flow to Oslo airport, but also the departure and arrival flows from/to Stockholm and Copenhagen airports.

This was necessary in order to simulate the above described AMAN-DMAN cooperation. Actual timetables for Oslo arrivals and Stockholm and Copenhagen departures/arrivals were obtained from Flightstats.com [25]. A random variation in departure/arrival time was put into the actual timetables to simulate the variation in departure/arrival times from day-to-day due to operational reasons. This process is explained in further detail in section 4.4.

A runway model setting departure and arrival sequences with the required separation between flights was used to simulate the departure/arrival flows. This model is described in section 4.3.

For each run the departure sequences at Stockholm and Copenhagen airports were set both with current operational procedures and with pop-up flights being locked to times/time spans so that it was possible to measure the effect this had on the departure sequences.

Segregated runway operations were used for all the airports included in the simulations. In segregated runway operations parallel runways are in use with departures on one runway and arrivals on the other. In the future it is possible that mixed-mode, a mix of departures and arrivals on two or more runways, will be used more frequently to handle the expected traffic increase. Using mixed-mode operations makes it possible to have less separation between two flights using the same runway compared to segregated mode and thus increases capacity.

The simulation runs were performed for three different traffic scenarios; current traffic levels, a 15% traffic increase over current levels and a 30% traffic increase. The amount of traffic for each airport included in the simulations for each traffic scenario is described in section 4.7. For each traffic scenario 60 runs were performed.

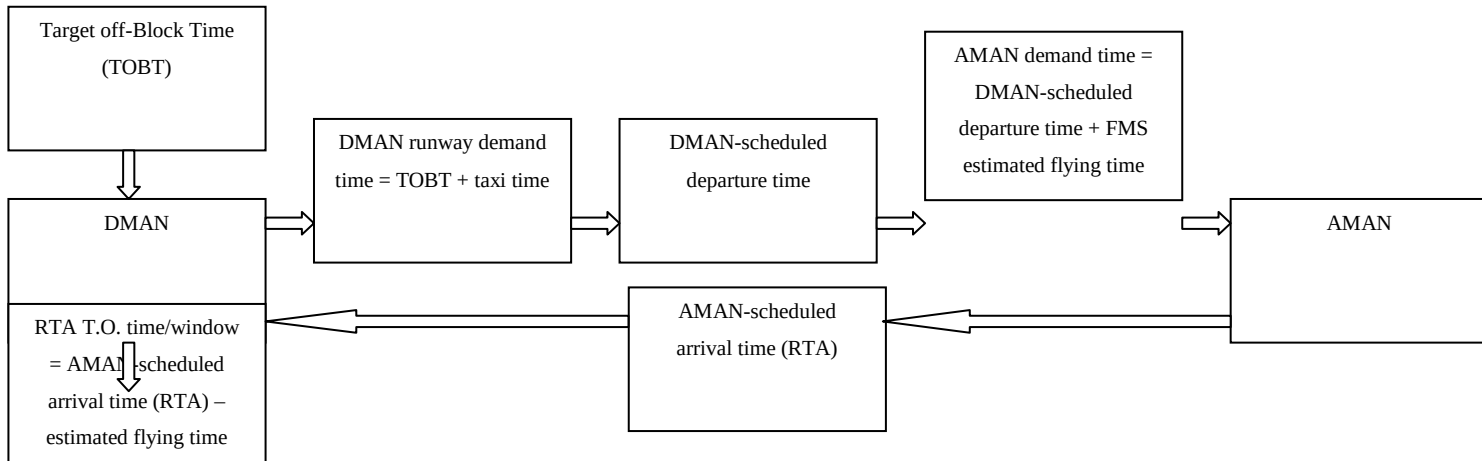
The BADA database was used in the simulations in the Sequencing and Scheduling model as described in section 4.3. It was also used to enable a fuel savings analysis of the delay-on-ground concept. BADA is an aircraft performance model maintained by Eurocontrol and commonly used in ATM simulations [27]. BADA consists of two parts; model specification and summary files containing the coefficients of the aircraft

performance model. The motion model in BADA is a Total Energy Model which equates the rate of work done by forces acting on the aircraft to the rate of increase in potential and kinetic energy. In the simulations performed in this work three of the summary files were used. The Operations Performance File (OPF), specifying thrust, drag, fuel coefficients, weights, speeds etc. for different aircraft types, was used in the simulations. The Global Parameters File (GPF), containing global parameters that are the same for all aircraft types, was also used in the simulations. One of the Performance Table Files (PTF), consisting of average aircraft performance summary tables for the different aircraft types, was used for the fuel savings analysis [28, 29].

An algorithm has been written in Matlab to automate the steps involved in each simulation run and to simulate the AMAN-DMAN cooperation. The algorithm is described in section 4.6.

4.2 The AMAN-DMAN cooperation

The AMAN-DMAN cooperation simulated in this work would involve the following steps in real operations, as shown in the flowchart below:



The pop-up flight is locked to its AMAN-scheduled time, i.e. the pop-up flight is guaranteed that time in the arrival queue as long as it meets its RTA. The DMAN locks the pop-up flight to its RTA take-off time/window, i.e. the pop-up flight is guaranteed that time/a time during the window on the departure runway to ensure that it meets its

RTA. The remaining departure traffic (non pop-up flights) is then sequenced around the pop-up flights' locked times/time spans, possibly leading to the amount of departure sequencing delay that non pop-up flights experience being affected.

How the AMAN-DMAN cooperation has been simulated in this work is described in section 4.6.

4.3 The Sequencing and Scheduling model

4.3.1 Introduction

The sequencer elements of an AMAN and a DMAN have been modelled by using the Sequencing and Scheduling model developed in the Environmentally Friendly Airport ATM Systems (EFAS) project [30, 17]. The EFAS project involved Thales, QinetiQ, NATS, SELEX, Helios and Manchester and Loughborough Universities. The Sequencing and Scheduling model creates a sequenced flow of arriving or departing traffic at a runway with the required separation between flights given the required input information. Access to the model has been obtained from one of the EFAS project members.

The model's algorithms and equations were verified in the EFAS project by comparing the model's calculations with manual calculations for a number of arrival and departure timetables. The model was validated by comparing the departure/arrival sequencing delay calculated by the model with actual departure/arrival sequencing delay experienced at an airport.

4.3.2 Separation

For the model to calculate the required time separation between flights the wake vortex categories of the lead and following aircraft need to be taken into account. For departures the SIDs in use also need to be taken into account. The wake vortex category of an aircraft is a measure of the strength of the wing tip vortices that it produces and depends on the maximum takeoff weight. There are three wake vortex categories defined by ICAO (International Civil Aviation Organization): heavy, medium and light. Each aircraft type belongs to one of these categories [31]. The model's aircraft

performance database contains the wake vortex category of each aircraft type and the required physical separation between aircraft depending on the wake vortex category to which they belong.

4.3.2.1 Arrivals

In the Sequencing and Scheduling model's calculations the required time separation between two consecutive arrivals depends on the wake vortex category of the lead and following aircraft.

Separation due to wake vortices

The required time separation between two arrivals is calculated taking the wake vortex category of the two aircraft into account. The required time separation is calculated according to the equation below. The model uses the lead aircraft as the reference and calculates the time taken for the lead aircraft to reach a safe separation distance from the following aircraft.

Time separation between two consecutive arrivals =

$$\frac{\text{Wake vortex physical separation distance}}{\text{Landing speed of lead aircraft}} \quad (\text{Equation 1})$$

The required wake vortex physical separation distance is specified in the wake_vortex_separation file which is described in section 4.3.4.6.

The landing speed for each arriving aircraft is calculated using a set of BADA equations and parameters as described below:

$$V_{\text{land}} = V_{\text{ref}} \times \sqrt{\frac{m_{\text{land}}}{m_{\text{ref}}}} \quad (\text{Equation 2})$$

$$V_{\text{ref}} = C_{\text{vmin}} \times (V_{\text{stall}})_{\text{ld}} \quad (\text{Equation 3})$$

$$m_{\text{land}} = m_{\text{min}} + \text{loadfactor} \times m_{\text{pyld}} \times 1.25 \quad (\text{Equation 4})$$

where:

V_{land} = landing speed

V_{ref} = reference speed

m_{land} = landing mass

m_{ref} = reference mass, specified by BADA for each aircraft type

$C_{v\text{min}}$ = minimum speed coefficient (specified as 1.3 for all aircraft types by BADA)

$(V_{\text{stall}})_{\text{ld}}$ = landing stall speed, specified by BADA for each aircraft type

m_{min} = minimum mass, specified by BADA for each aircraft type

m_{pyld} = maximum payload mass, specified by BADA for each aircraft type

loadfactor specifies how many percent of the aircraft's seats are taken up by passengers. This information is user-definable and is specified in the timetable_arrivals file (the timetable_arrivals file is described in section 4.3.4.1).

The BADA parameters that are used to calculate the landing speed for each flight are specified in the model's aircraft performance database file which is described in section 4.3.4.5.

4.3.2.2 Departures

In the Sequencing and Scheduling model's calculations the required time separation between two consecutive departures depends both on the wake vortex category of the aircraft and the SID being used by the aircraft. The separation required due to both factors is calculated and the largest separation is then imposed.

Separation due to wake vortices

The time separation due to wake vortices is calculated in a similar manner as for arrivals. Again, the model uses the lead aircraft as the reference and calculates the time taken for the lead aircraft to reach a safe separation distance from the following aircraft.

Time separation between two consecutive departures =

$$\frac{\text{Wake vortex physical separation distance}}{\text{Takeoff speed of lead aircraft}} \quad (\text{Equation 5})$$

The required wake vortex physical separation distance is specified in the wake_vortex_separation file which is described in section 4.3.4.6.

The takeoff speed for each departing aircraft is, as the landing speed for each arriving aircraft, calculated using a set of BADA equations and parameters as described below:

$$V_{to} = V_{ref} \times \sqrt{\frac{m_{to}}{m_{ref}}} \quad (\text{Equation 6})$$

$$V_{ref} = C_{vmin,to} \times (V_{stall})_{to} \quad (\text{Equation 7})$$

$$m_{to} = m_{min} + \text{loadfactor} \times (m_{max} - m_{min}) \quad (\text{Equation 8})$$

where:

V_{to} = takeoff speed

V_{ref} = reference speed

m_{to} = takeoff mass

m_{ref} = reference mass, specified by BADA for each aircraft type

$C_{vmin,to}$ = minimum speed coefficient for takeoff (specified as 1.2 for all aircraft types by BADA)

$(V_{stall})_{to}$ = takeoff stall speed, specified by BADA for each aircraft type

m_{min} = minimum mass, specified by BADA for each aircraft type

m_{max} = maximum mass, specified by BADA for each aircraft type

loadfactor specifies how many percent of the aircraft's seats are taken up by passengers. This information is user-definable and is specified in the timetable_departures file (the timetable_departures file is described in section 4.3.4.1).

The BADA parameters that are used to calculate the takeoff speed for each flight are specified in the model's aircraft performance database file which is described in section 4.3.4.5.

Separation due to SID usage

For departures, a required separation that depends on which SID is used by the lead and following aircraft is calculated by the Sequencing and Scheduling model. For the purpose of calculating this separation, aircraft types are divided into four speed groups. Different time separations need to be imposed between two consecutive departures depending on the speed groups of the lead and following aircraft and on whether the SIDs used by the aircraft are diverging or otherwise. For two SIDs to be considered as diverging they need to diverge by 45 degrees or more. The required separation between flights due to SID usage is specified in the model's sid_separation_diverging and sid_separation_non_diverging files. These files are described in sections 4.3.4.9 and 4.3.4.10 respectively.

4.3.3 Sequencing

In the model aircraft are sequenced one at a time. When deciding which departure/arrival to sequence next, the model considers a certain number of flights (parameter n, set by the user of the model) with maximum difference in demand time (variable t, set by the user of the model) and sequences the flight that requires the least time separation to the most recently sequenced flight. If a certain flight has been delayed by an unacceptable amount of time (parameter m, set by the user of the model) it will be sequenced next. Having the algorithm set up this way optimizes the use of the runway while making sure that no one flight incurs an unreasonable amount of delay.

4.3.4 Input files

For the model to perform the sequencing and separation activity a number of input files need to be programmed with the relevant information. The files are comma separated value (csv) files that are read by the model as it is running. The name of the files and the information they need to be fed with is as described below.

4.3.4.1 The timetable_departures and timetable_arrivals files

The timetable_departures and timetable_arrivals files detail information on flights that are scheduled to depart and arrive from/to the airports included in the simulations. Part of a timetable_departures and timetable_arrivals files is shown in Listing 4-1 and Listing 4-2 respectively. Each row shows information for one flight. In the real files used in the simulations there are several hundred rows, corresponding to the number of flights for one day.

Listing 4-1: Part of a timetable_departures file [32]

Code	Name	Dep ID	Sector	Code	Dep Time	AC Type	Seats	DLF	Dep Pax	Year	UID
xxx	xxxx	xxxxx	xxxxx	ARN	06:36:00	736	150	80	120	2004	D0
xxx	xxxx	xxxxx	xxxxx	RIX	06:37:00	J31	150	80	120	2004	D1

Listing 4-2: Part of a timetable_arrivals file [32]

Code	Name	Arr ID	Sector	Code	Arr Time	AC Type	Seats	ALF	Arr Pax	Year	UID
xxx	xxxx	xxxxx	xxxxx	OSL	08:00:01	736	150	80	120	2004	A0
xxx	xxxx	xxxxx	xxxxx	ARN	08:01:30	738	150	80	120	2004	A1

Below follows a description of the different input that the files require.

- **Code (column 1),Name, Dep ID/Arr ID and Sector**

These are parameters that can be used by the model, but they were not relevant for the simulations performed in this work. As an entry needs to be specified for the model to run, a number of ‘x’ characters have been entered in the relevant cells.

- **Code (column 5), Dep Time/Arr Time and AC Type**

These columns specify the IATA code for the destination/origin airport, the runway demand times for departures and arrivals in order of increasing demand time and the IATA code for the aircraft types of each flight.

- **Seats**

This column specifies the number of seats a particular aircraft type has. The parameter was not relevant for the calculations performed in this work and has been specified as 150 for all aircraft types.

- **DLF/ALF**

Departure load factor/Arrival load factor. This specifies the percentage of aircraft seats that are occupied by a passenger. This parameter has been specified as 80 for all flights which is seen as a reasonable assumption.

- **Dep Pax/Arr Pax**

This parameter specifies the number of passengers for a flight. The value was not relevant for the simulations performed in this work and has been specified as 120 for all flights.

- **Year**

This is a parameter that can be used by the model, but it was not relevant for the simulations performed in this work. As a value needs to be specified for the model to run a random value has been chosen for each flight.

- **UID**

This is a unique identification (UID) number for each flight that is specified as 'D0', 'D1' etc. for departures (referred to as 'D' numbers in this thesis) and 'A0', 'A1' etc. for arrivals (referred to as 'A' numbers in this thesis).

4.3.4.2 The preprocessing file

The preprocessing file specifies certain parameters relevant for the sequencing and scheduling activity. The preprocessing file consists of three parts; ‘timetable_perturb’, with parameters specified in row 2-3, ‘sands’, with parameters specified in row 5-11, and ‘amandman’, with parameters specified in row 13-15. The parts ‘timetable_perturb’ and ‘amandman’ were not relevant for the simulations performed in this work. An example preprocessing file is shown in Listing 4-3 below.

Listing 4-3: Example preprocessing file [17]

```
timetable_perturb
arrCDF,0,0,1
depCDF,0,0,1
sands
arrivals_rolling_window_max_time,300
arrivals_rolling_window_max_size,4
arrivals_maximum_delay_threshold,600
departures_rolling_window_max_time,300
departures_rolling_window_max_size,4
departures_maximum_delay_threshold,600
min_delay_required_for_stack,120
amandman
arrivalsAbsorp,0,0
departuresAbsorp,0,0
min_delay_required_for_stack,120
```

The parameters relating to the ‘sands’ (‘sequencing and separation’) part are described below.

- **departures/arrivals_rolling_window_max_time**

Maximum difference in demand time in seconds for flights that are considered for sequencing in one iteration. This parameter was set to an arbitrary value of 300 in the simulations performed in this work.

- **departures/arrivals_rolling_window_max_size**

Maximum number of flights to consider for sequencing in one iteration. In the simulations performed in this work, this parameter was set to an arbitrary value of 4 for most runs, and 5 for a small number of runs.

- **departures/arrivals_maximum_delay_threshold**

The maximum amount of delay in seconds that a flight can experience before being sequenced. This parameter was set to an arbitrary value of 600 in the simulations performed in this work

- **min_delay_required_for_stack**

This value was not relevant for the simulations performed in this work.

4.3.4.3 The airports file

The airports file contains the IATA and ICAO code for each airport that is specified in the timetable_departures and timetable_arrivals files. The file relates the IATA codes specified in the timetable_departures/timetable_arrivals files to the corresponding ICAO code. This is necessary, as the sid_airfield_mapping file (see below for description of this file) and the star_airfield_mapping file (see below for description of this file) specify the ICAO code for each airport. The latitude and longitude for each airport also needs to be specified in the airports file. This has been specified as 0, 0 for most airports as the location for each airport was not necessary information for the simulations performed in this work. Each row presents information for one airport. The number of rows for a real airports file therefore corresponds to the number of airports specified in the timetable_departures and timetable_arrivals files. Part of an airports file is shown in Listing 4-4.

Listing 4-4: Part of an airports file

Airport Codes

```
IATA,ICAO,Airport,Lat,Lon
CPH,EKCH,Copenhagen,0,0
SVG,ENZV,Stavanger,0,0
TRD,ENVA,Trondheim,0,0
```

4.3.4.4 The aircraft_lookup file

This file relates the IATA code of aircraft types, as specified in the timetable_departures and timetable_arrivals files, to the corresponding BADA notation for each aircraft type.

This information is required for the model to read information for each aircraft type from the aircraft performance database file (see below for description of this file). The speed group for each aircraft type is specified and is used for the calculation of the required separation for departures due to SID usage. The parameters: Emissions, INM and Class were not relevant for the simulations performed in this work. Each row presents information for one aircraft type. The first few rows of the aircraft_lookup file are shown in Listing 4-5.

Listing 4-5: Part of the aircraft_lookup file [30]

BADA,IATA,EMISSIONS,INM,speed group,Class
A30B__,AB4,A300,A300,4,HJET
A310__,313,A310,A310,4,HJET
A333__,333,A33034,A33034,4,HJET
A333__,330,A33034,A33034,4,HJET

4.3.4.5 The aircraft performance database file

This file contains aircraft performance characteristics for the aircraft types included in the simulations, such as ICAO wake vortex categories and speeds and masses for different aircraft types. The aircraft performance database file contains the BADA summary files the Operations Performance File (OPF) and the Global Parameters File (GPF). All except for one aircraft type are specified with aircraft performance characteristics according to these BADA summary files [18]. An additional aircraft type has then been added and is discussed in section 4.5.

4.3.4.6 The wake_vortex_separation file

This file specifies the physical separation, in nautical miles, that is required due to wake vortices between aircraft types belonging to the different wake vortex categories. The separation is calculated from the matrix shown in Table 4-1.

Table 4-1: Matrix for calculating the required separation between flights due to wake vortices [30]¹⁸

leader \ follower	H	Um	M	S	L
H	4	5	5	6	7
Um	3	3	4	4	6
M	3	3	3	3	5
S	3	3	3	3	3
L	3	3	3	3	3

In the Sequencing and Scheduling model the matrix is contained in the wake_vortex_separation file as shown in Listing 4-6.

Listing 4-6: The wake_vortex_separation file [30]¹⁹

```
Follower > ,H,Um,M,S,L
H,4,5,5,6,7
Um,3,3,4,4,6
M,3,3,3,3,5
S,3,3,3,3,3
L,3,3,3,3,3
```

The wake_vortex_separation file specifies the five UK wake vortex categories; heavy (H), upper medium (Um), medium (M), small (S) and light (L). Heavy, medium and light corresponds to the ICAO wake vortex categories. In the simulations only the ICAO wake vortex categories were used with each aircraft type belonging to one of these categories. In the wake_vortex_separation file there is one difference in the required separation compared to ICAO specified required separations. When an aircraft of category light follows an aircraft of category heavy the required separation is 6 nautical miles according to ICAO separations [31]. As can be seen from Listing 4-6; in the wake_vortex_separation file this separation is specified as 7 nautical miles.

4.3.4.7 The star_airfield_mapping_file

When an arrival sequence is set, each origin airport needs to have one or more STARs assigned to it. For an origin the percentage of flights travelling on each STAR is also

¹⁸ Separation unit = nautical miles.

¹⁹ Separation unit = nautical miles.

specified. The origin airport is specified with its ICAO code. Part of a `star_airfield_mapping` file is shown in Listing 4-7 below. Each row specifies which STAR is to be used for one origin airport. The number of rows for a real `star_airfield_mapping` file therefore corresponds to the number of origin airports included in the simulations. For the simulations performed in this work it was not relevant which STAR was assigned to the origin airports. Therefore a STAR name has been chosen at random for each origin airport.

Listing 4-7: Part of a `star_airfield_mapping` file

Origin,STAR,% a/c on STAR
EDDL,CDA,100
ENVA,SVD,100
ENBR,SVD,100
EVRA,ALM,100

4.3.4.8 The `sid_airfield_mapping` file

When a departure sequence is set, each destination airport needs to have one or more SIDs specified. For a destination airport the percentage of flights using each SID is also specified. The destination airport is recognized through its ICAO code. Part of a `sid_airfield_mapping` file is shown in Listing 4-8. Each row specifies which SID is to be used for one destination airport. The number of rows for a real `sid_airfield_mapping` file therefore corresponds to the number of destination airports included in the simulations. The model needs information on which SID is used by each flight and which SIDs are diverging and non-diverging from each other in order to calculate the required separation between departing flights, as described in section 4.3.2.2. The information on which SID is used for which destination (for flights leaving Stockholm airport and Copenhagen airport) has been obtained from Routefinder [33]. The geographical layout of the SIDs at Stockholm and Copenhagen airports has then been obtained from the Swedish Aeronautical Information Publication (AIP) [34, 35] and Danish AIP [36] respectively. From this information it has been possible to, in a separate file, programme the model with information on which SIDs are diverging and which are non-diverging from each other.

Listing 4-8: Part of a sid_airfield_mapping file [30]

```
Dest,SID,% a/c on SID
LCLK,SIMEG,100
LEMG,BISTA,100
LEPA,BISTA,100
LICC,BALOX,100
```

4.3.4.9 The sid_separation_diverging file

This file specifies the separation required, in seconds, between two aircraft departing on diverging SIDs. The required separation depends on the speed groups (SGs) of the lead and following aircraft. The separation is calculated from the matrix shown in Table 4-2.

Table 4-2: Matrix for calculating the required separation between flights departing on diverging SIDs [30]²⁰

leader	follower	SG1	SG2	SG3	SG4
SG1		60	120	120	120
SG2		60	60	120	120
SG3		60	60	60	120
SG4		60	60	60	60

In the Sequencing and Scheduling model the matrix is contained in the sid_separation_diverging file as shown in Listing 4-9.

Listing 4-9: The sid_separation_diverging file [30]²¹

```
Diverging
Follower > ,SG1,SG2,SG3,SG4
SG1,60,120,120,120
SG2,60,60,120,120
SG3,60,60,60,120
SG4,60,60,60,60
```

²⁰ Separation unit = seconds.

²¹ Separation unit = seconds.

4.3.4.10 The sid_separation_non_diverging file [30]

This file specifies the separation required, in seconds, between two aircraft departing on non-diverging SIDs. The required separation depends on the speed groups (SGs) of the lead and following aircraft. The separation is calculated from the matrix shown in Table 4-3.

Table 4-3: Matrix for calculating the required separation between flights departing on non-diverging SIDs [30]²²

leader	follower	SG1	SG2	SG3	SG4
SG1		120	180	240	300
SG2		120	120	180	240
SG3		60	120	120	180
SG4		60	60	120	120

In the Sequencing and Scheduling model the matrix is contained in the sid_separation_non_diverging file as shown in Listing 4-10.

Listing 4-10: The sid_separation_non_diverging file [17]²³

```
Non Diverging
Follower > ,SG1,SG2,SG3,SG4
SG1,120,180,240,300
SG2,120,120,180,240
SG3,60,120,120,180
SG4,60,60,120,120
```

4.3.5 Output files

The Sequencing and Scheduling model output file of interest in this work is the sequencing_scheduling file.

4.3.5.1 The sequencing_scheduling file

This file contains the DMAN/AMAN-scheduled sequence with the required DMAN/AMAN delay (departure/arrival sequencing delay) imposed on flights. Part of a

²² Separation unit = seconds.

²³ Separation unit = seconds.

sequencing_scheduling file is shown in Listing 4-11. Each row shows information for one flight. In the real files used in the simulations there are several hundred rows, corresponding to the number of flights for one day. Column 1 identifies the flights through their ‘D’ and ‘A’ numbers. Column 2 specifies the demand times of the flights and column 3 specifies the DMAN/AMAN-scheduled times of flights. Column 4 specifies which SID/STAR was used by the flight.

Listing 4-11: Part of a sequencing_scheduling file

UId,perturbarrdep,actualarrdep,sidstar
D0,06:36:00,06:36:00,KEMAX
D1,06:37:00,06:38:13,SIMEG

4.4 Modelling of delay, taxi times and flying times

In order to create demand timetables for each simulation run, delays (either positive or negative) have been applied to the timetable of scheduled arrivals and departures. Additionally, as the timetables obtained from Flightstats.com specify gate departure/arrival times, taxi times have been subtracted and added for departures and arrivals respectively in order to obtain runway demand times. To simulate the AMAN-DMAN cooperation it has also been necessary to obtain flying times between the airports included in the simulations. For each variable a number of real data values from operational flights was obtained from Flightstats.com. Random data was then generated, for use in the simulation runs, within the observed interval according to tables 4-4 to 4-18.

In order to obtain the most suitable real data values for delay, flights were divided into departures and arrivals and into the sector lengths: short-, medium- and long-hauls. As the aim was to create *demand* timetables the real data was obtained from airports during low traffic periods where it was possible to capture delay that was due to other factors than delay due to traffic at the airport (i.e. delay that is not departure/arrival sequencing delay at that airport). The times in the demand timetables represented the demand times that the trajectory predictor would calculate in the AMAN for arrivals and that the DMAN would calculate using the TOBT and estimated taxi time for departures. The real data was obtained from a few different airports to ensure that the data obtained was

not influenced by particular operational practices at one specific airport and that the data models the rest of the population as well as possible.

Taxi times were divided into departure and arrival taxi times at the different airports included in the simulations. The real data was obtained from the actual airports included in the simulations for one operational day. These taxi times were compared with taxi times from a different day at the airport to ensure that they represented an appropriate sample from the entire population and that no particular circumstance (such as weather) on the day had affected the data on taxi times obtained. The taxi times were compared for the different hours of the day and for the different aircraft types. This was done in order to find out if there are, for example, longer taxi times during peak hours and if there is a clear pattern between the taxi times for different aircraft types. As no such tendency or pattern could be found there was no reason to not use all the taxi times as one data set.

For the flying times the real data was obtained during low traffic periods to obtain real data that was affected by traffic congestion as little as possible. The variation in flying time was then due to weather conditions and cost index setting. This simulates that, if the delay-on-ground concept would be used in real operations, the FMS onboard the aircraft would communicate the estimated flying time, which would depend on current weather and the selected cost index setting and not traffic congestion. Real data from several days had to be obtained in order to get a sample that was large enough. For the flying times 100 samples were found for each route included in the simulations which was considered as large enough.

In order to confirm that using the generated random data for delay and taxi times has created demand timetables that are realistic the number of departures/arrivals per hour of each demand timetable has been output to a results file after each run. The number of departures/arrivals has then been compared with information from the Central Flow

Management Unit (CFMU)²⁴, which has shown that the created demand timetables were indeed realistic.

Tables 4-4 to 4-18 below present the parameters describing the real data for delays, taxi times and flying times. In Appendix B the probability densities of the observed delay times, taxi times and flying times are presented.

Table 4-4: Parameters describing short-haul arrivals delay

Mean (minutes)	-2.84
Standard deviation (minutes)	9.33
Minimum value (minutes)	-25.00
Maximum value (minutes)	40.00

Table 4-5: Parameters describing short-haul departures delay

Mean (minutes)	-1.46
Standard deviation (minutes)	6.35
Minimum value (minutes)	-20.00
Maximum value (minutes)	25.00

Table 4-6: Parameters describing medium-haul arrivals delay

Mean (minutes)	18.82
Standard deviation (minutes)	43.33
Minimum value (minutes)	-75.00
Maximum value (minutes)	215.00

Table 4-7: Parameters describing medium-haul departures delay

Mean (minutes)	29.18
Standard deviation (minutes)	34.55
Minimum value (minutes)	-15.00
Maximum value (minutes)	209.00

²⁴ CFMU data has been available only for Stockholm departures, the information has been actual number of departures per hour for part of two dates during 2010, the information has been obtained from Patrick Manzi, Aeronautical Engineer at the Swedish ANSP Luftfartsverket (November 2010).

Table 4-8: Parameters describing long-haul arrivals delay

Mean (minutes)	9.57
Standard deviation (minutes)	61.78
Minimum value (minutes)	-60.00
Maximum value (minutes)	125.00

Table 4-9: Parameters describing long-haul departures delay

Mean (minutes)	16.57
Standard deviation (minutes)	23.94
Minimum value (minutes)	-12.00
Maximum value (minutes)	126.00

Table 4-10: Parameters describing taxi time Oslo arrivals

Mean (minutes)	4.57
Standard deviation (minutes)	1.59
Minimum value (minutes)	1.00
Maximum value (minutes)	16.00

Table 4-11: Parameters describing taxi time Stockholm arrivals

Mean (minutes)	6.12
Standard deviation (minutes)	2.11
Minimum value (minutes)	2.00
Maximum value (minutes)	13.00

Table 4-12: Parameters describing taxi time Stockholm departures

Mean (minutes)	10.05
Standard deviation (minutes)	3.08
Minimum value (minutes)	4.00
Maximum value (minutes)	21.00

Table 4-13: Parameters describing taxi time Copenhagen arrivals

Mean (minutes)	5.78
Standard deviation (minutes)	1.74
Minimum value (minutes)	3.00
Maximum value (minutes)	14.00

Table 4-14: Parameters describing taxi time Copenhagen departures

Mean (minutes)	10.39
Standard deviation (minutes)	2.90
Minimum value (minutes)	3.00
Maximum value (minutes)	19.00

Table 4-15: Parameters describing flying time Copenhagen - Oslo

Mean (minutes)	51.29
Standard deviation (minutes)	3.64
Minimum value (minutes)	44.00
Maximum value (minutes)	61.00

Table 4-16: Parameters describing flying time Copenhagen - Stockholm

Mean (minutes)	53.47
Standard deviation (minutes)	2.88
Minimum value (minutes)	48.00
Maximum value (minutes)	61.00

Table 4-17: Parameters describing flying time Stockholm - Oslo

Mean (minutes)	42.48
Standard deviation (minutes)	2.41
Minimum value (minutes)	37.00
Maximum value (minutes)	49.00

Table 4-18: Parameters describing flying time Stockholm - Copenhagen

Mean (minutes)	54.45
Standard deviation (minutes)	3.09
Minimum value (minutes)	48.00
Maximum value (minutes)	63.00

4.5 Simulating locking of the pop-up flights to exact departure times

In the main set of runs pop-up flights were locked to their exact RTA recommended takeoff time. The Sequencing and Scheduling model does not model locking of flights to a particular departure time [30, 17]. It has therefore been necessary to find a way of achieving this locking functionality. To ensure that the pop-up flights would always be scheduled at their demand time (their RTA recommended takeoff time) they were scheduled with a fictitious aircraft type created in the aircraft performance database file of the Sequencing and Scheduling model with speed group 1 and wake vortex category S. The tables for SID separation due to speed group and separation due to wake vortex category were then changed so that when the flights were scheduled for departure the fictitious aircraft type always required a smaller separation to the preceding departure than all other aircraft types in the simulations. As the Sequencing and Scheduling model always schedules the departure that required the least separation to the previously scheduled departure next, the pop-up flights were always scheduled at their demand time. No other aircraft types in the database have the same speed group and wake vortex category as the fictitious aircraft type. The changes made to the tables then had no effect on any other aircraft types, but ensured that pop-up flights were scheduled at their demand time. The remaining aircraft performance characteristics for the fictitious aircraft type were the same as the characteristics specified for a Boeing 737-800 in the BADA database. This was considered suitable as all pop-up flights were flown either by a Boeing 737 or Airbus 320 aircraft type which have similar aircraft performance characteristics.

A first departure sequence was set with pop-up flights being scheduled with the fictitious aircraft type and thereby scheduled at their demand time. As described in the previous paragraph, the aircraft performance characteristics of the fictitious aircraft type

were such that the pop-up flights always required the least separation to the previously scheduled departure. The pop-up flights were therefore scheduled with less than the required separation to the preceding departure. To deal with this the simulation algorithm went through the first departure sequence and calculated if the separation between each pop-up flight and the flight sequenced immediately before it was sufficient. If it was not the flight sequenced before the pop-up flight was moved forward in the sequence to immediately after the pop-up flight. The algorithm moved all subsequent non pop-up flights forward to achieve the new and final departure sequence. This led to additional departure sequencing delay for some non pop-up flights in order to reserve the departure times for the pop-up flights. The simulation algorithm is explained in further detail in section 4.6.

When reserving exact departure times for pop-up flights in the manner as has been done in these simulations the effect on the departure sequencing delay for non pop-up flights is due to three factors:

1. The sequence is often less tightly packed before the pop-up flights. There is often some, but not enough, separation between the pop-up flight and the flight sequenced before it in the first departure sequence. The flight before the pop-up flight is then moved to behind the pop-up flight in the sequence. This creates a separation between the pop-up flight and the flight that is now sequenced before it that is slightly larger than the minimum required separation, which leads to a less tightly packed sequence and generates a knock-on effect of additional departure sequence delay on subsequent flights. This effect is, of course, the largest in the peak hours.

2. The order of flights is disturbed around the pop-up flights. This is related to the fact that often flights are moved from immediately before to immediately behind a pop-up flight to ensure separation. As described earlier, one of the goals of a DMAN is to optimize the order of flights to achieve the least overall departure sequencing delay. The order of the pop-up flight and the flight that is sequenced before it is decided by the fact that the pop-up flight needs to depart at a particular time. As discussed, the flight departing after the pop-up flight is often moved to after the pop-up flight to ensure that

the pop-up flight leaves at the required time²⁵. Thus, the DMAN sequencing is disturbed both immediately before and immediately after each pop-up flight. This leads to additional delay for some flights which can give a knock-on effect on many subsequent flights in peak hours.

3. Most pop-up flights have a different departure demand time with the delay-on-ground concept. All pop-up flights that have an AMAN delay change their departure demand time to slightly later in comparison to their demand time without the concept (on average more than half of the pop-up flights had an AMAN delay). This factor, unlike the other factors, can have both a positive (decrease in total departure sequencing delay) and negative (increase in total departure sequencing delay) effect on the departure sequence. The overall effect is positive or negative depending on if the pop-up flight requires the runway during a time window that has more or less aircraft demanding the runway than without the concept.

4.6 The simulation algorithm

An algorithm has been written in Matlab to automate the steps involved in each simulation run that is part of the main set of runs (all runs except for the runs where pop-up flights are locked to a time within their RTA takeoff window) and to simulate the AMAN-DMAN cooperation.

In the simulations two departure flows and three arrival flows were simulated by the Sequencing and Scheduling model. The two departure flows were Stockholm departures and Copenhagen departures. The three arrival flows were Oslo arrivals, Stockholm arrivals and Copenhagen arrivals.

In each simulation run the algorithm read and wrote a number of files. The files and their content are described in sections 4.6.1 and 4.6.2.

²⁵ It may be that there is a flight within the `departures_rolling_window_max_size` that requires less separation to the pop-up flight (the parameter `departures_rolling_window_max_size` is specified in the preprocessing file as described in section 4.3.4.2). However, to avoid penalizing individual flights too severely this flight is still sequenced immediately after the pop-up flight.

4.6.1 Input files

The input files are listed and described below.

- **The sequencing_scheduling file**
- **The scheduled demand files**
- **The delay files**
- **The taxi time files**
- **The flying time files**

The content of the sequencing_scheduling file is described in section 4.3.5.1. There are five sequencing_scheduling files, one for each departure and arrival flow.

The scheduled demand files contain the airline scheduled times of departures and arrivals. There are five scheduled demand files, one for each departure and arrival flow. The files also contain what the sector length is of flights (short-, medium- and long-haul), the IATA code for destination/origin and IATA code of the aircraft type of all flights. The flights are listed in order of increasing scheduled time of departure/arrival.

The delay files contain the random numbers generated to model delay. There are six delay files, one each for short departures, short arrivals, medium departures, medium arrivals, long departures and long arrivals.

The taxi time files contain the random numbers generated to model taxi time. There are five taxi time files, one each for Oslo arrivals, Stockholm departures, Stockholm arrivals, Copenhagen departures and Copenhagen arrivals.

The flying time files contain the random numbers generated to model flying time. There are four flying time files, one each for Stockholm-Oslo, Stockholm-Copenhagen, Copenhagen-Oslo and Copenhagen-Stockholm.

4.6.2 Output files

The output files are listed and described below.

- **The timetable_arrivals and timetable_departures files**
- **The hourly demand files**
- **The AMAN delay file**
- **The DMAN delay files**

The content of the timetable_arrivals and timetable_departures files is described in section 4.3.4.1. There are five timetable_arrivals and timetable_departures files, one for each arrival and departure flow.

The hourly demand files specify the number of aircraft that demanded the runway in each hour of the day. There are five hourly demand files, one each for Oslo arrivals, Stockholm departures, Stockholm arrivals, Copenhagen departures and Copenhagen arrivals. The purpose of having these files was to ensure that realistic demand timetables had been used in the simulations. It was shown that the demand timetables had a similar number of departures/arrivals demanding the runways per hour as in real operations for the current traffic amount. From this it can be assumed that realistic delay times and taxi times were generated from the density functions and that the demand timetables for the 15% and 30% traffic increase were also realistic.

The AMAN delay file contains the arrival sequencing delay (AMAN delay) that pop-up flights arriving into Oslo airport experienced in the simulations. In the file the delay is divided into the total for all pop-up flights and per departure airport. The information in this file forms the basis for the fuel savings analysis. The file also contains the demand time of each flight to enable the analysis of AMAN delay to be divided into per hour that the flights demanded the runway.

The DMAN delay files contain the departure sequencing delay (DMAN delay) that all non pop-up flights experienced in the simulations. The departure sequencing delay is specified both for when current operational procedures are used and for when pop-up flights are locked to exact departure times. The files also specify what the additional delay is due to locking the pop-up flights to exact departure times for each flight. The files also contain the demand time of each flight to enable the analysis of additional

departure sequencing delay to be divided into per hour that the flights demanded the runway. There are two of these files, one each for Stockholm departures and Copenhagen departures.

4.6.3 Flowchart of the algorithm

This section presents the simulation algorithm. The main steps of the algorithm are described in section 4.6.3.1. Section 4.6.3.2 contains a detailed flowchart.

4.6.3.1 The main steps of the algorithm

The main steps of the algorithm are presented below:

1. Create the demand timetables.
2. Put the departure flows through the sequencer²⁶.
3. Read the sequencing_scheduling files for the departure flows.

Departure sequencing delay with current operational procedures =
DMAN-scheduled time – DMAN demand time

4. AMAN demand time for pop-up flights =
DMAN-scheduled time for pop-up flights + flying time

5. Put the arrival flows through the sequencer.

6. Read the sequencing_scheduling files for the arrivals flows.

7. AMAN delay for pop-up flights =
AMAN-scheduled times for pop-up flights – AMAN demand times for pop-up flights

8. RTA recommended takeoff time for pop-up flights =
AMAN-scheduled times for pop-up flights – flying times

²⁶ The term 'sequencer' refers to the model of the AMAN/DMAN sequencer in the Sequencing and Scheduling model.

9. Put the pop-up flight departures only through the sequencer with their RTA recommended takeoff times as their demand times.

10. Read the sequencing_scheduling files for the departure flows. If a pop-up flight needs to be delayed by more than 3 minutes from its RTA recommended takeoff time due to a conflict with another pop-up flight its participation in the delay-on-ground concept will be cancelled.

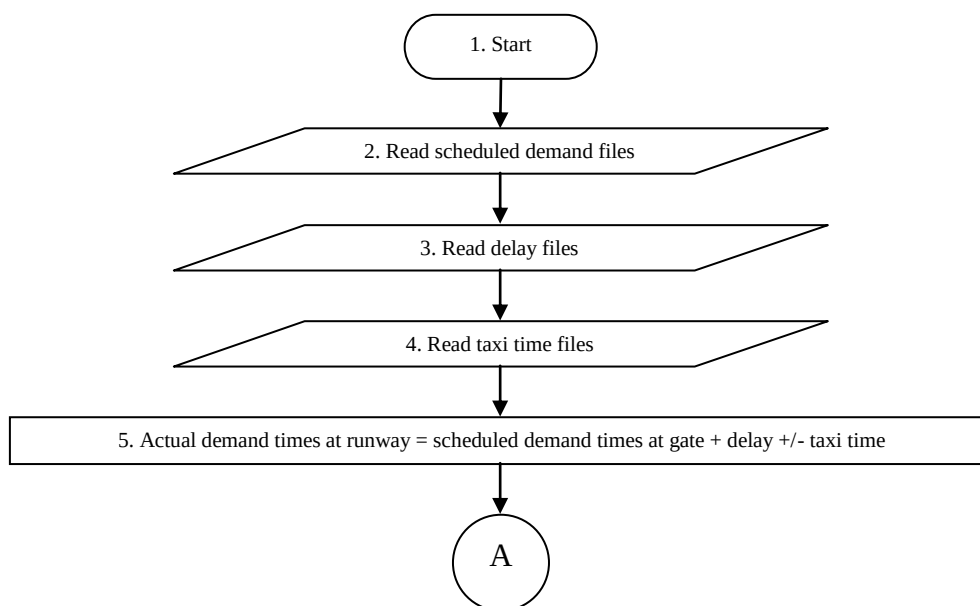
11. Put all the departures through the sequencer. The pop-up flights have their DMAN-scheduled time read in the sequencing_scheduling file in the previous step as their demand time and are locked to this time with the fictitious aircraft type with speed group 1 and wake vortex category S.

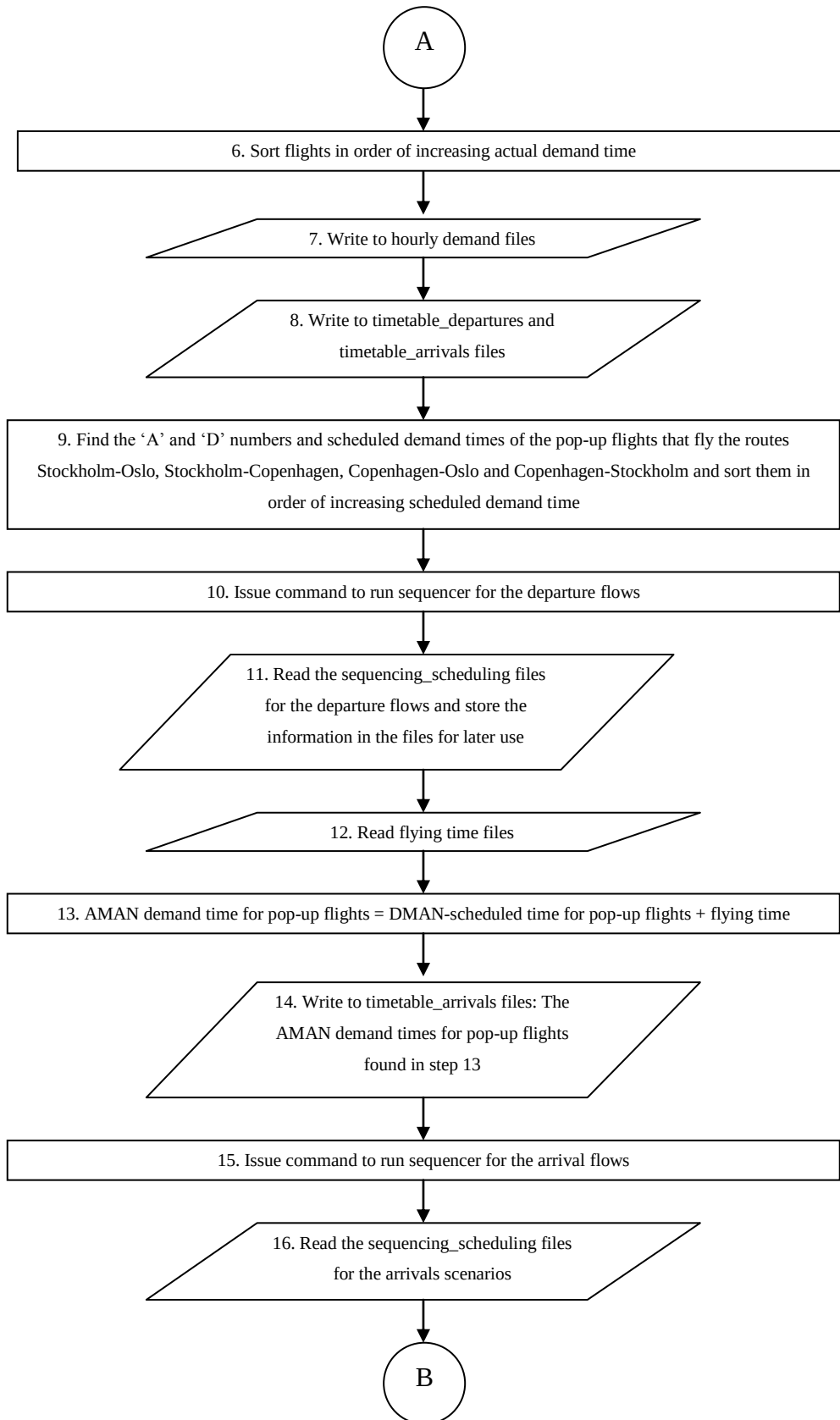
12. Read the sequencing_scheduling files for the departure flows. Search through the files and assign all flights a DMAN-scheduled time that ensure the required separation between departures.

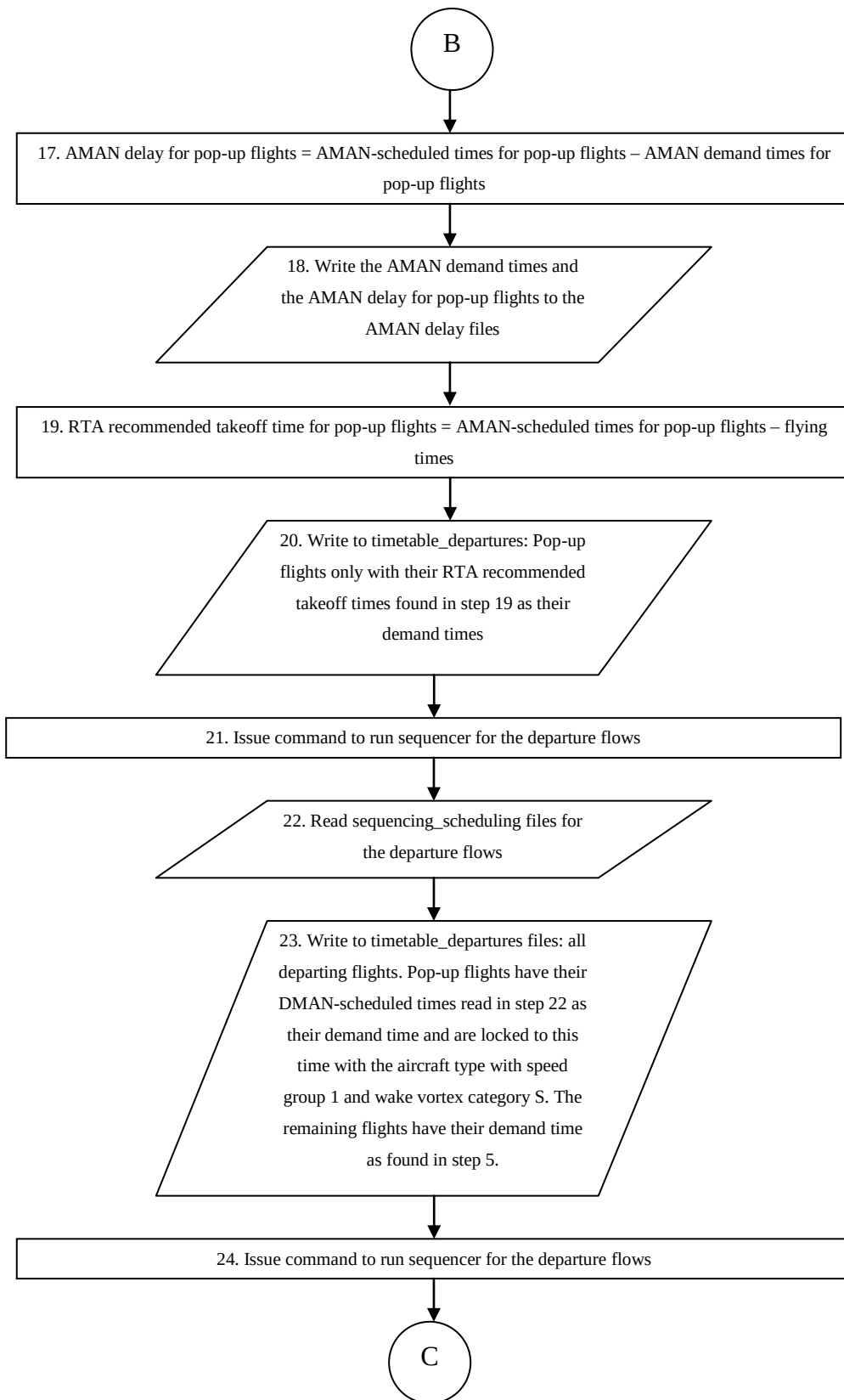
Departure sequencing delay when pop-up flights are locked to exact departure times =
DMAN-scheduled time – DMAN demand time

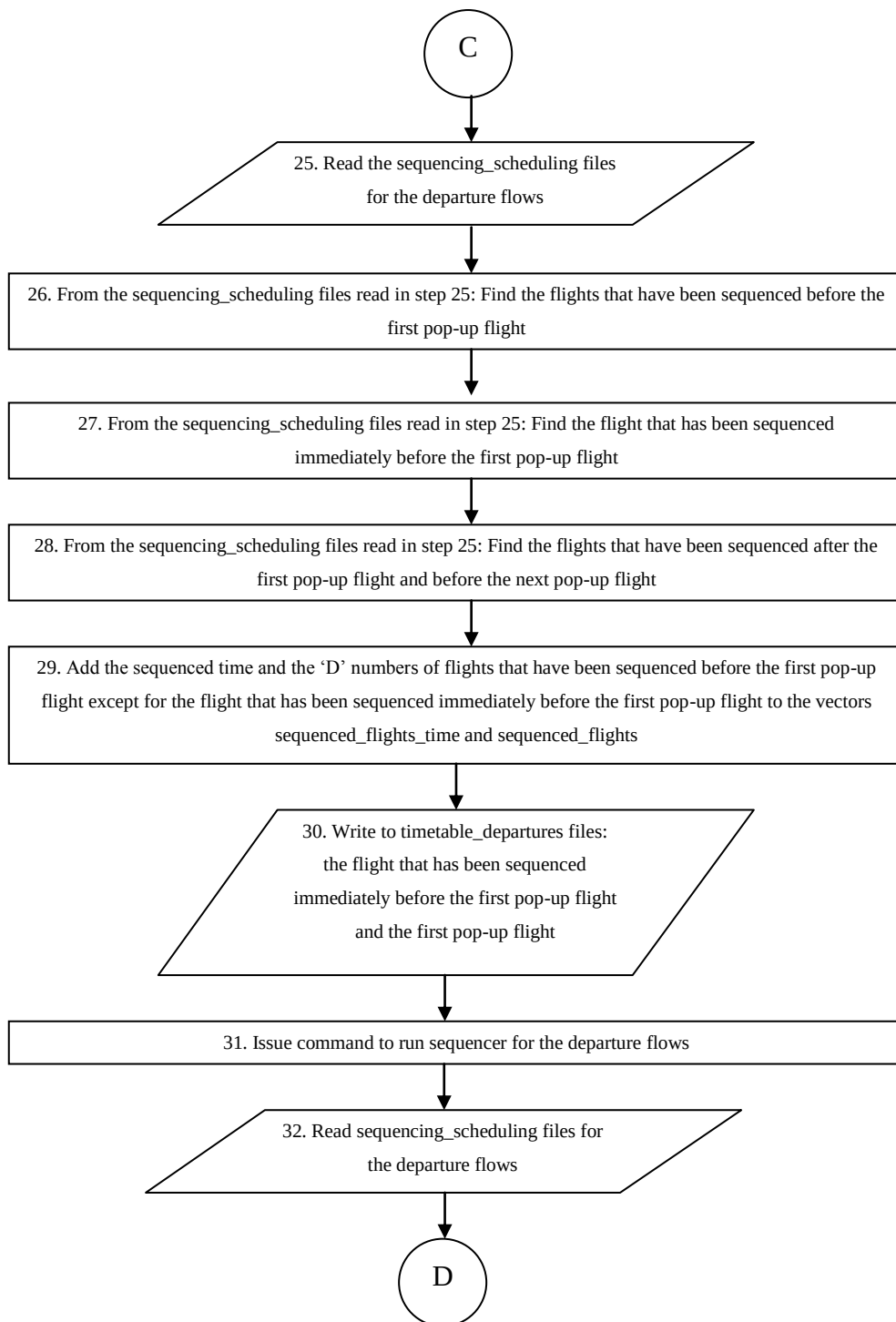
4.6.3.2 Detailed flowchart

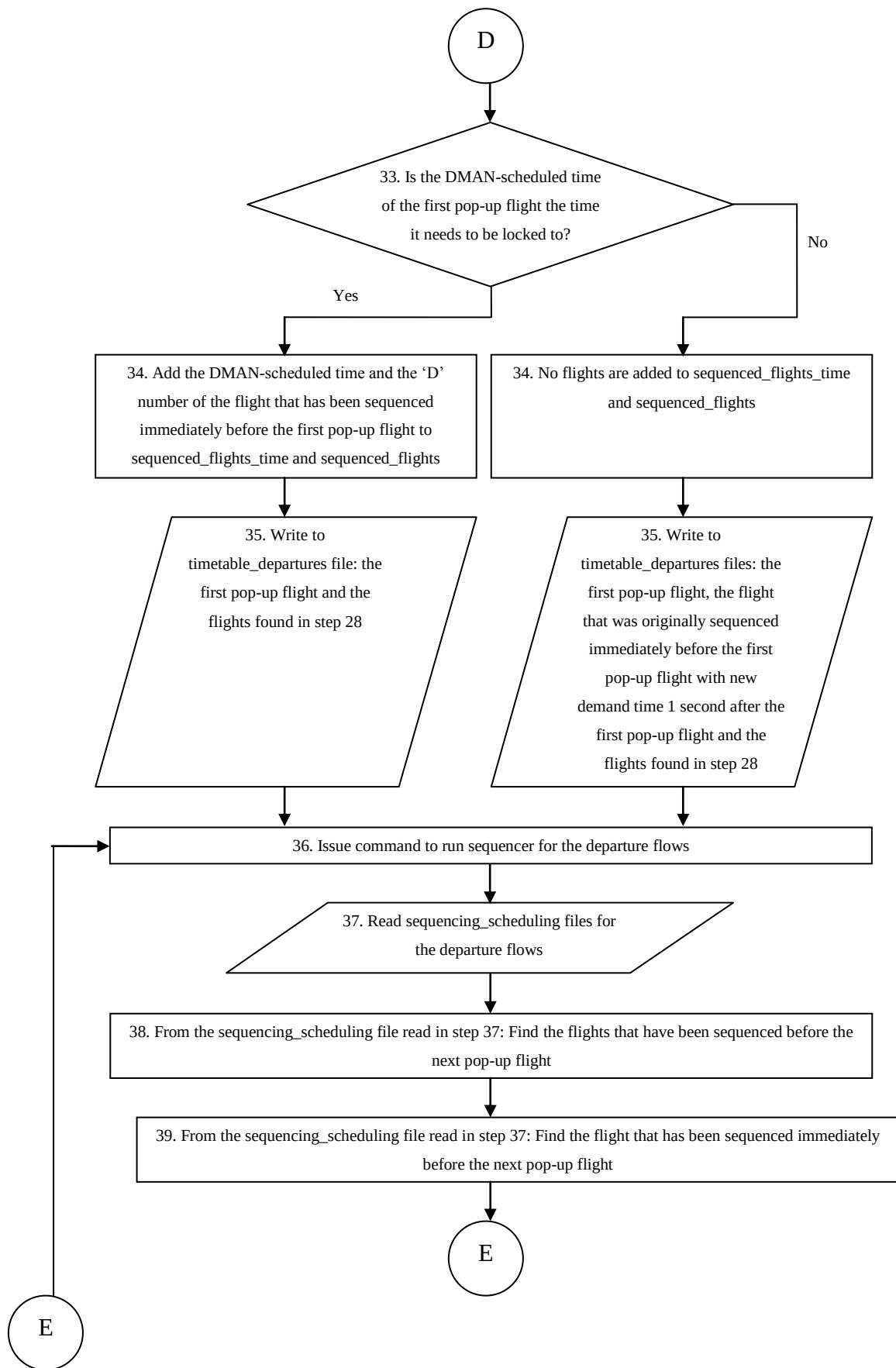
A detailed flowchart is presented below:

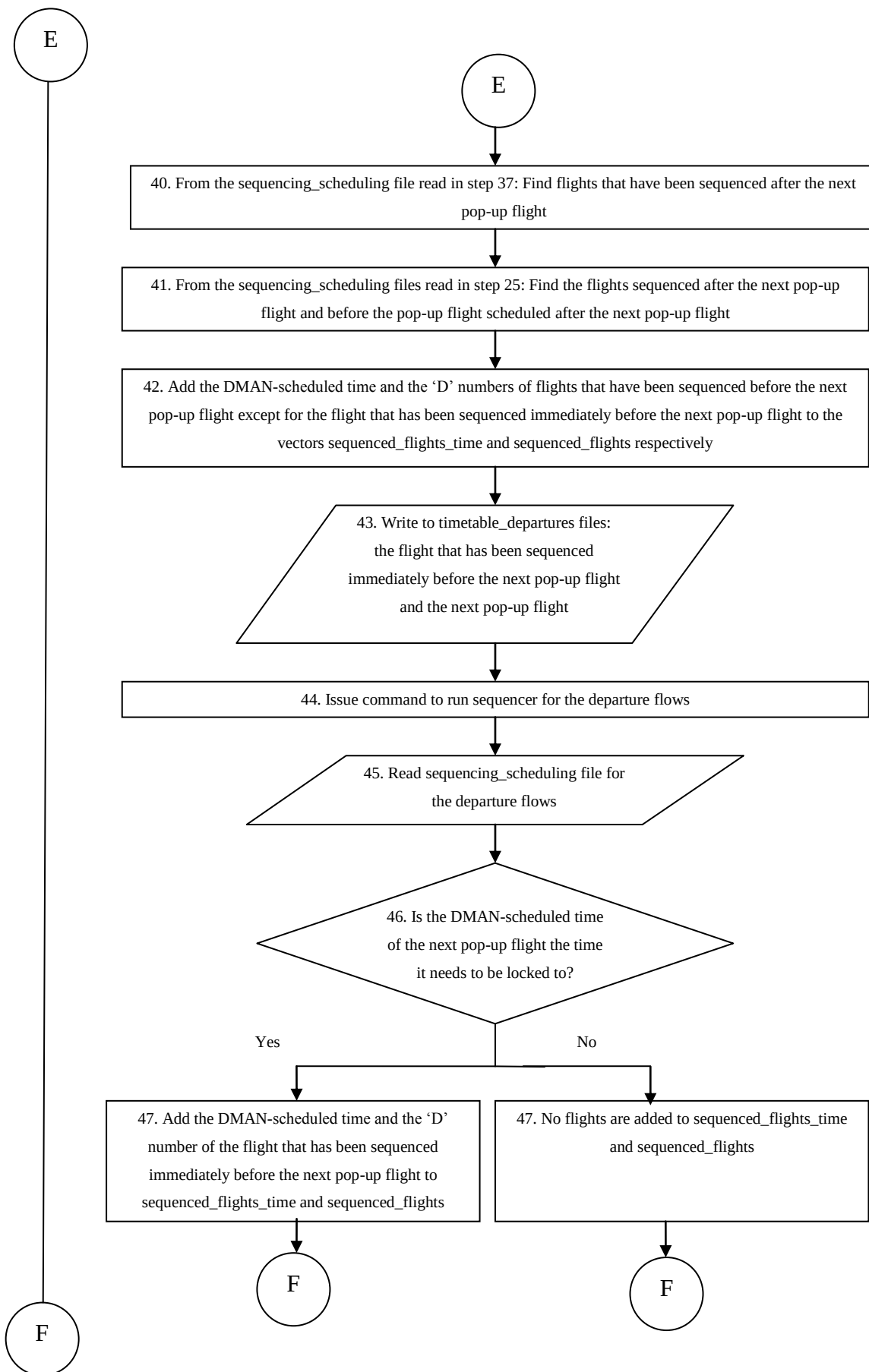


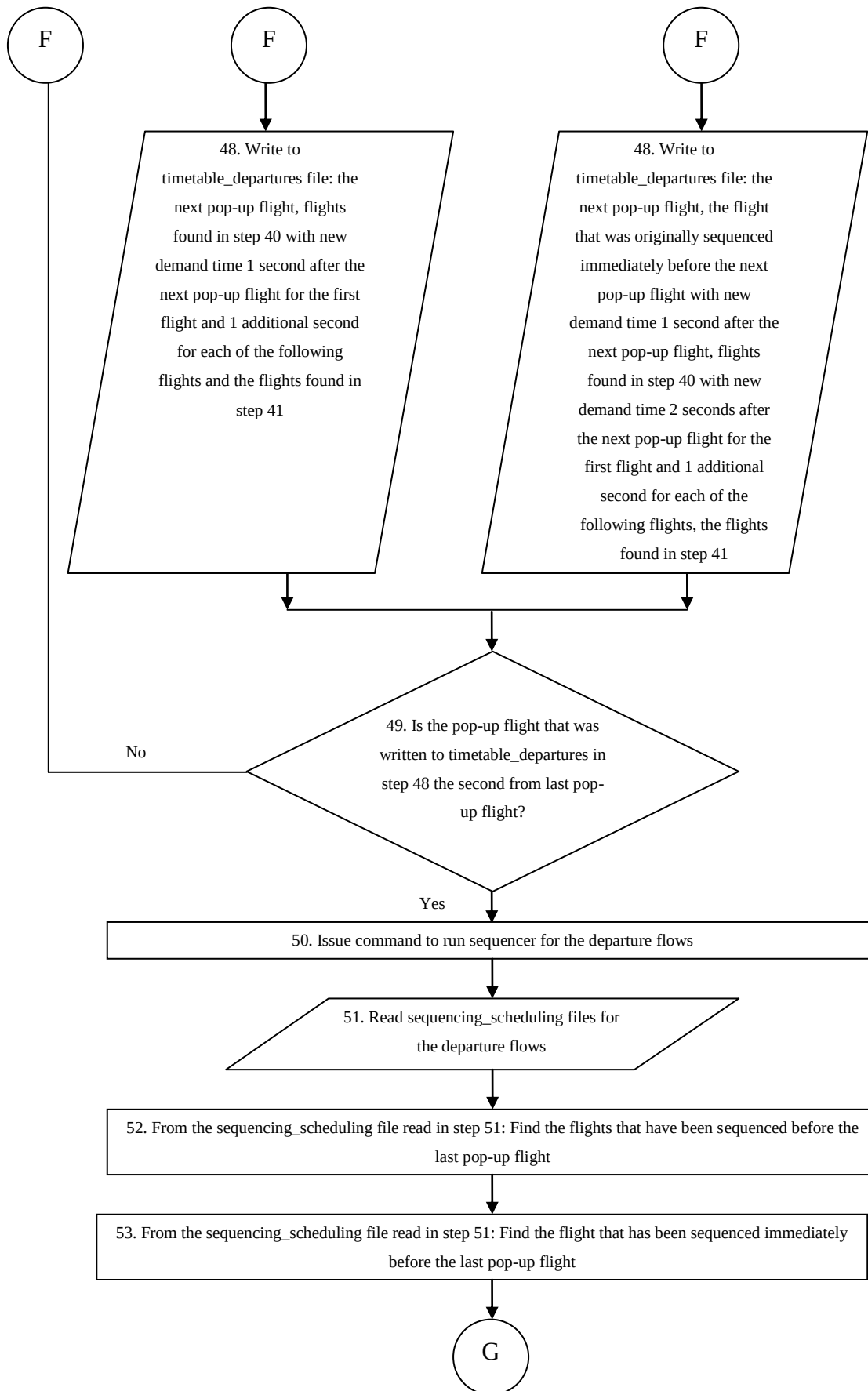


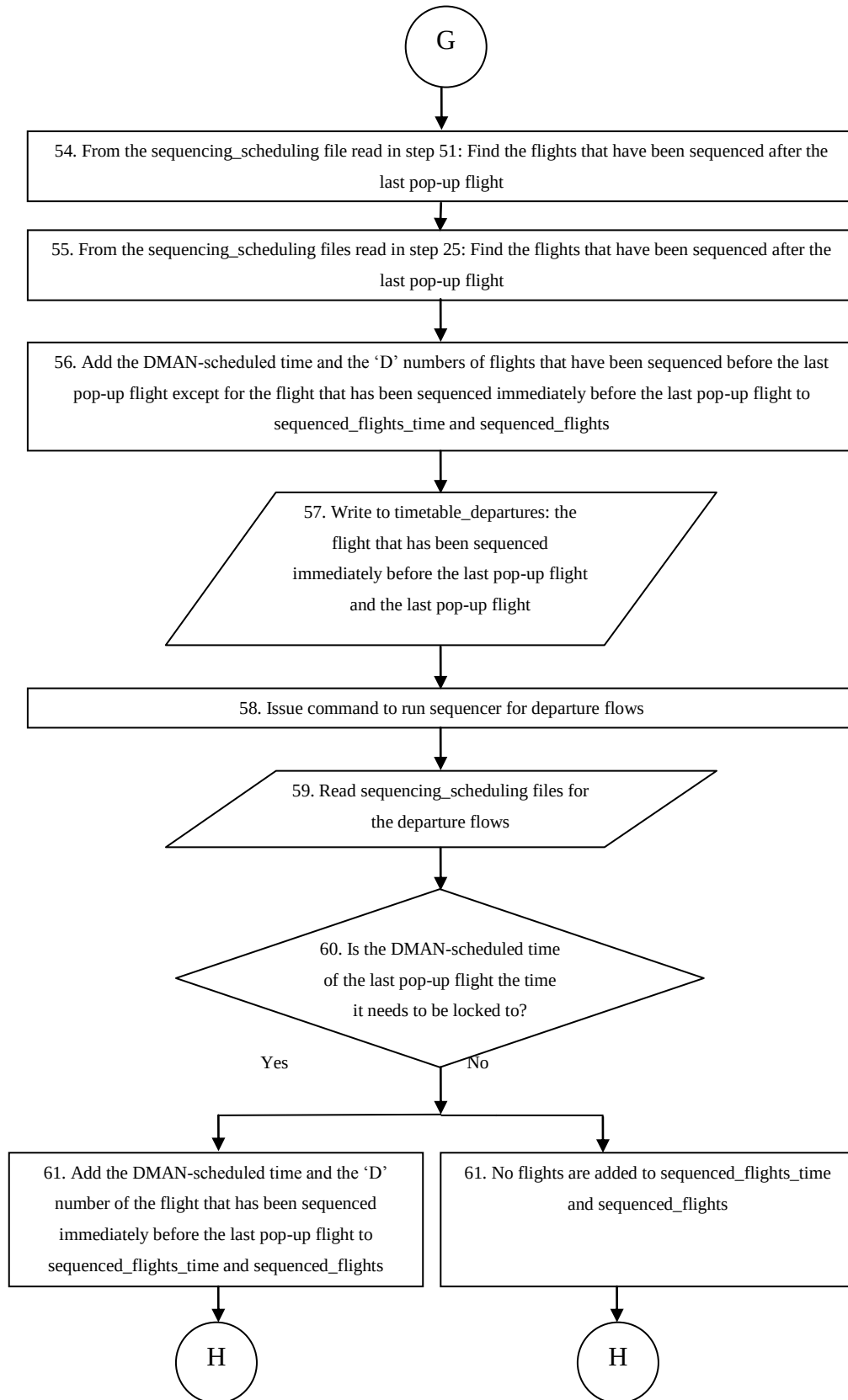


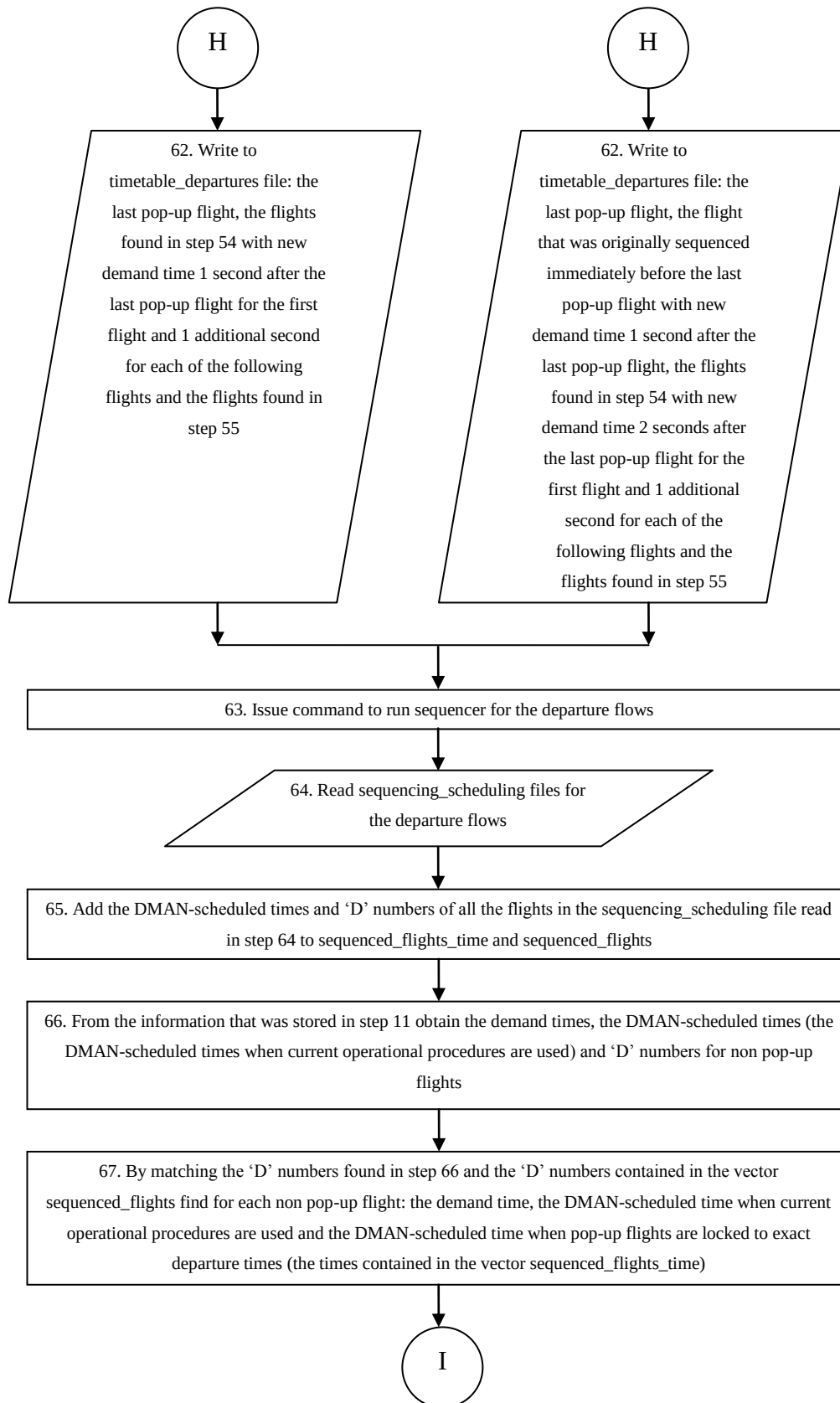


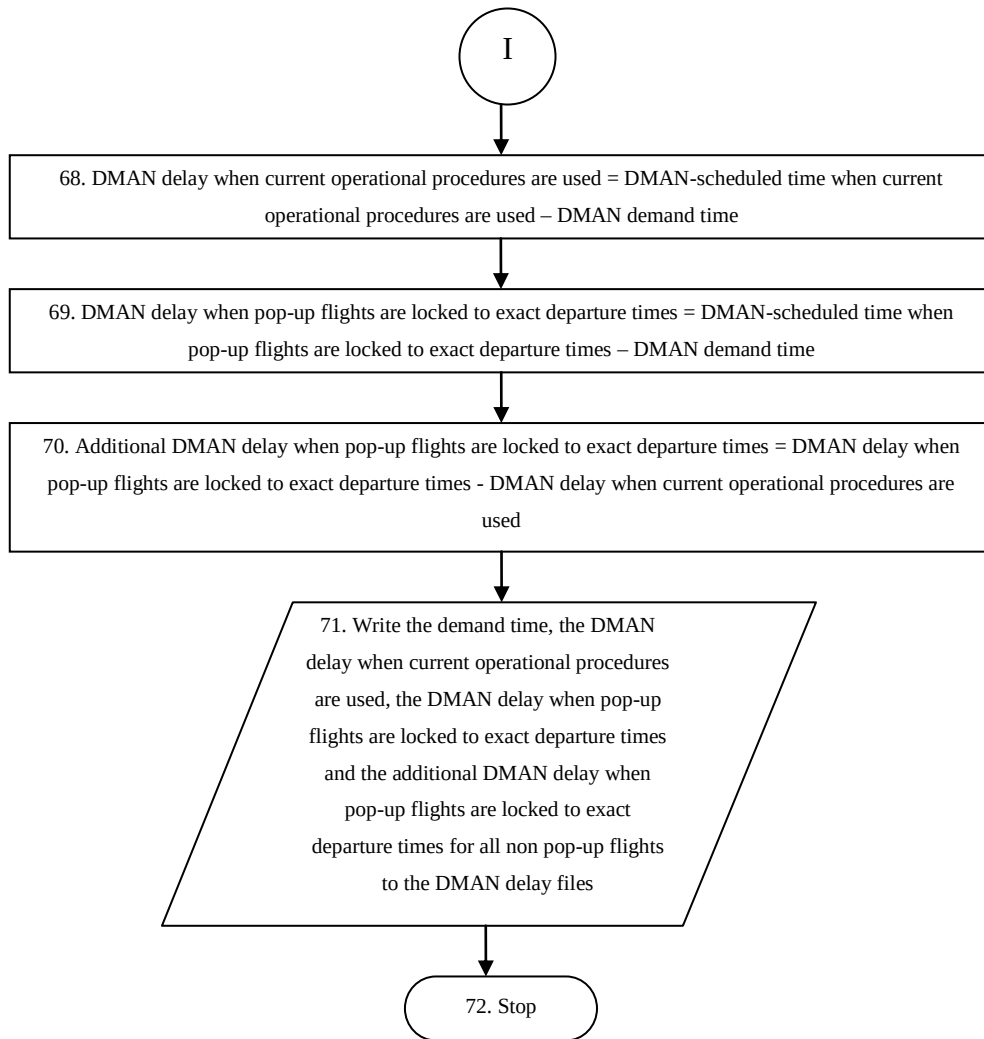












Presented below are some notes about the detailed flowchart:

1. The default for what is being read/written is all of the information in the files as specified in sections 4.6.1 and 4.6.2.
2. The term 'sequencer' in the flow chart refers to the model of the AMAN/DMAN sequencer in the Sequencing and Scheduling model.
3. The vector `sequenced_flights_time` contains the DMAN-scheduled time of flights that have been given their final location in the departure sequence (when the effect of locking the pop-up flights to exact departure times has been taken into account).

4. The vector `sequenced_flights` contains the ‘D’ numbers²⁷ of flights that have been given their final location in the departure sequence (when the effect of locking the pop-up flights to exact departure times has been taken into account).
5. Step 9 creates vectors with the ‘D’ numbers for pop-up flights at their departure airports in order of increasing scheduled departure time and vectors with the ‘A’ numbers²⁸ for pop-up flights at their arrival airports in order of increasing scheduled arrival time. This relates the ‘D’ and ‘A’ numbers corresponding to the same pop-up flights. It is necessary to do this for each run as even though the pop-up flights will always have the same scheduled departure and arrival time the actual demand times will change for every run. The purpose of relating the ‘A’ and ‘D’ numbers of pop-up flights is to enable the AMAN-DMAN cooperation.
6. The files read in step 11 are the `sequencing_scheduling` files for current operational procedures (when pop-up flights are not locked to exact departure times).
7. In step 14 the remaining information in the `timetable_arrivals` files is not changed.
8. In step 23 the pop-ups flights are de-conflicted from each other. If a flight needs to be delayed by more than 3 minutes from its RTA recommended takeoff time its participation in the delay-on-ground concept will be cancelled. Of course, how much a flight can be delayed by depends on where the RTA recommended takeoff time is in the RTA takeoff window (as explained in section 4.1 the RTA takeoff window is assumed to be 6 minutes long for all the simulated flights). A flight could also be moved to a bit earlier in its RTA takeoff window as long as its actual takeoff time is after its first DMAN-scheduled time. However, to get an appreciation of how big the problem of conflicts between pop-up flights on the departure runway is likely to be it has been assumed that the RTA recommended takeoff time for all flights is in the middle of the RTA takeoff

²⁷ The ‘D’ numbers are explained in section 4.3.4.1.

²⁸ The ‘A’ numbers are explained in section 4.3.4.1.

window and flights can therefore be delayed by 3 minutes and still takeoff within their RTA takeoff window.

9. For steps 33, 46 and 60: If the answer is yes there will have been enough separation between the pop-up flight and the flight sequenced immediately before the pop-up flight.
10. In step 35, 48 and 62: When flights are given new demand times 1 second, 2 seconds etc. after a pop-up flight it is to ensure that these flights are the first to have demand after the pop-up flight to guarantee that they are sequenced immediately after the pop-up flight.
11. From step 31 onwards the `departures_rolling_window_max_size` is set to 1. This is to ensure that the order of the non pop-up flights is maintained as it was in the `sequencing_scheduling` file read in step 25 to avoid penalizing individual flights too severely when pop-up flights are locked to exact departure times. The `departures_rolling_window_max_size` is part of the preprocessing file of the Sequencing and Scheduling model and is explained in section 4.3.4.2.

4.7 Traffic characteristics of the simulations

Three traffic scenarios were set up in the simulations, to represent current traffic levels, a 15% traffic increase from current levels and a 30% traffic increase. Timetables for scheduled arrivals to Oslo and arrivals and departures to/from Stockholm and Copenhagen were obtained from Flightstats.com for the current traffic scenario. To produce the timetables for 15% and 30% traffic increase, the timetables for current traffic were used as a baseline. To determine how much the traffic would increase by in each hour of the day a report on the EU-funded Gate-to-Gate project [37] was used for guidance. In the simulations performed in [37] traffic samples for 2004 and 2010 for Stockholm-Arlanda departures and arrivals were used. The increase in traffic between the two traffic samples was according to predictions by the Eurocontrol Air Traffic Statistics and Forecast Service (STATFOR). The same proportional increase per hour as was used in [37] was used for the traffic samples for all the departure and arrival flows in the simulations performed in this work. Two adjustments were then made. Both for

the scenario with a 15% traffic increase and 30% traffic increase, using [37] as guidance resulted in a very high number of Copenhagen departures in the hour 08:00-09:00 (50 and 57). To handle such a high number of departures in one hour, it would probably be necessary to use mixed mode operations. As segregated mode was used in the simulations performed in this work, some of the departures in this hour were moved to the hour after and the two hours before.

For the current traffic scenario only flights having scheduled departure/arrival time between 06:00-24:00 were included in the simulations, as the traffic between 24:00-06:00 is so low that the effect of including these flights in the simulations would have been negligible. As the forecast predicted that some of the traffic increase would need to occur in the hours 04:00-06:00, for a 15% and 30% increase in traffic, the simulations were run starting at 04:00. That is, for a 15% and 30% traffic increase each run simulated a departure/arrival flow between 04:00-24:00. The amount of traffic was still relatively low between 04:00-06:00 and no pop-up flights were scheduled in this time period for all the traffic scenarios. Therefore the results were plotted starting at 06:00. The purpose of running the simulations from 04:00 was to capture the effect of possible knock-on effect of flights being delayed in the hours 04:00-06:00.

The proportion of short-, medium- and long-haul flights in the current traffic scenario was kept for the scenarios with a 15% and a 30% traffic increase. For departures the increase in traffic was equally divided between the different SIDs. For simplicity, all flights that were part of the increase in traffic were flown by a Boeing 737-800 aircraft type. This was considered reasonable as the majority of the current traffic consists of flights scheduled with this aircraft type or an aircraft type with similar aircraft performance characteristics.

4.7.1 Number of total departures and arrivals

Figures 4-2 to 4-6 show the number of flights that were scheduled to depart and arrive from/to the airports included in the simulations for the three traffic scenarios. Table 4-19 shows the total daily number of departures and arrivals for the airports and scenarios.

Oslo airport regards the main peak hours to occur between 07:00 and 09:00²⁹. In the analysis performed in this work the peak hours have been considered to occur between 07:00-11:00 (morning peak) and 16:00-20:00 (afternoon peak) as in these hours the number of arrivals is at its highest and stays high for several hours.

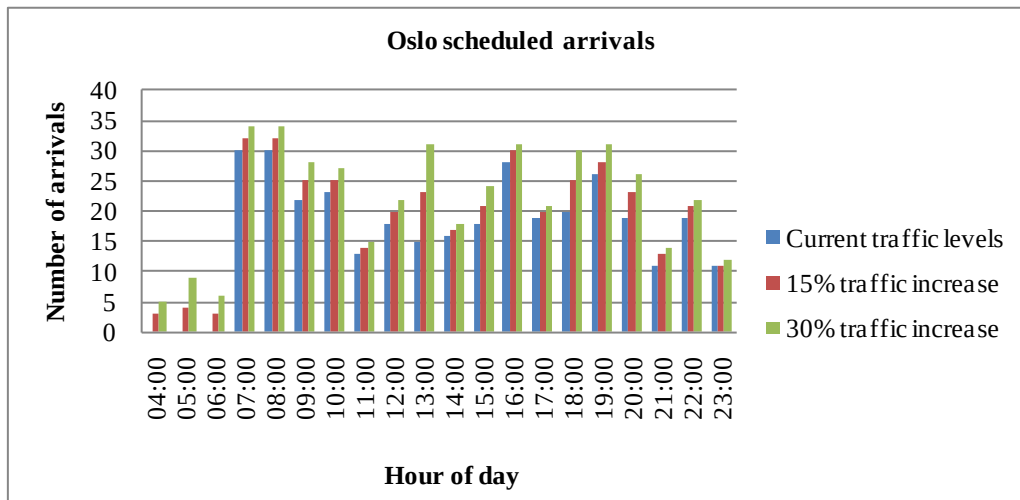


Figure 4-1: Oslo scheduled arrivals

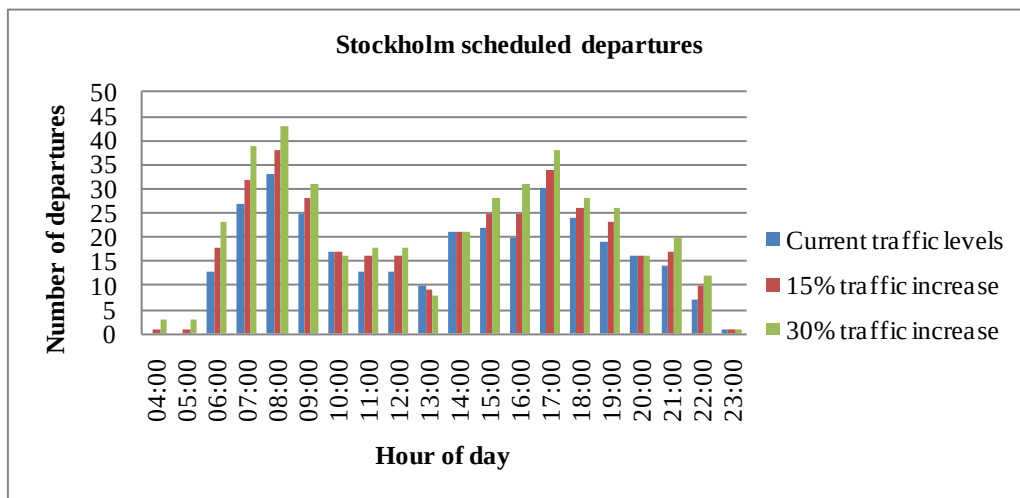


Figure 4-2: Stockholm scheduled departures

²⁹ The information has been obtained from Kristian Pjaaten, AMAN project leader at Oslo ATCC (March 2011).

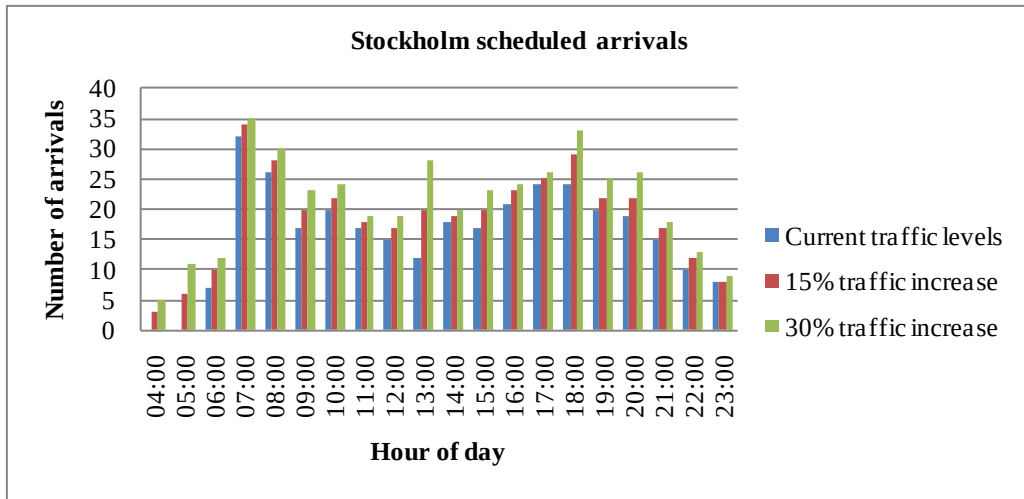


Figure 4-3: Stockholm scheduled arrivals

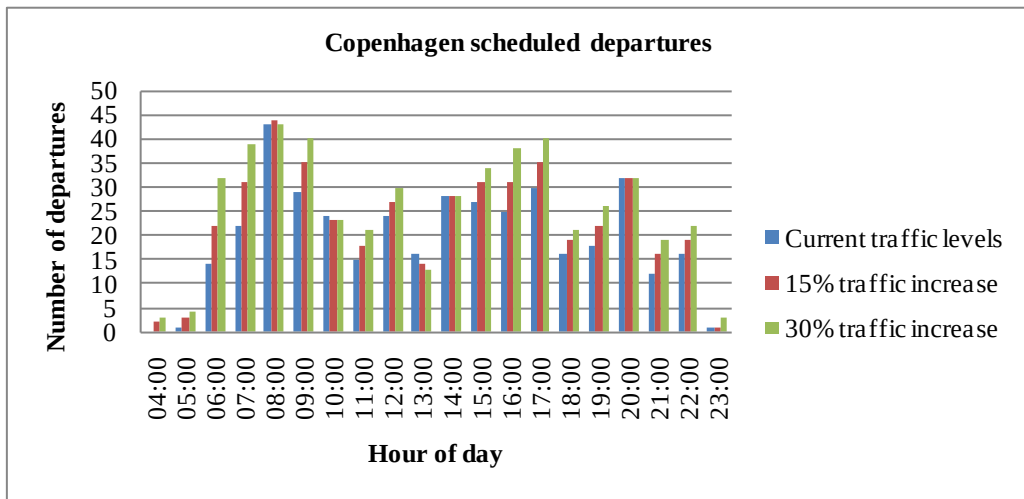


Figure 4-4: Copenhagen scheduled departures

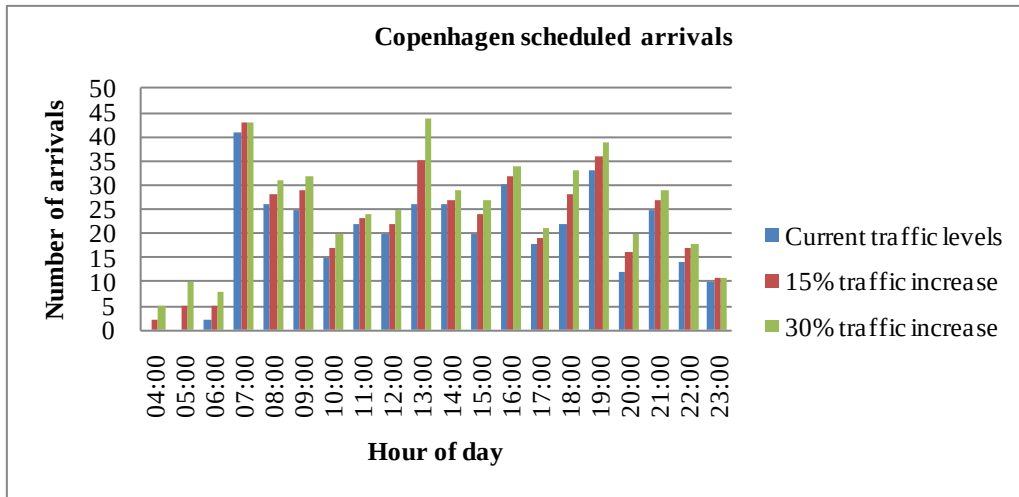


Figure 4-5: Copenhagen scheduled arrivals

Table 4-19: Total daily departures/arrivals for the airports included in the simulations

	Current traffic levels	15% traffic increase	30% traffic increase
Oslo arrivals	338	390	439
Stockholm departures	325	374	423
Stockholm arrivals	322	375	423
Copenhagen departures	393	453	511
Copenhagen arrivals	387	446	503

4.7.2 Number of pop-up flight departures and arrivals

Figures 4-7 to 4-9 show the number of pop-up flights scheduled to arrive to Oslo airport and depart from Stockholm and Copenhagen airports for each hour of the day in the simulation runs. The number of departing/arriving pop-up flights was intentionally kept the same for all the traffic scenarios: current traffic, 15% traffic increase and 30% traffic increase. That is, as the total number of departures/arrivals increased, the number of pop-up flights remained constant. Obviously, the likely scenario will be that as the total number of departures/arrivals increases so does the number of pop-up flight departures/arrivals. However, it was of interest to measure how the additional departure sequencing delay and the reduction in airborne delay due to the concept increased with

the traffic and isolate the reason for the increase. By keeping the number of pop-up flights the same it was possible to isolate the reason to the fact that the total number of departures/arrivals increased. Table 4-20 shows the total daily number of pop-up flight departures/arrivals for each airport. Table 4-21 details the number of pop-up flight arrivals into Oslo airport per departure airport from which they originate. As can be seen from Figure 4-7 the number of pop-up flight arrivals into Oslo is at its highest in the peak hours for total arrivals.

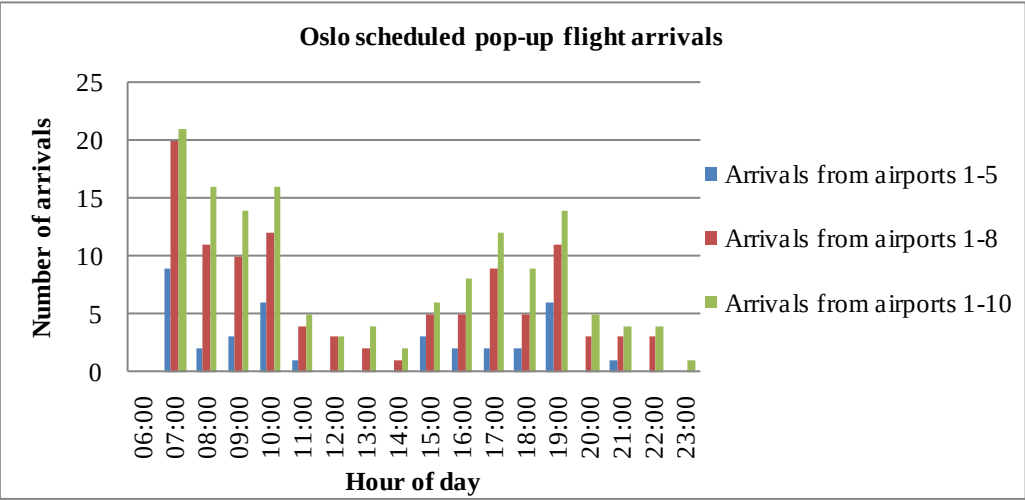


Figure 4-6: Oslo scheduled pop-up flight arrivals

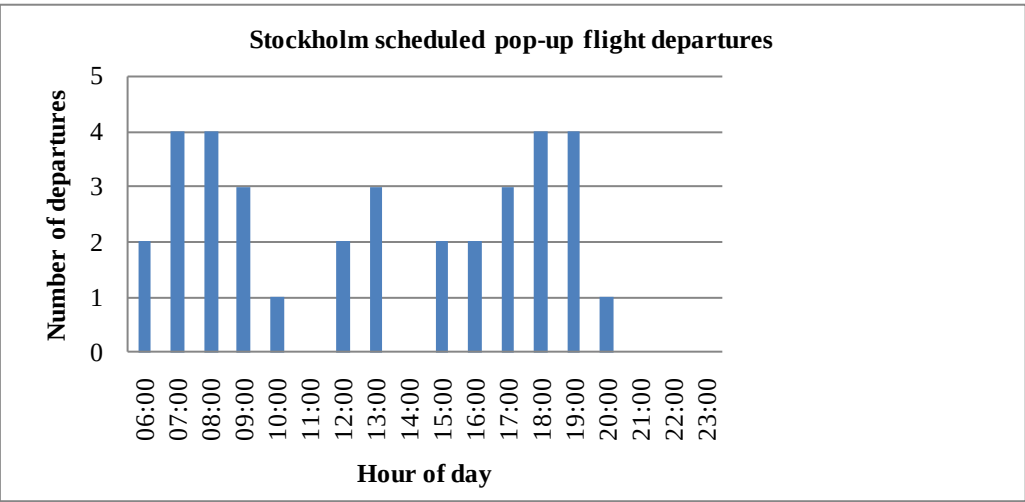


Figure 4-7: Stockholm scheduled pop-up flight departures

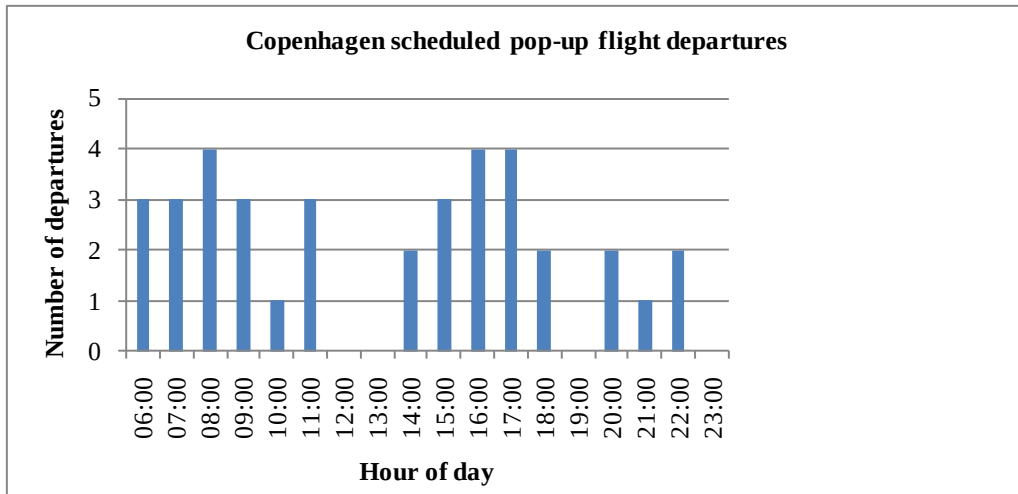


Figure 4-8: Copenhagen scheduled pop-up flight departures

Table 4-20: Total daily pop-up flight departures/arrivals

	Pop-up flight departures/arrivals
Stockholm departures	35
Copenhagen departures	37
Oslo arrivals	144

Table 4-21: Daily pop-up flight arrivals into Oslo per departure airport

	Pop-up flight arrivals
Kristiansund	4
Molde	6
Haugesund	8
Kristiansand	9
Aalesund	10
Stockholm	18
Copenhagen	19
Stavanger	21
Bergen	24
Trondheim	25

4.8 Summary of the assumptions and limitations of the simulation

4.8.1 Assumptions of the simulation

Below follows a summary of the assumptions in the simulation:

- A communication medium allowing real time information exchange has been available.
- Segregated runway mode has been used.
- It has been assumed that it has been possible for the tower air traffic controllers at departure airports 1-5 to ensure that the pop-up flights take off at their RTA take-off times/time spans to meet their AMAN slot without the support of AMAN-DMAN cooperation.
- The RTA take-off window of the pop-up flights has been approximated as 6 minutes wide.
- The hourly growth in traffic for the different traffic scenarios and airports has been assumed to follow the Eurocontrol Air Traffic Statistics and Forecast Service (STATFOR) forecast for Stockholm-Arlanda for the period 2004 to 2010.

4.8.2 Limitations of the simulation

Below follows a summary of the limitations of the simulation:

- No weather has been taken into account in the simulation.
- The aircraft performance model used in the simulation and fuel savings analysis is not the complete BADA model specification, but the BADA summary tables: the Operations Performance File (OPF), the Global Parameters File (GPF) and one of the Performance Table Files (PTF).
- A model setting arrival and departure sequences at the runways has been used taking into account wake vortex separation and the required SID separation between flights. Factors such as runway occupancy time and ATC strategies have not been taken into account in the model.

5 RESULTS AND ANALYSIS

The delay-on-ground concept has been simulated for the case study airport Oslo-Gardermoen for three traffic scenarios; current traffic levels, a 15% traffic increase from current levels and a 30% traffic increase. For each traffic scenario; 60 fast-time Monte Carlo simulation runs have been performed. The potential reduction in airborne delay and corresponding reduction in fuel consumption with the concept has been measured and is presented in section 5.1. The implications on the departure sequences of pop-up flights being locked to departure times to meet their RTAs have also been measured; this is presented in sections 5.2 and 5.3. It has also been of interest to measure the number conflicts between pop-up flights on the departure runways when they are locked to a departure time to meet their RTA; this is discussed in section 5.4. The figures presented in chapter 5 are also presented in table format in Appendix C.

5.1 Reduction in airborne delay

5.1.1 Results

This section presents the amount of arrival sequencing delay that the pop-up flights arriving into Oslo airport experienced. This delay represents the reduction in airborne delay that could be achieved with the delay-on-ground concept.

As already mentioned, sixty runs were performed for each of the three traffic scenarios. For each run the analysis was divided into hours that the pop-up flights demanded the arrival runway and the highest, mean and total arrival sequencing delay that pop-up flights experienced was found. The results are presented in Figures 5-1 to 5-3 below. Figure 5-1 shows the average over the 60 runs, of the highest arrival sequencing delay that one individual flight experienced in each hour of the day. Figure 5-2 shows the average of the mean arrival sequencing delay in each hour. Figure 5-3 shows the average of the total arrival sequencing delay for all pop-up flights in each hour.

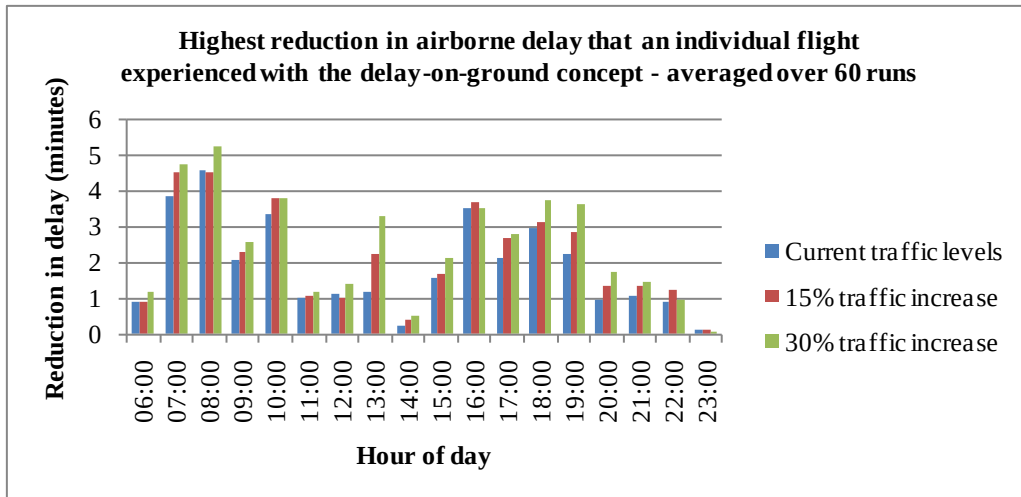


Figure 5-1: Highest reduction in airborne delay that an individual flight experienced with the delay-on-ground concept – averaged over 60 runs

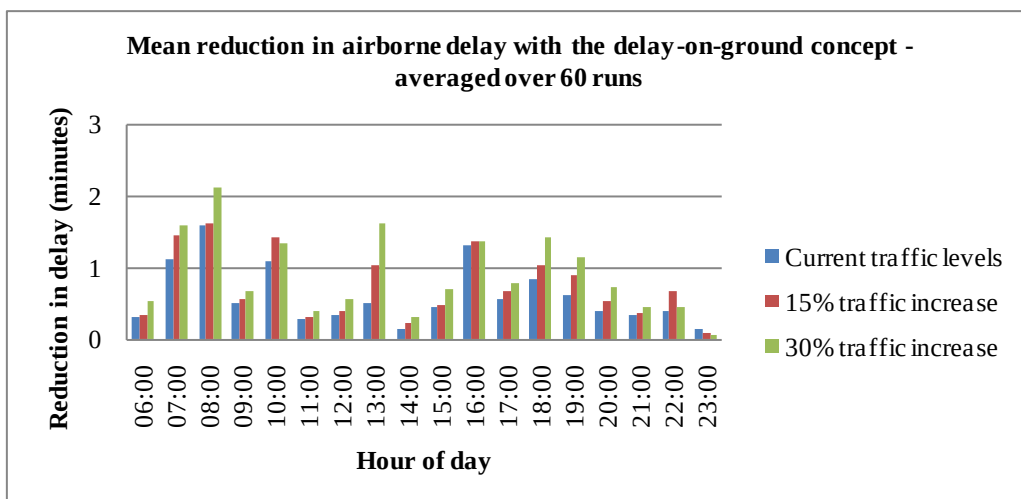


Figure 5-2: Mean reduction in airborne delay with the delay-on-ground concept – averaged over 60 runs

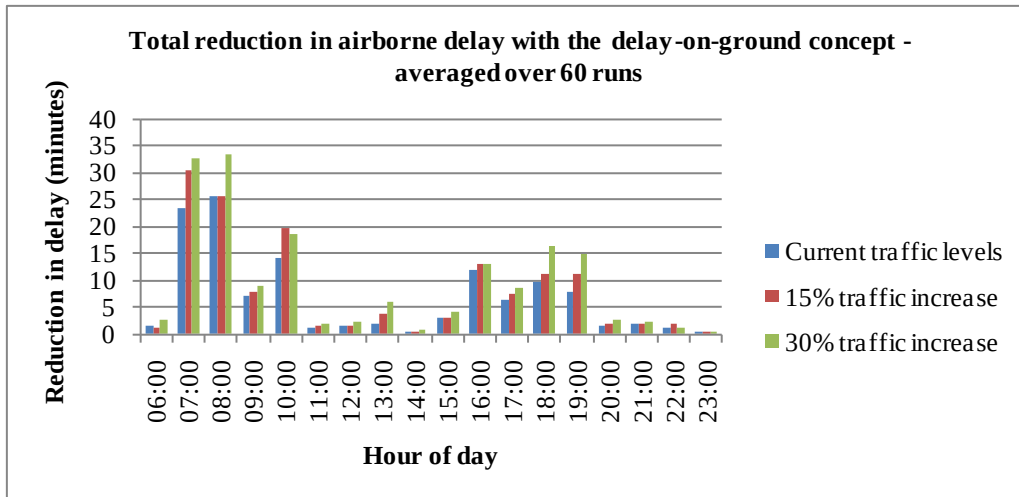


Figure 5-3: Total reduction in airborne delay with the delay-on-ground concept – averaged over 60 runs

Figure 5-4 shows the pop-up flights classified according to how much arrival sequencing delay they had to absorb.

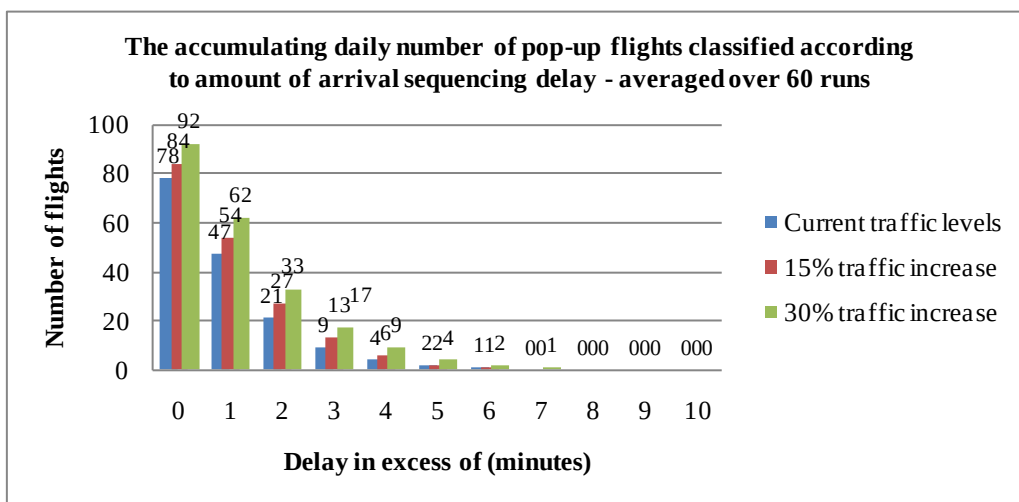


Figure 5-4: The accumulating daily number of pop-up flights classified according to amount of arrival sequencing delay – averaged over 60 runs

In Figure 5-5 the average daily reduction in airborne delay per departure airport from which the pop-up flights originate is presented.

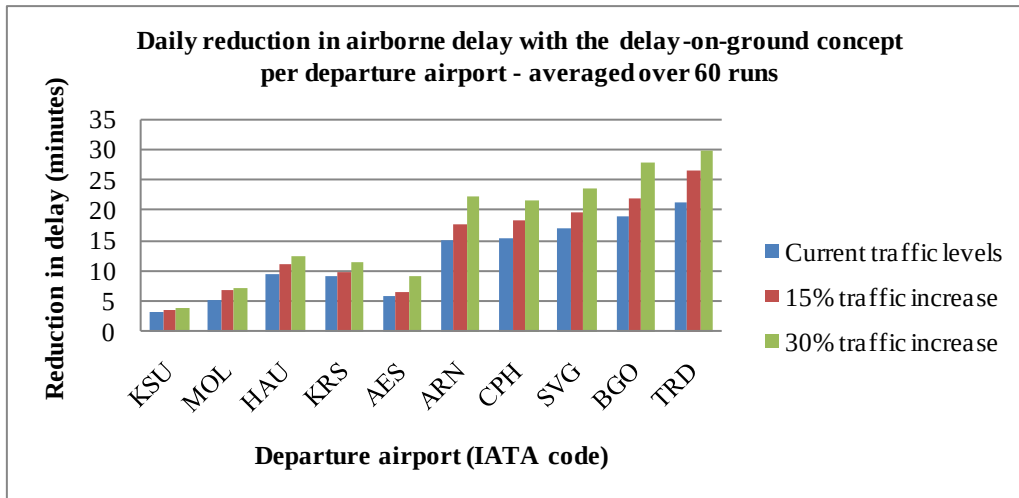


Figure 5-5: Daily reduction in airborne delay with the delay-on-ground concept per departure airport – averaged over 60 runs³⁰

The average total daily reduction in airborne delay is presented for two possible scenarios: one in which the concept would be used in all hours of the day and the other in which it would be used only in the peak hours. Table 5-1 shows the average daily reduction in airborne delay, if the concept is used during all hours of the day, for the three traffic scenarios divided into how many departure airports are included in the concept. As it can be considered likely that the concept would involve a certain increase in workload for air traffic controllers and flight crew [7, 9] it can be considered possible that the concept would only be implemented in peak hours where the efforts would result in high reduction in airborne delay. Table 5-2 presents the same information as Table 5-1 for a scenario where the delay-on-ground concept is used only in peak hours. As mentioned before, arrival peak hours into Oslo airport has been considered to occur between 07:00-11:00 and 16:00-20:00.

³⁰ The departure airports are presented on the x-axis in order of increasing number of daily pop-up flight arrivals into Oslo airport. For the full names of the airports refer to the list of airport IATA codes at the beginning of the thesis.

Table 5-1: Total daily reduction in airborne delay with the delay-on-ground concept – averaged over 60 runs, if concept in use all day

	Current traffic levels (HH:MM:SS)	15% traffic increase (HH:MM:SS)	30% traffic increase (HH:MM:SS)
Airports 1-5	00:32:32	00:37:56	00:44:11
Airports 1-10	02:00:22	02:24:07	02:50:30

The numbering of the airports corresponds to the numbering used in Table 3-1.

Table 5-2: Total daily reduction in airborne delay with the delay-on-ground concept – averaged over 60 runs, if concept in use only in peak hours

	Current traffic levels (HH:MM:SS)	15% traffic increase (HH:MM:SS)	30% traffic increase (HH:MM:SS)
Airports 1-5	00:30:29	00:36:07	00:41:13
Airports 1-10	01:46:43	02:07:05	02:26:41

The numbering of the airports corresponds to the numbering used in Table 3-1.

The potential fuel saving that the average daily reduction in airborne delay corresponds to is presented in Table 5-3. In current arrival operations at Oslo airport arrival sequencing delay up to 2 minutes is absorbed in a sequencing leg at FL100-FL120. If a flight has more delay than this, 2 minutes is absorbed at FL100-FL120 in a sequencing leg and the remainder is absorbed at FL240-FL300 in a circular holding pattern³¹. A fuel consumption of 31.9 kilograms per minute has been used to calculate the potential fuel saving. This is the fuel consumption of a Boeing 737-800 during cruise at FL120 with a low mass level according to the BADA Performance Table File (PTF) for the aircraft type. Using the fuel consumption for a Boeing 737-800 was considered a good estimate as all pop-up flights are flown either by a Boeing 737 or Airbus 320 aircraft type which have similar aircraft performance characteristics. According to BADA data the fuel consumption at FL240-300 is slightly higher than the consumption at FL100-FL120. It is however seen as a good estimate to use the BADA fuel consumption at FL120 for all the delay minutes, particularly as the majority of the flights have a delay below 2

³¹ The information on how arrival sequencing delay is absorbed at Oslo airport has been obtained from Kristian Pjaaten, AMAN project leader at Oslo ATCC (June 2011).

minutes as shown in Figure 5-4. It was considered reasonable to use the fuel consumption for a low mass level (BADA specifies fuel consumption for low, nominal and high mass level) as the aircraft is at the end of its flight and is likely to have used most of its fuel [38].

Table 5-3: Daily fuel savings potential with the delay-on-ground concept – averaged over 60 runs, if concept in use only in peak hours

	Current traffic levels (kg)	15% traffic increase (kg)	30% traffic increase (kg)
Airports 1-5	972	1152	1315
Airports 1-10	3404	4078	4679

The numbering of the airports corresponds to the numbering used in Table 3-1.

5.1.2 Discussion of results

It is important to emphasize that the number of pop-up flights was kept the same for all traffic scenarios in the simulations. It is, of course, likely that as the total traffic increases so does the number of pop-up flights. Therefore, as the traffic increases, the average reduction in airborne delay and potential fuel saving due to the concept is likely to be higher than that achieved in the simulations, as the number of pop-up flight arrivals would be higher.

As expected, the peaks in arrival sequencing delay that pop-up flights experience occur in the peak hours, as can be seen from Figures 5-1 to 5-3. This is particularly evident in Figure 5-3. Obviously, the total arrival sequencing delay experienced in the peak hours is high both due to the fact that the mean arrival sequencing delay is high and that the number of pop-up flight arrivals is high.

Figure 5-5 shows the general trend that the higher the daily pop-up flight arrivals per departure airport the higher is the daily reduction in airborne delay. The exceptions to this are Kristiansand (KRS) and Aalesund (AES). This effect is shown by Haugesund (HAU) having a higher average daily reduction in airborne delay compared to KRS and AES while having a lower number of daily pop-up flight departures. This shows that, as expected, the amount of reduction in airborne delay does not only depend on the total

number of pop-up flight arrivals but also on the hours in which the flights arrive. Haugesund (HAU) has all of its pop-up flights arriving into Oslo airport at peak hours, whereas Kristiansand (KRS) has one flight arriving outside of peak hours and Aalesund (AES) has three flights arriving outside of peak hours.

In the Cassis live trials an arrival sequencing delay of over 3 minutes was regarded as a significant amount of delay [7]. From Figure 5-4 it can be seen that, on average, there were 9 (at current traffic levels), 13 (15% traffic increase) and 17 (30% traffic increase) pop-up flights that had an arrival sequencing delay exceeding 3 minutes every day. Absorbing this delay in holding or vectoring is obviously very fuel inefficient. The results indicate that the amount of delay will increase with the traffic, adding to the motivation to change the current system.

From Figure 5-1 it can be seen that outside of peak hours the average highest delay rarely exceeded 1 minute. Thus, it can be concluded that the flights that experienced higher delay than 1 minute mostly arrived in the peak hours. Tables 5-1 - 5-2 show that there is only a small difference in the average daily reduction in airborne delay when the concept is used only in the peak hours compared to during all hours of the day. That is, most of the arrival sequencing delay is experienced in the peak hours. This is expected as the total number of arrivals and pop-up flight arrivals is the highest in the peak hours. These findings confirm that most of the benefit of the concept would be realized in the peak hours, both overall and for individual flights, and it is therefore recommended to implement the concept only in the peak hours.

As can be seen from Table 5-2, if the delay-on-ground concept was used only in peak hours and airports 1-10 were included in the concept, a total of, almost 2 hours (01:46:43) could be saved in airborne delay for the current traffic levels. This can be compared to the average daily overall arrival sequencing delay experienced at Oslo airport which was slightly over 4 hours (04:18:41). That is, 41% of the airborne arrival sequencing delay that is experienced at Oslo airport today could be saved by using the delay-on-ground concept if AMAN-DMAN cooperation was available and all of the ten airports from which RTA-equipped traffic departs were included in the concept. This corresponds to an average daily potential fuel saving of 3.4 tons, as can be seen in Table 5-3. With a 15% and 30% traffic increase this average daily potential fuel saving

increases to 4.1 and 4.7 tons respectively, indicating the impact the concept can have on future air transport operations. A significant reduction in airborne delay minutes could be attainable even without AMAN-DMAN cooperation; if airports 1-5 alone were included in the delay-on-ground concept during peak hours, just over 30 minutes of airborne delay could be saved daily for the current traffic amount. This is a 12% reduction in airborne delay and corresponds to an average daily potential fuel saving of 972 kilograms. With a 15% and 30% traffic increase the average daily potential fuel saving increases to 1.2 and 1.3 tons respectively. As discussed, the fuel savings figure for a 15% and 30% traffic increase is likely to be higher than what is shown in these results as in reality the number of pop-up flight arrivals would increase as the total number of arrivals increases.

5.2 Departure sequencing delay when pop-up flights are locked to a time within their RTA takeoff window

5.2.1 Results

The realistic scenario when the delay-on-ground concept is to be used in real operations is that pop-up flights will be locked to a DMAN specified time within their RTA takeoff window rather than their exact RTA recommended takeoff time, thus facilitating a certain level of flexibility when pop-up flights are scheduled for departure. The results of the simulation runs in which the pop-up flights were locked to a time within their RTA takeoff window is presented in this section.

Fifteen runs, five runs for each traffic scenario, have been run with the pop-up flights departing somewhere within their RTA takeoff window rather than at their exact RTA recommended takeoff time. As discussed, in real operations it would be recommended that the DMAN aims to assign pop-up flights a time during the first part of the window. In the simulation runs pop-up flights have been assigned a departure time at some point during the window, not always during the first part of the window. However, these simulation runs are considered to give a good indication of how the departure sequences would be affected if pop-up flights were locked to a time in their RTA takeoff window. The flexibility in the departure time for pop-up flights leads to a tightly packed sequence being maintained and the DMAN sequencer has freedom to optimize the order

of departing flights. Thus, when the delay-on-ground concept is implemented by locking the pop-up flights to a departure time within the RTA takeoff window the difference in departure sequencing delay compared to current operations is due only to the fact that most pop-up flights have a different departure demand time with the delay-on-ground concept. This is the third factor as described in section 4.5. As described in section 4.5 this factor can cause both a decrease and an increase in total departure sequencing delay.

As the simulation algorithm was set up to lock the pop-up flights to exact departure times these runs have been performed manually. Due to the time consuming task of performing these runs only fifteen runs were simulated. All the runs were performed for Copenhagen departures.

Tables 5-4 to 5-6 show the total daily departure sequencing delay that was experienced for all non pop-up flights in the runs, both for when current operational procedures were used and when the delay-on-ground concept was used by locking pop-up flights to a time within their RTA takeoff window.

Table 5-4: Total daily departure sequencing delay with current operational procedures and when pop-up flights were locked to DMAN specified departure times within their RTA takeoff windows, current traffic levels

	Run 1 (HH:MM:SS)	Run 2 (HH:MM:SS)	Run 3 (HH:MM:SS)	Run 4 (HH:MM:SS)	Run 5 (HH:MM:SS)
Current operational procedures	09:39:02	11:05:56	10:39:10	10:50:32	11:41:43
Pop-up flights locked to DMAN specified departure times within their RTA takeoff windows	09:16:05	10:35:38	10:16:59	10:35:49	11:13:41
Difference when pop-up flights were locked to DMAN specified departure times within their RTA takeoff windows	-00:22:57	-00:30:18	-00:22:11	-00:14:43	-00:28:02

Table 5-5: Total daily departure sequencing delay with current operational procedures and when pop-up flights were locked to DMAN specified departure times within their RTA takeoff windows, 15% traffic increase

	Run 6 (HH:MM:SS)	Run 7 (HH:MM:SS)	Run 8 (HH:MM:SS)	Run 9 (HH:MM:SS)	Run 10 (HH:MM:SS)
Current operational procedures	18:07:52	12:24:58	11:26:49	12:43:04	10:26:14
Pop-up flights locked to DMAN specified departure times within their RTA takeoff windows	17:38:16	11:48:31	11:16:16	12:22:07	10:24:52
Difference when pop-up flights were locked to DMAN specified departure times within their RTA takeoff windows	-00:29:36	-00:36:27	-00:10:33	-00:20:57	-00:01:22

Table 5-6: Total daily departure sequencing delay with current operational procedures and when pop-up flights were locked to DMAN specified departure times within their RTA takeoff windows, 30% traffic increase

	Run 11 (HH:MM:SS)	Run 12 (HH:MM:SS)	Run 13 (HH:MM:SS)	Run 14 (HH:MM:SS)	Run 15 (HH:MM:SS)
Current operational procedures	20:09:04	16:20:04	21:17:59	18:15:41	21:48:04
Pop-up flights locked to DMAN specified departure times within their RTA takeoff windows	18:04:39	16:10:42	22:10:06	17:43:45	21:29:24
Difference when pop-up flights were locked to DMAN specified departure times within their RTA takeoff windows	-02:04:25	-00:09:22	00:52:07	-00:31:56	-00:18:40

5.2.2 Discussion of results

When the delay-on-ground concept was implemented by locking pop-up flights to a time within their RTA takeoff window some non pop-up flights had a decrease in departure sequencing delay compared to when the concept was not used and some had an increase in delay. The flights that had demand time in the periods where the pop-up flights had demand time without the concept experienced less delay. The flights that had demand time in the periods where the pop-up flights had demand time with the concept experienced more delay. In most runs, overall, this increase and decrease in delay that some non pop-up flights experienced had a tendency to cancel itself out. That is, the increase or decrease in delay was very small, particularly when put in relation to the delay that was experienced at current operational procedures. In one run the decrease in delay was more than 2 hours, this can be compared to the run with the smallest difference in delay which was just over 1 minute. In the run where the delay decreased by 2 hours the pop-up flights have changed their demand time when the delay-on-ground concept was in use to a time that was less busy on the runway more often than they changed it to a time that was busier. All except for one run had less total departure sequencing delay when the concept was in use compared to when it was not. Thus, for almost all runs the shift in demand times for the pop-up flights due to the concept was of benefit for the overall departure sequence. Whether this is a general trend or not cannot be concluded after only a small number of runs. What can be concluded is that the delay-on-ground concept as such is not penalizing for the overall departure sequences.

5.3 Departure sequencing delay when pop-up flights are locked to exact departure times

5.3.1 Results

Again, it needs to be emphasized that the realistic scenario is that, in a delay-on-ground concept, pop-up flights will be locked to a time during their RTA takeoff window. However, the implications on the departure sequences of having a relatively inflexible system where pop-up flights are locked to their exact RTA recommended takeoff times

has been explored as well in the simulations. The results of these simulation runs are presented in this section.

For each simulation run the departure sequences were set both with pop-up flights not being locked to a takeoff time to simulate current operations, (referred to as “Current operational procedures” in figures) and with the delay-on-ground concept in use and pop-up flights being locked to their exact RTA recommended takeoff times (referred to as “Pop-up flights locked to exact departure times” in figures). For each run the mean departure sequencing delay and the total departure sequencing delay for all non pop-up flights was found, divided per hour in which the flights demanded the departure runway. The average of the sixty runs for each hour was then found for each traffic scenario.

It should be noted that a small amount of non pop-up flights experienced a decrease in departure sequencing delay when pop-up flights were locked to exact departure times compared to current operations. This is due to the fact that with the delay-on-ground concept all pop-up flights that have an arrival sequencing delay have departure demand time slightly later than the demand time they had with current operational procedures. Consequently, some non pop-up flights demanding the runway around the same time as these pop-up flights did with current operational procedures experience a decrease in departure sequencing delay when pop-up flights are locked to exact departure times. This still occurred relatively rarely, as the locking of flights to exact departure times lead to, particularly in busy hours, a knock-on effect causing additional delay to many subsequent flights. This resulted in many flights departing well after a pop-up flight experiencing additional departure sequencing delay so that the effect of a time slot being available was cancelled out and did not always lead to a decrease in delay.

5.3.1.1 Stockholm airport

Figures 5-6 to 5-8 present the mean departure sequencing delay, with current operational procedures and with pop-up flights locked to exact departure times, for the three traffic scenarios. For each traffic scenario, the results are divided into per hour of the day and averaged over the 60 runs.

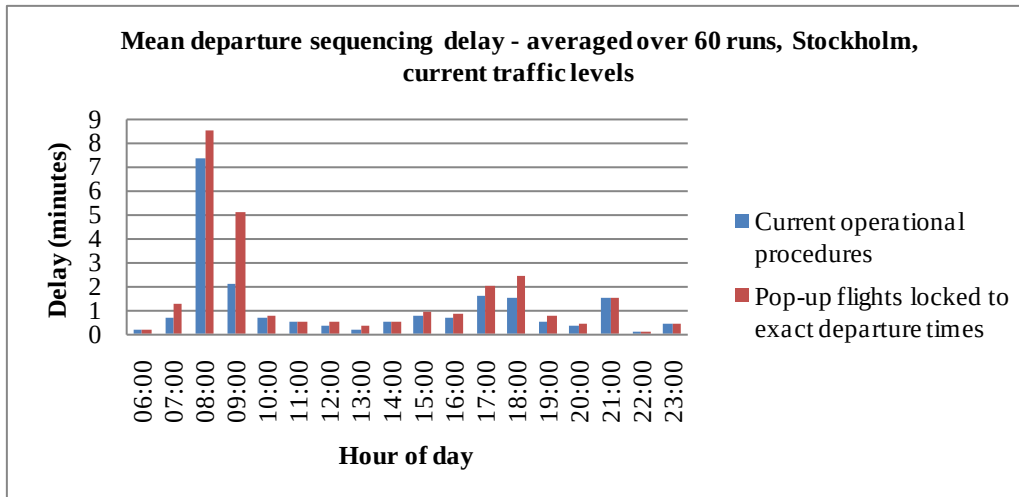


Figure 5-6: Mean departure sequencing delay – averaged over 60 runs, Stockholm, current traffic levels

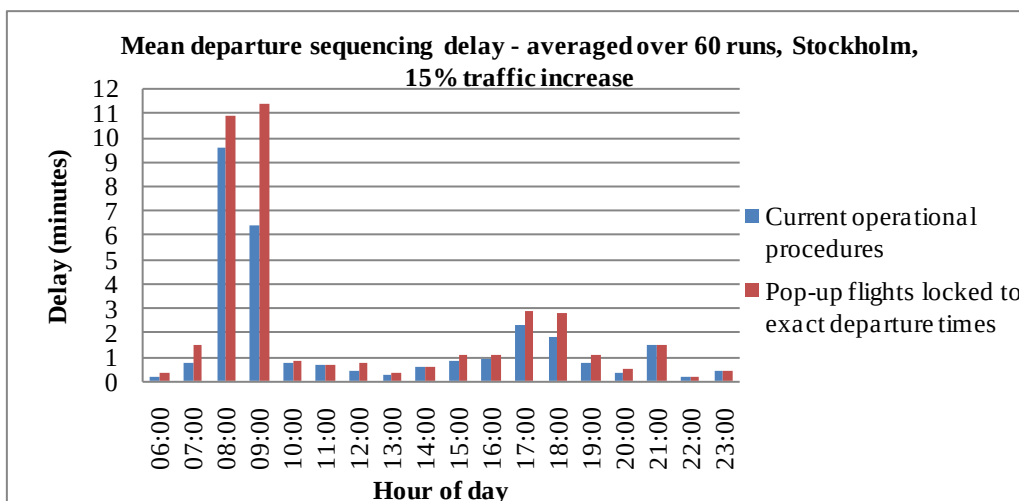


Figure 5-7: Mean departure sequencing delay – averaged over 60 runs, Stockholm, 15% traffic increase

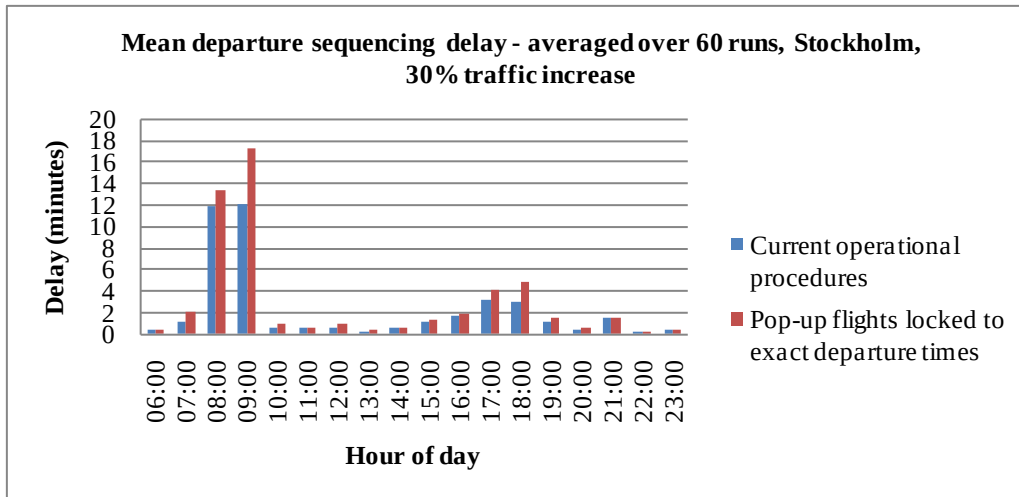


Figure 5-8: Mean departure sequencing delay – averaged over 60 runs, Stockholm, 30% traffic increase

The average mean increase in departure sequencing delay when flights were locked to exact departure times is presented in Figure 5-9, divided into per hour of the day.

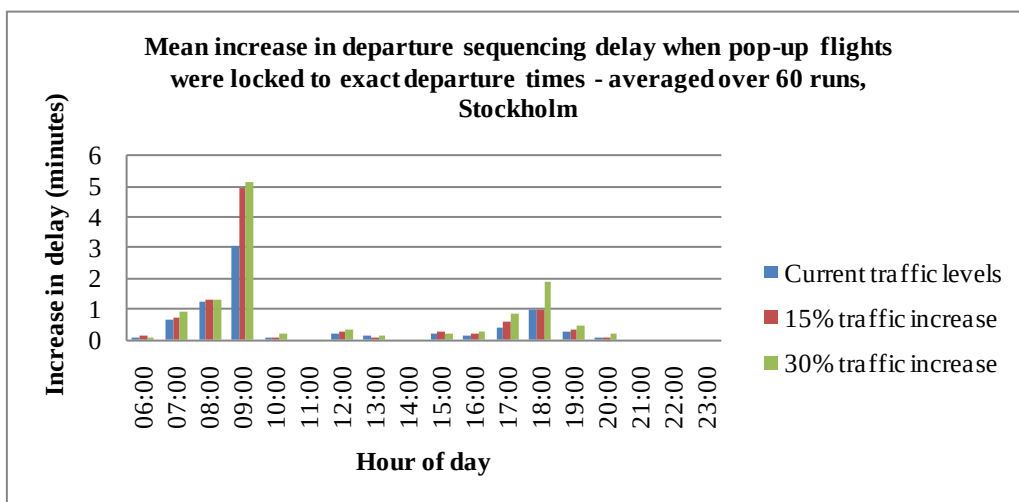


Figure 5-9: Mean increase in departure sequencing delay when pop-up flights were locked to exact departure times – averaged over 60 runs, Stockholm

Figures 5-10 to 5-12 present the total departure sequencing delay, with current operational procedures and with pop-up flights locked to exact departure times, for the

three traffic scenarios. For each traffic scenario, the results are divided into per hour of the day and averaged over the 60 runs.

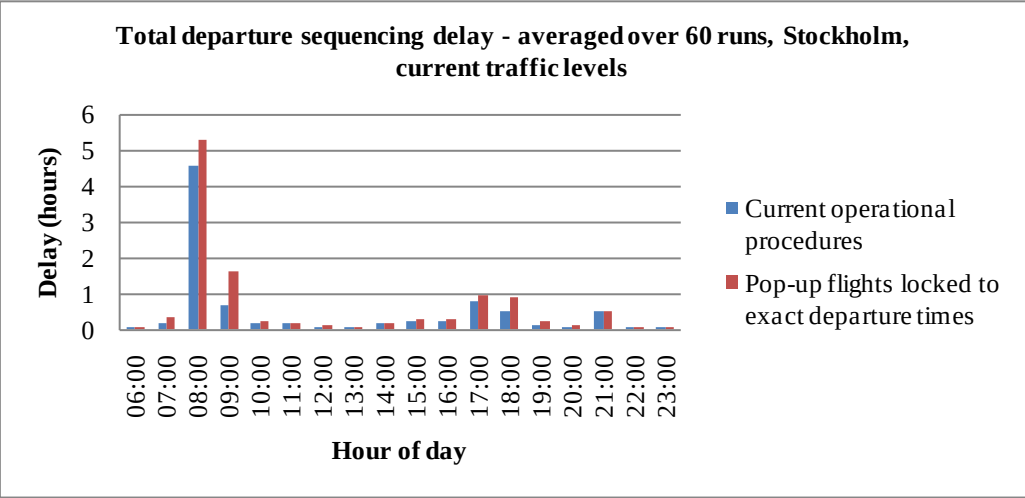


Figure 5-10: Total departure sequencing delay – averaged over 60 runs, Stockholm, current traffic levels

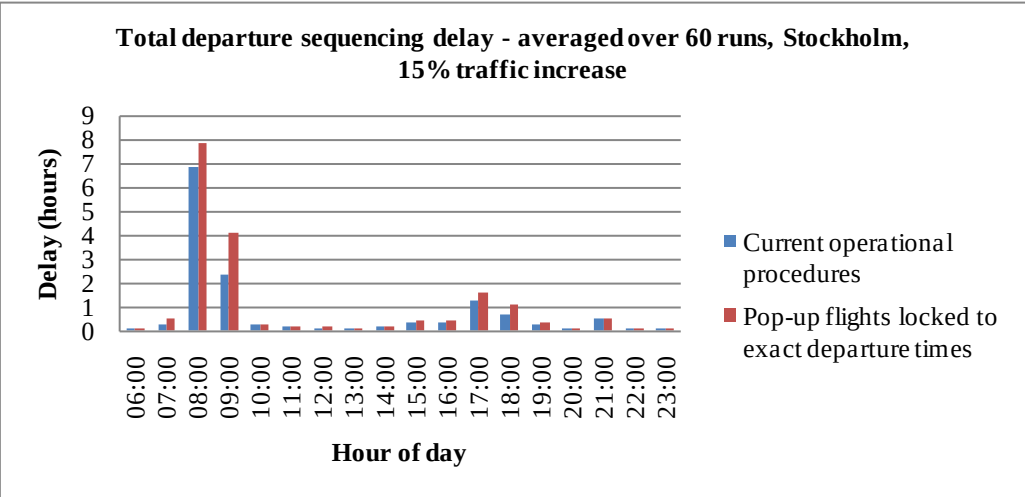


Figure 5-11: Total departure sequencing delay – averaged over 60 runs, Stockholm, 15% traffic increase

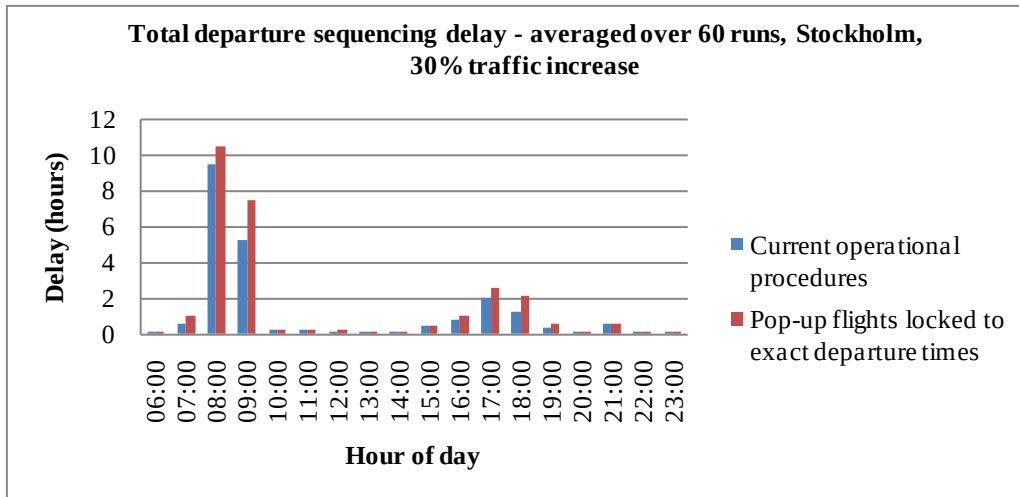


Figure 5-12: Total departure sequencing delay – averaged over 60 runs, Stockholm, 30% traffic increase

The average total increase in departure sequencing delay when flights were locked to exact departure times is presented in Figure 5-13, divided into per hour of the day.

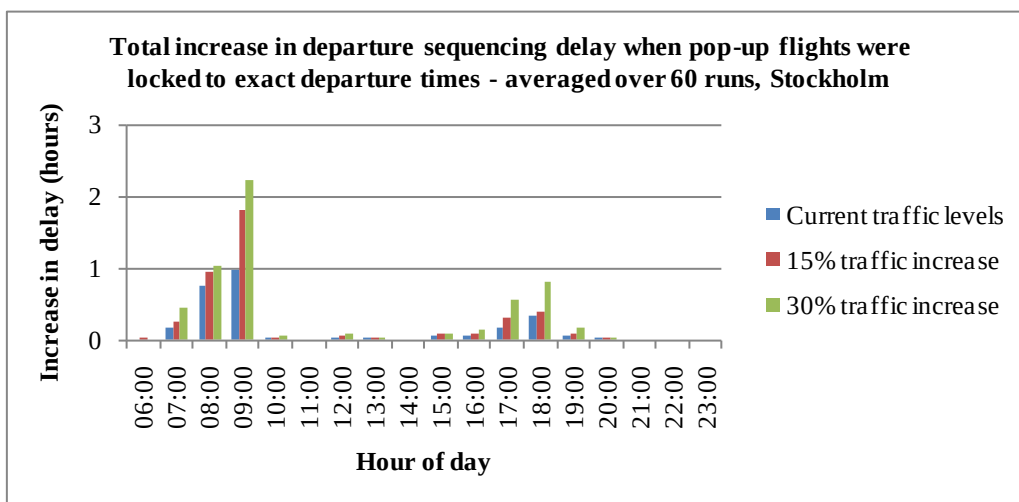


Figure 5-13: Total increase in departure sequencing delay when pop-up flights were locked to exact departure times – averaged over 60 runs, Stockholm

The average highest increase in delay that one individual flight incurred in every hour is presented in Figure 5-14.

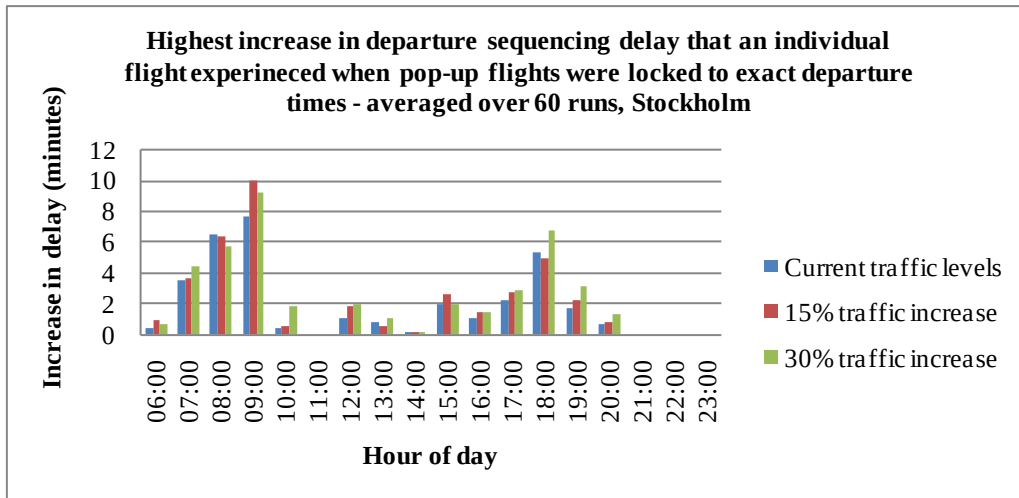


Figure 5-14: Highest increase in departure sequencing delay that an individual flight experienced when pop-up flights were locked to exact departure times – averaged over 60 runs, Stockholm

The average number of flights that experienced an increase in delay is shown in Figure 5-15, divided into per hour of the day.

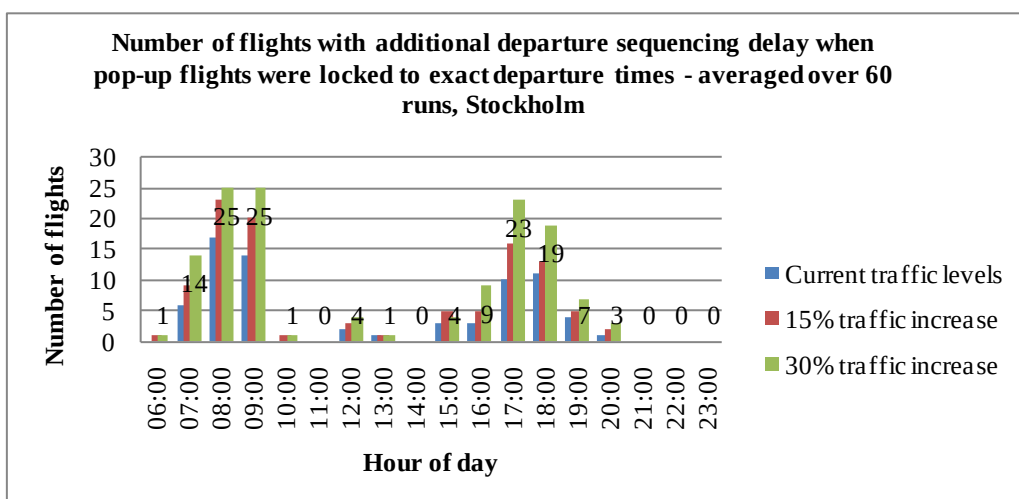


Figure 5-15: Number of flights with additional departure sequencing delay when pop-up flights were locked to exact departure times – averaged over 60 runs, Stockholm

Table 5-7 presents the average daily number of flights with departure sequencing delay with current operational procedures and when pop-up flights were locked to exact departure times.

Table 5-7: Daily number of flights with departure sequencing delay – averaged over 60 runs, Stockholm

	Current traffic levels	15% traffic increase	30% traffic increase
Current operational procedures	161	205	252
Pop-up flights locked to exact departure times	174	219	267

Figure 5-16 presents the flights classified according to amount of additional departure sequencing delay.

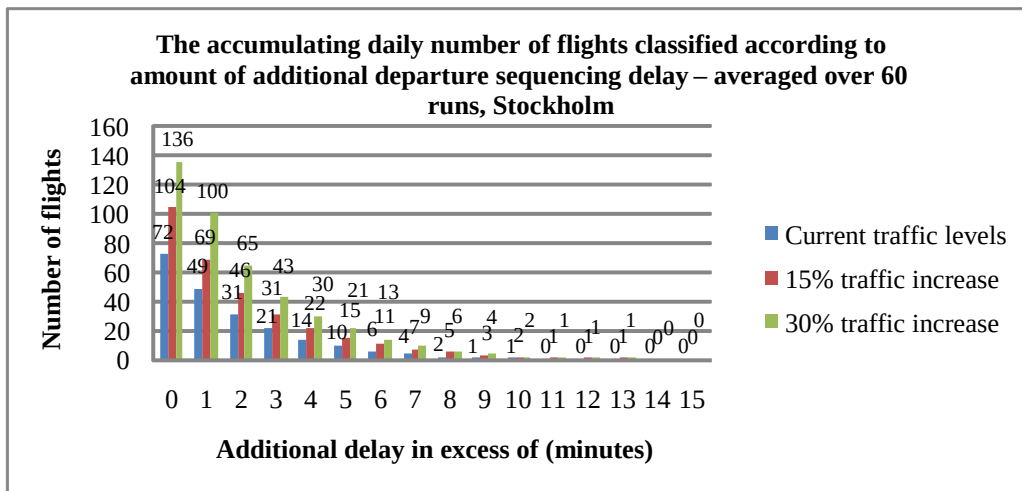


Figure 5-16: The accumulating daily number of flights classified according to amount of additional departure sequencing delay – averaged over 60 runs, Stockholm

Table 5-8 presents the average total daily departure sequencing delay with current operational procedures and when pop-up flights were locked to exact departure times.

Table 5-8: Total daily departure sequencing delay with current operational procedures and when pop-up flights were locked to exact departure times – averaged over 60 runs, Stockholm

	Current traffic levels (HH:MM:SS)	15% traffic increase (HH:MM:SS)	30% traffic increase (HH:MM:SS)
Current operational procedures	08:32:32	13:47:50	21:50:46
Pop-up flights locked to exact departure times	11:11:13	17:56:22	27:30:46
Increase when pop-up flights are locked to exact departure times	02:38:41	04:08:31	05:40:00

5.3.1.2 Copenhagen airport

Figures 5-17 to 5-19 present the mean departure sequencing delay, with current operational procedures and with pop-up flights locked to exact departure times, for the three traffic scenarios. For each traffic scenario, the results are divided into per hour of the day and averaged over the 60 runs.

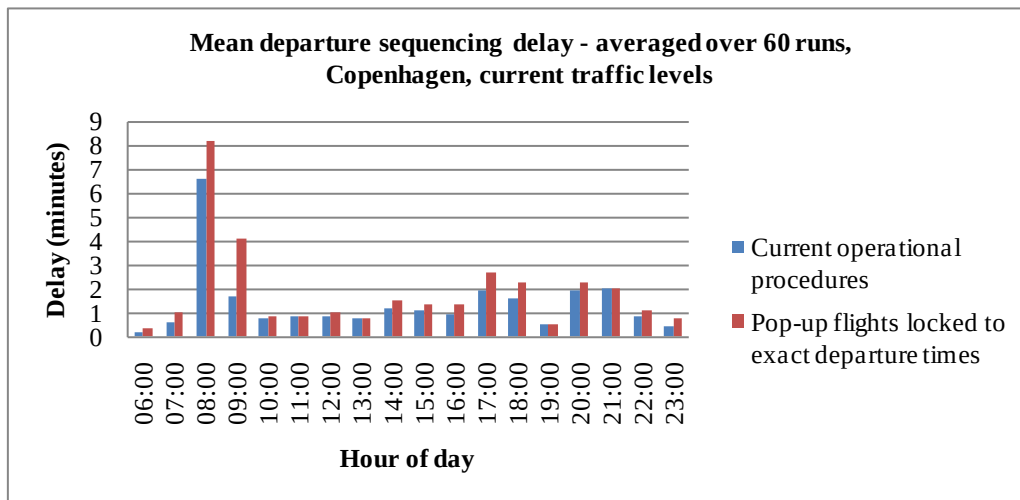


Figure 5-17: Mean departure sequencing delay – averaged over 60 runs, Copenhagen, current traffic levels

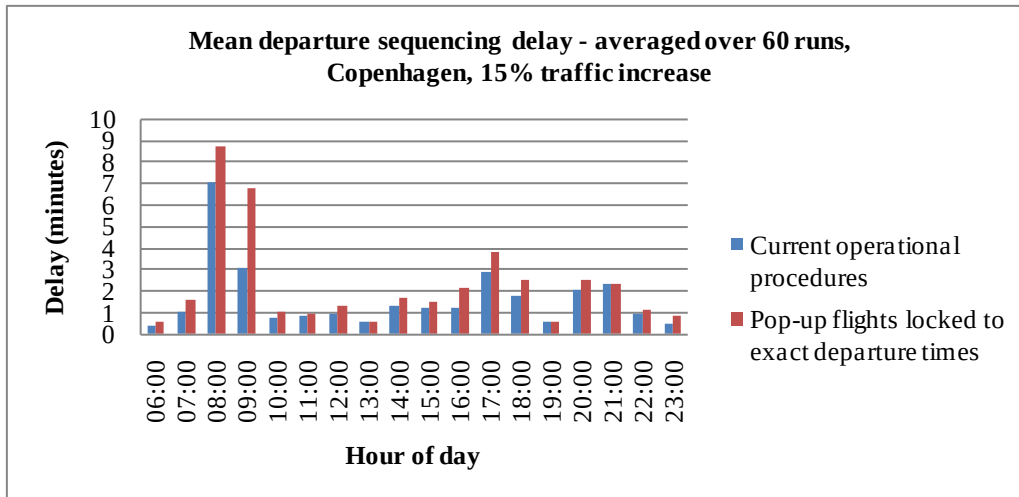


Figure 5-18: Mean departure sequencing delay – averaged over 60 runs, Copenhagen, 15% traffic increase

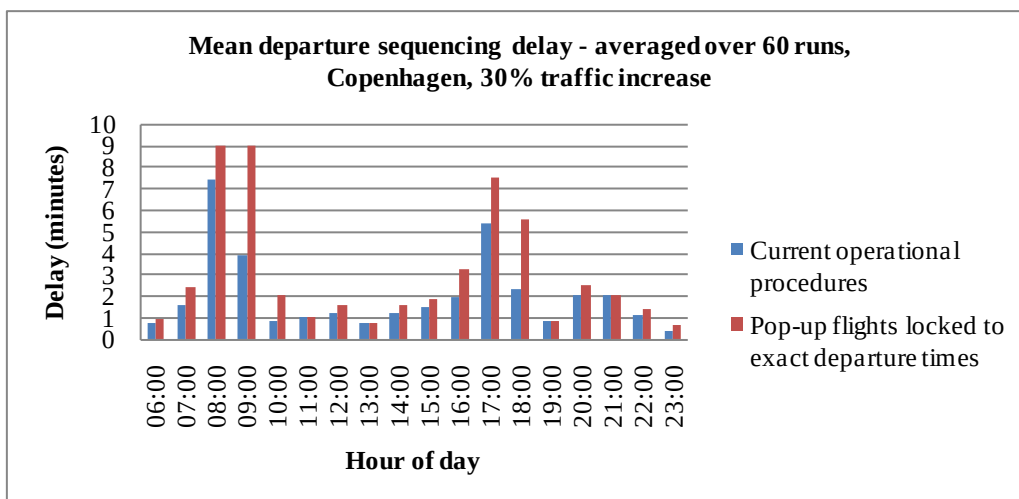


Figure 5-19: Mean departure sequencing delay – averaged over 60 runs, Copenhagen, 30% traffic increase

The average mean increase in departure sequencing delay when flights were locked to exact departure times is presented in Figure 5-20, divided into per hour of the day.

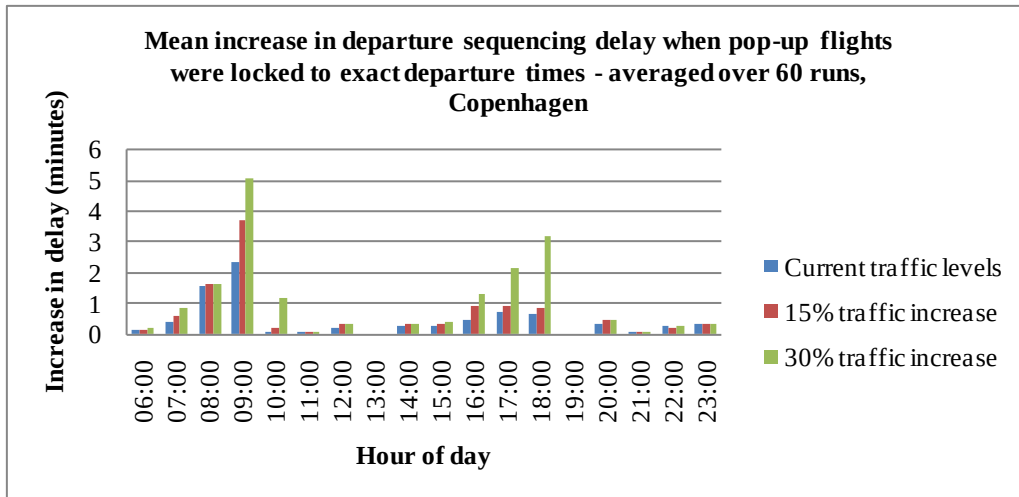


Figure 5-20: Mean increase in departure sequencing delay when pop-up flights were locked to exact departure times – averaged over 60 runs, Copenhagen

Figures 5-21 to 5-23 present the total departure sequencing delay, with current operational procedures and with pop-up flights locked to exact departure times, for the three traffic scenarios. For each traffic scenario, the results are divided into per hour of the day and averaged over the 60 runs.

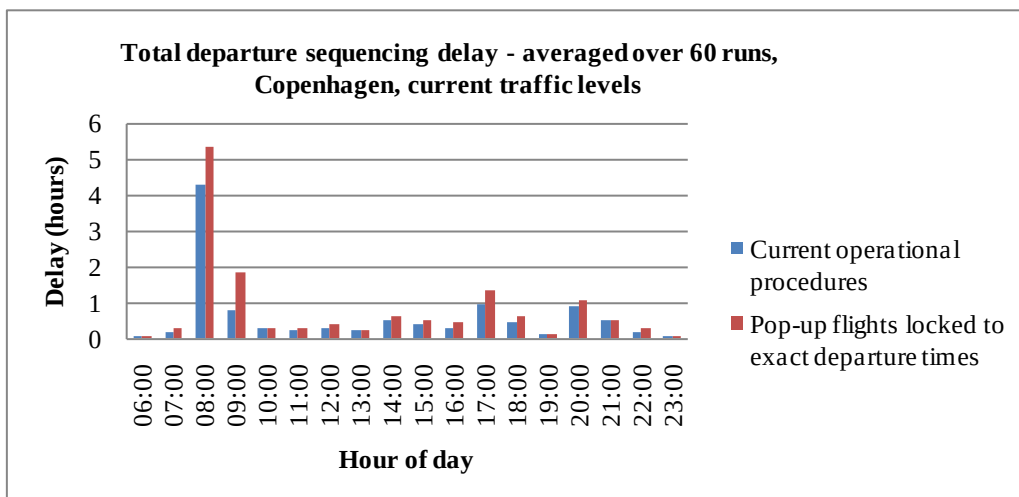


Figure 5-21: Total departure sequencing delay – averaged over 60 runs, Copenhagen, current traffic levels

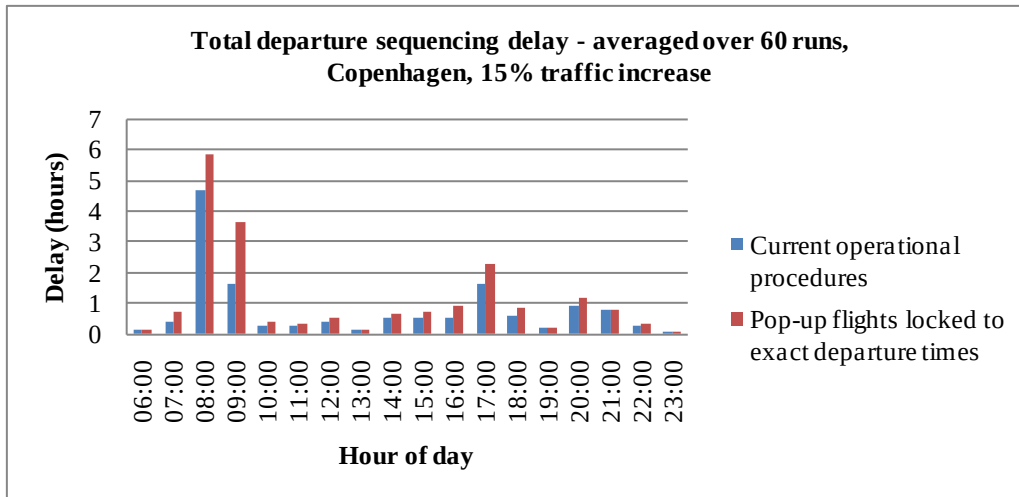


Figure 5-22: Total departure sequencing delay – averaged over 60 runs, Copenhagen, 15% traffic increase

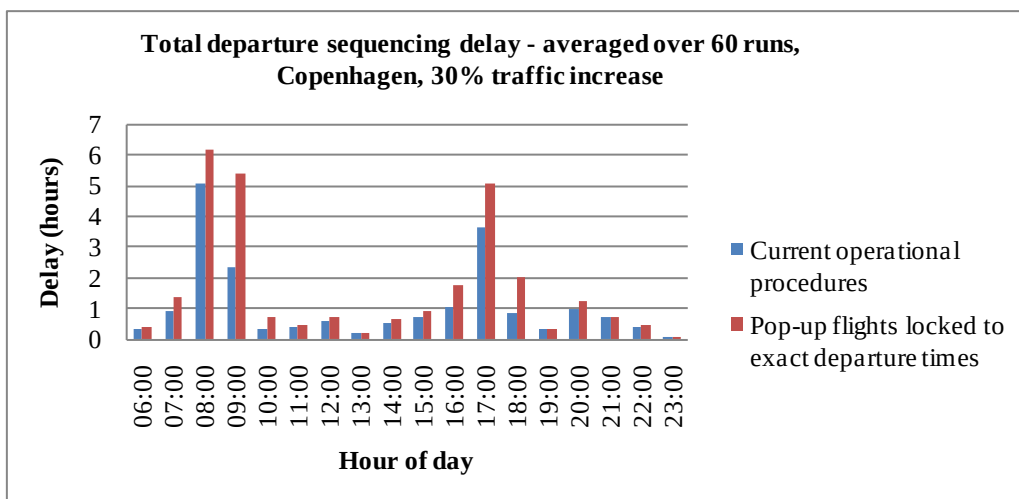


Figure 5-23: Total departure sequencing delay – averaged over 60 runs, Copenhagen, 30% traffic increase

The average total increase in departure sequencing delay when flights were locked to exact departure times is presented in Figure 5-24, divided into per hour of the day.

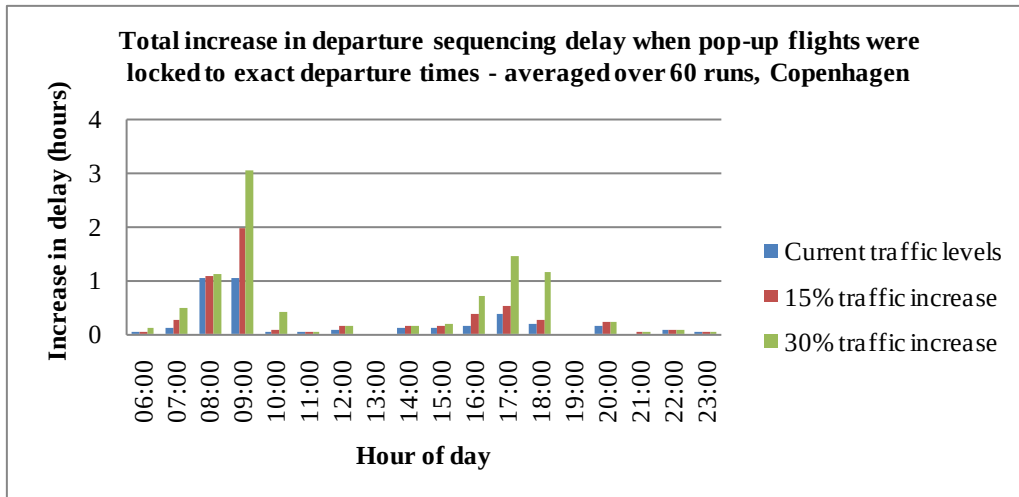


Figure 5-24: Total increase in departure sequencing delay when pop-up flights were locked to exact departure times – averaged over 60 runs, Copenhagen

The average highest increase in delay that one individual flight incurred in every hour is presented in Figure 5-25.

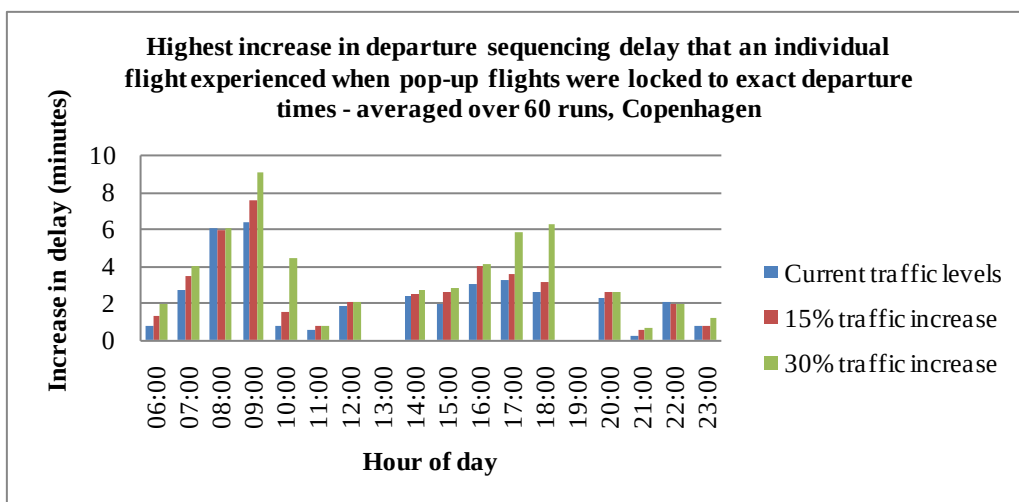


Figure 5-25: Highest increase in departure sequencing delay that an individual flight experienced when pop-up flights were locked to exact departure times – averaged over 60 runs, Copenhagen

The average number of flights that experienced an increase in delay is shown in Figure 5-26, divided into per hour of the day.

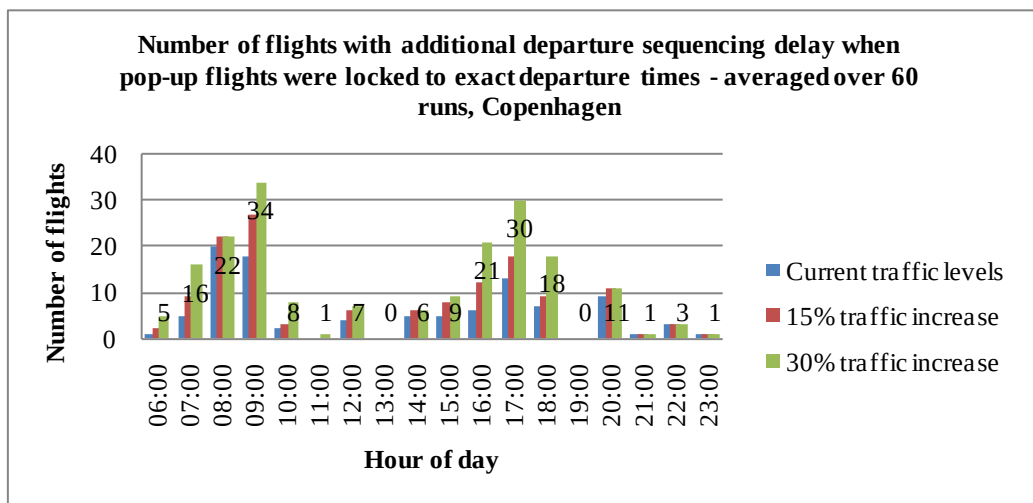


Figure 5-26: Number of flights with additional departure sequencing delay when pop-up flights were locked to exact departure times – averaged over 60 runs, Copenhagen

Table 5-9 presents the average daily number of flights with departure sequencing delay with current operational procedures and when pop-up flights were locked to exact departure times.

Table 5-9: Daily number of flights with departure sequencing delay – averaged over 60 runs, Copenhagen

	Current traffic levels	15% traffic increase	30% traffic increase
Current operational procedures	221	279	340
Pop-up flights locked to exact departure times	236	295	360

Figure 5-27 presents the flights classified according to amount of additional departure sequencing delay.

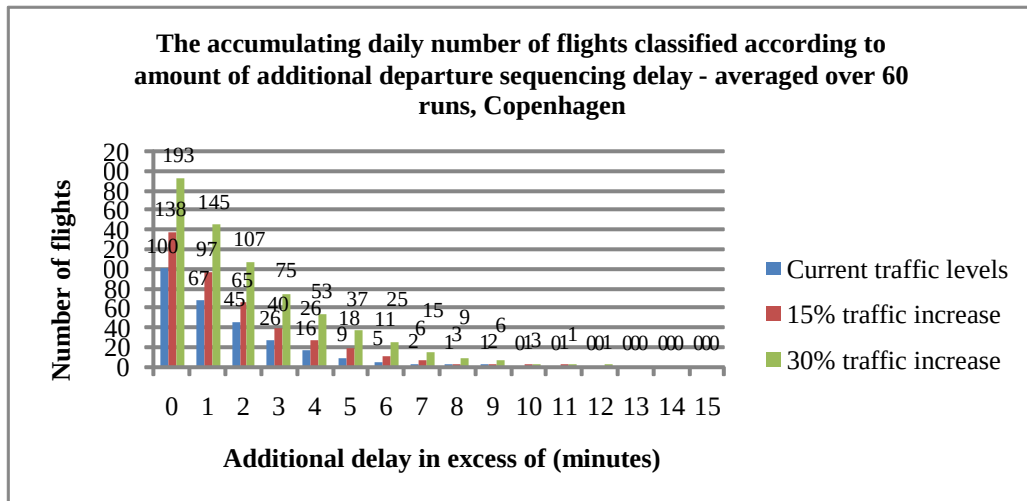


Figure 5-27: The accumulating daily number of flights classified according to amount of additional departure sequencing delay – averaged over 60 runs, Copenhagen

Table 5-10 presents the average daily departure sequencing delay with current operational procedures and when pop-up flights were locked to exact departure times.

Table 5-10: Total daily departure sequencing delay with current operational procedures and when pop-up flights were locked to exact departure times – averaged over 60 runs, Copenhagen

	Current traffic levels (HH:MM:SS)	15% traffic increase (HH:MM:SS)	30% traffic increase (HH:MM:SS)
Current operational procedures	10:43:20	13:58:03	19:20:12
Pop-up flights locked to exact departure times	14:13:31	19:37:14	28:39:45
Increase when pop-up flights are locked to exact departure times	03:30:11	05:39:11	09:19:33

5.3.2 Discussion of results

5.3.2.1 Stockholm airport

Departure sequencing delay with current operational procedures

From Figures 5-6 to 5-8 and Figures 5-10 to 5-12 it is clear that there are two peaks in the departure sequencing delay; at 08:00-10:00 and at 17:00-19:00. This is as expected as it is within the traffic peaks for Stockholm departures. The largest peak is at 08:00-10:00 for all the traffic scenarios. Observing Figure 4-3 showing the number of total departures from Stockholm it is clear that the morning peak has a higher peak with very large number of departures over a few hours whereas the afternoon peak is more evenly spread over more hours than in the morning. This explains why the morning peak experiences more departure sequencing delay than the afternoon peak.

From Table 5-8 it can be observed that as the traffic increases, there is a significant increase in the departure sequencing delay. The increase in average daily departure sequencing delay when the traffic increases by 15% is slightly over 5 hours, which is an increase of 62%. As the traffic increases by a further 15% the average daily departure sequencing delay increases by just over 8 hours, an increase of 58%. This results in close to 22 hours of average daily departure sequencing delay. It is clear that it is difficult for the departure runway to cope when being operated with such high demands. It may be that it will be required to employ mixed-mode operations to deal with this

traffic increase efficiently. In the future it is possible that mixed-mode, a mix of departures and arrivals on two or more runways, will be used more frequently to handle the expected traffic increase. Using mixed-mode operations makes it possible to have less separation between two flights using the same runway compared to segregated mode and thus increases capacity.

Increase in departure sequencing delay when pop-up flights are locked to exact departure times

It would be expected to see a large increase in departure sequencing delay in the hours where there are a large number of total departures (and therefore a large departure sequencing delay even with current operational procedures) as well as a large number of pop-up flight departures. For Stockholm airport the peak in pop-up flight departures occurs between 07:00-10:00 and 17:00-20:00 which is within the hours having the highest number of total departures. Therefore it is expected that the highest increase in departure sequencing delay occurs in these hours, which is also the case as can be seen from Figure 5-9 and Figure 5-13. The highest increase occurs in the morning peak, also as expected, as this is the largest peak in terms of total departures. There is still some additional delay in some of the other hours, but because these hours are not peak hours and do not have a peak in number of pop-up departures the effect is not as large. Figure 5-15 confirms that the large effect on the departure sequence is contained to the peak hours, with only a small number of flights being affected outside of the peak hours. In some hours no flights experienced an increase in departure sequencing delay. This was either due to no pop-up flights departing in the hour or that the pop-up flight(s) departed in a period with low number of total departures where it did not affect any other flights.

Also of interest is that the hour experiencing the greatest increase in departure sequencing delay is not 08:00-09:00 that has the most departures, but 09:00-10:00. This shows that the effect on the departure sequence is the highest towards the end of a peak period as the number of total departures and pop-up departures has been high for several hours and there is a large knock-on effect of flights having been moved to later departure slots.

Figure 5-14 shows that some individual flights experienced a large increase in departure sequencing delay. The average highest increase that one flight experienced was almost 8 minutes, almost 10 minutes and slightly more than 9 minutes for the three traffic scenarios respectively. Figure 5-16 shows that only a small number of flights had this high additional departure sequencing delay and that most flights only incurred a small increase in delay. The effect the additional delay has on an individual flight depends on if a flight is running on, behind or ahead of schedule when it incurs the additional delay. Obviously, for a flight that is already running behind schedule even a small amount of additional delay could result in a flight experiencing knock-on effects such as problems with the scheduling of the aircraft, passengers missing connections etc. due to the concept. In this work, 4 minutes of additional departure sequencing delay has been considered the limit of acceptability for an individual flight. That is, it has been assumed that if a flight incurs an additional delay below this it does not cause knock-on effects for that flight. Only 14 flights have an additional delay exceeding 4 minutes with the current traffic levels, 22 flights with a 15% traffic increase and 30 with a 30% traffic increase. For all traffic scenarios this is a relatively low number of flights. Still, the flights that do incur a large additional departure sequencing delay due to the concept may suffer large knock-on effects. That is, for all the traffic scenarios, implementing the delay-on-ground concept by locking pop-up flights to their exact RTA recommended takeoff time is likely to cause a large negative effect on some departing non pop-up flights.

Table 5-7 shows that there was only a small increase in the number of flights that had departure sequencing delay when pop-up flights were locked to exact departure times compared to current operational procedures. However, there was a fairly large amount of flights that had an increase in *their amount* of departure sequencing delay, as can be seen in Figure 5.16. That is, most of the flights that had an increase in departure sequencing delay due to the concept already had some departure sequencing delay in current operations. This is due to the fact that most of the effect on the departure sequence occurred in the peak hours where many flights had departure sequencing delay even in current operations.

Before the simulations were carried out one hypothesis made was that as the total traffic increases the penalty (in terms of increase in departure sequencing delay) of locking flights to exact departure times on the departure runway would go up. The results from the simulations have shown that this was indeed the case. From Table 5-8 it can be seen that for Stockholm airport the increase in total departure sequencing delay when pop-up flights are locked to exact departure times is just over 2.5 hours for the current traffic scenario, just over 4 hours for the scenario with a 15% traffic increase and just over 5.5 hours for the scenario with a 30% traffic increase. For all of the traffic scenarios the average daily increase in departure sequencing delay when pop-up flights are locked to exact departure times is significant and would be likely to cause large negative effects in real operations. As the results have shown, the effect on individual flights is mainly small and as the additional delay minutes would be taken at gate with engines off there would be no additional fuel consumption. However, the results have also shown that some individual flights are likely to suffer knock-on effects due to the additional delay that they incur. Furthermore, it is likely that the overall surface operations at the departure airports would be negatively affected, with possible congestion at gates, aprons and other surfaces of the airports. Thus, to be able to include Stockholm airport in the delay-on-ground concept in an efficient manner the pop-up flights will need to be locked to a time within their RTA takeoff window rather than their exact RTA recommended takeoff time on the departure runway.

5.3.2.2 Copenhagen airport

Departure sequencing delay for current operational procedures

From Figures 5-17 to 5-19 and Figures 5-21 to 5-23 it can be observed that the main peaks in departure sequencing delay occurs at 08:00 - 10:00 and 17:00 - 18:00, which is within the traffic peak for Copenhagen departures. The morning peak experiences significantly higher departure sequencing delay compared to the afternoon peak for all traffic scenarios. This is similar to what was observed at Stockholm airport and again due to the fact that the morning peak consists of a higher peak where a lot of flights demand the departure runway during only a few hours, as can be seen from Figure 4-5. Several hours in the afternoon have fairly high departure sequencing delay due to high number of departures.

From Table 5-10 it can be observed that as the traffic increases there is a significant increase in the departure sequencing delay, again similar to Stockholm airport. When the traffic is increased by 15% the average daily departure sequencing delay increases by just over 3 hours, an increase of 30%. When the traffic is increased by a further 15% the average daily departure sequencing delay increases by a bit over 5 hours, an increase of 38%. This results in more than 19 hours in average daily departure sequencing delay. Again, as for Stockholm airport, it is clear that it is difficult for the departure runway to cope when being operated with such high demands. It may be that it will be required to employ mixed-mode operations to deal with this traffic increase efficiently. In the future it is possible that mixed-mode, a mix of departures and arrivals on two or more runways, will be used more frequently to handle the expected traffic increase. Using mixed-mode operations makes it possible to have less separation between two flights using the same runway compared to segregated mode and thus increases capacity.

Increase in departure sequencing delay when pop-up flights are locked to exact departure times

The peak in number of pop-up flight departures occur between 06:00-10:00 and 15:00-18:00, which falls within the hours of highest number of total departures from Copenhagen, except for the period 06:00-07:00. So what would be expected would be to have the highest amount of increase in departure sequencing delay between 07:00-10:00 and 15:00-18:00. From Figure 5-20 and Figure 5-24 it can be observed that there is a large delay increase in all of these hours. In the afternoon, the peak in additional delay occurs at 16:00-19:00 rather than at 15:00-18:00. This is due to the knock-on effect of additional delay that can be observed for a while after a period where the number of total and pop-up flight departures has been high. As expected, the largest increase occurs in the morning peak. There is some additional delay in the non-peak hours as seen in Figure 5-20 and Figure 5-24. Because these hours are not peak hours in terms of total departures or pop-up flight departures the effect is obviously not as significant. Figure 5-26 shows that only a small number of flights had additional departure sequencing delay outside of the peak hours. As with Stockholm airport, the large effect on the departure sequence is contained to the peak hours. Again, in the hours where no flights experienced an increase in departure sequencing delay, this could either have

been due to no pop-up flights departing in that hour or that the pop-up flight(s) departed in a period with low number of total departures where it did not affect any other flights.

Similarly to Stockholm airport and due to the same reasons, the increase in delay is higher between 09:00 and 10:00 than 08:00 and 09:00, even though the total number of departures is higher between 08:00 and 09:00.

Figure 5-25 shows that some individual flights experienced a large increase in departure sequencing delay. The average highest increase that one flight experienced was almost 6.5 minutes, almost 8 minutes and slightly more than 9 minutes for the three traffic scenarios respectively. Figure 5-27 shows that only a small number of flights had this high additional departure sequencing delay and that most flights only incurred a small increase in delay. The effect the additional delay has on an individual flight depends on if a flight is running on, behind or ahead of schedule when it incurs the additional delay. Obviously, for a flight that is already running behind schedule even a small amount of additional delay could result in a flight experiencing knock-on effects such as problems with the scheduling of the aircraft, passengers missing connections etc. due to the concept. In this work, 4 minutes of additional departure sequencing delay has been considered the limit of acceptability for an individual flight. That is, it has been assumed that if a flight incurs an additional delay below this it does not cause knock-on effects for that flight. Only 16 flights have an additional delay exceeding 4 minutes with the current traffic levels and 26 flights with a 15% traffic increase. For a 30% traffic increase though, this number increases significantly to 53 flights. For the current traffic scenario and with a 15% traffic increase, this is a relatively low number of flights. Still, the flights that do incur a large additional departure sequencing delay due to the concept may suffer large knock-on effects. That is, for all the traffic scenarios, implementing the delay-on-ground concept by locking pop-up flights to their exact RTA recommended takeoff time is likely to cause a large negative effect on some departing non pop-up flights.

Table 5-9 shows that there was only a small increase in the number of flights that had departure sequencing delay when pop-up flights were locked to exact departure times compared to current operations. However, there was a fairly large amount of flights that had an increase in *their amount* of departure sequencing delay, as can be seen in Figure

5.27. That is, most of the flights that had an increase in departure sequencing delay due to the concept already had some departure sequencing delay in current operations. This is due to the fact that most of the effect on the departure sequence occurred in the peak hours where many flights had some departure sequencing delay already in current operations.

Similar to Stockholm airport, the hypothesis that as the total traffic increases the penalty (in terms of increase in departure sequencing delay) of locking flights to exact departure times on the departure runway would go up has been confirmed. From Table 5-10 it can be seen that the increase in delay for Copenhagen airport is just over 3.5 hours for the current traffic scenario, just over 5.5 hours for a 15% traffic increase and almost 9.5 hours for a 30% traffic increase. For all of the traffic scenarios the average daily increase in departure sequencing delay when pop-up flights are locked to exact departure times is significant and would be likely to cause large negative effects in real operations. As the results have shown, the effect on individual flights is mainly small and as the additional delay minutes would be taken at gate with engines off there would be no additional fuel consumption. However, the results have also shown that some individual flights are likely to suffer knock-on effects due to the additional delay that they incur. Furthermore, it is likely that the overall surface operations at the departure airports would be negatively affected, with possible congestion at gates, aprons and other surfaces of the airports. Thus, to be able to include Copenhagen airport in the delay-on-ground concept in an efficient manner the pop-up flights will need to be locked to a time within their RTA takeoff window rather than their exact RTA recommended takeoff time on the departure runway.

5.4 Conflicts between pop-up flights on the departure runways

One of the things considered of interest to find out from the simulations was if there would be many conflicts between pop-up flights when they were to be locked to times at the departure runways. In all of the simulation runs, both when pop-up flights were locked to exact departure times and when they were locked to a time within their RTA takeoff window, no pop-up flights had to cancel taking part in the delay-on-ground concept due to a conflict with other pop-up flights. That is, all flights could take off

within their RTA takeoff window. For all the simulation runs in which the aim was to lock pop-up flights to exact departure times, no pop-up flights were delayed by more than 3 minutes from their most optimal takeoff time and therefore no pop-up flights had to cancel taking part in the delay-on-ground concept. In these runs only a few pop-up flights at most per run were delayed by a small amount from their most optimal takeoff time for both Stockholm and Copenhagen. Thus, for Stockholm and Copenhagen airports and for airports with similar amounts of hourly pop-up flight departures it is likely that it will be possible to facilitate that all pop-up flights depart somewhere within their RTA takeoff windows and thereby participate in the delay-on-ground concept.

6 DISCUSSION AND CONCLUSION

6.1 Discussion

Previous work has shown that it is possible to use a delay-on-ground concept in which RTA-equipped pop-up flights enter the AMAN queue when at the departure gate by being issued with an RTA set to a TMA entry point at the destination airport. Live trials performed previous to this work have shown that the RTAs can be met with high accuracy and thereby it is possible to avoid airborne holding at arrival airport for these flights, if the aircraft departs at the appropriate time at the departure airport to allow it to arrive at the RTA at the TMA entry point of the destination airport. Also, the literature review has given an indication that RTA operations will be acceptable for ATC. Both pilots and air traffic controllers have generally had a positive view on working with RTAs in live trials. Current FMS RTA capability only allows the effective setting of an RTA to altitudes at and above 10,000 feet. With future FMS enhancements and improved predictions of winds during descent it may be possible to move the RTA point further down in descent, closer to the runway. For the delay-on-ground concept to be used in daily operations it will be necessary to have a new communication network in which information can be exchanged between departure towers and the ATCC handling the AMAN. It will also be necessary to have AMAN-DMAN cooperation for pop-up flights arriving from medium to large airports to be included in the delay-on-ground concept. This does not exist today, but is expected to be introduced in the future.

The simulations performed in this work have shown that there is potential for a significant reduction in airborne delay minutes and fuel consumption if the delay-on-ground concept was to be implemented at the case study airport Oslo-Gardermoen. It has been shown that, if AMAN-DMAN cooperation were to be available and all of the ten airports from which RTA-equipped traffic departs were included in the concept during peak hours, 41% (close to 2 hours daily) of the airborne arrival sequencing delay that is currently experienced at Oslo-Gardermoen airport could be eliminated with the delay-on-ground concept. This corresponds to an average daily fuel savings potential of 3.4 tons. In the simulations, when the traffic increased by 15% the average daily reduction in airborne delay minutes increased to slightly above 2 hours, corresponding

to a fuel savings potential of 4.1 tons. When the traffic increased by 30% the average daily reduction in airborne delay minutes increased to 2.5 hours, corresponding to a fuel savings potential of 4.7 tons. A significant reduction in airborne delay minutes could be attainable even without AMAN-DMAN cooperation, where, if the five departure airports with the least number of daily movements were to be included in the delay-on-ground concept during peak hours, 12% (approximately 30 minutes daily) of the airborne arrival sequencing delay would be avoided with the concept at current traffic levels. This corresponds to an average daily fuel savings potential of 972 kilograms. In the simulations, when the traffic increased by 15% the average daily reduction in airborne delay minutes increased to 36 minutes, corresponding to a fuel savings potential of 1.2 tons. When the traffic increased by 30% the average daily reduction in airborne delay minutes increased to 41 minutes, corresponding to a fuel savings potential of 1.3 tons. The increase in the potential reduction in airborne delay minutes and corresponding fuel savings potential as the traffic increases is likely to be even higher in practice, as the number of pop-up flights is expected to be higher than those used in the simulations. In the simulations the number of pop-up flights was kept constant for all the traffic scenarios.

It is recommended that the delay-on-ground concept be used only in arrival peak hours at Oslo-Gardermoen. Most of the potential fuel saving occurs in the peak hours, and the improvements through the use of the concept outside of these hours provide results of secondary value. Furthermore, the concept would require an increase in workload for the air traffic controller managing the AMAN (increased coordination with departure towers and pilots) and pilots (communication before departure to get an RTA, ensure that the flight departs at/during the RTA takeoff time/window) [7, 9]. This further emphasizes the value of restricting the concept to peak hours. Also, in peak hours there would be a reduction in workload for the air traffic controller handling the traffic in the TMA as, as long as the pop-up flights meet their RTAs, the aircraft will arrive in a coordinated manner and it will not be necessary to instruct them to go into holding or vectoring. There would also be a corresponding reduction in pilot workload in this phase of flight as the FMS can plan the flight from takeoff all the way to TMA entry and the pilot will not need to put the aircraft into holding or vectoring. In the future, if the RTA point can be moved to further down in the descent (maybe the runway

eventually) that will increase predictability and reduce controller and pilot workload in this phase of flight further.

It is also recommended that a first implementation step of the delay-on-ground concept for the case study airport should include the five departure airports with the least number of daily movements, as it is likely that AMAN-DMAN cooperation would not be required. It is therefore reasonable to assume that including these airports would be possible in the shorter term compared to the departure airports with a larger number of daily movements. What would be needed to include these airports is a new communication network.

For departure airports of the size of Stockholm-Arlanda and Copenhagen-Kastrup to be included in the delay-on-ground concept, the pop-up flights will need to depart somewhere within their RTA takeoff window, rather than at their exact RTA recommended takeoff time. This is because the simulations have shown that locking flights at the departure runways at Stockholm-Arlanda and Copenhagen-Kastrup airports to exact departure times is very penalizing in terms of total daily additional departure sequencing delay for non pop-up flights and is therefore not advantageous. For Stockholm-Arlanda airport the average increase in total daily departure sequencing delay when pop-up flights were locked to their exact RTA recommended takeoff times was close to 3 hours for the current traffic levels. With a 15% and 30% traffic increase this figure increased to slightly above 4 hours and close to 6 hours respectively. For Copenhagen-Kastrup airport the average increase in total daily departure sequencing delay when pop-up flights were locked to their exact RTA recommended takeoff times was 3.5 hours. With a 15% and 30% traffic increase this figure increased to close to 6 hours and slightly over 9 hours respectively. It is reasonable to expect that all airports with similar and higher number of movements as Stockholm-Arlanda and Copenhagen-Kastrup airports would experience similar amounts of additional departure sequencing delay if pop-up flights were locked to their exact RTA recommended takeoff time. It is true that the additional delay for each individual flight is mostly small and can be taken at the gate with no fuel penalty. However, the results have also shown that some individual flights are likely to suffer knock-on effects due to the additional delay that they incur. Also, the average total daily increase in departure sequencing delay is

significant and could lead to congestion at gates, aprons and other surfaces of the airports. It has been shown that, for all traffic scenarios, when the delay-on-ground concept is implemented by allowing the pop-up flights to depart somewhere within their RTA takeoff window the overall departure sequencing delay for non pop-up flights can either decrease or increase compared to for current operations. The change is not due to the concept as such, but is due to the fact that the pop-up flights change their demand times on the departure runway when the delay-on-ground concept is in use. That is, locking pop-up flights to a time within their RTA takeoff window is not penalizing for the departure sequences. When pop-up flights are locked to a time in their RTA takeoff window they are still as likely to meet their RTA and AMAN-scheduled time with high accuracy. Thus, to be able to include medium to large departure airports in the delay-on-ground concept in an efficient manner the pop-up flights will need to be locked to a DMAN specified time within their RTA takeoff window rather than their exact RTA recommended takeoff time on the departure runway. The DMAN should aim to allow pop-up flights to depart at the beginning of their RTA takeoff window. This would ensure that the flight is flown with a low cost index with low fuel consumption.

In the simulations performed in this work, segregated runway operations were assumed. It may be that to deal with a 15% and 30% traffic increase it will be necessary to employ mixed-mode operations to deal with the traffic increase efficiently. Using mixed-mode operations (a mix of departures and arrivals on two or more runways) makes it possible to have less separation between two flights using the same runway compared to segregated mode and thus increases capacity.

During the simulations no pop-up flights had to cancel taking part in the delay-on-ground concept due to a conflict with another pop-up flight on the departure runway. Thus, for Stockholm-Arlanda and Copenhagen-Kastrup airports and for airports with similar amounts of hourly pop-up flight departures it is likely that it will be possible to facilitate that all pop-up flights depart somewhere within their RTA takeoff windows and thereby participate in the delay-on-ground concept.

6.2 Suggestions for future work

Before the delay-on-ground concept investigated in this work can be used on a wide scale in daily operations the following activities need to be carried out:

1. The development and implementation of a new communication network between departure and arrival airports.
2. Further live trials for air traffic controllers and pilots to gain experience working with the concept and to learn from those experiences.
3. Improvement of A-CDM procedures so that DMANs can set valid departure sequences earlier than what they can today.
4. Implementation of AMAN-DMAN cooperation.

Also of interest for future work is:

5. The implementation of full Trajectory Based Operations. A new communication network in which the required information to achieve the delay-on-ground concept can be exchanged will be required. In the short-term, one solution could be that the departure tower has access to the AMAN sequence and is able to provide the AMAN with information about the pop-up flights. This was one of the suggestions from the Cassis project [9]. Pop-up flights will need to communicate to the departure tower when they are ready for takeoff and what the FMS estimated flying time is. For a pop-up flight to calculate its estimated flying time it will need to know the STAR it will use. This information will need to be provided by the ATCC handling the AMAN. Ideally, this information should automatically be given to the departure tower, possibly presented on the same screen as the AMAN sequence. The departure tower will need to communicate the STARs to the pop-up flights. The departure tower controller will then insert the first possible takeoff time and flying time into the AMAN which will use this information to calculate an AMAN demand time and thereby insert the pop-up flights into the AMAN queue. As the departure tower would have access to the AMAN sequence the tower controller would be able to see what the AMAN-scheduled times are for pop-up flights and issue these times as RTAs to the flights. For the departure

airports with a low number of movements the pop-up flights should then be able to insert the RTAs into their FMSs and plan their takeoff times accordingly. For medium to large airports where AMAN-DMAN cooperation will be required it is recommended that the DMAN, as part of the AMAN-DMAN cooperation, rather than the departure tower controller, automatically communicates the first possible takeoff time (first DMAN-scheduled time) and estimated flying time to the AMAN. Before this, the STAR will have needed to be communicated to the pop-up flight. For medium to large airports it is recommended that the information of which STAR to use is given directly from the ATCC handling the AMAN to the aircraft, possibly via AOC. The estimated flying time will need to be communicated directly from the aircraft to the DMAN (or directly to the AMAN), possibly via AOC. The AMAN will then need to be able to automatically communicate to the DMAN or to the aircraft what the AMAN-scheduled time (RTA) is. For this communication to occur between ATCC, AMAN, DMAN and cockpit/AOC a capable datalink will need to be available. Using knowledge of the RTA and the estimated flying time the DMAN should be able to calculate what the RTA recommended takeoff window is. Alternatively, the RTA recommended takeoff window can be calculated by the FMS and communicated to the DMAN. The DMAN would then schedule the flight for departure somewhere in this window (preferably at the beginning of the window as discussed previously). The time at which the DMAN has scheduled the pop-up flight for takeoff will be communicated by the departure tower controller to the pilots. This, as well as all communication between aircraft and departure tower, will probably be carried out through voice communication initially and through datalink in the longer term. The benefit of the type of solution described above would be that the controller handling the AMAN (who is likely to have a heavy workload during peak hours) would not need to be actively involved in the information exchange. The only difference that the AMAN controller would experience in operations is that pop-up flights would enter the AMAN queue much earlier than today. For medium to large departure airports the departure tower controller should also be involved in the information exchange as little as possible as described above to not increase their workload to an unacceptable amount.

In the long-term of SESAR the solution of a suitable communicating medium is expected to come through SWIM. SWIM is one of the most important enablers of the

SESAR Concept of Operations. The goal of SWIM is to make the needed information available to all ATM stakeholders (in Europe and globally) through interoperable web-based services. In today's ATM system a lot of information is already exchanged, but through many different custom communication protocols point-to-point, each having their own data formats and self-contained information systems. SWIM will move from point-to-point sharing of information to a system in which stakeholders publish relevant information so that it is available to all stakeholders that are interested in the information, through a communication mean that has system-wide interoperability and the required integrity and security. As the SWIM system will develop ATM information standards through Europe and globally will need to be built. Stakeholders that will provide and consume information through SWIM include AOCs, ANSPs, airport operators and flight crews. The information that is expected to be shared includes: 4DTs of flights from planning up to and through execution (the SBT and then the RBT before execution and any possible updates to the RBT during execution), meteorological data, surveillance data, aeronautical information, runways in use [39]. The benefit of SWIM compared to the short-term solution described above is that all information would be available to all people and systems. This would mean that, information needing to be conveyed between the arrival airport and the pop-up flight, such as STAR, aircraft readiness for departure etc., would not need to go through the departure tower.

Further live trials of the delay-on-ground concept will be required for pilots and controllers to gain experience working with the concept (using the RTA concept and sharing information earlier on through a new communication network), and to provide operational testing of the concept.

It is likely that A-CDM processes will improve during SESAR so that valid departure sequences can be set earlier on than today. This will benefit individual airports with more predictability and operational efficiency. It can also lead to the possibility to integrate the constraints of departure and arrival airports (AMAN-DMAN cooperation) and is a prerequisite for including medium to large departure airports in the delay-on-ground concept. Further work will also be required to enable AMAN and DMAN systems to communicate and integrate their constraints to enable a delay-on-ground concept in which departure airports of medium to large size are included.

It is recommended that the FMS RTA function is developed further and predictions of winds during descent improved so that the RTA point can be set further down in the descent in the future. It is likely that in the initial implementation of the delay-on-ground concept the RTA will be set to a TMA entry point and that the RTA will be set to further down in the descent in the future. Setting the RTA to further down in the descent would, as discussed, lead to additional benefits.

Future work will include the move to full Trajectory Based Operations, one of the cornerstones of the SESAR Concept of Operations. The 4DT (SBT) for a flight will be communicated a certain time before execution. This trajectory will represent how the airspace user wants to fly and take into account ATM constraints gate-to-gate. Using this information strategic de-confliction of trajectories will be performed. This may result in revised trajectories for some flight, so called RBTs. The RBTs may include RTAs set at one or more waypoints along the flight path. On the day of execution of the trajectory the FMS on-board the aircraft will display the RBT. The RBT that is activated in the FMS will be published to ground systems through SWIM. The taxi route and the Target Take-off Time (TTOT) will be published by a Surface Manager (SMAN) tool and displayed in the FMS in the cockpit to help the flight crew comply with the RBT. The SMAN will calculate the TTOT from the TOBT and the estimated taxi time. After the flight takes off the predicted RBT including the time dimension is updated by the FMS according to the actual take-off time and made available in SWIM. If an agreed RTA along the trajectory can no longer be achieved a new RTA is assigned, this leads to a new reference trajectory being calculated by the FMS. This trajectory is shared via SWIM. In Trajectory Based Operations, pop-up flights will continue, as in Time Based Operations, to be assigned a slot in the AMAN queue (RTA) that is issued before take-off [5]. Non pop-up flights will not be subject to detailed sequencing and assigned an RTA for a point during descent until they reach the AMAN planning horizon [6].

For Trajectory Based Operations to be implemented significant changes to both air and ground systems will be required. The FMS is expected to be allowed to calculate and fly along its most efficient trajectory (taking certain constraints into account, such as an RTA). For ATC to accommodate this, the FMS will need to continuously downlink the current position and 4DT of the aircraft. For this downlink to be possible a real-time

datalink with the sufficient bandwidth is needed. SWIM will need to be implemented to share the business trajectories. Ground systems will need to be developed with sophisticated conflict tools that will perform strategic de-confliction of RBTs and continue to alert the controller in case a conflict is predicted between two or more RBTs during execution. In case of a conflict the ground system will need to calculate the best alteration to one or more RBTs to achieve de-confliction, considering the effect of the alteration on the entire ATM system.

In Trajectory Based Operations the nature of ATM will change from the current, mainly tactical system to one of strategic de-confliction in which aircraft fly closed-loop with respect to time to assigned RTAs. This will change the role of the air traffic controller significantly. To assess the implications of this real time human-in-the-loop simulations and live trials will need to be performed. Some of the factors that need to be examined in these simulations and live trials are the effect of Trajectory Based Operations on the air traffic controller situational awareness, what additional information except for the 4DT that needs to be downlinked to the ground system (such as expected speeds and altitudes at waypoints), aircraft behavior when controlling to an RTA and how tactical interventions will affect the RTA.

6.3 Conclusion

The literature review has shown that it is possible to use current FMS RTA capability together with an AMAN to enable a delay-on-ground concept in which flights of 1 hour duration or less absorb their arrival sequencing delay at the departure gate. For the concept to be used in daily operations, however, a new communication network enabling information exchange between the departure towers and the ATCC handling the AMAN will be required. For medium to large departure airports to be included in the concept it will also be necessary to have a cooperation between the AMAN(s) at the arrival airport(s) and the DMAN(s) at the departure airport(s). This does not exist today, but is expected to exist in the future. The simulations performed in this work have shown that there is value in putting the delay-on-ground concept in practice for the case study airport. It has been shown that a significant reduction in airborne delay minutes and fuel consumption can be achieved if the concept was to be used in daily operations

at the case study airport. The simulations have shown that a possible future implementation of AMAN-DMAN cooperation would bring benefits as it would increase the reduction in airborne delay and fuel consumption that can be achieved with the delay-on-ground concept. It has been shown that for medium to large departure airports to be included in the delay-on-ground concept it is advantageous that the pop-up flights depart somewhere within their RTA takeoff window, rather than at their exact RTA recommended takeoff time. Since, reserving exact departure times causes a significant amount of additional departure sequencing delay for non pop-up flights. It has been shown that locking the pop-up flights to a time within their RTA takeoff window does not affect the departure sequences negatively.

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APPENDICES

Appendix A Cassis pilot questionnaires

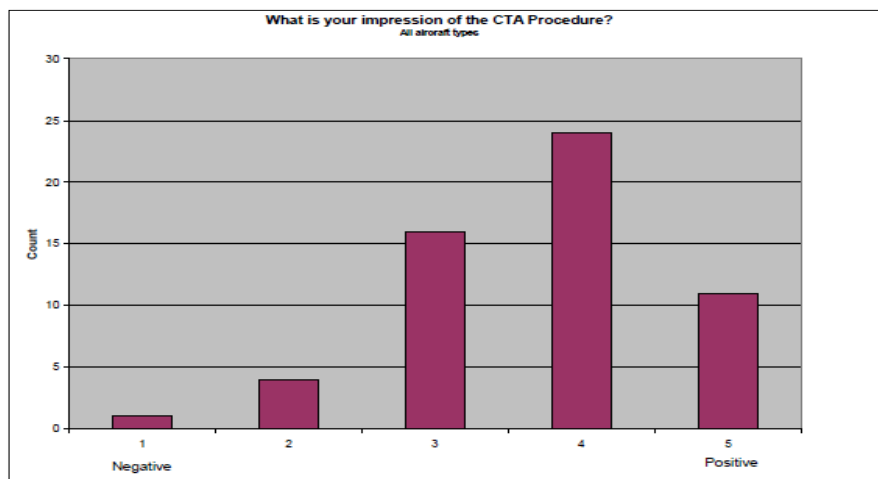


Figure 7-1: Cassis 2008 trials pilot questionnaire - 1 [9, p. 18]

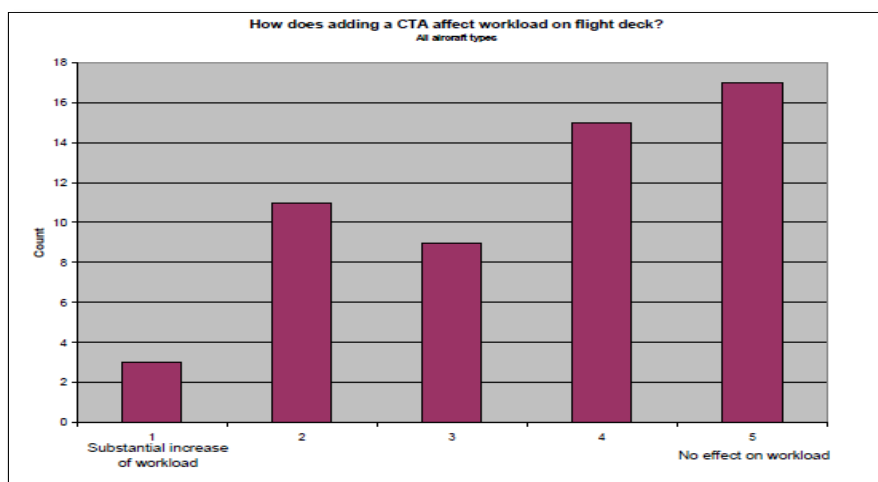


Figure 7-2: Cassis 2008 trials pilot questionnaire – 2 [9, p. 19]

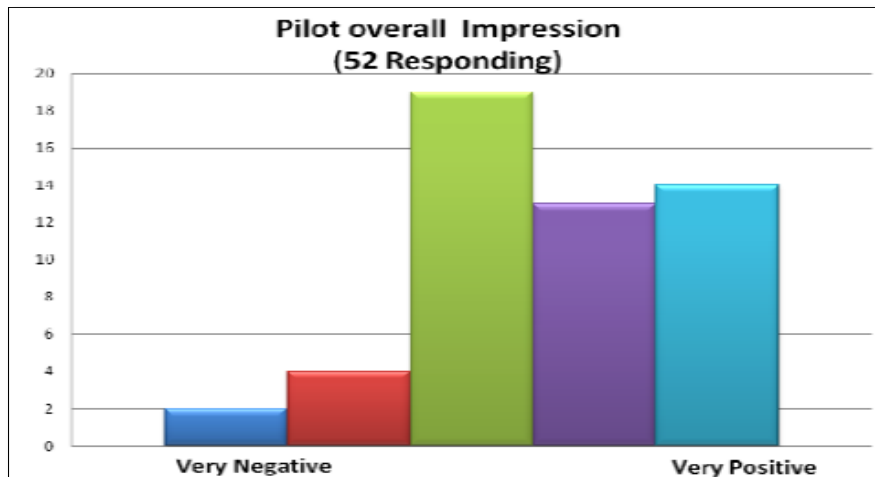


Figure 7-3: Cassis 2009 trials pilot questionnaire – 1 [7, p. 18]

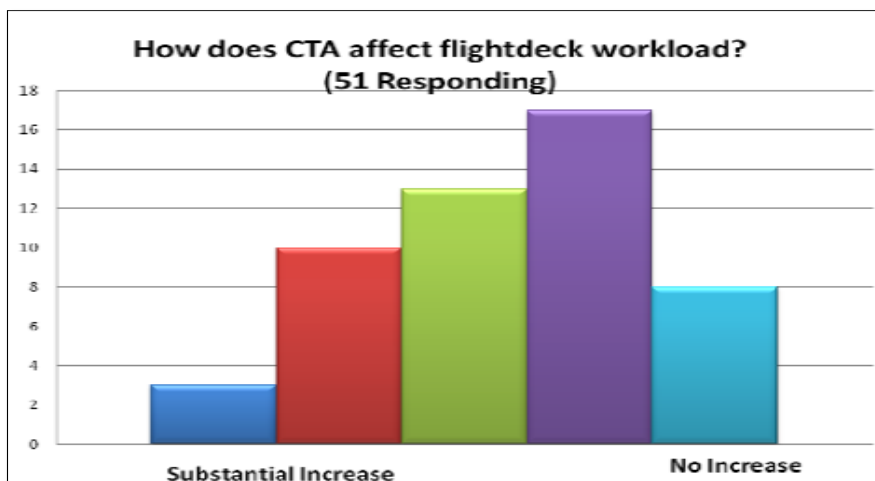


Figure 7-4: Cassis 2009 trials pilot questionnaire – 2 [7, p. 18]

Appendix B

Probability densities of the actual observed delay times, taxi times and flying times. Presented below are the graphs for the probability density functions of the actual observed data for the variables delay times, taxi times and flying times, as well as the tables containing the parameters describing the observed data.

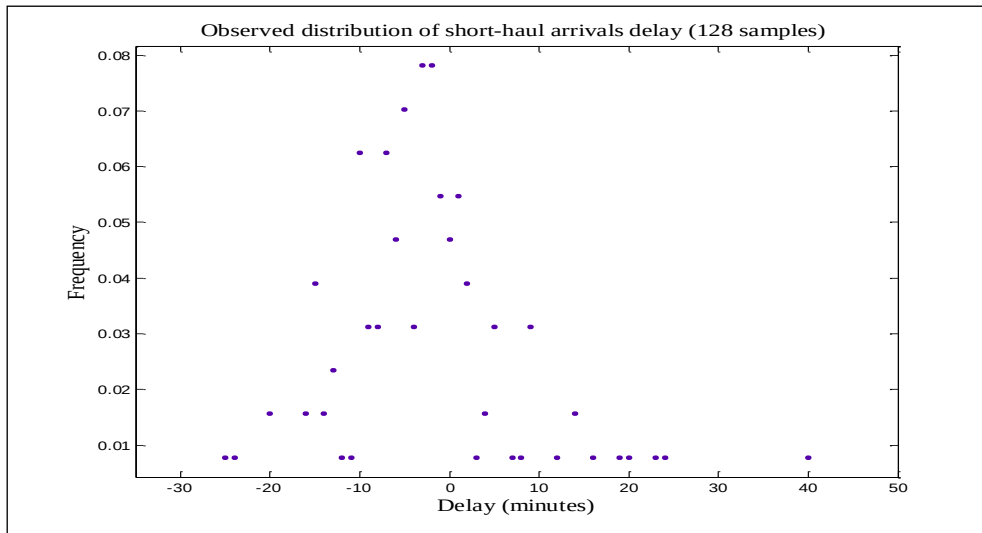


Figure 7-5: Observed distribution of short-haul arrivals delay

Table 7-1: Parameters describing short-haul arrivals delay

Mean (minutes)	-2.84
Standard deviation (minutes)	9.33
Minimum value (minutes)	-25.00
Maximum value (minutes)	40.00

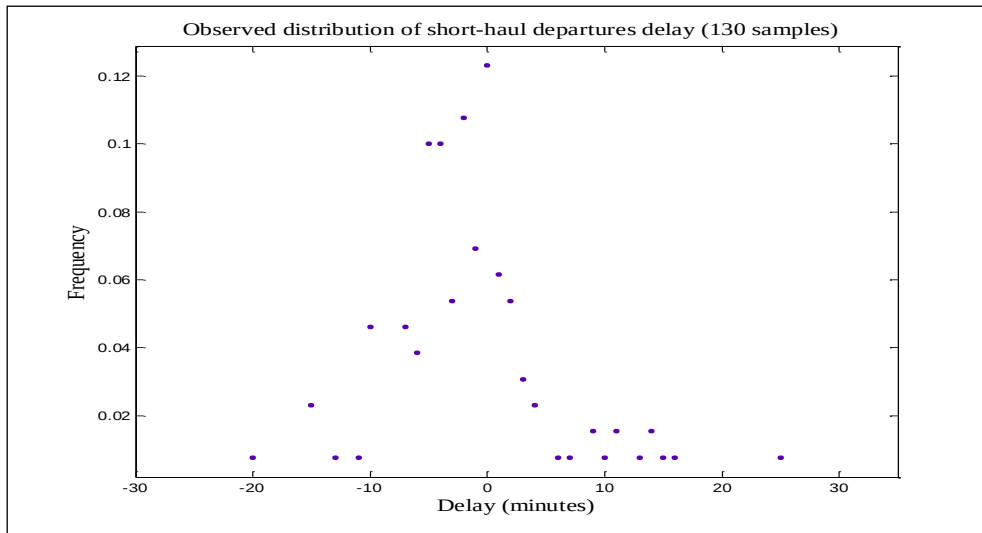


Figure 7-6: Observed distribution of short-haul departures delay

Table 7-2: Parameters describing short-haul departures delay

Mean (minutes)	-1.46
Standard deviation (minutes)	6.35
Minimum value (minutes)	-20.00
Maximum value (minutes)	25.00

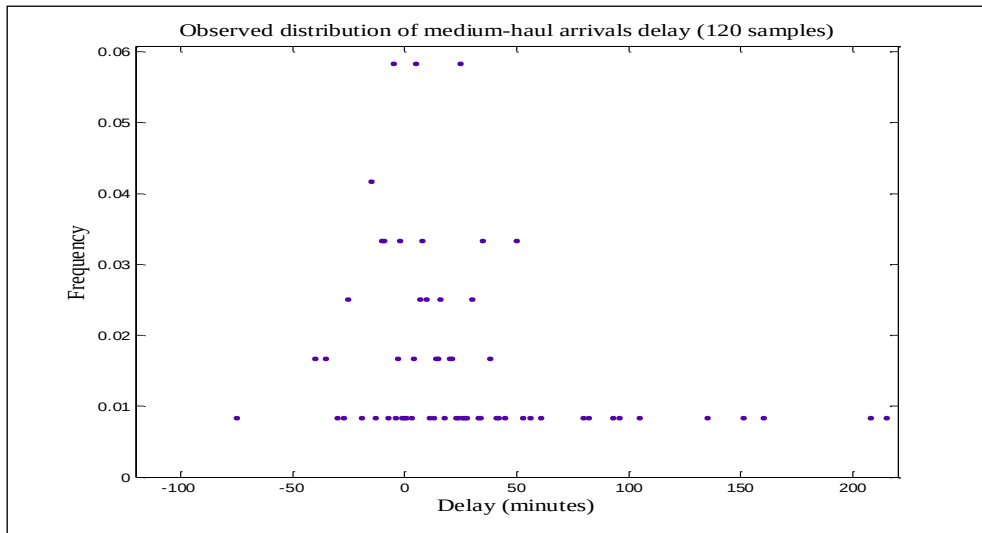


Figure 7-7: Observed distribution of medium-haul arrivals delay

Table 7-3: Parameters describing medium-haul arrivals delay

Mean (minutes)	18.82
Standard deviation (minutes)	43.33
Minimum value (minutes)	-75.00
Maximum value (minutes)	215.00

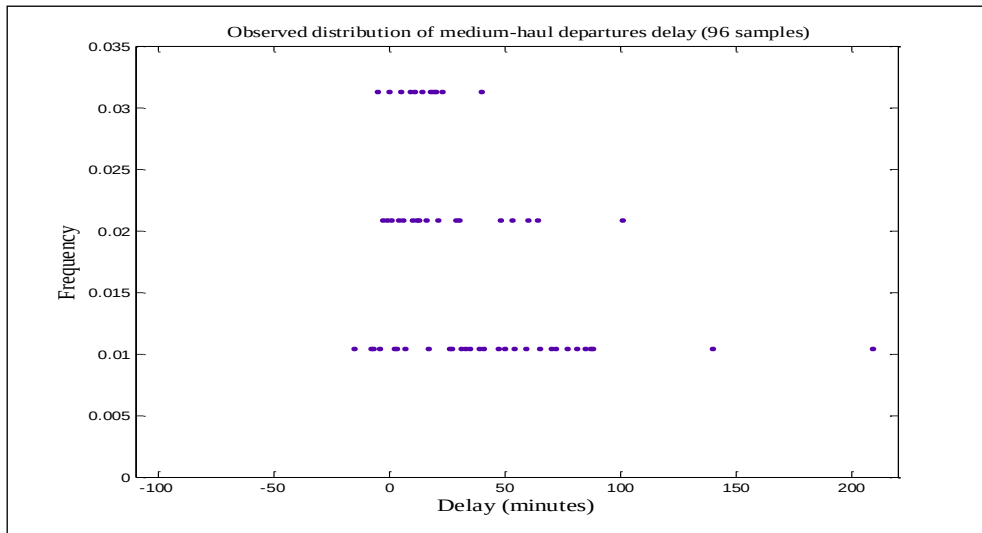


Figure 7-8: Observed distribution of medium-haul departures delay

Table 7-4: Parameters describing medium-haul departures delay

Mean (minutes)	29.18
Standard deviation (minutes)	34.55
Minimum value (minutes)	-15.00
Maximum value (minutes)	209.00

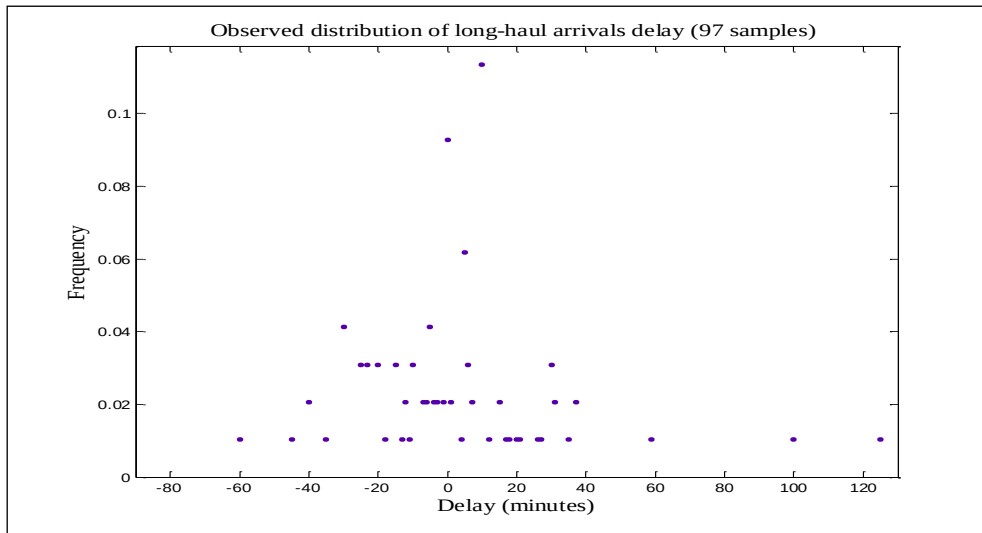


Figure 7-9: Observed distribution of long-haul arrivals delay

Table 7-5: Parameters describing long-haul arrivals delay

Mean (minutes)	9.57
Standard deviation (minutes)	61.78
Minimum value (minutes)	-60.00
Maximum value (minutes)	125.00

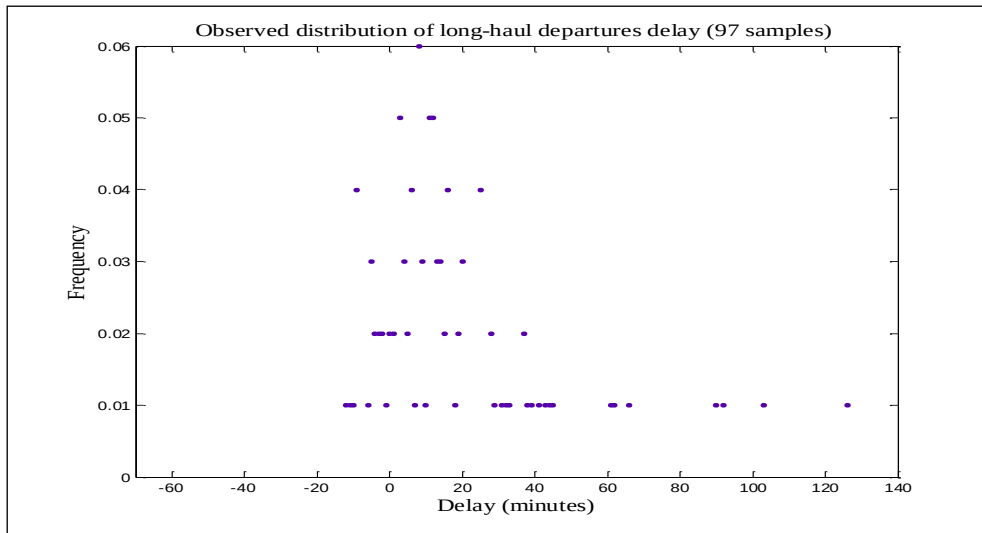


Figure 7-10: Observed distribution of long-haul departures delay

Table 7-6: Parameters describing long-haul departures delay

Mean (minutes)	16.57
Standard deviation (minutes)	23.94
Minimum value (minutes)	-12.00
Maximum value (minutes)	126.00

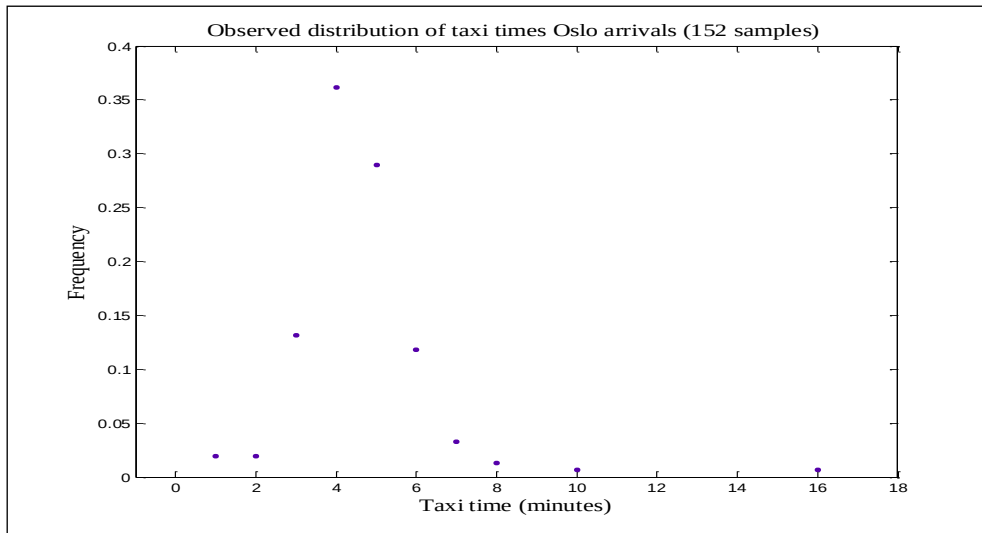


Figure 7-11: Observed distribution of taxi time Oslo arrivals

Table 7-7: Parameters describing taxi time Oslo arrivals

Mean (minutes)	4.57
Standard deviation (minutes)	1.59
Minimum value (minutes)	1.00
Maximum value (minutes)	16.00

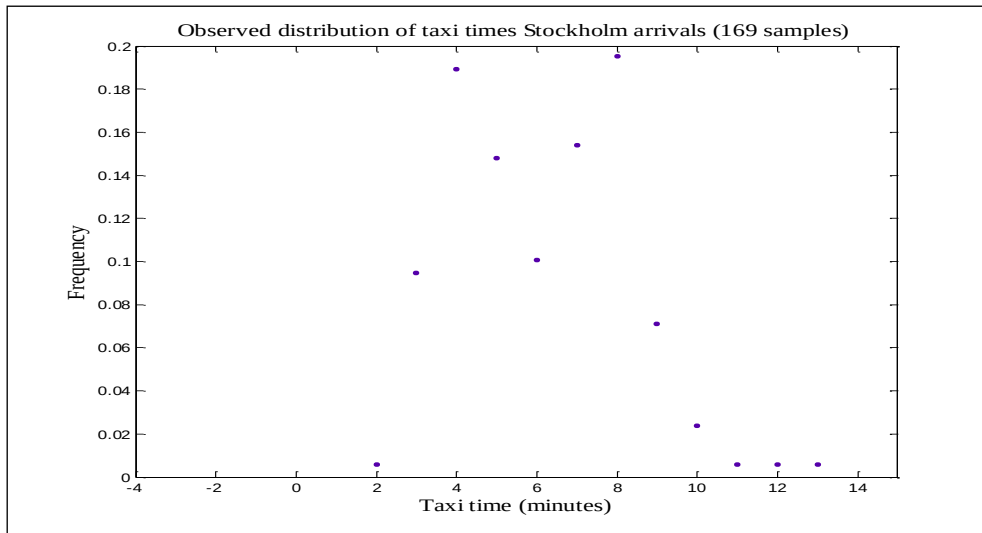


Figure 7-12: Observed distribution of taxi time Stockholm arrivals

Table 7-8: Parameters describing taxi time Stockholm arrivals

Mean (minutes)	6.12
Standard deviation (minutes)	2.11
Minimum value (minutes)	2.00
Maximum value (minutes)	13.00

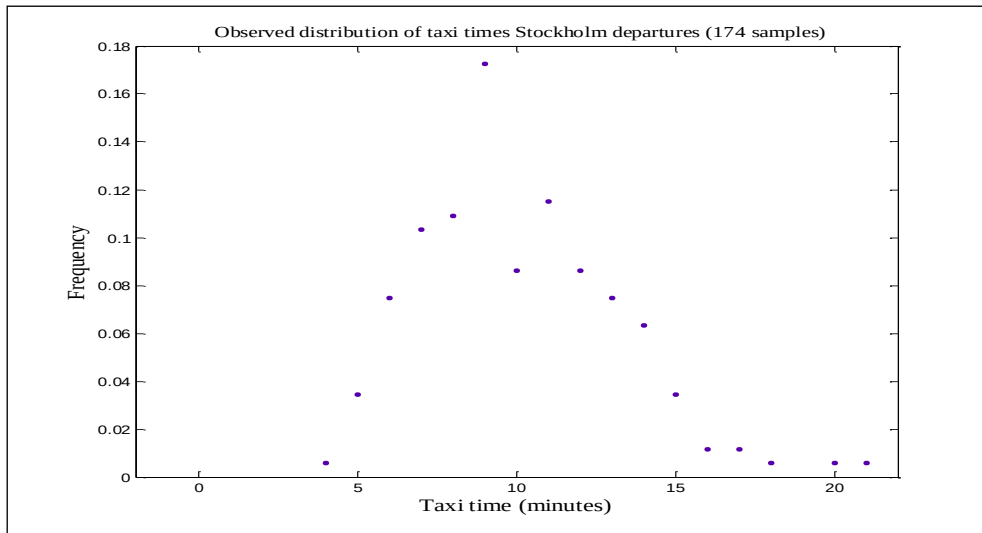


Figure 7-13: Observed distribution of taxi time Stockholm departures

Table 7-9: Parameters describing taxi time Stockholm departures

Mean (minutes)	10.05
Standard deviation (minutes)	3.08
Minimum value (minutes)	4.00
Maximum value (minutes)	21.00

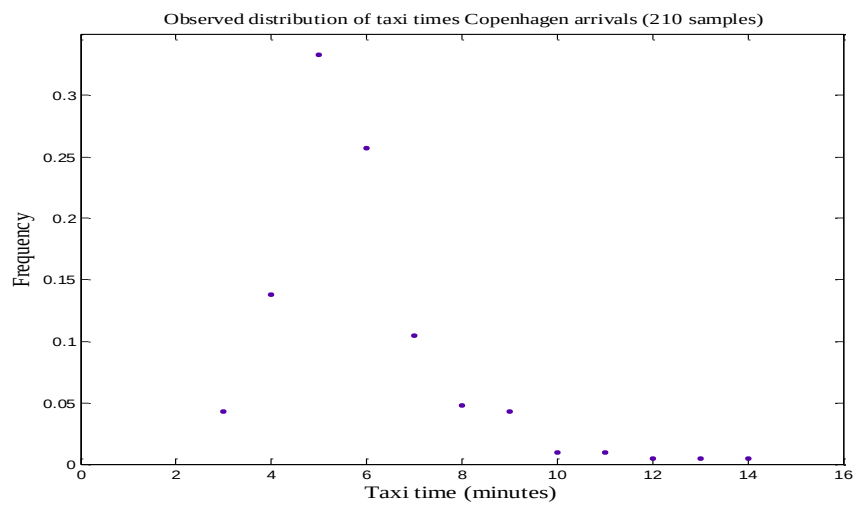


Figure 7-14: Observed distribution of taxi time Copenhagen arrivals

Table 7-10: Parameters describing taxi time Copenhagen arrivals

Mean (minutes)	5.78
Standard deviation (minutes)	1.74
Minimum value (minutes)	3.00
Maximum value (minutes)	14.00

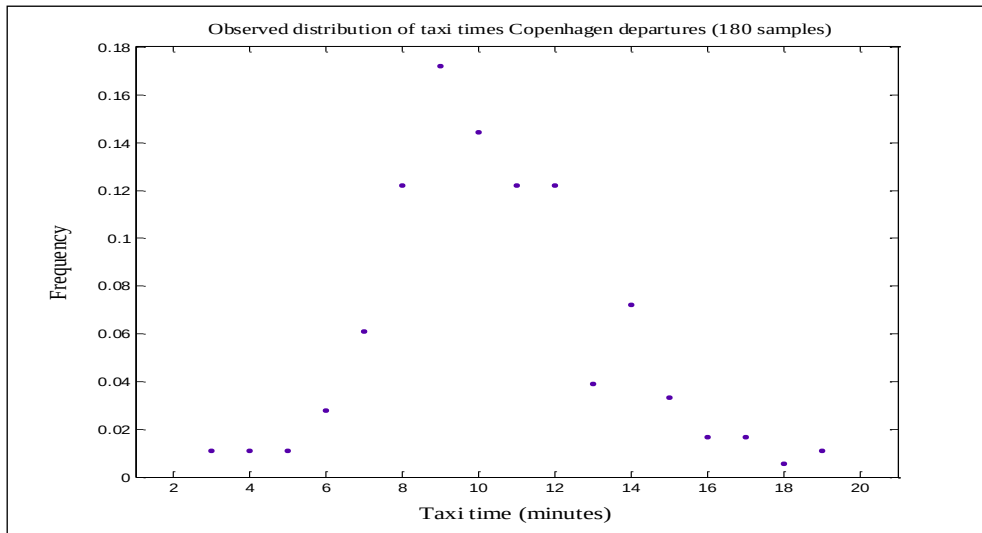


Figure 7-15: Observed distribution of taxi time Copenhagen departures

Table 7-11: Parameters describing taxi time Copenhagen departures

Mean (minutes)	10.39
Standard deviation (minutes)	2.90
Minimum value (minutes)	3.00
Maximum value (minutes)	19.00

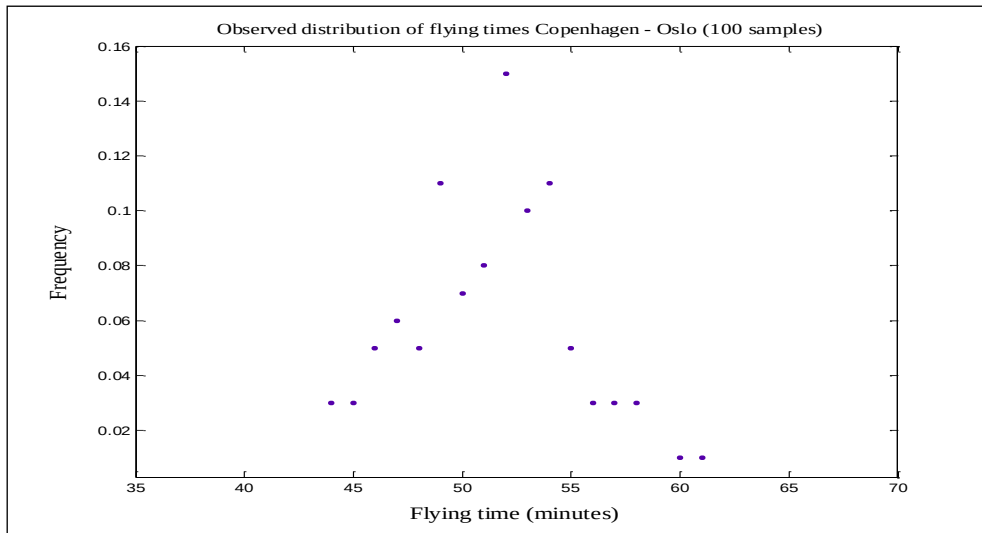


Figure 7-16: Observed distribution of flying time Copenhagen – Oslo

Table 7-12: Parameters describing flying time Copenhagen - Oslo

Mean (minutes)	51.29
Standard deviation (minutes)	3.64
Minimum value (minutes)	44.00
Maximum value (minutes)	61.00

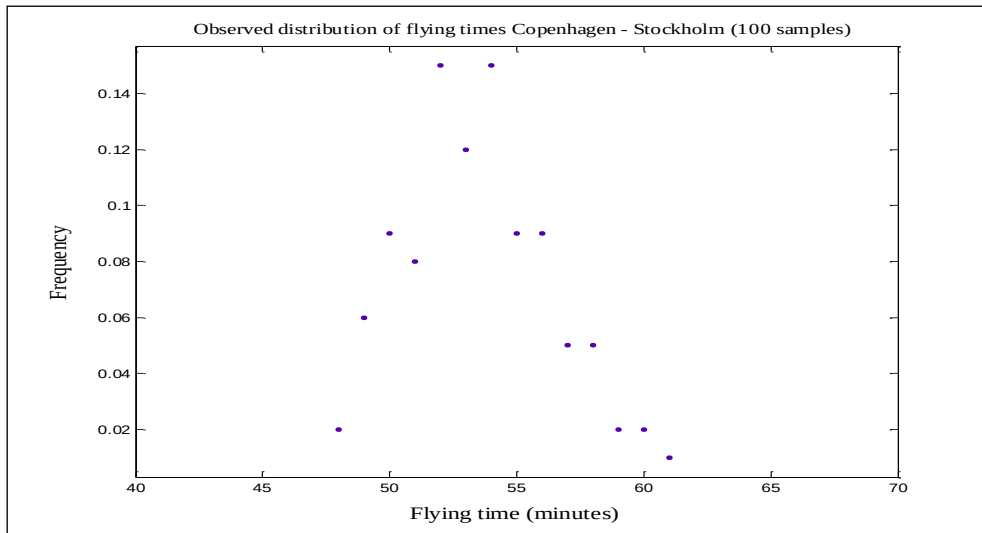


Figure 7-17: Observed distribution of flying time Copenhagen – Stockholm

Table 7-13: Parameters describing flying time Copenhagen – Stockholm

Mean (minutes)	53.47
Standard deviation (minutes)	2.88
Minimum value (minutes)	48.00
Maximum value (minutes)	61.00

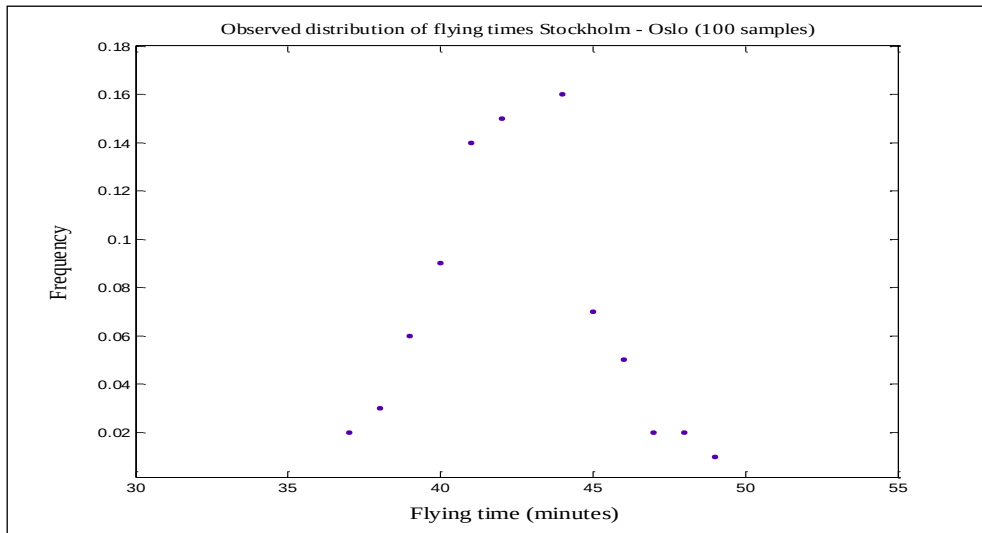


Figure 7-18: Observed distribution of flying time Stockholm – Oslo

Table 7-14: Parameters describing flying time Stockholm – Oslo

Mean (minutes)	42.48
Standard deviation (minutes)	2.41
Minimum value (minutes)	37.00
Maximum value (minutes)	49.00

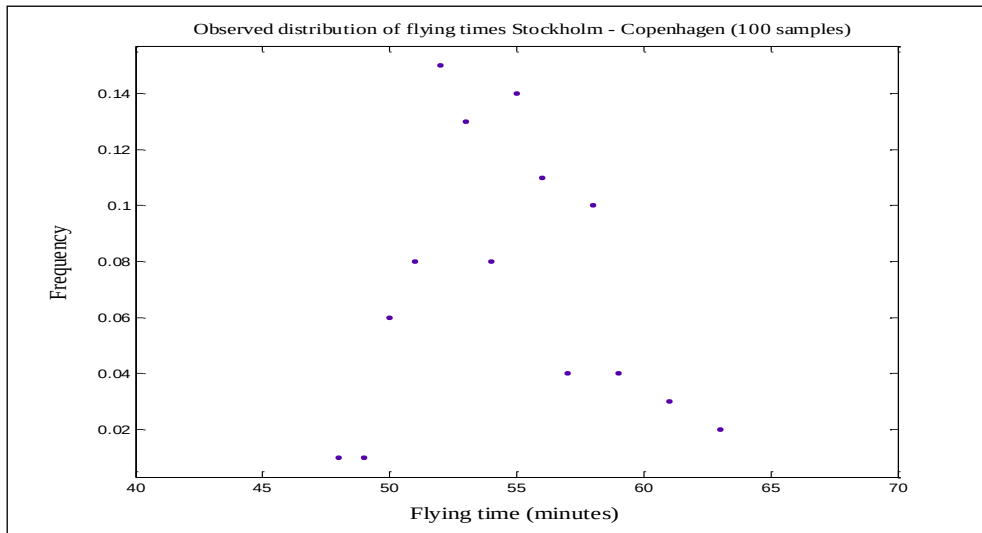


Figure 7-19: Observed distribution of flying time Stockholm – Copenhagen

Table 7-15: Parameters describing flying time Stockholm – Copenhagen

Mean (minutes)	54.45
Standard deviation (minutes)	3.09
Minimum value (minutes)	48.00
Maximum value (minutes)	63.00

Appendix B Results – detailed tables

Presented below are the figures presented in chapter 5 in table format.

Table 7-16: Highest reduction in airborne delay that an individual flight experienced with the delay-on-ground concept – averaged over 60 runs (Figure 5-1)

Highest reduction in airborne delay that an individual flight experienced with the delay-on-ground concept – averaged over 60 runs (HH:MM:SS)			
Time	Current traffic levels	15% traffic increase	30% traffic increase
06:00	00:00:52	00:00:53	00:01:12
07:00	00:03:52	00:04:30	00:04:43
08:00	00:04:33	00:04:30	00:05:15
09:00	00:02:04	00:02:16	00:02:33
10:00	00:03:19	00:03:48	00:03:46
11:00	00:01:01	00:01:04	00:01:12
12:00	00:01:07	00:01:02	00:01:24
13:00	00:01:12	00:02:14	00:03:18
14:00	00:00:13	00:00:22	00:00:32
15:00	00:01:33	00:01:39	00:02:07
16:00	00:03:30	00:03:42	00:03:30
17:00	00:02:06	00:02:41	00:02:48
18:00	00:02:56	00:03:07	00:03:44
19:00	00:02:15	00:02:51	00:03:37
20:00	00:00:59	00:01:19	00:01:43
21:00	00:01:05	00:01:20	00:01:26
22:00	00:00:53	00:01:15	00:00:58
23:00	00:00:08	00:00:06	00:00:03

Table 7-17: Mean reduction in airborne delay with the delay-on-ground concept – averaged over 60 runs (Figure 5-2)

Mean reduction in airborne delay with the delay-on-ground concept – averaged over 60 runs (HH:MM:SS)			
Time	Current traffic levels	15% traffic increase	30% traffic increase
06:00	00:00:19	00:00:20	00:00:31
07:00	00:01:07	00:01:27	00:01:35
08:00	00:01:36	00:01:38	00:02:08
09:00	00:00:30	00:00:34	00:00:40
10:00	00:01:05	00:01:26	00:01:21
11:00	00:00:16	00:00:18	00:00:23
12:00	00:00:21	00:00:23	00:00:33
13:00	00:00:30	00:01:02	00:01:38
14:00	00:00:09	00:00:13	00:00:19
15:00	00:00:27	00:00:29	00:00:42
16:00	00:01:19	00:01:23	00:01:23
17:00	00:00:34	00:00:41	00:00:47
18:00	00:00:51	00:01:01	00:01:26
19:00	00:00:37	00:00:53	00:01:09
20:00	00:00:24	00:00:31	00:00:44
21:00	00:00:20	00:00:22	00:00:27
22:00	00:00:24	00:00:40	00:00:27
23:00	00:00:08	00:00:06	00:00:03

Table 7-18: Total reduction in airborne delay with the delay-on-ground concept – averaged over 60 runs (Figure 5-3)

Total reduction in airborne delay with the delay-on-ground concept – averaged over 60 runs (HH:MM:SS)			
Time	Current traffic levels	15% traffic increase	30% traffic increase
06:00	00:01:30	00:01:14	00:02:29
07:00	00:23:23	00:30:36	00:32:49
08:00	00:25:42	00:25:49	00:33:30
09:00	00:07:09	00:07:54	00:09:08
10:00	00:14:14	00:19:37	00:18:35
11:00	00:01:20	00:01:28	00:01:54
12:00	00:01:30	00:01:33	00:02:10
13:00	00:01:54	00:03:44	00:06:07
14:00	00:00:13	00:00:24	00:00:38
15:00	00:02:50	00:03:03	00:04:15
16:00	00:12:06	00:13:01	00:12:53
17:00	00:06:29	00:07:33	00:08:34
18:00	00:09:41	00:11:16	00:16:24
19:00	00:08:00	00:11:18	00:14:47
20:00	00:01:23	00:01:54	00:02:40
21:00	00:01:45	00:01:52	00:02:20
22:00	00:01:06	00:01:44	00:01:13
23:00	00:00:08	00:00:06	00:00:03

Table 7-19: The accumulating daily number of pop-up flights classified according to amount of arrival sequencing delay – averaged over 60 runs (Figure 5-4)

The accumulating daily number of pop-up flights classified according to amount of arrival sequencing delay – averaged over 60 runs			
Delay in excess of (minutes)	Current traffic levels	15% traffic increase	30% traffic increase
0	78	84	92
1	47	54	62
2	21	27	33
3	9	13	17
4	4	6	9
5	2	2	4
6	1	1	2
7	0	0	1
8	0	0	0
9	0	0	0
10	0	0	0

Table 7-20: Daily reduction in airborne delay with the delay-on-ground concept per departure airport – averaged over 60 runs (Figure 5-5)

Daily reduction in airborne delay with the delay-on-ground concept per departure airport – averaged over 60 runs (HH:MM:SS)			
Departure airport (IATA code)	Current traffic	15% traffic increase	30% traffic increase
KSU	00:03:11	00:03:38	00:03:50
MOL	00:05:02	00:06:47	00:07:02
HAU	00:09:18	00:11:00	00:12:34
KRS	00:09:04	00:09:53	00:11:29
AES	00:05:57	00:06:38	00:09:16
ARN	00:15:06	00:17:40	00:22:22
CPH	00:15:30	00:18:12	00:21:41
SVG	00:17:01	00:19:37	00:23:28
BGO	00:19:01	00:21:49	00:27:48
TRD	00:21:13	00:26:31	00:29:49

Table 7-21: Mean departure sequencing delay – averaged over 60 runs, Stockholm, current traffic levels (Figure 5-6)

Mean departure sequencing delay – averaged over 60 runs, Stockholm, current traffic levels (HH:MM:SS)		
Time	Current operational procedures	Pop-up flights locked to exact departure times
06:00	00:00:10	00:00:12
07:00	00:00:40	00:01:17
08:00	00:07:21	00:08:33
09:00	00:02:06	00:05:07
10:00	00:00:42	00:00:44
11:00	00:00:33	00:00:33
12:00	00:00:21	00:00:31
13:00	00:00:12	00:00:19
14:00	00:00:32	00:00:32
15:00	00:00:43	00:00:55
16:00	00:00:42	00:00:51
17:00	00:01:37	00:02:00
18:00	00:01:29	00:02:28
19:00	00:00:31	00:00:46
20:00	00:00:20	00:00:25
21:00	00:01:32	00:01:32
22:00	00:00:07	00:00:07
23:00	00:00:26	00:00:26

Table 7-22: Mean departure sequencing delay – averaged over 60 runs, Stockholm, 15% traffic increase (Figure 5-7)

Mean departure sequencing delay – averaged over 60 runs, Stockholm, 15% traffic increase (HH:MM:SS)		
Time	Current operational procedures	Pop-up flights locked to exact departure times
06:00	00:00:12	00:00:19
07:00	00:00:46	00:01:28
08:00	00:09:35	00:10:56
09:00	00:06:23	00:11:21
10:00	00:00:48	00:00:50
11:00	00:00:38	00:00:38
12:00	00:00:26	00:00:44
13:00	00:00:15	00:00:19
14:00	00:00:35	00:00:35
15:00	00:00:50	00:01:06
16:00	00:00:54	00:01:07
17:00	00:02:17	00:02:52
18:00	00:01:50	00:02:50
19:00	00:00:44	00:01:04
20:00	00:00:23	00:00:30
21:00	00:01:27	00:01:27
22:00	00:00:13	00:00:13
23:00	00:00:26	00:00:26

Table 7-23: Mean departure sequencing delay – averaged over 60 runs, Stockholm, 30% traffic increase (Figure 5-8)

Mean departure sequencing delay - averaged over 60 runs, Stockholm, 30% traffic increase (HH:MM:SS)		
Time	Current operational procedures	Pop-up flights locked to exact departure times
06:00	00:00:21	00:00:22
07:00	00:01:12	00:02:08
08:00	00:11:58	00:13:17
09:00	00:12:10	00:17:17
10:00	00:00:39	00:00:52
11:00	00:00:39	00:00:39
12:00	00:00:32	00:00:52
13:00	00:00:15	00:00:23
14:00	00:00:30	00:00:30
15:00	00:01:04	00:01:15
16:00	00:01:40	00:01:56
17:00	00:03:10	00:04:03
18:00	00:02:57	00:04:50
19:00	00:01:03	00:01:33
20:00	00:00:25	00:00:35
21:00	00:01:33	00:01:33
22:00	00:00:12	00:00:12
23:00	00:00:27	00:00:27

Table 7-24: Mean increase in departure sequencing delay when pop-up flights were locked to exact departure times – averaged over 60 runs, Stockholm (Figure 5-9)

Mean increase in departure sequencing delay when pop-up flights were locked to exact departure times – averaged over 60 runs, Stockholm (HH:MM:SS)			
Time	Current traffic	15% traffic increase	30% traffic increase
06:00	00:00:02	00:00:06	00:00:01
07:00	00:00:38	00:00:42	00:00:55
08:00	00:01:14	00:01:20	00:01:18
09:00	00:03:04	00:04:58	00:05:06
10:00	00:00:02	00:00:02	00:00:12
11:00	00:00:00	00:00:00	00:00:00
12:00	00:00:10	00:00:17	00:00:20
13:00	00:00:06	00:00:03	00:00:08
14:00	00:00:00	00:00:00	00:00:00
15:00	00:00:11	00:00:15	00:00:11
16:00	00:00:08	00:00:13	00:00:16
17:00	00:00:23	00:00:35	00:00:53
18:00	00:01:00	00:01:00	00:01:53
19:00	00:00:15	00:00:19	00:00:29
20:00	00:00:05	00:00:06	00:00:11
21:00	00:00:00	00:00:00	00:00:00
22:00	00:00:00	00:00:00	00:00:00
23:00	00:00:00	00:00:00	00:00:00

Table 7-25: Total departure sequencing delay – averaged over 60 runs, Stockholm, current traffic levels (Figure 5-10)

Total departure sequencing delay – averaged over 60 runs, Stockholm, current traffic levels (HH:MM:SS)		
Time	Current operational procedures	Pop-up flights locked to exact departure times
06:00	00:01:06	00:01:18
07:00	00:11:24	00:21:43
08:00	04:33:29	05:17:53
09:00	00:40:47	01:38:15
10:00	00:12:00	00:12:31
11:00	00:08:51	00:08:51
12:00	00:04:04	00:05:50
13:00	00:01:54	00:02:54
14:00	00:09:06	00:09:08
15:00	00:13:55	00:17:30
16:00	00:13:49	00:16:43
17:00	00:45:43	00:56:33
18:00	00:31:18	00:52:04
19:00	00:08:31	00:12:20
20:00	00:04:31	00:05:38
21:00	00:29:16	00:29:16
22:00	00:00:41	00:00:41
23:00	00:02:04	00:02:04

Table 7-26: Total departure sequencing delay – averaged over 60 runs, Stockholm, 15% traffic increase (Figure 5-11)

Total departure sequencing delay – averaged over 60 runs, Stockholm, 15% traffic increase (HH:MM:SS)		
Time	Current operational procedures	Pop-up flights locked to exact departure times
06:00	00:02:03	00:03:07
07:00	00:17:18	00:32:44
08:00	06:52:39	07:49:26
09:00	02:18:42	04:08:10
10:00	00:14:15	00:14:52
11:00	00:12:03	00:12:03
12:00	00:06:04	00:10:02
13:00	00:02:28	00:03:03
14:00	00:09:18	00:09:22
15:00	00:19:00	00:24:40
16:00	00:21:36	00:26:41
17:00	01:15:14	01:34:27
18:00	00:42:01	01:05:04
19:00	00:13:58	00:19:58
20:00	00:05:55	00:07:25
21:00	00:31:14	00:31:14
22:00	00:01:45	00:01:45
23:00	00:02:20	00:02:20

Table 7-27: Total departure sequencing delay – averaged over 60 runs, Stockholm, 30% traffic increase (Figure 5-12)

Total departure sequencing delay – averaged over 60 runs, Stockholm, 30% traffic increase (HH:MM:SS)		
Time	Current operational procedures	Pop-up flights locked to exact departure times
06:00	00:05:18	00:05:26
07:00	00:34:55	01:01:15
08:00	09:28:30	10:30:05
09:00	05:17:20	07:30:43
10:00	00:11:15	00:14:46
11:00	00:12:12	00:12:12
12:00	00:08:47	00:14:24
13:00	00:02:34	00:03:46
14:00	00:07:54	00:07:57
15:00	00:25:53	00:30:26
16:00	00:49:45	00:57:36
17:00	01:59:45	02:33:22
18:00	01:16:13	02:05:06
19:00	00:23:31	00:34:12
20:00	00:06:02	00:08:40
21:00	00:36:05	00:36:05
22:00	00:02:08	00:02:08
23:00	00:02:38	00:02:38

Table 7-28: Total increase in departure sequencing delay when pop-up flights were locked to exact departure times – averaged over 60 runs, Stockholm (Figure 5-13)

Total increase in departure sequencing delay when pop-up flights were locked to exact departure times – averaged over 60 runs, Stockholm (HH:MM:SS)			
Time	Current traffic	15% traffic increase	30% traffic increase
06:00	00:00:13	00:01:04	00:00:08
07:00	00:10:36	00:15:27	00:26:20
08:00	00:45:49	00:56:47	01:01:35
09:00	00:58:17	01:49:27	02:13:23
10:00	00:00:33	00:00:38	00:03:31
11:00	00:00:00	00:00:00	00:00:00
12:00	00:01:49	00:03:59	00:05:37
13:00	00:01:00	00:00:35	00:01:11
14:00	00:00:02	00:00:04	00:00:03
15:00	00:03:39	00:05:40	00:04:33
16:00	00:02:53	00:05:05	00:07:51
17:00	00:10:52	00:19:13	00:33:37
18:00	00:20:58	00:23:03	00:48:53
19:00	00:03:57	00:06:00	00:10:41
20:00	00:01:12	00:01:30	00:02:37
21:00	00:00:00	00:00:00	00:00:00
22:00	00:00:00	00:00:00	00:00:00
23:00	00:00:00	00:00:00	00:00:00

Table 7-29: Highest increase in departure sequencing delay that an individual flight experienced when pop-up flights were locked to exact departure times – averaged over 60 runs, Stockholm (Figure 5-14)

Highest increase in departure sequencing delay that an individual flight experienced when pop-up flights were locked to exact departure times – averaged over 60 runs, Stockholm (HH:MM:SS)			
Time	Current traffic	15% traffic increase	30% traffic increase
06:00	00:00:23	00:00:56	00:00:43
07:00	00:03:31	00:03:38	00:04:26
08:00	00:06:31	00:06:23	00:05:44
09:00	00:07:40	00:09:57	00:09:17
10:00	00:00:25	00:00:30	00:01:50
11:00	00:00:00	00:00:00	00:00:00
12:00	00:01:00	00:01:47	00:02:00
13:00	00:00:44	00:00:32	00:01:01
14:00	00:00:02	00:00:04	00:00:02
15:00	00:01:57	00:02:35	00:01:54
16:00	00:01:06	00:01:28	00:01:30
17:00	00:02:17	00:02:44	00:02:52
18:00	00:05:17	00:04:56	00:06:49
19:00	00:01:44	00:02:12	00:03:10
20:00	00:00:43	00:00:47	00:01:18
21:00	00:00:00	00:00:00	00:00:00
22:00	00:00:00	00:00:00	00:00:00
23:00	00:00:00	00:00:00	00:00:00

Table 7-30: Number of flights with additional departure sequencing delay when pop-up flights were locked to exact departure times – averaged over 60 runs, Stockholm (Figure 5-15)

Number of flights with additional departure sequencing delay when pop-up flights were locked to exact departure times - averaged over 60 runs, Stockholm			
Time	Current traffic levels	15% traffic increase	30% traffic increase
06:00	0	1	1
07:00	6	9	14
08:00	17	23	25
09:00	14	20	25
10:00	0	1	1
11:00	0	0	0
12:00	2	3	4
13:00	1	1	1
14:00	0	0	0
15:00	3	5	4
16:00	3	5	9
17:00	10	16	23
18:00	11	13	19
19:00	4	5	7
20:00	1	2	3
21:00	0	0	0
22:00	0	0	0
23:00	0	0	0

Table 7-31: The accumulating daily number of flights classified according to amount of additional departure sequencing delay – averaged over 60 runs, Stockholm (Figure 5-16)

The accumulating daily number of flights classified according to amount of additional departure sequencing delay – averaged over 60 runs, Stockholm			
Additional delay in excess of (minutes)	Current traffic levels	15% traffic increase	30% traffic increase
0	72	104	136
1	49	69	100
2	31	46	65
3	21	31	43
4	14	22	30
5	10	15	21
6	6	11	13
7	4	7	9
8	2	5	6
9	1	3	4
10	1	2	2
11	0	1	1
12	0	1	1
13	0	1	1
14	0	0	0
15	0	0	0

Table 7-32: Mean departure sequencing delay – averaged over 60 runs, Copenhagen, current traffic levels (Figure 5-17)

Mean departure sequencing delay – averaged over 60 runs, Copenhagen, current traffic levels (HH:MM:SS)		
Time	Current operational procedures	Pop-up flights locked to exact departure times
06:00	00:00:12	00:00:20
07:00	00:00:38	00:01:02
08:00	00:06:36	00:08:11
09:00	00:01:43	00:04:05
10:00	00:00:44	00:00:49
11:00	00:00:50	00:00:52
12:00	00:00:49	00:01:02
13:00	00:00:45	00:00:45
14:00	00:01:13	00:01:30
15:00	00:01:05	00:01:20
16:00	00:00:53	00:01:23
17:00	00:01:57	00:02:40
18:00	00:01:36	00:02:16
19:00	00:00:30	00:00:30
20:00	00:01:55	00:02:15
21:00	00:01:59	00:02:00
22:00	00:00:50	00:01:08
23:00	00:00:26	00:00:45

Table 7-33: Mean departure sequencing delay – averaged over 60 runs, Copenhagen, 15% traffic increase (Figure 5-18)

Mean departure sequencing delay – averaged over 60 runs, Copenhagen, 15% traffic increase (HH:MM:SS)		
Time	Current operational procedures	Pop-up flights locked to exact departure times
06:00	00:00:25	00:00:32
07:00	00:01:00	00:01:37
08:00	00:07:06	00:08:43
09:00	00:03:03	00:06:46
10:00	00:00:47	00:01:01
11:00	00:00:52	00:00:55
12:00	00:00:59	00:01:20
13:00	00:00:36	00:00:36
14:00	00:01:17	00:01:39
15:00	00:01:12	00:01:33
16:00	00:01:16	00:02:10
17:00	00:02:54	00:03:48
18:00	00:01:44	00:02:33
19:00	00:00:36	00:00:36
20:00	00:02:00	00:02:29
21:00	00:02:19	00:02:21
22:00	00:00:56	00:01:09
23:00	00:00:29	00:00:51

Table 7-34: Mean departure sequencing delay – averaged over 60 runs, Copenhagen, 30% traffic increase (Figure 5-19)

Mean departure sequencing delay – averaged over 60 runs, Copenhagen, 30% traffic increase (HH:MM:SS)		
Time	Current operational procedures	Pop-up flights locked to exact departure times
06:00	00:00:44	00:00:58
07:00	00:01:36	00:02:27
08:00	00:07:24	00:09:02
09:00	00:03:56	00:09:03
10:00	00:00:51	00:02:01
11:00	00:01:01	00:01:03
12:00	00:01:14	00:01:34
13:00	00:00:43	00:00:43
14:00	00:01:15	00:01:37
15:00	00:01:28	00:01:52
16:00	00:01:56	00:03:14
17:00	00:05:22	00:07:32
18:00	00:02:20	00:05:33
19:00	00:00:49	00:00:49
20:00	00:02:03	00:02:31
21:00	00:02:03	00:02:05
22:00	00:01:07	00:01:22
23:00	00:00:23	00:00:42

Table 7-35: Mean increase in departure sequencing delay when pop-up flights were locked to exact departure times – averaged over 60 runs, Copenhagen (Figure 5-20)

Mean increase in departure sequencing delay when pop-up flights were locked to exact departure times – averaged over 60 runs, Copenhagen (HH:MM:SS)			
Time	Current traffic	15% traffic increase	30% traffic increase
06:00	00:00:07	00:00:07	00:00:13
07:00	00:00:24	00:00:37	00:00:51
08:00	00:01:35	00:01:36	00:01:37
09:00	00:02:22	00:03:43	00:05:06
10:00	00:00:05	00:00:13	00:01:09
11:00	00:00:02	00:00:02	00:00:03
12:00	00:00:12	00:00:20	00:00:19
13:00	00:00:00	00:00:00	00:00:00
14:00	00:00:17	00:00:21	00:00:21
15:00	00:00:15	00:00:20	00:00:23
16:00	00:00:29	00:00:54	00:01:17
17:00	00:00:43	00:00:53	00:02:10
18:00	00:00:39	00:00:49	00:03:12
19:00	00:00:00	00:00:00	00:00:00
20:00	00:00:20	00:00:29	00:00:28
21:00	00:00:01	00:00:01	00:00:02
22:00	00:00:17	00:00:13	00:00:14
23:00	00:00:20	00:00:21	00:00:19

Table 7-36: Total departure sequencing delay – averaged over 60 runs, Copenhagen, current traffic levels (Figure 5-21)

Total departure sequencing delay – averaged over 60 runs, Copenhagen, current traffic levels (HH:MM:SS)		
Time	Current operational procedures	Pop-up flights locked to exact departure times
06:00	00:01:49	00:02:50
07:00	00:10:34	00:17:07
08:00	04:19:25	05:21:17
09:00	00:46:36	01:50:06
10:00	00:15:57	00:17:43
11:00	00:15:00	00:15:32
12:00	00:18:09	00:22:45
13:00	00:12:50	00:12:50
14:00	00:30:15	00:37:33
15:00	00:25:17	00:31:26
16:00	00:17:57	00:27:44
17:00	00:57:55	01:19:19
18:00	00:27:03	00:38:32
19:00	00:08:20	00:08:20
20:00	00:53:01	01:02:08
21:00	00:30:32	00:30:46
22:00	00:11:36	00:15:32
23:00	00:01:04	00:02:01

Table 7-37: Total departure sequencing delay – averaged over 60 runs, Copenhagen, 15% traffic increase (Figure 5-22)

Total departure sequencing delay – averaged over 60 runs, Copenhagen, 15% traffic increase (HH:MM:SS)		
Time	Current operational procedures	Pop-up flights locked to exact departure times
06:00	00:06:28	00:08:25
07:00	00:25:26	00:41:23
08:00	04:42:29	05:51:49
09:00	01:36:12	03:37:33
10:00	00:17:11	00:22:16
11:00	00:16:52	00:17:50
12:00	00:24:06	00:32:49
13:00	00:09:45	00:09:53
14:00	00:31:31	00:40:55
15:00	00:32:21	00:41:50
16:00	00:32:20	00:56:05
17:00	01:39:13	02:14:58
18:00	00:34:21	00:51:21
19:00	00:12:03	00:12:09
20:00	00:55:32	01:09:57
21:00	00:45:56	00:46:45
22:00	00:14:51	00:18:38
23:00	00:01:26	00:02:37

Table 7-38: Total departure sequencing delay – averaged over 60 runs, Copenhagen, 30% traffic increase (Figure 5-23)

Total departure sequencing delay – averaged over 60 runs, Copenhagen, 30% traffic increase (HH:MM:SS)		
Time	Current operational procedures	Pop-up flights locked to exact departure times
06:00	00:19:02	00:24:54
07:00	00:53:13	01:21:27
08:00	05:03:08	06:09:29
09:00	02:21:35	05:25:11
10:00	00:18:24	00:42:59
11:00	00:24:25	00:25:32
12:00	00:33:50	00:42:27
13:00	00:11:11	00:11:11
14:00	00:32:00	00:41:06
15:00	00:42:31	00:53:56
16:00	01:02:20	01:44:09
17:00	03:38:41	05:05:46
18:00	00:51:49	02:02:13
19:00	00:19:46	00:19:46
20:00	00:59:17	01:13:00
21:00	00:44:10	00:45:03
22:00	00:22:38	00:27:34
23:00	00:02:12	00:04:02

Table 7-39: Total increase in departure sequencing delay when pop-up flights were locked to exact departure times – averaged over 60 runs, Copenhagen (Figure 5-24)

Total increase in departure sequencing delay when pop-up flights were locked to exact departure times – averaged over 60 runs, Copenhagen (HH:MM:SS)			
Time	Current traffic	15% traffic increase	30% traffic increase
06:00	00:01:00	00:01:47	00:05:52
07:00	00:06:33	00:15:34	00:28:14
08:00	01:01:52	01:04:37	01:06:20
09:00	01:03:30	01:59:02	03:03:36
10:00	00:01:46	00:04:40	00:24:35
11:00	00:00:32	00:00:47	00:01:06
12:00	00:04:36	00:08:33	00:08:37
13:00	00:00:00	00:00:00	00:00:00
14:00	00:07:17	00:08:58	00:09:06
15:00	00:06:10	00:09:14	00:11:25
16:00	00:09:47	00:23:21	00:41:49
17:00	00:21:24	00:31:37	01:27:05
18:00	00:11:29	00:16:38	01:10:25
19:00	00:00:00	00:00:00	00:00:00
20:00	00:09:07	00:13:33	00:13:43
21:00	00:00:14	00:00:33	00:00:53
22:00	00:03:56	00:03:34	00:04:56
23:00	00:00:58	00:01:08	00:01:50

Table 7-40: Highest increase in departure sequencing delay that an individual flight experienced when pop-up flights were locked to exact departure times – averaged over 60 runs, Copenhagen (Figure 5-25)

Highest increase in departure sequencing delay that an individual flight experienced when pop-up flights were locked to exact departure times – averaged over 60 runs, Copenhagen (HH:MM:SS)			
Time	Current traffic	15% traffic increase	30% traffic increase
06:00	00:00:45	00:01:20	00:02:00
07:00	00:02:43	00:03:25	00:03:58
08:00	00:06:04	00:05:58	00:06:02
09:00	00:06:24	00:07:34	00:09:08
10:00	00:00:45	00:01:30	00:04:29
11:00	00:00:33	00:00:44	00:00:44
12:00	00:01:49	00:02:06	00:02:04
13:00	00:00:00	00:00:00	00:00:00
14:00	00:02:22	00:02:33	00:02:42
15:00	00:01:57	00:02:36	00:02:50
16:00	00:02:59	00:04:03	00:04:05
17:00	00:03:19	00:03:38	00:05:52
18:00	00:02:38	00:03:06	00:06:14
19:00	00:00:00	00:00:00	00:00:00
20:00	00:02:15	00:02:37	00:02:38
21:00	00:00:11	00:00:32	00:00:42
22:00	00:02:03	00:01:55	00:02:00
23:00	00:00:49	00:00:49	00:01:09

Table 7-41: Number of flights with additional departure sequencing delay when pop-up flights were locked to exact departure times – averaged over 60 runs, Copenhagen (Figure 5-26)

Number of flights with additional departure sequencing delay when pop-up flights were locked to exact departure times - averaged over 60 runs, Copenhagen			
Time	Current traffic levels	15% traffic increase	30% traffic increase
06:00	1	2	5
07:00	5	9	16
08:00	20	22	22
09:00	18	27	34
10:00	2	3	8
11:00	0	0	1
12:00	4	6	7
13:00	0	0	0
14:00	5	6	6
15:00	5	8	9
16:00	6	12	21
17:00	13	18	30
18:00	7	9	18
19:00	0	0	0
20:00	9	11	11
21:00	1	1	1
22:00	3	3	3
23:00	1	1	1

Table 7-42: The accumulating daily number of flights classified according to amount of additional departure sequencing delay – averaged over 60 runs, Copenhagen (Figure 5-27)

The accumulating daily number of flights classified according to amount of additional departure sequencing delay - averaged over 60 runs, Copenhagen			
Additional delay in excess of (minutes)	Current traffic levels	15% traffic increase	30% traffic increase
0	100	138	193
1	67	97	145
2	45	65	107
3	26	40	75
4	16	26	53
5	9	18	37
6	5	11	25
7	2	6	15
8	1	3	9
9	1	2	6
10	0	1	3
11	0	1	1
12	0	0	1
13	0	0	0
14	0	0	0
15	0	0	0