Dynamic Airline Centric Inbound Priority Sequencing

A case study on Westerly morning arrivals for KLM at Schiphol

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TU Delft

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by

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Time has literally flown by...

H.J. Hoogendoorn
Las Meloneras, October 2022

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List of Abbreviations

A-CDM	Airport Collaborative Decision Making
ABM	Agent Based Modeling
ACARS	Aircraft Communications Addressing and Reporting System
ACC	Area Control Center
ACNL	Airport Coordination Netherlands
AFP	Airspace Flow Program
ALP	Aircraft Landing Problem
AMAN	Arrival Manager
ANSP	Air Navigation Service Provider
AS&S	Arrival Sequencing and Scheduling
ASM	Airspace Management
ASP	Aircraft Sequencing & Scheduling Problem
ATC	Air Trafic Control
ATFCM	Air Traffic Flow and Capacity Management
ATFM	Air Trafic Flow Management
ATM	Air Traffic Management
ATO	Actual Time Over
ATP	Aircraft take-Off Problem
ATS	Air Traffic Services
BZO	Limited Visibility Conditions (*Dutch: Beperkt Zicht Omstandigheden*)
CCTOT	Company Calculated Take-Off Time
CDA	Continuous Descent Arrival
CDM	Collaborative Decision Making
CFMU	Central Flow Management Unit
CTA	Control Area
CTOT	Calculated Take-Off Time
CTR	Control Zone
DP	Dynamic Programming
DSSE	Dynamic Sequence Searching and Evaluation
E-AMAN	Extend Arrival Manager

EDA	Estimation of Distribution Algorithm
EHAM	Schiphol Airport (*ICAO code: Europe Holland AMsterdam*)
EIBT	Estimated In Block Time
ELDT	Estimated Landing Time
EOBT	Estimated Off Block Time
ETO	Estimated Time Over
FAF	Final Approach Fix
FCFS	First Come First Served
FIR	Flight Information Region
FL	Flight Level
GDP	Ground Delay Program
HSF	High Speed Flying
IAF	Initial Approach Fix
ICA	Intercontinental Flight
ICAO	International Civil Aviation Organisation
IFR	Instrument Flight Rules
IPS	Inbound Priority Sequencing
KDC	Knowledge and Development Centre Schiphol
KLM	Royal Dutch Airlines (*Dutch: Koninklijke Luchtvaart Maatschappij*)
LFV	Loss of Future Value
LSF	Low Speed Flying
LVNL	Air Traffic Control the Netherlands (*Dutch: Luchtverkeersleiding Nederland*)
MC	Missec Connection
MCT	Minimum Connecting Time
McTMA	Multi-Center Traffic Management Advisor
MIP	Mixed Integer Programming
MUAC	Maastricht Upper Control Center
OCC	Operation Control Center
OD	Origin - Destination
OTP	On Time Performance
PMS	Point Merge System
QRC	Quick Reference Card
RCH	Receding Horizon Control
RNLAF	Royal Netherlands Air Force (*Dutch: Koninklijke Nederlandse Luchtmacht*)

RSP	Runway Scheduling Problem
RVSM	Reduced Vertical Separation Minima
SID	Standard Instrument Departure
STA	Scheduled Time of Arrival
STAR	Standard Arrival Route
TAS	True Airspeed
TBO	Trajectory Based Operations
TFM	Traffic Flow Management
TMA	Terminal Menoeuvring Area
TOBT	Targt Off Block Time
TTO	Target Time Over
TTOT	Target Take-Off Time
UDP	Uniform Daylight Period
UTA	Upper Airspace
VNS	Variable Neighborhood Search
WTC	Wake Turbulence Category

Introduction

Despite the recent tough COVID-19 years for aviation, it is expected air travel will grow again as it used to do over the past decades. Many major international route areas are for example already exceeding their pre-COVID levels [1]. This also means the airspace congestion problems that were experienced before COVID, are back on the table. These airspace congestions cause flight delays which are inconvenient for passengers and cost the airlines money. Especially network airlines are vulnerable to these delays as their business model consists out of offering passengers connecting flights via their hub airport. And in case of congested airspaces surrounding this hub airport, missed passenger connections are more likely to occur.

At the moment of writing several solutions exists to sequence arrival flights in such a way congestions and delays are minimized. However, most of these solutions tend to have the perspective of Air Traffic Control who has little insight in the preferences and priorities of airlines. Luckily, some research has already stepped in that gap by including airline preferences in the arriving sequence, by means of developing en-route Inbound Priority Sequencing (IPS) models. The problem with these models is they are static and deterministic, meaning all information is known beforehand and sequence calculations are performed for the entire arrival sequence at once.
This thesis therefore adds to the existing IPS research, by developing a dynamic IPS model that adapts the arrival sequence each time new information is available, whilst ensuring a stable sequence. Furthermore the model has an extra degree of freedom for so-called popup flights. These flights have a departure aerodrome that lies within the action horizon of the IPS model. Within the proposed modified model they can receive a Company Calculated Take-Off Time (CCTOT) that can delay their take-off in favor of the arrival sequence.

The research has been performed in collaboration with KLM Royal Dutch Airlines. This enabled the opportunity to perform a case study on Westerly morning arrivals to test the IPS model. A unique aspect is that the model has been validated using shadow runs of the model under real-time operation. For this validation the model has been connected to operational live flight data. Besides the ability to use KLM data, the company provided valuable input to the thesis as they have extensive operational knowledge. That, in combination with the academic input from Delft University of Technology, laid the foundation for this thesis.

Research Objective

The main research objective of this thesis is formulated as:

> "To create an optimal arrival traffic sequence at the initial approach fixes from an airline perspective, by developing and testing a dynamic decision support tool for the use of a network airline that specifically includes popup flights."

To achieve this research objective, the following main research question can be answered:

> "How can an arrival sequence be altered in the tactical phase in favor of a network airline in order to minimize additional delay cost?"

Report Structure

This thesis report consists out of three main parts. In Part I the self-contained scientific paper of the performed research is shown. Then Part II shows the literature study that laid the foundation of the for the thesis. An extensive analysis of existing research is conducted within this literature study, in combination with background information on the general subject of sequencing arrival traffic. Finally, Part III contains supporting work for the research. A Monte Carlo simulation of the IPS model is discussed within this part, together with an in-house fuel model that needed to be developed and an in-depth description of the real-time shadow running of the IPS model.

[1] https://www.iata.org/en/pressroom/2022-releases/2022-07-07-02/

I

Scientific Paper

Extended Arrival Manager: Dynamic Inbound Priority Sequencing at Initial Approach Fix

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Abstract

During arrival waves at hub airports the surrounding airspaces can be congested, resulting in flight delays. To solve this congestion problem one of the current solutions is to sequence flights whilst they are still en-route by using an Extended Arrival Manager (E-AMAN). This paper aims at improving this E-AMAN concept by tackling two of its limitations. The first one is that priorities are not considered when sequencing the flights, as sequences are currently defined according to the First-Come-First-Served (FCFS) principle. The second limitation is that it is difficult to sequence so-called popup flights when creating the arrival sequence. These popup flights are defined as flights that have a departure airport that lies within the en-route horizon of the E-AMAN. The first limitation is tackled by proposing a dynamic Inbound Priority Sequencing (IPS) model for the use of a network carrier at their hub airport. The model sequences air traffic en-route in favor of the network carrier, by trading off the (potential delay) costs of individual flights. Each flight then receives a Target Time Over their Initial Approach Fix (TTO IAF). At the same time competitive traffic is not negatively influenced. The other limitation of E-AMAN is tackled by giving popup flights from small regional airports a so-called Company Calculated Take-Off Time (CCTOT) next to a TTO IAF, which is used to delay those flights whilst still on the ground. By the time flights enter the arrival Air Traffic Control (ATC) centers, the FCFS is applied up until landing, meaning ATC does not have to change their working principles. The objective of the IPS model is to minimize the overall arrival cost for the network carrier, consisting of optimizing for fuel cost, passenger missed connection cost, and Loss of Future Value cost. The model is formulated as a mixed-integer quasi-linear program. A novelty of the model, in addition to specifically including popup flights, is the fact that the sequence is recalculated each time new information is available. This information can be a new flight entering the action horizon of the model or a new Estimated Off Block Time for a departing flight at the hub to which passengers of an arriving flight have to connect to. At the same time the stability of the sequence is kept in mind by including a cost penalty for adjusting the TTO IAF. Results of a case study performed at Amsterdam Airport Schiphol for a Dutch network carrier show cost savings of 12% compared to the traditional FCFS without en-route sequencing in a simulation environment. During validation of the model, by means of performing shadow runs using real-time flight data, it turned out the model can indeed be of help to reduce costs for a network carrier.

1 Introduction

The nature of a hub-and-spoke carrier or network carrier requires inbound and outbound peaks. During these peaks the demand exceeds the capacity of the hub and the surrounding airspaces, causing traffic congestions and therefore delays. These congestions are called traffic bunches and result in speed restrictions and flying holdings until there is capacity available for flights to start their approach towards the hub airport. Especially for network carriers this delay is harming their business case as it relies on connecting passengers that need to transfer to another flight at the hub. In case of missed connections, there is not only the cost of rebooking passengers or booking a hotel, but also passenger inconvenience cost and the fact that a passenger is less likely to book a ticket with the airline in the future.

In current practice there are measures in place to smoothen the demand (during peaks) in order to reduce the aforementioned type of delays. In Europe for example, flights can become regulated, meaning they will receive a Calculated Take-Off Time (CTOT) to which they have to adhere to. In the United States there is the Ground Delay Program (GDP) and Airspace Flow Program (AFP) that have the objective to absorb delays on the ground and in the air respectively. Then there are the short term measures where Air Traffic Control (ATC) gives speed restrictions or instruct flights into a holding. A current trend is to extend the 'horizon' of ATC in order to give speed restrictions to flights during their en-route phase (E-AMAN: Extended Arrival MANager). This paper follows this trend and tries to improve this E-AMAN, by tackling two of its current limitations.

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The first limitation of (E-)AMAN is that so-called popup flights are difficult to be sequenced within the arrival sequence. These popup flights are flights that have a departure airport that lies within the horizon of an arrival manager (AMAN). In Figure 1 this problem is visualized. Within the horizon of the AMAN, flights have received a spot in the arrival sequence. However, it is difficult to provide popup flights a spot due to the involved uncertainties regarding the departure times of these flights. When the horizon of the AMAN is extended, this problem only becomes bigger as more flights will become popup flights.

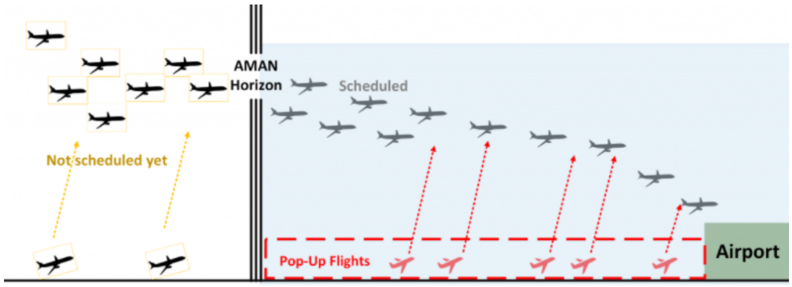

Figure 1: The problem of popup flights visualized (taken from [Vanwelsenaere et al., 2018])

The second limitation of (E-)AMAN lies in the fact that it is performed from an ATC perspective, using the First-Come-First-Served principle (FCFS). It entails the sequence is being determined by the order in which arriving flights enter the horizon of control of the respective ATC unit. The reason for this is the equity principle that states no airline can be privileged over another airline. As this principle does not hold within an airline, flights could swap positions in the arrival sequence. This brings up the idea of sequencing the arrival flights from an airline perspective. Flights with a lot of connecting passengers on board are, for example, more important for an airline compared to flights with almost no connecting passengers. Another example is if the crew or aircraft itself need to be used for a next flight with a short turn around time. This mentioned information about flights can then be used to determine the most favorable sequence for an airline.

Conceptual methods in the context of E-AMAN that take airline priorities into account already exist, but these methods are static and do not specifically take popup flights into account. With 'static' meaning that the sequence is only calculated once and new information (when available) is not taken into account. Therefore this paper aims at closing that research gap, by developing a dynamic model that performs Inbound Priority Sequencing (IPS) from an airline perspective that specifically includes popup flights.

First, the state-of-the-art literature is mentioned in Section 2. This is then followed by an explanation of the methodology and the model itself in Section 3. To test this model, a case study has been performed, which can be found in Section 4. The results of the model, together with a sensitivity analysis and validation, are then shown in Section 5. Then a discussion takes place in Section 6. Finally, conclusions and recommendations about the (performance of) the model are made in Section 7.

2 Literature Review

The topic of this paper belongs to the the aircraft sequencing and scheduling problem (ASP). In the context of the described problem in the introduction (section 1), ASP sequences a given incoming flow of aircraft in an effective and efficient manner. Three papers form the backbone in describing existing research on the ASP. The first paper is written by [Bennell et al., 2011] and gives an overview of different approaches to the problem until the year 2010. From 2010 onward [Ikli et al., 2021] are consulted and describe the research field of the more recent years. The third paper is a thesis performed at Delft university of technology in 2020 by [Vervaat, 2020] who investigated the possibility of giving flights en-route speed restrictions, in order to solve for arrival congestions.

In most literature the ASP is formulated as a Mixed Integer Program (MIP). Since the problem is NP-hard, often metaheuristics are being used to solve the problem ([Bennell et al., 2011]). In most recent research mathematical programming is sometimes used and combined with metaheuristics, resulting in matheuristics ([Ikli et al., 2021]).

In literature, different objectives have been investigated, of which the most important objectives will be addressed briefly. The first objctive being to incorporate different stakeholders such as airlines, airports, air traffic control, and even the government. To achieve this, bi- or multi-objectives are used. Another important objective is the exact topic of this research proposal, namely adherence to airline priorities within their own flights. One should think of passenger cost (both hard and soft cost [Cook and Tanner, 2015]), fuel cost, but also crew and aircraft itineraries. The last important objective found in literature is maximizing fairness amongst airlines: The equity principle states that no airline may be privileged over another airline.

Moving towards the methods on how to solve the ASP, a distinction can be made between exact, stochastic, and other methods. Starting with the exact methods, MIP is used most frequently as already stated before. The most cited research is of [Beasley et al., 2000] as it contains a baseline formulation that has been used by other researchers afterwards. Dynamic programming is also sometimes used, where the foundation has been developed by [Psaraftis, 1978]. In current research dynamic programming is often combined with multi-objective functions ([Bennell et al., 2017]). Looking at the stochastic methods used in the context of the ASP, some research is inspired by nature, such as ant colony optimization or genetic algorithms (sometimes even combined) [Bencheikh et al., 2009, Vervaat, 2020]. Then there are the more common approaches like tabu search, simulated annealing or variable neighborhood search [Furini et al., 2015, Ouyang and Xu, 2019, Rodríguez-Díaz et al., 2017]. Regarding other methods, agent based modeling (ABM), machine learning and dynamic scheduling are being used. ABM can be used allowing different parties or stakeholders to negotiate with each other ([Molina et al., 2014]). Machine learning is one of the latest developments in the ASP, which is sometimes complemented with reinforcement learning ([Ikli et al., 2020, Ikli et al., 2021]). Last but not least there is the dynamic scheduling in which not all information is known beforehand. One of the first addressing the ASP dynamically was [Ji et al., 2017]. Also [Santos et al., 2017] have implemented a dynamic model by including a receding horizon in the context of airline delay management.

In the remainder of this literature review, the research that forms the foundation of this paper will be discussed. This is done by firstly addressing the research of [Vanwelsenaere et al., 2018] on popup flights. Then the research of [Vervaat, 2020] and [Lernbeiss, 2016] about scheduling based on airline priorities will be touched upon. Lastly, the research of [Khassiba et al., 2020] will be discussed, in which chance constraints have been added into a deterministic model.

Vanwelsenare is one of the few that conducted research regarding popup flights ([Vanwelsenaere et al., 2018]). He investigated the effect of these flights in the context of E-AMAN. Using the ATM simulator BlueSky ([Hoekstra and Ellerbroek, 2016]), Vanwelsenare found that popup flights have a significant effect on delay costs and the stability of the arrival sequence. Also the workload of air traffic controllers and flight crews is increased when more popup flights occur. The main takeaway of his research is when to schedule a popup flight in the arrival sequence. The answer depends on the take-off adherence. If a popup flight can have an Actual Take-Off Time (ATOT) which deviates less than two minutes from a Target Take-Off Time (TTOT) it is beneficial to schedule the flight whilst still being on the ground. In all other cases the flight should only be scheduled once airborne. Otherwise the arriving sequence will deteriorate.

Lernbeiss and Vervaat (conceptual paper and thesis respectively) did research on the ASP from an airline perspective. The cost function of Lernbeiss consists out of three items, being the ticket prices (negative yield), the second one being passenger cost containing missed connection costs and the cost involved of rebooking a passenger, and the last being the cost function containing flight related costs that depend on cruise speed and arrival time. Unfortunately the algorithms behind the cost function and the optimization method itself are not discussed. It is however said that the aim is to minimize the cost and maximize profit, and that multiple iterations are done in order to linearize the cost function. Still, there are cases where the final solution is a local optimum from which no escape is possible in the used model.
Vervaat goes a bit more in depth. His cost function consists out of fuel costs and passenger costs, for which the cost function is minimized. Linearization is achieved by applying a first order Taylor approximation.
Both the output of Vervaat and Lernbeiss result in speed restrictions for incoming aircraft.

The models of Vervaat and Lernbeiss are both static and deterministic, meaning all the information is known beforehand and the simulation only runs once. To make it stochastic or probabilistic instead of deterministic, the research of [Khassiba et al., 2020] comes into play. She includes chance constraints into a deterministic two-stage stochastic model that minimizes the arrival sequence length. In her paper she proves that chance constraints can replace deterministic constraints if two conditions are being satisfied: (1) there can only be one probability distribution function involved which has to be normally distributed. (2) The probability that the constraint is not violated, should be larger than 50%.

Summarizing current literature, one can say the airline perspective is not a common point of interest, as mostly the air traffic controller's perspective is chosen. Also, most models come in the form of a static, deterministic linearized integer program.

3 Methodology

This section describes the methodology of the research. It starts with a description of the concept of operations in section 3.1. Then the Inbound Priority Sequencing model itself is touched upon in section 3.2. Finally, the assumptions and limitations of the model are provided in section 3.3.

3.1 Modelling Approach: Inbound Priority Sequencing

As already mentioned in the introduction, this paper tries to tackle two limitations of E-AMAN: (1) Airline preferences are not taken into account (in a dynamic manner), and (2) popup flights are difficult to schedule in the arrival sequence. The proposed model that tries to solve these limitations continues on the work of [Vervaat, 2020] in which a static Inbound Priority Sequencing (IPS) model was proposed in the form of a Mixed Integer Linear Program (MILP). In the newly proposed model sequence calculations are made dynamic with a rolling horizon, and specifically now include popup flights. The newly proposed model will be referred to as the IPS model. If the model of Vervaat is meant, this will be specifically mentioned. Both the model of Vervaat and the newly proposed IPS model optimize the sequence from an airline perspective, by making a trade-off beween the (potential delay) costs of individual flights.

In Figure 2 the concept of operations for the IPS model is shown. Around an airport of interest two circles will be drawn, which can be seen in Figure 2. The outer circle is called the action horizon with radius r_2 in *nm*. When arriving flights enter this circle, they will be assigned a spot in the arrival sequence. The inner circle is called the freeze horizon with radius r_1 in *nm*. When arriving flights enter this circle, the sequence is fixed. So far the concept of the IPS model is the same as for the concept of Vervaat. Within the newly proposed IPS model however, a specific distinction is made between arriving flights and popup flights. The former are flights that have a departure airport outside the Action Horizon. Popup flights, on the other hand, have their departure airport within the Action Horizon. Furthermore it was decided to optimize the arrival sequence before flights fly over their Initial Approach Fix (IAF). The IAF is chosen as it is a merge point that connects different Standard Arrival Routes (STARs) with each other. Each flight from the network carrier will then receive a Target Time Over their IAF (TTO IAF).

In line with Vervaat, flights are sequenced in a most optimal way for a single network carrier that has a major stake in the traffic volume at the (hub) airport of interest. These flights will be referred to as controllable flights. Other arriving traffic is not touched, which is in line with the equity principle that states no airline can be privileged over another airline. These flights will be referred to as uncontrollable flights.

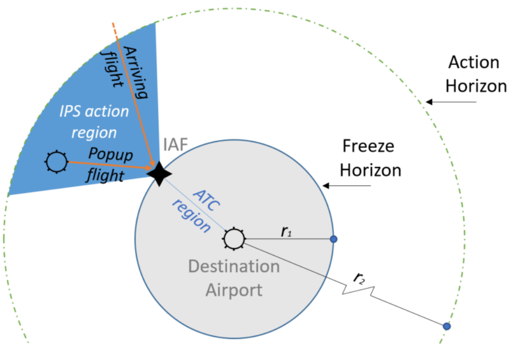

Figure 2: IPS horizon overview, adapted from [Vervaat, 2020]

Dynamic Inbound Priority Sequencing

When new information becomes available, a recalculation of the arrival sequence is triggered. This new information could be a new flight entering the Action Horizon (either a popup flight or an arriving flight), or an update regarding a departure time of an outgoing flight. The latter has to do with the connection time of passengers. If passengers have a short connection time, their incoming flight will have a high associated cost, resulting in a high chance of getting priority in the arrival sequence. If there happens to be an update that their connecting flight is delayed, their connection time is less critical and their incoming flight can reduce its speed to save fuel. To speed up the calculation of the optimal sequence, the output of each calculation is used as an initial guess for the next sequence calculation. For practical purposes the program aims to limit the amount of sequence deviations by including a cost threshold that needs to be reached before the actual sequence will be changed. For the same reason a cost penalty for changing the current TTO IAF is included. This cost penalty also ensures a stable sequence, as it is undesirable for a pilot to constantly have to change their TTO IAF.

Popup flight Inbound Priority Sequencing
Popup flights can include flights from the network carrier, or from competitive airlines. Popup flights from the network carrier will be referred to as scheduled popup flights. Depending on the departure airport of these scheduled popup flights, they can receive a Company Calculated Take-Off Time (CCTOT). This is based on the findings of [Vanwelsenaere et al., 2018]. Vanwelsenaere found that scheduling take-off times of popup flights can be beneficial for the arrival sequence if they can adhere to their CCTOT with a maximum deviation of two minutes. Additionally, a cost penalty is included within the model to penalize longer ground time at the departure airport. Within the IPS model there are therefore three types of popup flights. The first is an uncontrollable popup flight, which is a flight that will not be touched. The second and third type are both controllable, but depending on the departure airport one only receives a TTO IAF, whereas the other receivs an additional CCTOT.

3.2 Mixed Integer Linear Programming model formulation

This section describes the notation of the IPS model in Subsection 3.2.1. Then the model objective is shown and explained in Subsection 3.2.2. Finally the constraints will be touched upon in Subsection 3.2.3.

3.2.1 Notation

The notation of the model is divided into four parts. The first being the different sets, the second being the input parameters, the third one being the passenger and flight parameters, and the last one being the decision variables.

Sets
Within the model there are different sets regarding flights (F) and passengers (PAX). Within F, i denotes the i^{th} flight ($i \in F$), with $1 \leq i \leq n$, where n is the total number of flights. Regarding the passengers onboard of flight i, $PAX_i; k \in PAX_i$ represents the k^{th} passenger. The model contains the following subsets:

F^A:	Set of all arriving flights	$F^A \in F$
F^C:	Set of controllable flights	$F^C \in F^A$
F^{NC}:	Set of non-controllable flights	$F^{NC} = F^A \backslash F^C$
F^P:	Set of popup flights	$F^P \in F^A$
F^{ICA}:	Set of intercontinental flights	$F^{ICA} \in F^A$
F^{SP}:	Set of scheduled popup flights	$F^{SP} \in F^P$
F^D:	Set of departing flights	$F^D \in F$
PAX^C:	Set of connecting passengers	$PAX^C \in PAX$
PAX^{NC}:	Set of non-connecting passengers	$PAX^{NC} = PAX \backslash PAX^C$

Input Parameters
The following input parameters are included within the IPS model:

IAF^{ALT}:	[*ft*]	Altitude of the IAF and altitude of holding
IAF^{SPD}:	[*kcas*]	Speed restriction at the IAF and in the holding
IAF^{SEP}:	[*sec*]	Minimum separation at the IAF
MCT:	[*sec*]	Minimum Connecting Time
PMC:	[*eur/pax*]	Price of a missed connection
PF:	[*eur/kg*]	Price of fuel
$EIBT^{offset}$:	[*sec*]	Average time it takes from the IAF to In-Blocks
RAD:	[*nm*]	Action horizon of the IPS-model
M:	[-]	Big M-constant
$FCFS$:	[-]	Set IPS-model to First-Come-First-Serve
$CCTOT^{airports}$:	[-]	List of applicable CCTOT airports
t_i^{taxi}	[*sec*]	Average taxi-time from gate to runway
P^{TOD}:	[eur/min]	Take-Off Delay penalty for popup flights
P^{TTO}:	[eur/min]	Given a TTO IAF, the penalty to change this TTO
C^{thr}:	[eur]	Global threshold that needs to be reached before the sequece is allowed to change

Flight and Passenger Parameters

The following variables deal with the flights and passengers on those flights within the optimization:

N:	Number of flights in set F	N $\in$ F
ETO_i^{IAF}:	Estimated Time Over IAF of flight i	$\forall\ i \in F^A$
dt_i:	Take-off delay of flight i	$\forall\ i \in F^P \cap F^C$
E_i:	Earliest possible time over IAF for flight i	$\forall\ i \in F^C$
L_i:	Latest possible time over IAF for flight i	$\forall\ i \in F^C$
$SIBT_i$:	Scheduled In Block Time of flight i	$\forall\ i \in F^C$
$AIBT_i$:	Actual In-Block Time of flight i	$\forall\ i \in F^C$
H_i:	Amount of holdings for flight i	$\forall\ i \in F^A$
D_i^{total}:	Total delay for flight i	$\forall\ i \in F^C$
$C_{i_{0,1,2}}$:	Fuel coefficients of flight i	$\forall\ i \in F^C$
$FF_i^{holding}$:	Fuel flow of flight i during holding	$\forall\ i \in F^C$
STD_i:	Scheduled Time of Departure of flight i	$\forall\ i \in F^D \cap F^P$
ETD_i:	Estimated Time of Departure of flight i	$\forall\ i \in F^D$
$ACT_{i,j}$:	Actual Connecting Time between flight i and j	$\forall\ i \in F^C \cap F^D$
TTO_i^{IAF}:	Target Time Over the IAF, which is previous model output	$\forall\ i \in F^C$
$STOT_i$:	Scheduled Take-Off Time of flight i	$\forall\ i \in F^P$
$PAX_{i,j}$:	Set of passengers on flight i that need to connect to flight j	$\forall\ i, j \in PAX^C$
$\Delta_i^{LFV}(D^{total})$:	Loss of Future Value as a function of total delay D_i^{total}	
$FF_i^x(V, A)$:	Fuel flow function in kg/sec for flight i under flight condition x as a function of airspeed V and altitude A	

Decision Variables

All the decision variables are listed below:

T_i^{IAF}:	Time over the IAF for flight i	$\forall\ i \in F^A$	*integer*
H_i:	Amount of holdings for flight i	$\forall\ i \in F^A$	*integer*
$CCTOT_i$:	Company Calculated Take-Off Time	$\forall\ i \in F^C \cap F^P$	*integer*
dt_i:	Take-off delay	$\forall\ i \in F^C \cap F^P$	*integer*
δ_{ij}:	equals 1 if flight i is over the IAF before flight j, 0 otherwise	$\forall\ (i, j) \in F^A$	*binary*

3.2.2 Objective function

The objective of the model is to minimize the total delay cost for an airline. The function is built up from two major components, being fuel and passenger cost. The fuel cost is divided into the fuel spent during the Inbound Priority Sequencing (IPS) and in holding fuel in case of congestions. The passenger cost is divided up into loss of future value cost and missed connection cost. However, a third part is added to the objective, being the 'Trade-off Cost'. In this part the take-off delay of popup flights is minimized, as well as the cost penalty associated with changing an existing TTO IAF. This all can be seen in Equation 1a.

The objective function of the model also includes a subobjective, as seen in equation 1b. This subobjective minimizes the number of holdings for all non-controllable flights. This subobjective is necessary in order to avoid an unfair advantage for the controllable flights in terms of number of holdings, because the objective function of the IPS model already minimizes the number of holdings for controllable flights. By including this subobjective, both uncontrollable and controllable flights are equally prioritized again in terms of avoiding holdings. Note that although the trajectories of uncontrollable flights cannot be influenced (as the term uncontrollable implies), the IPS model still has to de-conflict all traffic at the IAF and thus imposing holdings may still be necessary, also for the uncontrollable flights.

$$\min \sum_{i \in F^C} (\underbrace{C_i^{\text{IPS}} + C_i^{holding}}_{\text{Fuel Cost}} + \underbrace{C_i^{LFV} + C_i^{mc}}_{\text{Passenger Cost}} + \underbrace{C_i^{TOD} + C_i^{TTO}}_{\text{Trade-ff Cost}}) \tag{1a}$$

$$\min \sum_{i \in F^{NC}} H_i \tag{1b}$$

IPS Cost
The fuel cost due to the IPS is calculated using an aircraft (sub)type specific fuel consumption model that is dependent on airspeed, altitude and flight phase: climb, descend, and horizontal flight. Horizontal flight is chosen over a cruise phase, as holdings are a form of horizontal flight. The fuel model is based on actual aircraft data collected between 2014 and 2022 and has been developed for the purpose of this research. In total 12 aircraft subtypes have been included within the fuel model where on average 16,000 per subtype have been analyzed. The output of the fuel model is the fuel consumption in kg/sec. In order to use the fuel model in the IPS model it had to be converted, as airspeed or altitude are not decision variables. Therefore the fuel model is converted to have decision variable T_i^{IAF} as input, and the cost of the total fuel consumption C_i^{fuel} up until reaching the IAF as output. This is achieved by determining the corresponding airspeeds to the feasible arrival window over the IAF ($[E_i, L_i]$), taking into account the filed route and flight phases.

In reality the fuel flow function of an aircraft is parabolic, therefore it was decided to implement a (convex) quadratic constraint within the IPS model, which is possible within the used commercial solver Gurobi [1]. For all controllable arrival flights the total fuel consumption is calculated by means of eq. (2a). In this equation the fuel coefficients C_{i_0},C_{i_1} and C_{i_2} are dependent on the aircraft (sub)type, airspeed, and flight phase. These have then been converted to have time stamps over the IAF as input, as described in the previous paragraph.

For the controllable popup flights the equation is slightly modified by adding dt to the T_i^{IAF}, which is shown in Equation 2b. This dt represents the take-off delay due to the Company Calculated Take-Off Time (CCTOT). More about this dt can be found in Section 3.2.3.

$$C_i^{IPS} = \Big(C_{i_0}(T_i^{IAF})^2 + C_{i_1}(T_i^{IAF}) + C_{i_2}\Big)\cdot PF \quad \forall\, i \in F^C \cap F^{ICA} \tag{2a}$$

$$C_i^{IPS} = \Big(C_{i_0}(T_i^{IAF} + dt_i)^2 + C_{i_1}(T_i^{IAF} + dt_i) + C_{i_2}\Big)\cdot PF \quad \forall\, i \in F^C \cap F^P \tag{2b}$$

Holding Cost
Flights are to be sequenced before reaching the IAF. However, sometimes the IPS model cannot prevent ATC delay in the form of holdings. Therefore the IPS model takes this into account when creating the sequence. The associating fuel cost can be determined by using Equation 3, where $FF_i^{holding}$ is the fuel flow of flight i in kg/sec for the published holding speed IAF_{SPD} and altitude IAF_{ALT}. It is assumed only full holdings can be flown where each holding takes 4 minutes (*240 seconds*).

$$C_i^{holding} = FF_i^{holding}(IAF^{ALT}, IAF^{SPD}) \cdot 240H_i \cdot PF \quad \forall\, i \in F^C \tag{3}$$

Loss of Future Value Cost
When a passenger arrives at its destination with a delay, there is not necessarily a direct cost for the airline (except for legal claims if the delay reaches a certain threshold). However, experiencing a delay could result in a decreased likelihood of traveling with the same airline in the future. To express this into cost, a loss of future value function is used ($\Delta_i^{LFV}(D^{total})$). This function does not apply to connecting passengers as a delay at the hub airport will cause either a shorter connection time or a missed connection. If the latter is the case, the involved cost is captured by the missed connection cost. This missed connection cost also includes loss of future value.

The total delay D_i^{total} of flight i is calculated according to Equation 4b, where the Scheduled In Block Time (SIBT) is subtracted from the Actual In Block Time (AIBT). Within the model the AIBT is calculated by adding holding delay ($240H_i$) and an Estimated In Block Time (EIBT) offset to the output time at which flight i should be over the IAF. This can be seen in Equation 4a. The EIBT offset is the time it takes to go from the IAF to the gate.

$$AIBT_i = T_i^{IAF} + EIBT^{offset} + 240H_i \quad \forall\, i \in F^A \tag{4a}$$

$$D_i^{total} = AIBT_i - SIBT_i \quad \forall\, i \in F^A \tag{4b}$$

With the total delay known, the future loss cost can be calculated. There are four type of passengers distinguished, which can be seen in Figure 3. In this figure the cost per passenger is shown as a function of total flight delay. Please note that the function for short haul is used for popup flights. In Equation 5a and 5b one can see how the total future value loss for a flight is calculated. Depending on the type of flight (arrival or

[1] `https://www.gurobi.com/`

popup) the corresponding $\Delta_i^{LFV}(D^{total})$ is taken. For both economy and business passengers one should add the corresponding *SH* and *LH* lines from Figure 3 to each other to obtain the total loss of future value cost for a flight. To make sure no money is earned by arriving early, Equation 5c is added.

$$\Delta_i^{LFV-E}(D^{total}) = |PAX^{NC-E}| \cdot \Delta_i^{LFV-E}(D^{total}) \quad \forall\, i \in F^C \tag{5a}$$

$$\Delta_i^{LFV-B}(D^{total}) = |PAX^{NC-B}| \cdot \Delta_i^{LFV-B}(D^{total}) \quad \forall\, i \in F^C \tag{5b}$$

$$C_i^{LFV} = \max(\Delta_i^{LFV-E}(D^{total}) + \Delta_i^{LFV-B}(D^{total}), 0) \quad \forall\, i \in F^C \tag{5c}$$

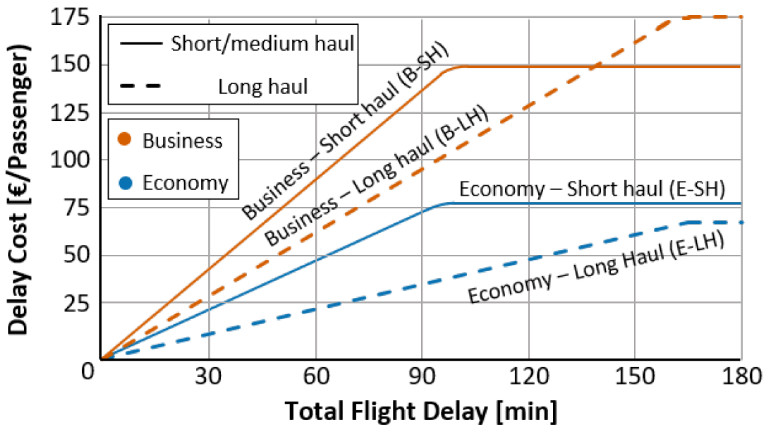

Figure 3: Loss of future value function taken from [Vervaat, 2020]

Missed Connection Cost

In case of a missed connection the corresponding cost for the airline is built up from several aspects, such as rebooking the passenger, cash compensation, and legal claims (if the delay is more than x hours). The mentioned cost is referred to as hard cost. The other cost component is the loss of future value as described for the non-connecting passengers. In this model the cost of a misconnection is, however, modelled as a fixed constant that both includes hard and soft cost.

In order to know the total cost involved for all missed connections within the IPS model, the Actual Connection Time (ACT) needs to be calculated for each passenger on flight i with a connection to flight j. This is done by subtracting the Actual In Block Time (AIBT) of the arriving flight from the Estimated Departure Time (EDT) of the connecting flight. This can be seen in Equation 6a. With all the Actual Connection Times known, the set of passengers that have missed their connection can be calculated as can be seen in Equation 6b. Finally the total involved cost can be calculated, which is shown in Equation 6c.

$$ACT_{ij} = EDT_j - AIBT_i \quad \forall\, i \in F^C \ \wedge \ \forall\, j \in F^D \tag{6a}$$

$$PAX_i^{mc} = \{|PAX_{ij}| \in PAX^C : ACT_{ij} < D_i^{total}\} \tag{6b}$$

$$C_i^{mc} = |PAX_i^{mc}| \cdot PMC \quad \forall\, i \in F^C \tag{6c}$$

Take-Off Delay Cost

Controllable popup flights can receive a CCTOT in order to arrive over the IAF at a more suitable time. It is however undesirable that flights stay on the ground for too long. This could happen as the delay costs for a popup flight could be lower compared to an intercontinental flight. To come around this, Cost function 7 is added. The longer a popup flight is delayed (dt), the more it will cost.

$$C_i^{TOD} = dt_i \cdot P^{TOD} \forall\, i \in F^P \cap F^C \tag{7}$$

Deviation of TTO IAF Cost

One of the requirements for a decision support tool for an airline in the tactical phase, is that the outcome of the tool should be robust. Given a flight already has a TTO IAF from a previous model output, a deviation from this TTO in a new run will come with a penalty (modelled as a fictitious cost within the objective function). To achieve this, Cost function 8 is added, where the absolute value is taken from the subtraction of the decision variable T_i^{IAF} and the TTO IAF of flight i. This is then multiplied with the penalty associated with this absolute difference.

$$C_i^{TTO} = |T_i^{IAF} - TTO_i^{IAF}| \cdot P^{TTO} \forall\, i \in F^P \cap F^C \tag{8}$$

3.2.3 Constraints

This section describes the constraints used in the IPS model. Below, all equations concerning the constraints are listed. Thereafter these will be elaborated upon.

$$E_i \leq T_i^{IPS} \leq L_i \quad \forall\, i \in F^C \cap F^{ICA} \tag{9a}$$
$$E_i + dt_i \leq T_i^{IPS} \leq L_i + dt_i \quad \forall\, i \in F^P \cap F^C \tag{9b}$$

$$CCTOT_i = STOT_i + dt_i \quad \forall\, i \in F^P \cap F^C \tag{10a}$$
$$dt_i \geq 0 \quad \forall\, i \in F^P \cap F^C \tag{10b}$$

$$\delta_{ij} + \delta_{ji} = 1 \quad \forall\, (i,j) \in F^A \tag{11}$$

$$T_j^{IPS} \geq T_i^{IPS} - (1 - \delta_{ij})M \quad \forall\, (i,j) \in F^A \tag{12a}$$
$$T_j^{IPS} + 240H_j \geq T_i^{IPS} + 240H_i + IAF^{SEP} - (1 - \delta_{ij})M \quad \forall\, (i,j) \in F^A \tag{12b}$$

$$T_j^{IAF} - T_i^{IAF} \geq \begin{cases} IAF^{SEP}, & \text{if } ETO_j^{IAF} - ETO_i^{IAF} \geq IAF^{SEP} \\ ETO_j^{IAF} - ETO_i^{IAF}, & \text{otherwise} \end{cases} \quad \forall\, i \in F^C,\ j \in F^{NC} \tag{13}$$

Equations 9a and 9b describe the time range a flight can be over the IAF. Equation 9a describes the controllable arrival flights. The earliest possible time E_I and the latest possible time L_i depend on the aircraft subtype (feasible speed ranges) and on planned flight plan speeds. The latter has to do with the fuel on board. If the IPS model wants a flight to fly faster than the flight plan speed, it will cost more fuel which was not anticipated upon when fueling the aircraft. For controllable popup flights a dt is added (eq. (9b)). This dt represents the take-off delay due to a possible CCTOT. Non-controllable flights are included in the IPS model as constants. When these flights enter the action horizon (either by entering the circular boundaries or by taking-off), their estimated time over the IAF is calculated to which the T_i^{IAF} is then fixed to.

Equations 10a and 10b describe scheduling the take-off time for the applicable popup flights. First, the Scheduled Take-Off Time $STOT$ needs to be calculated by adding an average taxi time t^{taxi} to the Scheduled Time of Departure STD. Then the CCTOT can be calculated by adding a take-off delay dt to the STOT (eq. (10a)). In Equation 11 the sequence is determined with the help of the variable δ. It states that either flight i has to be over the IAF before flight j, or the other way around. Equation 12 continues to determine the sequence. 12a describes the actual time over the IAF. It states that the time of flight j shall always be larger or equal to the time of flight i. Equation 12b then makes sure the correct spacing is achieved. If it turns out flight j will be over the IAF less than the minimum required separation IAF_{SEP}, it will receive ATC delay in the form of a holding, where one holding lasts 4 minutes (*240 seconds*).

Equation 13 ensures the equity principle is applied for the airlines operating the non-controllable flights. Based on FCFS the estimated time over the IAF is calculated for each flight. If it turns out a controllable flight flies before a non-controllable flight, the difference in ETOs is calculated. If this difference is larger than the minimum required separation over the IAF, the TTO IAF of the controllable flight cannot be less than this minimum separation. This ensures the non-controllable flight does not get a (possible extra) delay. In case of a difference less than the minimum IAF separation, the TTO IAF for the controllable flight can have the difference in ETOs as a minimum separation, or improve. This is visualized in Figure 4. In the first case the controllable traffic has an estimated time over the IAF which is larger than the required minimal separation. Therefore it can decrease its speed to arrive over the IAF on the boundary of IAF_{SEP}, or it should let the non-controllable traffic overtake itself. In the second case the controllable traffic cannot decrease speed anymore, so it should let the other traffic overtake itself, or increase its own speed. In the third and last case the ETO of the controllable flight (without manipulating the flight) is less than the required minimal separation. Under normal FCFS operation the non-controllable traffic would have to decrease its speed or go into a holding. Therefore the minimal IAF separation is overruled in this case within the IPS model.

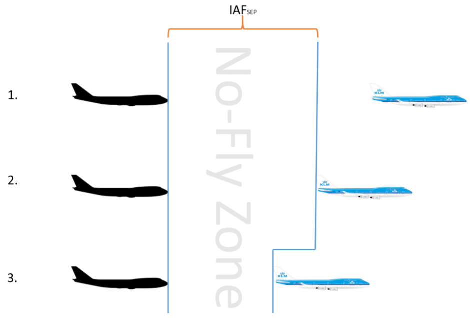

Figure 4: Minimum separation over the IAF based on the equity principle

3.3 Assumptions & Limitations

As with any research, this research comes with assumptions and limitations. The most profound ones will be mentioned in this section.

- Except for a minimal (horizontal) separation over the IAF, no separation rules exist within the model;
- If it turns out the minimum separation over the IAF is violated after applying the IPS algorithm, the only option is to assign holdings to flights;
- Non controlable flights cannot receive speed restrictions. In case of a bunch over the IAF, they will be assigned to a holding;
- Wind conditions are not considered when computing flight times and fuel consumption;
- The time it takes from touch down to arriving at the gate (used to calculate the estimated arrival time) is fixed for all flights. Hence, it does not take into account the runway a flight lands on and the gate it has to park at;
- Although the data used in the fuel model originated from real aircraft data, these costs can be off by 12% compared to individual aircraft;
- The model only optimizes until the IAF. The advantage is the IAF can be seen as a single runway. The model can be run on each IAF of an airport. One of the limitations in case of multiple IAFs is that after reaching the IAF ATC can give flights speed restrictions. This has to do with the fact there are two merge points before landing in case of multiple IAFs. This can be seen in Figure 5;
- The model uses the aircraft climb performances as programmed in the BlueSky simulator [2]. In case of an 'unknown' aircraft type, a standard value of 16.62 m/s of climb performance is used. For descending a standard value of 3000 ft per 10 nm is used for all aircraft;
- Crew and specific tail number itineraries are not taken into account. Therefore delaying a specific flight could be beneficial according to the model, whereas in reality the aircraft itself or crew has a short turn around, resulting in additional costs for the airline on the next flight(s). Also crew duty periods are not taken into account;

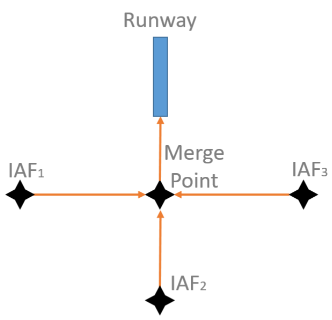

Figure 5: Second Point-Merge-System during approach in case of multiple IAFs

[2] https://github.com/TUDelft-CNS-ATM/bluesky/

4 Description of the Case Studies

The IPS model is tested using a case study with KLM Royal Dutch Airlines (from now on referred to as KLM) being the network carrier and Amsterdam Airport Schiphol (from now on referred to as Schiphol) as the hub airport. KLM is the Dutch flag carrier, serving over 90 European and 70 intercontinental destinations (pre-Covid) using a hub-and-spoke network structure, with Schiphol being its home base. [Bouwens and Ogier, 2020] Schiphol is the third-biggest airport [3] in Europe, serving 21 million passengers, of which over 40% are transfer passengers. [4] The airport has three IAFs, being SUGOL, ARTIP and RIVER. In Subsection 4.1 the scenario is introduced and in Subsection 4.2 the input parameters of the scenario are given.

4.1 Scenario Description

The full set of scenarios entails eighteen Westerly morning arrival waves from June and August in 2022. Every day the scenario starts at 04:00 UTC and ends at 08:00 UTC. For the case study SUGOL is chosen as the IAF to analyze. SUGOL is shown in Figure 8 in which the red lines are the different Standard Arrival Routes (STARs) that connect the FIR boundary with the IAF. The reason for choosing SUGOL is that in the (early) morning most bunching takes place at this IAF. Popup flights originate from the UK and Ireland, whereas intercontinental flights originate from the USA, Canada, and the Caribbean. The scenarios are played back twice in the ATM simulator BlueSky. One time using the proposed IPS scheme and one time using First-Come-First-Served (FCFS). The latter serves as a baseline to compare the IPS scheme to.

The maximum capacity of SUGOL is 26 flight per hour according to Air Traffic Control the Netherlands. In Figure 6 one can see the demand of each scenario, including the differentiation of KLM and non-KLM traffic. In five scenarios the peak demand is higher than the maximum declared capacity, resulting in a traffic bunch. To visualize the peak demand during a single scenario, Figure 7 has been added, including the spread of (popup) flights of KLM and other airlines. This figure shows the demand based on scheduled flights. Note that for this particular day the peak demand is reached between 06:00 and 07:00 UTC where the highest demand is between 06:00 and 06:15 UTC.
In total there are 843 flights, of which 435 are operated by KLM (51.6%). All the intercontinental flights (52.9%) are originating from Canada or the USA, whereas the popup flights originate from the UK or Ireland. Breaking all flights down into intercontinental and popup flights, the KLM percentage is 59.7% and 43.9% respectively.

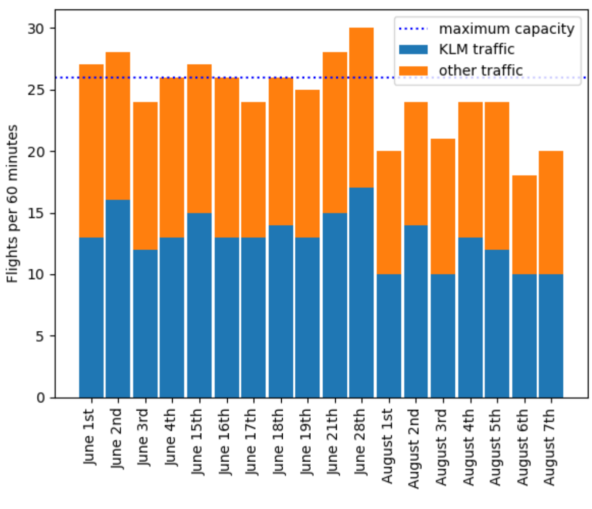

Figure 6: Peak demand per scenario over SUGOL

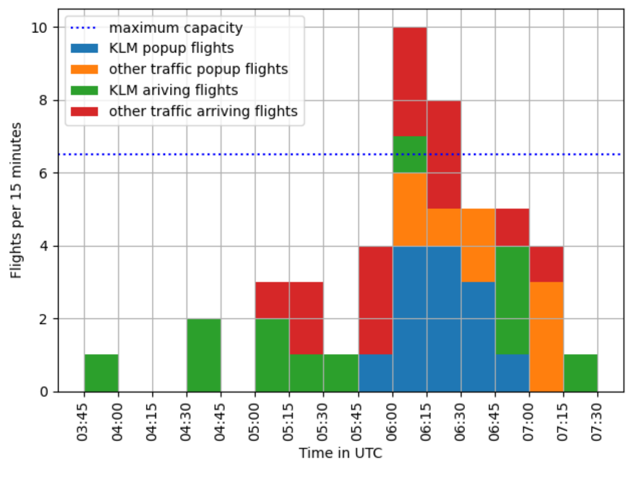

Figure 7: Overfly demand of SUGOL based on scheduled arrivals on June 2nd 2022

[3]In the year 2019
[4]https://www.schiphol.nl/en/route-development/page/amsterdam-airport-schiphol-airport-facts/

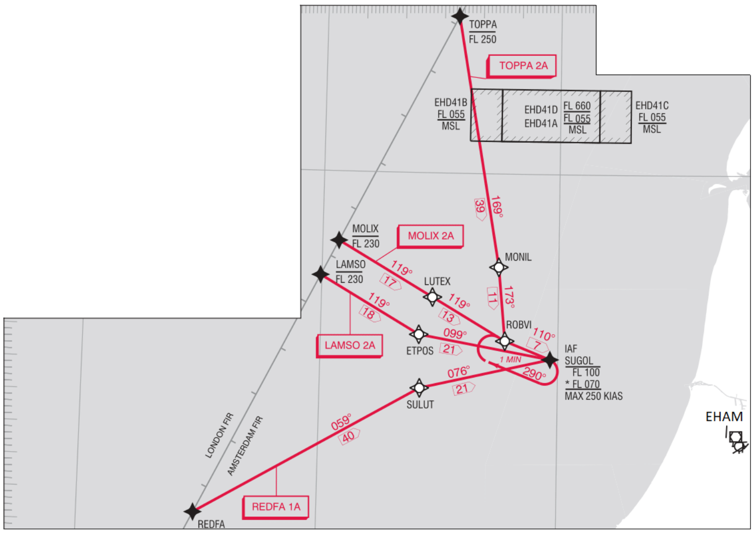

Figure 8: Standard Arrival Chart for Schiphol, zoomed in at IAF SUGOL [LVNL, 2022]

4.2 Scenario Parameters

In Table 1 all the input parameters for the case study are shown. If one looks to the published arrival procedures, only a maximum speed is given for overflying SUGOL (see Figure 8). It turns out the average overfly speed is 230 KIAS, therefore this value has been chosen. The minimum connection time is assumed to be equal for all connections. In reality there is a difference between European and intercontinental flights. Even individual city pairs can have different connecting times. The $EIBT^{offset}$ is determined based on received data from Air Traffic Control the Netherlands in which one month of arrival traffic data from 2019 has been analyzed. To come up with suitable CCTOT airports, an analysis has been performed in which the differences between actual and scheduled take-off times have been investigated. The airports Cork and Norwich were the only two popup airports for which the average difference was smaller than three minutes. According to research ([Vanwelsenaere et al., 2018]) the difference should be less than two minutes, but in that case no suitable airports would have been found.

Table 1: Input parameters for the case study

Input Parameter	Unit	Value
IAF^{ALT}	$[ft]$	10,000
IAF^{SPD}	$[kcas]$	230
IAF^{SEP}	$[sec]$	139 (26 flights per hour)
MCT	$[sec]$	3000 (50 minutes)
PMC	$[eur/pax]$	450
PF	$[eur/kg]$	1.12
$EIBT^{offset}$:	$[sec]$	1200 (20 minutes)
RAD	$[nm]$	800
M	[-]	1e7
$CCTOT_{airports}$	[-]	Cork and Norwich (EICK, EGSH)
t_i^{taxi}	$[sec]$	360 (6 minutes)
P^{TOD}	$[eur/min]$	1
P^{TTO}	$[eur/min]$	1
C^{thr}	$[eur]$	500

5 Results

Within this section all the results will be discussed in Subsection 5.1. In Subsection 5.2 a sensitivity analysis will be outlined. All scenarios are analyzed using a ThinkPad DEPLOY W10 STD V20H2.02 / Node W10 STD US V20H2.01 laptop which had 16 GB of RAM and a 64-bit operating system and a Intel(R) i5-10310U CPU. The model is solved using the commercial solver Gurobi version 9.5.1. Each arrival wave was simulated in the open source ATM simulator BlueSky and took around 7 minutes in which on average 36 sequence calculations are performed.

5.1 Case Study Results

A summary of all key results can be found in Table 2. In this table the outcome of both the IPS model as FCFS is split into the results originating from the full set of scenarios, and the scenarios where there was under-/over demand. In the over demand scenarios bunches are more likely to occur, as the demand exceeds the maximum declared capacity. Please note that N is referring to the number of flights within all scenarios combined, this explains why, in the over demand case, this N is lower than for the under demand case. There were fewer scenarios with over demand as can be seen in Figure 6. Within this subsection these results will be analyzed and a few deep dive examples will be given.

Table 2: Comparison of IPS model performance compared to FCFS for KLM. Costs have been rounded to the nearest 100 euro

	Full set N=843,N_{KLM}=435		Under demand N=645,N_{KLM}=333		Over demand N=198,N_{KLM}=102	
	FCFS	IPS	FCFS	IPS	FCFS	IPS
OTP-15 (%)	91.5	92.0	93.4	93.7	85.3	86.3
IPS sequence calculations (-)	-	651	-	499	-	152
Missed Connections (-)	1102	698	860	587	242	111
CCTOTs (-)	-	19	-	18	-	1
Total Fuel Cost (EUR)	3,308,000	3,061,000	2,558,000	2,348,400	750,000	712,600
Total LFV Cost (EUR)	298,900	233,400	187,700	154,100	111,200	79,300

To start off, the On-Time Performance (OTP-15) has been analyzed. The '15' refers to the maximum delay in minutes a flight is allowed to have, to still be 'on-time'. This can be calculated by subtracting the Scheduled Time of Arrival (STA) from the Actual Time of Arrival (ATA), which can be seen in Equation 14. In all three cases the IPS model outperforms the FCFS, ranging from 0.3% in case of under demand to 1.0% in case of over demand. Furthermore the average arrival delay per flight for KLM decreases from -239 seconds (arriving early) to -217 seconds. This means that on average the flights of KLM arrive 22 seconds later under the scheme of IPS. For non-KLM flights the average flight delay remains -566 seconds for both FCFS as IPS, indicating the equity principle is applied correctly.

$$OTP\text{-}15 = \frac{1}{|F^C|}|\{i \in F^C : (ATA_i - STA_i) \leq 900\}| \tag{14}$$

Using IPS the number of missed passenger connection decreases with respect to FCFS. For the total set of scenarios there is a decrease of 36%. For the over demand scenarios this number even increases to 54%. Moving on to the costs, the IPS model again outperforms the FCFS. When looking at the total cost (missed connections [5] + fuel cost + loss of future value), the total savings when using IPS compared to FCFS are 494,300 euros or 12%. Lastly, on individual components, the saved costs for missed passenger connections is within the same order of magnitude as the saved fuel costs. When zooming in on specific flights, the cost savings can be seen in Figure 9. Here a box plot is shown of the cost savings for popup and ICA flights. The ▲ represents the mean, which is positive for both types of flight. It is interesting to note that almost all ICA flights have positive savings with no negative outliers, whereas individual popup flights do get more negative cost savings. This is in line with the expectation as popup flights are cheaper to operate, there are fewer passengers on board and the used aircraft consume less fuel. In Figure 10 the time savings are shown for individual flights. The results shown in this figure are in line with the previous mentioned average (negative) delay increase. On average flights arrive early, meaning cost savings can be achieved by slowing down those flights.

[5] multiply the amount of missed connections with 450 euros.

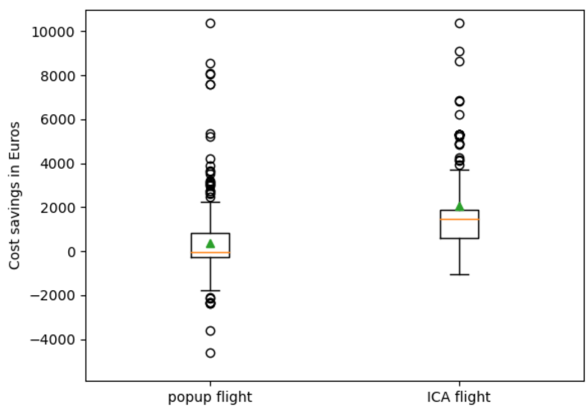

Figure 9: Cost savings of sequencing using IPS instead of FCFS per flight

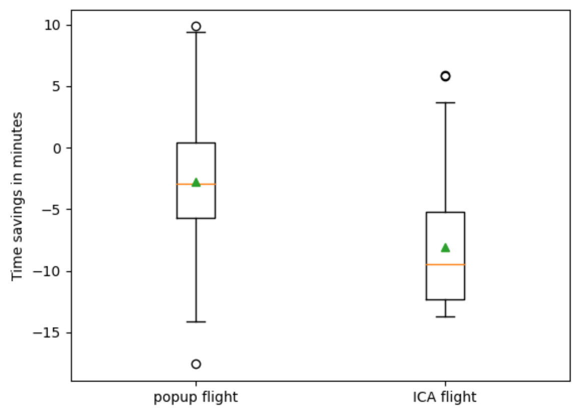

Figure 10: Time savings of sequencing using IPS instead of FCFS per flight

The IPS model is designed to give flights new target times over the IAF each time new information comes available. For the full set of scenarios, on average, a flight receives 3.6 times a new TTO, where the average deviation is only 5 seconds compared to the previous model output. This average of 5 seconds however does not represent the TTO changes well as can be seen in Figure 11. Within this figure the relative frequency of the difference between the decision variable T_i^{IAF} and the TTO_i^{IAF} can be seen for all flights that had a TTO_i^{IAF}. Zooming in on specific flights, Figure 12 is added. It shows most flights do not receive a TTO update which is beneficial for the stability of the arrival sequence. Over 90% of all new model outputs the T_i^{IAF} remains the same as TTO_i^{IAF}. Note that the number of sequence calculations is lower than the total number of traffic movements. This can be explained by the fact the model searches for updates every minute. Within this minute multiple flights can enter the action horizon.

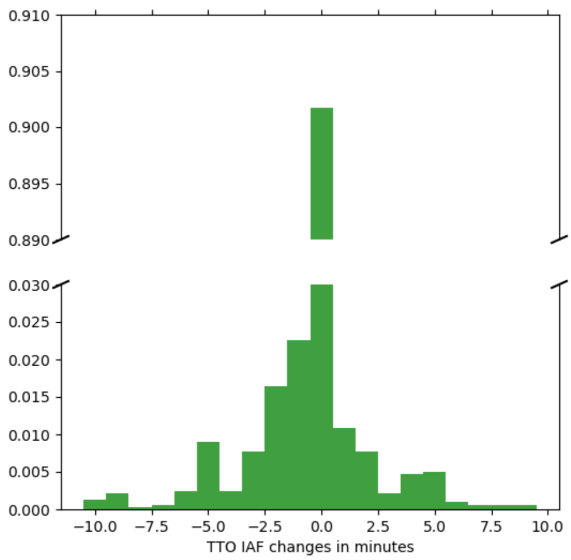

Figure 11: Relative frequency of the difference between a new TTO and the previous TTO

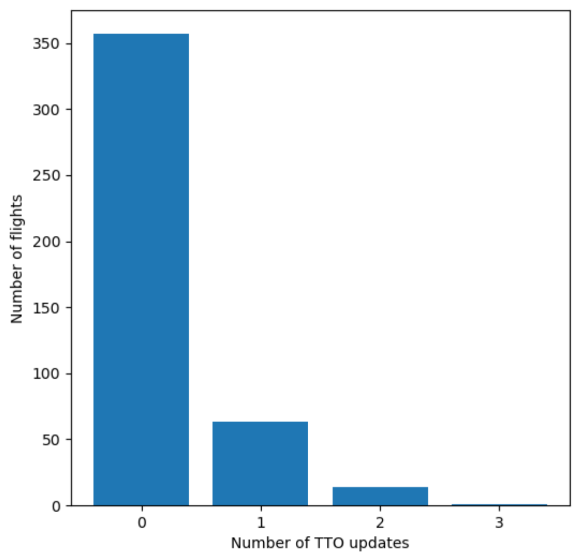

Figure 12: Cost savings of sequencing using IPS instead of FCFS per flight

As mentioned in the scenario description, popup flights originating from Norwich or Cork can obtain a CCTOT. In total 19 CCTOTs have been issued of which 18 during low demand and 1 during high demand, whereas in total 34 flights could have gotten a CCTOT. On average the CCTOT results in a delay of 6 minutes. The minimum CCTOT value is 1 minute and the maximum CCTOT value 19 minutes.

Zooming out from the cost savings, one can have a look at the demand for overflying SUGOL after the IPS scheduling took place. In Figure 14 this can be seen for June 2nd 2022. Only between 06:15 and 06:30 UTC the demand exceeds the capacity. These results can be compared with Figure 13. This figure should not be confused with Figure 7 in which the scheduled flights are shown (cancelled flights are not shown). In reality flights do not arrive exactly on their scheduled time.

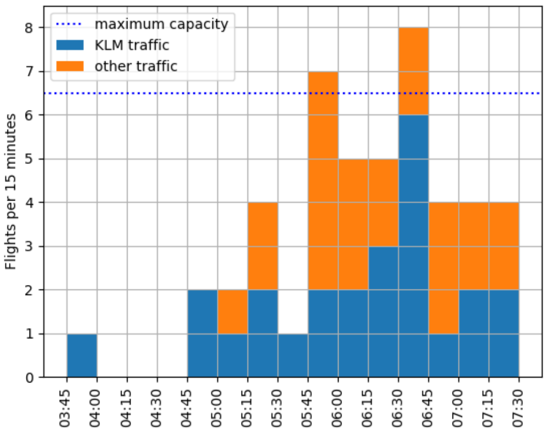

Figure 13: Traffic bunch over SUGOL after applying FCFS

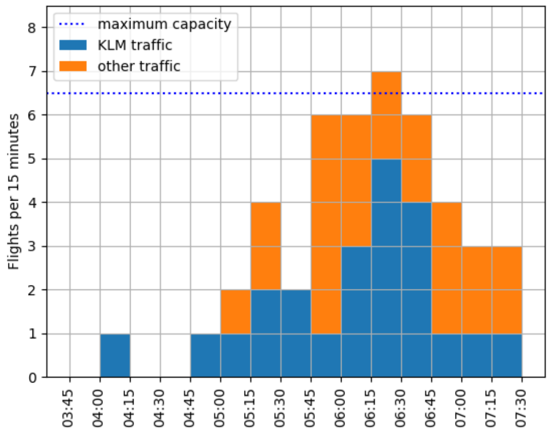

Figure 14: Traffic bunch over SUGOL after applying IPS

Deep Dive with scenario snapshot

To understand the reasons behind the choices of the IPS model a deep dive will be shown regarding three flights KL1058, KL646 and DL0072 that flew on June 21, 2022. The individual results for these three flights are shown in Table 3. The FCFS and IPS time stamps consist out of three columns. One should add the number of holdings (four minutes each) to the TTO IAF to arrive at the *Result* column. The scheduled IAF time is the scheduled arrival time minus $EIBT^{offset}$.

With FCFS the flights are placed in a bunch. The KL1058 arrives slightly later than the DL0072, resulting in a holding as the minimum separation is violated. Then the KL0646 arrives slightly later than the KL1058. As KL1058 was already assigned a holding, the KL0646 is assigned two holdings (FCFS principle within the holding). With IPS on the other hand, the KL1058 arrives before the DL0072 whereas the KL0646 arrives after the DL0072.

This example shows the IPS model optimizes for a global optimum. The cost reduction of KL0646 comes at the expense of KL1058. In both cases the DL0072 overflies the IAF at the same time, meaning the equity principle is not violated. One should note that in reality the bunch created in FCFS will most probably not take place as ATC will vector[6] those flights. However, the sequence itself, will remain the same in reality, as ATC works with the FCFS principle.

Table 3: Snapshot from flights on June the 21st

Flight	FCFS Time Stamps			IPS Time Stamps			Scheduled IAF time	Δ Missed Conn.	Δ Cost *EUR*
	TTO IAF	Holdings	Result	TTO IAF	Holdings	Result			
KL1058	05:43:27	1	05:47:27	05:39:36	0	05:39:36	05:55:00	0	212,-
DL0072	05:42:38	0	05:42:38	05:42:38	0	05:42:38	05:50:00	-	-
KL0646	05:44:41	2	05:52:41	05:45:16	0	05:45:16	05:25:00	-3	-3531,-

[6]Flights are given instructions to deviate from their original flight path and can receive speed instructions. In this way ATC tries to minimize the number of holdings flown

5.2 Sensitivity Analysis

Two types of sensitivity analysis have been performed. The first one is to slightly change input parameters, or turn on/off functions. The other type of sensitivity analysis comes in the form of a Monte Carlo simulation to show the robustness of the model. The former is discussed in Subsection 5.2.1 and the latter is discussed in Subsection 5.2.2.

5.2.1 Changing input parameters

Tables 4 and 5 state the results for the Westerly morning arrival waves consisting out of four days: June 2nd, June 28t, August 1st and August 6th. These four dates have been chosen as during the first two waves the demand is higher than the capacity, whereas in the last two waves the demand was lower than the capacity. In both tables the model output is compared to the baseline IPS parameter settings.

Table 4 shows the sensitivity analysis of varying the Missed Connection cost (MC) and Loss of Future Value cost (LFV) by 10% compared to their reference values used in the case study. Varying the fuel price is also included in this table, but instead of varying it with 10% around the reference value of 0.9105 Euro/liter, 0.70 and 1.00 Euro/liter have been chosen. The reason being the fuel price used to be 0.70 Euro/liter before covid. The 1.00 Euro/liter is chosen arbitrarily. Note that the actual input parameter is in Euro/kg. However, fuel prices are based on Euro/liter. For the conversion a fuel density of 0.81 kg/liter is used.
Table 5 shows the parameters that are binary: either on/included or off/excluded. The only exception is the IPS range. In reality this parameter can be varied by enlarging or decreasing the range, but due to the set-up of the scenarios increasing the value was not possible, unfortunately. Therefore the range is only changed to 600 nm.

Turning off the equity principle (Table 5) results in more fuel burn compared to the reference scenarios. This is due to the fact KLM flights can fly slightly faster to overtake a non-KLM flight. This non-KLM flight then is negatively affected as it has to slow down to ensure the minimum required separation over the IAF. This is for example the case for flight KL602 on the second of June that is sequenced beyond a small bunch of non-KLM traffic when the equity principle is enabled. With the equity principle disabled, the KL602 takes over this small bunch, resulting in a 3-minute delay for those three non-KLM flights. The OTP-15 shown is of KLM flights only. If one looks at the OTP-15 of other airlines (not shown in Table 5) it also remains the same as for the baseline case. This is due to the fact that on average flights arrive early, meaning with a delay of a couple of minutes the OTP-15 is not affected. Please note that the sole purpose of turning off the equity principle is to test the model's behavior. In reality it is not possible to apply priority sequencing without the equity principle, as ATC would then intervene.
In reality flights are fueled up to fly at a certain cost index or speed. Therefore it might not be realistic to have the ability to speed up when entering the IPS action horizon. That is the reason Table 5 includes the column 'only slowing down'. Please note that the number of missed passenger connections is 55% higher than the number in the reference case. This can already be achieved with a few flights. On June 2nd for example KL662 goes from 0 to 14 missed connections and KL1070 goes from 1 to 18 missed connections in case no increase of speed is allowed in the IPS scenarios.
For the column 'Including more CCTOT airports' all airports within the UK and Ireland are added. This resulted in one extra CCTOT airport which was Aberdeen. If however the CCTOT delay penalty is excluded in the model, 14 CCTOTS are issued as can be seen in the column 'Penalty CCTOT excluded'. On average a popup flight then receives 172 seconds ground delay where the smallest delay is 47 seconds and the largest delay 274 seconds.

Table 4: Sensitivity analysis of missed connection cost, fuel price and the loss of future value function

Scenario	Ref. values	MC *90%*	MC *110%*	Fuel Price *0.70 Eur/Ltr*	Fuel Price *1.00 Eur/Ltr*	LFV *90%*	LFV *110%*
OTP-15 (%)	85.4	85.4	85.4	85.4	85.4	85.4	85.4
Missed Connections (-)	146	147	145	144	147	146	145
CCTOTs	3	3	3	3	3	4	2
Total Fuel Consumption (ltrs)	792,600	792,500	792,600	798,600	792,000	791,500	794,700
Total LFV Cost (EUR)	98,800	98,800	98,800	95,700	97,600	87,900	107,500

Table 5: Sensitivity analysis of the equity principle, speed limits, IPS range, CCTOT airports and both TTO as CCTOT delay penalties

Scenario	Ref. values	Equity Principle off	Only slowing down	IPS range 600 nm	Including more CCTOT airports	Penalty CCTOT excluded	Penalty TTO IAF excluded
OTP (%)	85.4	85.4	79.2	84.4	84.4	84.4	84.4
Missed Connections (-)	146	146	227	144	147	146	140
CCTOTs	3	2	1	1	4	14	1
Total Fuel Consumption (ltrs)	721,700	722,600	738,800	834,500	721,400	721,200	724,000
Total LFV Cost (EUR)	98,800	95,400	113,500	96,600	98,800	98,800	97,200

A sensitivity analysis for the maximum allowed optimization runtime is not shown in Table 4 or 5. In the case study the maximum allowed runtime is set to 100 seconds. When the model is run without a maximum runtime, the results stay the same compared to the reference scenarios. The only difference is the time it takes to obtain a solution can go up to 725 or even 900 seconds. This should not be confused with the earlier mentioned 7 minutes it takes to run one entire scenario containing the arrival wave.

5.2.2 Monte Carlo Simulation

The performed case study shows the IPS model works for a particular scenario, being a morning arrival wave at Schiphol, where the traffic is coming from the West. To show the model will also work in other scenarios for Schiphol, a Monte Carlo simulation has been performed. In Appendix A this Monte Carlo simulation is described in full detail. Within this subsection, only the highlights will be discussed.

It was decided to take a snapshot of six flights from a real historic scenario at Schiphol. The snapshot consisted out of four controllable flights of which two popup flights. These flights have been modified such that congestion is likely to take place. In this way it is not needed to simulate an entire morning arrival wave. In reality the six flights have a different Scheduled Time of Arrival (STA), but for this simulation the STAs were set equal to each other (to simulate congestion).

To create different Monte Carlo simulations, three variables are slightly varied within each simulation run. The first variable is the moment in time a flight enters the action horizon. The second one is the amount of time connecting passengers will have at the hub. The last one is that the connecting time of passengers will dynamically change, simulating changes of EOBTs of outgoing flights at the hub. The variables have been modelled as independent random variables that follow a normal distribution. For the moment of entering the action horizon the mean and standard deviation of the difference between actual and scheduled arrival times are taken from the six chosen flights, based on a period from January 2010 until August 2022. The normal distribution regarding the connecting time is based on taking the mean and standard deviation of all passenger bookings of the summer season of 2022 of KLM. This connecting time is then used for the last two variables, by adding the connecting time dynamically to the STA.

In the end 34 Monte Carlo simulation runs have been performed in which the IPS model calculated the most optimal sequence 229 times. As this Monte Carlo simulation's sole purpose is to show the robustness of the model, it was decided to only use the total cost output per sequence calculation and look if the solutions of the model are feasible. To do this, the coefficient of variation is used to know how many simulation runs were needed. The coefficient of variation is the division of the standard deviation of the model output and the mean value of the model output. When one plots the coefficient for each simulation outcome and it converges, enough simulation runs have been performed. For the performed Monte Carlo simulation it turned out that after 15 simulation runs the coefficient already reached a stabilization, hence it can be concluded that the chosen 34 simulation runs are enough to show the robustness of the model.

5.3 Validation

To validate the proposed IPS model, a live shadow run has been performed using a converted version of the IPS model. During this shadow run live aircraft position and (connecting) passenger data is collected and put into the model as input. The goal was not to only validate the model's functioning itself, but also to find the quality of the input data used.

The shadow run took place in week 41 and 42 of 2022 and consisted out of sequencing traffic during the Westerly morning arrival wave over SUGOL from 04:00 until 04:30 UTC. During this time interval the first popup flights depart from the UK, resulting in a mix of popup flights and intercontinental flights. Only intercontinental/long haul flights have been sequenced. Popup flights were only taken into account once airborne, meaning no CCTOTs have been issued. The reason was a lack of actual departure time information. The actual results will not be shown for proprietary reasons. Instead, the global findings will be stated.

During the shadow run ADS-B data from Flightradar24[7] is used for live aircraft positions, in combination with their estimated landing times. From Air Traffic Control the Netherlands an Innovation Labs[8] data dump is obtained containing flight messages from the Network Manager of EuroControl, originating from 2019. This data is then used to calculate the estimated time over the IAF, based on the estimated landing time received from Flightradar24. Lastly, data is obtained from an airline regarding fuel consumption, flight plans, and passenger cost data.

In total 51 flights have been included in the shadow running of which 27 flights belonged to the controllable flights set. Of these 27 flights, 11 flights should have been re-sequenced according to the IPS model. The calculated TTO SUGOL resulted in a five-minute delay in the most extreme case. In some cases a delayed flight was delayed even more, although this resulted in additional passenger costs. By extra delaying however, the fuel savings were higher compared to the additional passenger costs, resulting in a net cost saving.

One aspect of the shadow running was to validate the model input. It turned out the estimated times over the IAF have an average deviation of 2.7 minutes based on 17 flights that are played back afterward to see the actual time over the IAF. For flights that had accurate positions in Flightradar24 the estimate could be off by 5 minutes. This includes the error of the estimated landing time based on Flightradar24 and the backward calculation from touch down towards the IAF. Flights that did not have accurate positions (their position is extrapolated from the last known accurate position) turned out to have deviations as large as 30 minutes.

6 Discussion

Within this section the results of the IPS model will be discussed. In Section 6.1 the results of the case study will be discussed. Section 6.2 then touches upon some limitations of the case study.

6.1 Discussion on the case study results

Looking at the results of the case study several interesting things can be seen. The first of which that the average delay per flight increases from -239 to -217 seconds. One could argue this change is negligible, but it indicates the IPS model saves fuel in this case as there are no passenger penalties for arriving early. Moving to the cost savings per flight there is the interesting fact that intercontinental flights do not result in negative savings whereas this is the case for popup flights. This is in line with the expectation as popup flights have lower operating costs, there are fewer passengers on board and the used aircraft consume less fuel.
As mentioned in the results section, over 90% of all TTO IAF changes are 0 minutes and only a maximum of 3 TTO updates for single flights occurred. This is beneficial for the sequence as it guarantees stability. When this penalty is excluded, not only the stability of the sequence is affected, also the results of the model are affected according to the sensitivity analysis. This is favorable for passengers, as there are less missed connections and lower LFV costs.

6.2 Limitations of the simulation

The proposed IPS model shows it could help an airline to anticipate upon an expected traffic bunch and plan its own flights in such a way that cost savings are achieved compared to the currently used FCFS algorithm. Even when there is no traffic bunch (lower demand than the maximum capacity), the IPS model can help to achieve cost savings. Also competing traffic is not negatively affected.
There are however a few limitations of the case study. The simulation only shows results for the Westerly arrival waves at Schiphol. To prove the model is robust and also performs in other scenarios a Monte Carlo simulation has been performed which turned out the IPS model always outputs feasible solutions.
Another issue with the case study is that it is deterministic and that the passenger cost function was a basic linear function in case of LFV and a fixed value in case of a missed connection. To find out how the model performs in real operation the model shadow runs have been performed during which it became clear the model itself can be of great help for an airline by reducing operational costs. The only problem were the estimated times over the IAF. Within the case study these could be calculated deterministically for all flights, whereas

[7] flightradar24.com
[8] https://www.lvnl.nl/over-lvnl/innovationlabs

this is not possible in reality. When compared with the actual time over for individual flights, the deviation between estimated time and actual time could be as large as 5 minutes, which is too large considering the fact that the minimum separation is a little over 2 minutes for SUGOL. The shadow run did however bring some insights, being that the sequence of controllable flights itself can be altered. Each controllable flight does have an accurate estimated time over the IAF in their Flight Management Computer (FMC). It also became clear that flights do not always fly their planned cost index, meaning besides slowing down, they can also increase their speed as they have fuel on board for a higher cost index.

7 Conclusion and Recommendations

In this paper a dynamic Inbound Priority Sequencing (IPS) model for the use of a network carrier is proposed that specifically includes popup flights. The model is formulated as a mixed-integer quasi-linear program that turned out to be feasible in all simulation runs, including in a Monte Carlo simulation to test the robustness. Arrival flights will receive a Target Time Over (TTO) the Initial Approach Fix (IAF) to which they have to adhere to. Popup flights can also receive a Company Calculated Take-Off Time (CCTOT) that gives an extra degree of freedom in assigning those flights a spot in the arrival sequence.
The results of an eighteen-day morning arrival wave case study simulation showed that the proposed model can achieve 12% of cost savings compared to the first-come-first-served algorithm, that is used currently in air traffic management. Despite the dynamic nature of the model, over 90% in all recalculations of the sequence the target time over the IAF does not change. This is beneficial for the stability of the sequence.

During live shadow running of the IPS model it became clear that given the model input, cost savings can be achieved. Currently, however, it is difficult to accurately predict the estimated time over the IAF, which is needed to successfully use the model in real operation. This deviation can go up to 5 minutes when calculated 2 hours in advance, which is too large to trial the model in real operation. Therefore further research should be conducted in which it should be investigated how to improve (the calculation of) this estimated time over the IAF. For example by looking into the possibilities of using ADS-C data or by automatically sending the estimated time over using ACARS.
Looking at the CCTOTs it turned out only two airports were feasible due to the requirement of adhering to the CCTOT within a margin of a maximum of three minutes. Therefore it could be investigated if this margin can go up, or how popup flights could adhere more to their target take-off times on smaller airports within the action horizon of the IPS model. Also it should be investigated what an optimal delay cost penalty for longer ground time should be. For example, a possibility could be to make it airport dependent.
A final recommendation is to stimulate data sharing between airlines and air traffic control. During setting up the shadow running of the IPS model, it became clear air traffic control has the same problem with inaccurate estimated times over the initial approach fix or flight information boundary. Airlines could therefore share their accurate estimated times in exchange for knowing the estimated times of other carriers.

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Appendices

A Monte Carlo Simulation

The performed case study shows the IPS model is working for a particular scenario, being a morning arrival wave at Amsterdam Airport Schiphol, where the traffic is coming from the West. To show the model will also work in other scenarios for Schiphol or any airport, a Monte Carlo simulation has been performed. This appendix briefly describes this simulation, by showing the set-up, results and a conclusion.

A.1 Simulation set-up

It is impossible to perform a simulation that includes all possible real world scenarios for all hub airports around the globe. Therefore it was decided to take a snapshot of flights from a real historic scenario at Schiphol and modify it such, that it will show the robustness of the IPS model.

The snapshot taken consist out of the following flights:

- 2 controllable long haul flights;
- 1 uncontrollable long haul flight;
- 2 controllable popup flights (including calculating CCTOTs);
- 1 uncontrollable popup flight.

In reality these six flights have a different Scheduled Time of Arrival (STA), but for this simulation the STAs were set equal to each other. In this way congestion is simulated, as all flights want to land at the same time, and thus want to be over the IAF at the same time.

To create different Monte Carlo simulations, three variables are slightly varied within each simulation run. The first variable is the moment in time a flight enters the action horizon. The second one is the amount of time connecting passengers will have at the hub. The last one is that the connecting time of passengers will dynamically change, simulating changes of EOBTs of outgoing flights at the hub. The last two variables are simulated using one variable, being the EOBT of outgoing flights which can be seen in equation 15. Here the dynamic connecting time is added to the STA which is fixed.

The two Monte Carlo variables are modelled as independent random variables that follow a normal distribution:

- X_i^{CT}: The connecting time $\forall\ i \in PAX^C$
- X_i^{MA}: The moment of appearance of an arrival flight i $\forall\ i \in F^A$

The normal distribution regarding the connecting time is based on taking the mean and standard deviation of all passenger bookings of the summer season of 2022 of KLM. For the appearance in the action horizon the mean and standard deviation of the difference between actual and scheduled arrival times are taken from the six chosen flights, based on a period from January 2010 until August 2022.

$$EOBT_j^{new} = STA + X_i^{CT} \quad \forall\ j \in F^D, \forall\ i \in PAX^C \tag{15}$$

A.2 Results

In the end 34 Monte Carlo simulation runs have been performed in which the IPS model calculated the most optimal sequence 229 times. As this Monte Carlo simulation sole purpose is to show the robustness of the model, it was decided to only use the total cost output per sequence calculation. To do this, the coefficient of variation is used to know how many simulation runs were needed. In equation 16 this coefficient can be seen. It is the division of the standard deviation of the model output and the mean value of the model output. When one plots the coefficient for each simulation outcome and it converges, enough simulation runs have been performed. In figure 15 the results are shown and it can be seen that after 100 sequence calculations (15 simulation runs) the coefficient has reached a stabilization. Therefore it can be said that the chosen 34 simulation runs are enough to show the robustness of the model.

$$c_v = \frac{\sigma(o)}{\mu(o)} \tag{16}$$

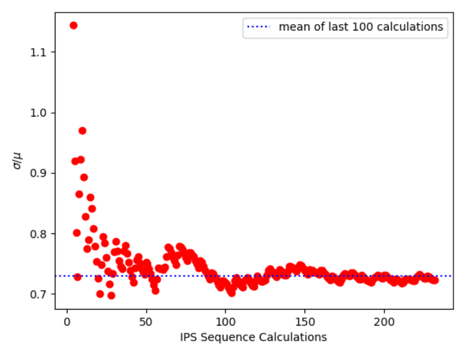

Figure 15: Stabilization of the coefficient of variation

II

Literature Study previously graded under AE4020

1

Introduction

Due to the nature of a hub-and-spoke carrier there exist inbound and outbound peaks. During these peaks the demand exceeds the capacity at the hub and the surrounding airspaces, causing traffic congestions and therefore delays. Especially for hub-and-spoke carriers this delay is harming their business case as it relies on connecting passengers that need to transfer to another flight at the hub. In case of missed connections, there is not only the cost of rebooking passengers or booking a hotel, but also passenger inconvenience cost and the fact he or she is more unlikely to book a ticket with the airline in the future.

In current practice there are measures in place to smoothen the demand (during peaks) in order to reduce delays. In Europe for example, flights can become regulated, meaning they will receive a Calculated Take-Off Time (CTOT) to which they have to adhere to. In the United States there is the Ground Delay Program (GDP) and Airspace Flow Program (AFP) that have the objective to absorb delays on the ground and in the air respectively. Then there are the short term measures where Air Traffic Control (ATC) gives speed restrictions or put flights into a holding. A current trend is to extend the 'horizon' of ATC in order to give speed restrictions to flights during their cruise phase in order to absorb arrival delays (E-AMAN: Extended Arrival MANager).

This brings up the topic of the Arrival Sequencing and Scheduling Problem (ASP). Currently ATC determines the arrival sequence based on the First Come First Served principle (FCFS). It entails the sequence is determined by the order in which arriving flights enter the horizon of control of the respective ATC unit. The reason for this is the equity principle that states no airline can be privileged over another airline. As this principle does not hold within an airline, flights could swap positions in the arrival sequence. The latter brings up the idea of sequencing the arrival flights from an airline perspective. Flights with a lot of connecting passengers on board are for example more important for an airline compared to flights with almost no connecting passengers. Another example is if the crew or aircraft itself needs to be used for a next flight with a short turn around time.

The aim of this literature study is to find out the existing possibilities of sequencing arrival flights from an airline perspective, especially during peak periods in which traffic bunches occur at the Flight Information Region (FIR) boundaries. The scope is to take the horizon of E-AMAN as a basis in order to give instructions in the form of speed restrictions or Target Times Over (TTO) waypoints to flights during their cruise phase in order to arrive smoothly in the optimal arrival sequence.

The remainder of this literature study consists out of two main chapters. It will start off with section 1.1. In this chapter necessary background information will be given that will enable the reader to understand the described problem in this introduction better. With this knowledge chapter 2 is about existing research in the field of Airline Scheduling and Sequencing. Common objectives, methods and subfields will be discussed. chapter 3 then gives concluding remarks that are based on both section 1.1 and chapter 2. These two chapters combined can give practical research gaps that form the basis of the final chapter: chapter 4. In this final chapter the research proposal for the thesis will be presented.

1.1. Background

This literature study is about mitigation of arrival congestions at Initial Approach Fixes (IAFs). The origin of the interest in this topic for this literature study comes from a large network airline in the Netherlands. During peak arrival periods several aircraft arrive at approximately the same time at the Flight Information Region (FIR) of the Netherlands. Air traffic control then sequences those flights, but an optimal arrival sequence from an air traffic control perspective may not necessarily be an optimal sequence from an airline perspective. From the latter perspective it may be beneficial to sequence a delayed flight in the beginning of the sequence due to connecting passengers for example. Also a part of the problem is the occurrence of so-called 'popup' flights that occur more frequently due to the implementation of the Extended Arrival Manager. The latter is a tool for air traffic controllers to sequence incoming aircraft in a more early stage (en-route versus whilst already in their descent). The former are flights that have a departure within the action horizon of an (extended) arrival manager.

The topic of this literature study falls within the domain of the Aircraft Sequencing & Scheduling Problem (ASP). This ASP considers both landings (Aircraft Landing Problem; ALP) and take-offs (Aircraft Take-off Problem; ATP). However, sometimes these three problems (ASP, ALP and ATP) are combined and called the Runway Scheduling Problem (RSP) [36]. Due to the fact this literature study will not focus on scheduling aircraft for a specific runway, 'ASP' will be mentioned through the rest of this report, except where otherwise is stated.

To be able to understand the concepts used in ASP this chapter provides background information for readers with little prior knowledge. This will be done be first giving an overview of the Air Traffic Management domain in section 1.2. This is followed by section 1.3 about the airspace structure and flight procedures within the Dutch FIR. Then in section 1.4 it is explained why airports and airspaces have a certain capacity. In section 1.5 it is explained briefly what type of airlines exist and on what type of airline this literature study focuses. With this knowledge, important timetable planning aspects will be touched upon in section 1.6. The second last section is about flight regulations (section 1.7) such as slot regulations at airports or arrival managers. The chapter concludes with section 1.8 about the effect of delays on (network) airlines.

1.2. Overview of Air Traffic Management Structure

Air Traffic Management (ATM) can be seen together with airports as the infrastructure for transport in the air and to fly safely from A to B [7]. Therefore it is necessary to introduce ATM within this literature review to be able to understand the current way of operating within the aviation industry. To achieve safe operation, ATM is highly regulated on both international and national levels. ATM is provided by the upper institutions called Air Navigation Service Providers (ANSPs). These ANSPs are from origin nationally based. However current trends (in Europe) move towards more European wide cooperation between different countries such as is the case with Maastricht Upper Area Control Center (MUAC) ANSP [24]. This cooperation is beneficial when using new technologies such as Extended Arrival Manager (E-AMAN). This E-AMAN will be discussed in section 1.7.1, but it comes down to regulate flights en-route in order to reduce congestions at their final destination.

In the Netherlands there are three ANSPs. For all upper civil airspaces that is Maastricht Upper Area Control Center (MUAC). For the lower civil airspaces it is Luchtverkeersleiding Nederland (LVNL). For all military airspaces it is the Royal Netherlands Air Force (RNLAF) [56].

ATM itself consists out of three parts being Airspace management (ASM), Air Traffic Flow Management (ATFM) and Air Traffic Services (ATS). ASM is about the location, design and use of all airspaces according to ICAO [33]. One can for example think of which airspaces are available for military or civil users. ATFM is about regulating traffic flows in such a way that Air Traffic Control (ATC) capacity is utilized to its maximum, whilst keeping in mind safe operations. This ATC is part of the ATS and is about preventing collisions and maintaining orderly traffic flows [33]. In fig. 1.1 an overview is given of the mentioned ATM parts. Please note that this figure is simplified for this literature study, as in reality more aspects are involved.

Another way of looking at the different aspects within ATM is by looking at the affected timespan before the operation of actual flights, which can be seen in fig. 1.2. The objective of each phase is to balance the capacity and demand in order to guarantee safe operations. To solve this issue, each phase has its own solutions. The strategic phase starts up to six months in advance. Within this phase planning is carried out between ATC

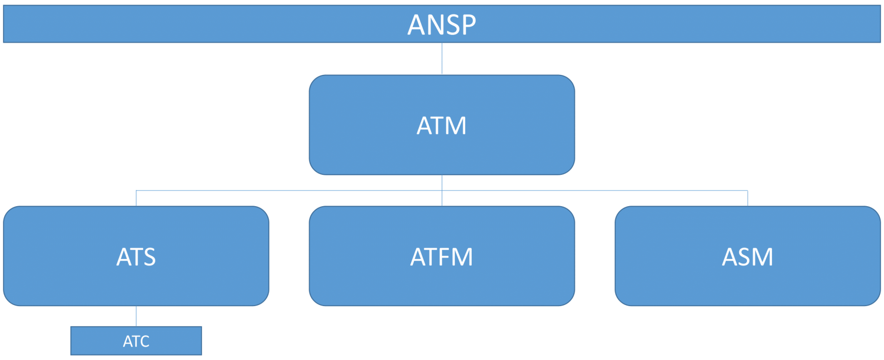

Figure 1.1: Simplified ATM structure for literature review purpose

and the aircraft operators. The demand for the upcoming period is determined and where needed actions are taken to assure no capacity demand imbalance. These actions consist out of:

- Making sure the ATC authority provides enough capacity;
- Reschedule flights if possible;
- reroute certain traffic flows;
- Identify possible (pre-)tactical ATFM measures.

The pre-tactical phase is up to a week before the actual operation. it is the fine-tuning of the previous phase. Certain traffic flows can be rerouted and decisions will be made about the tactical measures. Within this tactical phase during the day of operation, the measures of the previous phase are executed, and traffic flows are monitored to ensure the measures have the desired effect [34].

Figure 1.2: Different ATM phases [59]

1.3. Airspace Structure and Procedures in the Amsterdam FIR

As this literature study is about air traffic congestions at the FIR boundaries of the Netherlands (Amsterdam FIR), it is important to have basic knowledge about the airspace structure and procedures. The structure is explained in section 1.3.1 and the procedures are described in section 1.3.2.

1.3.1. Airspace Structure

Within the Amsterdam FIR there are several types of controlled airspaces that can be seen in fig. 1.3. This figure shows the situation for Schiphol (EHAM).

Control Zone (CTR)

Arriving and departing traffic in the vicinity of an airport (up to 8 NM and 3000FT) is protected by the CTR in which tower controllers give permission for landing or take-off.

Terminal Maneuvering Area (TMA)

TMAs are designed to protect traffic that is climbing from or descending to an airport. For descending flights this type of airspace connects the Initial Approach Fix (IAF) to the Final Approach Fix (FAF) after which control is handed over to the tower controller in the CTR.

Control Area (CTA)

CTAs are intended for overflights that follow airways ('highways' of the sky). However, due to the relative small size of the TMAs, Dutch CTAs have to deal with climbing and descending flights as well. Flights within the CTA are under control of Area Control Center (ACC). Schiphol has divided its CTA into five sectors which are shown in fig. 1.4. The reason there is no sector in the South, North and a small part of the East is due to the presence of military airspace.

Upper Airspace (UTA)

Within the upper airspace flights are in their en-route phase and follow airways. In the Netherlands the lower boundary of the UTA is defined as FL 245 (*24,500 feet*). Civil airspaces are under the control of MUAC and military airspaces are under control of RNLAF.

Control Area (CTA)

As with the UTA CTAs are intended for overflights that follow the different airways. However, due to the relative small size of the TMAs, Dutch CTAs have to deal with climbing and descending flights as well. Flights within the CTA are under control of Area Control Center (ACC).

Holdings

The only item not yet discussed of fig. 1.3 is the holding or stack. This is used when there is congestion and flights have to wait before getting clearance from approach control to enter the TMA.

1.3.2. Procedures

Schiphol has several departure and arrival routes. Departures are in the form of a Standard Instrument Departure (SID) that connects the runway to the initial point of an airway. The end of a SID is usually on the edge of the Schiphol TMA. Arrivals come in the form of a Standard Arrival Route (STAR). It connects the last route waypoint to the IAF. Schiphol has three IAFs [52]:

- ARTIP (near Lelystad);
- RIVER (near Rotterdam);
- SUGOL (above the North Sea)

These three IAFs together with all available STARs are shown in fig. 1.5. This figure is not indented to be read (size is too small), but to show that each IAF can be seen as a Point Merge System (PMS). All red lines are STARs which end at one of the three IAFs. This is important knowledge when developing a tool for optimizing the arrival traffic sequence at the FIR boundary, as it may be better to focus on the IAF instead. This thought could even be extended to the landing runway as there will be an additional PMS. Currently Schiphol has two types of PMS. The first type can be seen as the pre-sorting in fig. 1.5 where the PMS starts at the beginning of

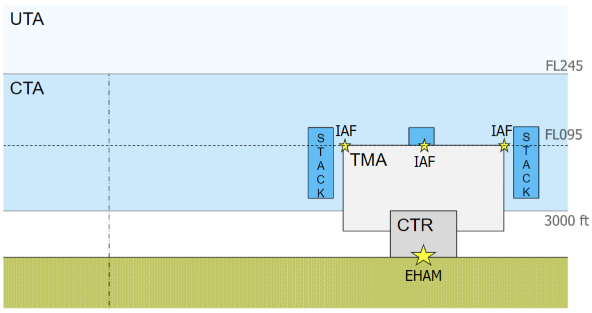

Figure 1.3: Simplified overview of the airspaces around EHAM [37]

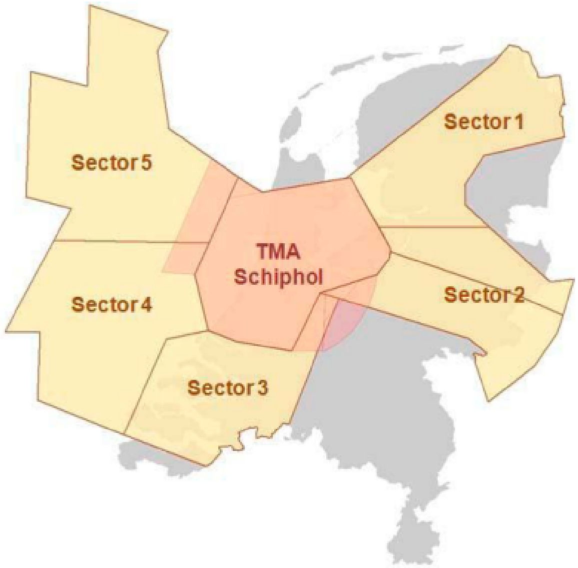

Figure 1.4: EHAM TMA and CTA sectors [56]

each STAR (mostly FIR boundary) and ends at the IAF. The second type of PMS is indeed sorting the flights for their landing runway, where these flights come from the different IAFs. This second PMS has an upper and lower boundary of 5500 FT and 2000 FT respectively. Furthermore the sequencing length is 13.5 NM [63]. The current way of operating these PMS is by means of the First Come First Served (FCFS) principle. This technique is widely used by ATC centers across the globe as it enables the equity principle among all different flight operators.

As this literature study focuses on creating an optimal arrival sequence from an airline perspective at the FIR boundaries, the first PMS should be taken into account when developing the model together with assuring the equity principle is not violated in favor of the particular network airline.

Airport Collaborative Decision Making
Airport Collaborative Decision Making (A-CDM, or CDM in short) is about improving the Air Traffic Flow and Capacity Management (ATFCM) at airports. Especially the start-up procedure is positively affected as limited resources (such as pushback trucks) will be used more optimally. This is done by including all different stakeholders and asking them to share relevant operational information with each other. These stakeholders are the airport itself, flight operators, ground handlers, network controller (Eurocontrol) and last but not least air traffic control [23][65]. Although it focuses primarily on the pre-departure and turnaround processes, it also contains information about arrival times, which makes it interesting for this thesis research. This estimated landing time could for example be used to determine the Estimate Time Over (ETO) the FIR boundary or IAF for all arriving flights. Later on in this thesis research, this could be used to ensure equity for all arrival flights, by ensuring non-network airlines will not negatively be affected in their landing times.

1.4. Capacity

Airports are complex and multifunctional traffic nodes of which the capacity is based on multiple aspects. Most of the time this weakest link is the runway capacity [27]. This is due to the fact the public is involved in increasing the maximum throughput time due to for example noise and CO2 emissions. In total, the airport capacity is influenced by the following actors [61]:

1. Weather;
2. Air Traffic Control;
3. Mix of the different types of aircraft;
4. Nature of operations;

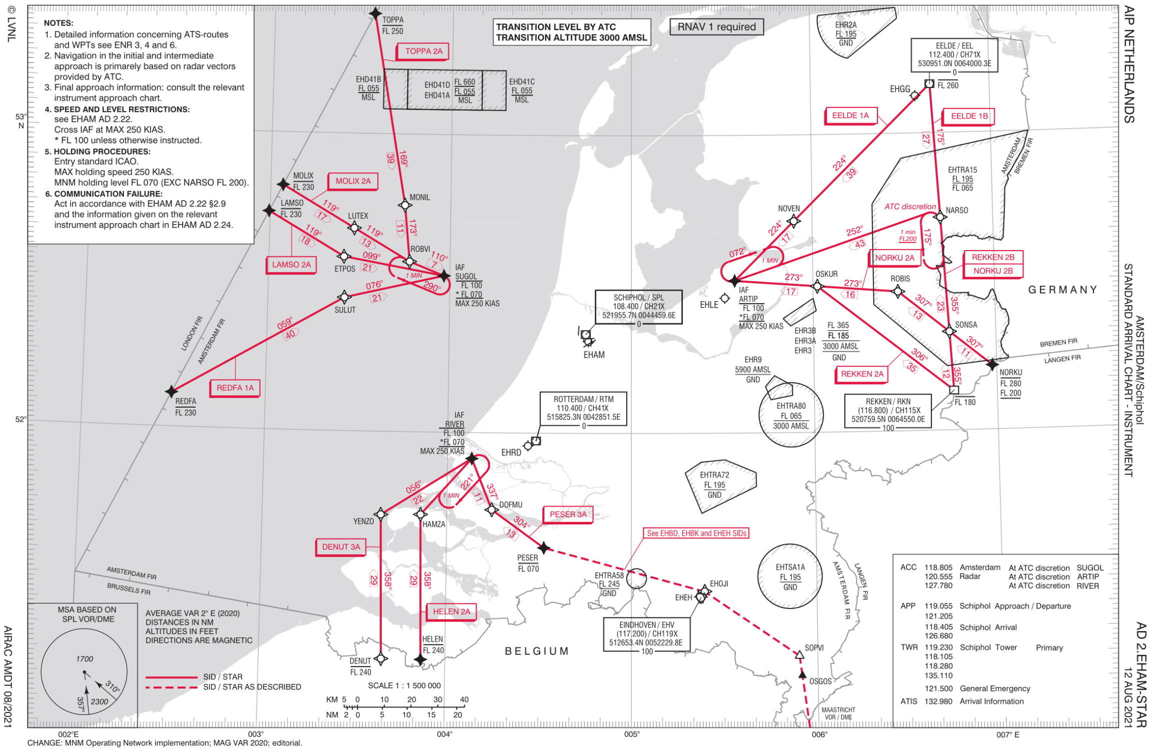

Figure 1.5: Standard arrival chart for EHAM [52]

5. Environmental conditions;
6. Runway System layout.

The first three items will be explained in more detail within this section. The final three are of less importance for this literature review as they are fixed by (4) the flight schedule of the airport, (5) the government, and (6) evolvement of history. One could say the mix of aircraft types is also fixed by the flight schedule, but in the sequencing process in the air, small adjustments can be made in favor of wake turbulence categories for example.

Weather

The weather can highly affect the capacity when there is low visibility, low ceilings or strong winds. Airports declare beforehand their capacity based on the weather predictions and airlines can act upon that. Still, chances are high flights will receive (additional) delay. In those cases it can be beneficial for an airline to have a decision support tool to see which aircraft has the highest priority to land. This can then be sent to air traffic control for example.

Air Traffic Control

Air traffic control is of importance as it 'steers' all the flights. This is done via speed restrictions, rerouting, holding, queuing and aircraft vectoring [41]. They also have to make sure the minimum separation distances are met for all flights, both longitudinally and vertically. These distances differ for en-route and approach [34]. For flights under Instrument Flight Rules (IFR) the minimum vertical separation below FL290 is 1000ft. Above FL290 it is 2000ft, except if Reduced Vertical Separation Minima (RVSM) are applied. The minimum longitudinal separation distances are shown in table 1.1. Note that on final approach depending on the Wake Turbulence Category (WTC) of two successive landing aircraft, different minima apply which can be seen in table 1.2.

Mix of different aircraft

Area	Situation	Separation Minimum
En-route	Same level and track	≥ 15 min
	Idem, but between two navigation aids	≥ 10 min
	Front A/C flies ≥ 20 kts faster	≥ 5 min
	Front A/C flies ≥ 40 kts faster	≥ 3 min
Under ATC surveillance	By default	≥ 5 nm
	If system's capabilities permit	≥ 3 nm
	Within 10 nm of RWY threshold	≥ 2.5 nm*

Table 1.1: Minimum distance between two aircraft [34]. *Depending on the WTC, different distances (in min) apply.

As already mentioned, depending on the WTC, there are different minimum separation distances during the final phase of the approach (or initial phase of departure). These minima are shown in table 1.2. Although this thesis is about optimizing a traffic sequence from an airline's perspective, the final approach minima can be taken into account in case it is beneficial to maximize the runway throughput.

Leader / Follower	A	B	C	D	E	F
A	3	4	5	5	6	8
B		3	4	4	5	7
C		*	3	3	4	6
D						5
E						4
F						3

Table 1.2: Minimum separation on approach and departure in nm based on WTC [22]. *can be set to 2.5 nm as mentioned in table 1.1

Schiphol has declared its capacity for all different type of landing and take-off runway configurations in a Quick Reference Card (QRC). This declared capacity depends on [51]:

- In-/outside Uniform Daylight period (UDP);
- BZO (Limited Visibility Conditions) A: visibility < 1.5 km and ceiling between 60 and 100 m;
- BZO B: visibility on runways ≤ 550 m and ceiling < 60 m;
- BZO C: visibility on runways < 350 m;
- BZO D: visibility on runways < 200 m;
- amount of controllers;
- Inbound-/outbound-/off-peak.

Depending on the weather forecast and own experience LVNL declares its actual capacity during the day. Sometimes the actual capacity will be less than according to the published QRC. During strong Westerly winds for example, runway 27 is used with a capacity according to the QRC of 38 flights per hour. In reality this will be around 30 flights per hour caused by a low taxi exit speed from the runway. This low taxi speed is needed due to the strong winds that blow against the vertical tail surfaces of aircraft, causing issues [19].

1.5. Different type of airlines

In the aviation industry it is hard or even impossible to come up with two identical airlines. [1] On one side there are charter airlines versus scheduled airlines. One can also differentiate airlines by their domain of service. Then there are major, national and regional airlines. Then there is the business model in which legacy airlines can be differentiated from (ultra) low-cost airlines. Also the ownership is different for each airline, some are public-owned, others are state-owned. For this literature review however, the most important feature, is the network structure. The two main distinct network structures, being a so-called hub and spoke network and a point-to-point network.

Point-to-point implies there is a direct connection between origin and Destination. With a hub and spoke system on the other hand, one travels from his origin via a hub to its destination. The benefit of a hub and spoke network is that with the same number of flights a bigger network can be served compared to point-to-point. This is visualized in fig. 1.6, but can also be proved mathematically. Suppose one wants to connect D destinations with each other. This results in $D \cdot (D-1)$ connections. To offer direct flights between all destinations $2 \cdot (D-1)$ flights are needed, whereas with a central hub $D \cdot (D-1)$ flights are needed.

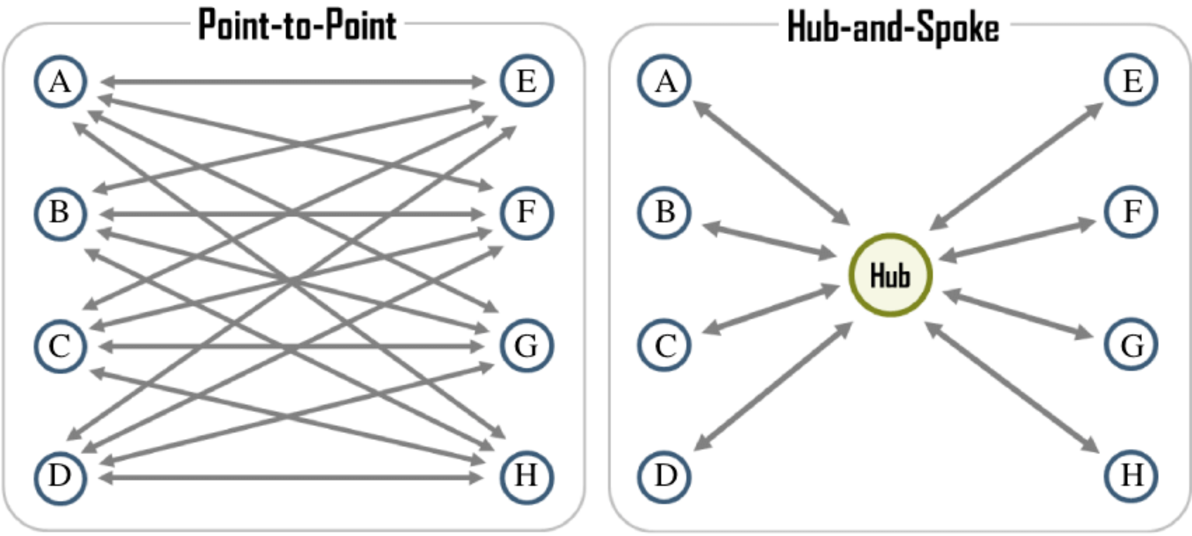

Figure 1.6: Visualization of the difference between a point-to-point and a hub and spoke network [67]

In literature the opposite of a low-cost carrier is often called a full service carrier where all kind of different services such as drinks and food are included in the ticket price. Furthermore, traditionally the name of full service carrier is often associated with hub and spoke whereas a low-cost carrier is associated with a point-to-point network. However, due to competition the traditional business models are subjected to change and distinctions are becoming more vague. [46] Therefore it is decided to name a hub-and-spoke carrier within this literature review report a network airline or network carrier instead of a full service carrier.

1.6. Network Airline Timetable Planning Aspects

This section is not about the process of creating a timetable, but is meant to provide the reader necessary background information to understand the problem statement of the thesis. Regarding the timetable planning it is important to know it is part of the broader scheduling development process which consists out of [9]:

- Frequency planning;
- Timetable development;
- Fleet assignment;
- Aircraft rotation planning.

Frequency planning is about how often an airline should fly a selected route. For this thesis this is not of importance. The timetable development on the other hand, is of importance. It is about scheduling the times of departure which can result in traffic bunches. The fleet assignment is about which type of aircraft should be used, and the aircraft rotation planning is about how to balance each aircraft type within the network. These latter two are also not of importance for this thesis.

Time banks

A network airline uses a hub and spoke network. A core feature of this is a time bank (or sometimes called a wave). They align scheduled flights at a hub, by maximizing the amount of connecting traffic [1]. This means it is tried to maximize the amount of possible ODs for passengers. A schematic visualization is given in fig. 1.7. When creating a time bank a couple of things should be taken into account, first of which the Minimum Connecting Time (MCT). This MCT indicates the minimum time needed to be able to catch a connecting flight. it can be determined per city pair and includes a buffer time. This buffer time makes sure the incoming flight can arrive with a small amount of delay, without passengers missing their connection. The opposite of the MCT is the maximum connecting time. One can imagine passengers do not want to wait for too long before going onto their connection. Then there is the choice how to connect the different city pairs. During the day there are several time banks, some of which where the incoming flights are coming from the West, others of which the incoming flights are coming from the East for example. One of the limitations of these time banks is congestion at the hub due to the large amount of flights in a short time period [1].

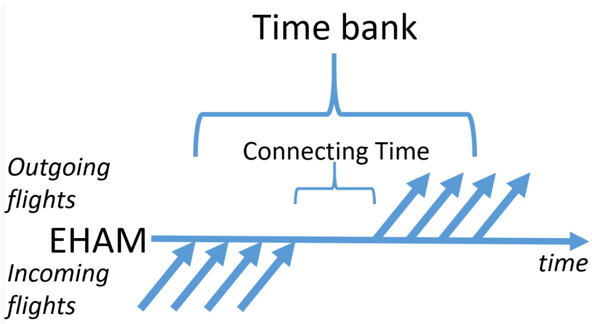

Figure 1.7: Illustration of a time bank

fleet and crew assignment
When the timetable is created, tail numbers (aircraft) and crew have to be assigned to flights. The process of assigning crew and tail numbers is out of the scope of this literature review, but one has to know aircraft have an entire schedule on its own just like crew. If an incoming flight is delayed, not only the transfer passengers can be affected, but also the next flight with the aircraft itself and/or the next flight with the crew of the incoming flight. A global overview of the scheduling process after having published a timetable is shown in fig. 1.8.

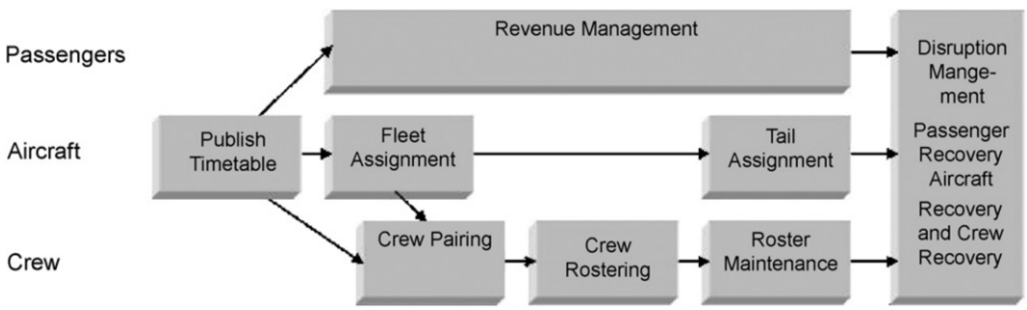

Figure 1.8: Simplified illustration of the airline scheduling process [45]

1.7. Flight Regulations

A few days until a few hours before operation ATFM will regulate traffic in order to guarantee capacity constraints are not violated. This regulating of traffic is done by the Central Flow Management Unit (CFMU) and is based on filed flight plans. If the demand is higher than the capacity in certain bottlenecks the CFMU can make flights 'regulated', meaning those flights will get a Calculated Take-Off Time (CTOT) to which they have to adhere to with a margin of - 5/ + 10 minutes. With these CTOTs the CFMU can spread out the demand [4]. In the United States there is the Ground Delay Program (GDP) and Airspace Flow Program (AFP). Controlling congestions at airports is then done via GDPs which can be seen as the equivalent to the European CTOTs. Changing speeds, routes and altitudes is then done using the AFPs. The GDP and AFP have the same objective, being to absorb delays (caused by capacity-demand imbalance) on the ground and en-route rather than in the TMAs [38]. One of the drawbacks of using a GDP is that airports itself become capacity bottlenecks.

The above-mentioned regulations are meant to make use of the available capacity as optimal as possible. In practice this sometimes does not function properly. If a flight is delayed by a CTOT for example, the flight crew will try its best to speed up during the flight in order to arrive on schedule again [13]. This results in unpredicted traffic bunches [41] which is part of the topic of this literature review.

In the remainder of this section one can read about the (Extended) Arrival Manager in section 1.7.1 where the so-called 'popup' flights will be introduced as well. Regulation by means of slots at airports is discussed in section 1.7.2.

1.7.1. (Extended) Arrival Manager

To reduce the workload for air traffic controllers there is the Multi-Center Traffic Management Advisor (McTMA) and arrival manager (AMAN) in the United Stated and Europe respectively [70] [66]. AMANs create an optimal arrival sequence based on the input of an air traffic controller. It takes into account the predicted landing times and the wake turbulence categories. Therefore the Aircraft Landing Problem (ALP) is the theoretical core of AMAN [50].

While flights can enter holdings close to the TMAs, en-route they are also allowed to receive speed restrictions and detours. These detours and speed restrictions mostly result in 'linear' holdings which are preferred in terms of safety. As these linear holdings are most effectively when flights are still en-route the AMAN's horizon (typically around 200 NM, 40 minutes prior to landing) is extended up to 500 NM or up to 2 hours prior to landing. This new system is the so-called Extended Arrival Manager (E-AMAN) [42].

This E-AMAN is currently being investigated in the Dutch airspace redesign program [57] which can be seen as a roadmap towards the year 2035. The goal is that E-AMAN will be used in combination with Continuous Descent Arrivals (CDA) and Trajectory Based Operations (TBO) which will result in more efficient flight paths (reduction of fuel usage and emissions). Especially in the Amsterdam FIR this E-AMAN would be beneficial due to the limited scale of the Amsterdam FIR in which only AMAN can be used. This is emphasized by the fact an important aspect of AMAN is the planning phase which is created ideally when a flight is still in its en-route phase [57]. In fig. 1.9 the E-AMAN concept is shown for Schiphol where the ranges are still smaller than described in the previous paragraph, namely 100 NM (180 km) for the AMAN and 190 NM (350 km) for E-AMAN.

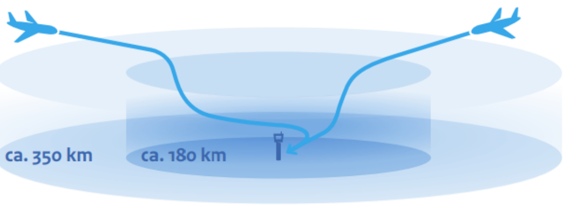

Figure 1.9: AMAN (inner block) versus E-AMAN (outer block) for arrival flights at EHAM (concept)[57]

In E-AMAN (or advanced AMAN) the ELDT is of importance. This time is then used to calculate back the ETO for all route waypoints using a trajectory predictor. It is then made sure minimum separation between flights will be assured and flights will be merged when entering their IAF. This merging will be realized with the help of TBO. Therefore a number of waypoints need to be defined in the pre-arrival area to which a flight can be redirected [57].

Although this E-AMAN concept results in less fuel burn for flight operators and a reduction of workload for air traffic controllers, nothing is said about the sequence in which flights will be entering the IAF. Therefore it could still be beneficial for flight operators to use a decision support tool with which they can pre-sequence their flights already.

Popup flights
Popup flights are short haul flights that depart within the horizon of AMAN. This causes challenges for air traffic control as the already existing arrival sequence within the AMAN horizon needs to be altered to make space for a popup flight (Visualized in fig. 1.10). One can imagine that with the introduction of E-AMAN this problem only increases. Currently there are three ways of coping with these popup flights [73]:

- Only once popup flights are airborne and are captured by radar, they are included in the arrival sequence, meaning rescheduling the existing arrival sequence;
- Slots are reserved for popup flights beforehand in the arrival sequence;
- Popup flights are delayed on the ground until there is a slot available in the arrival sequence.

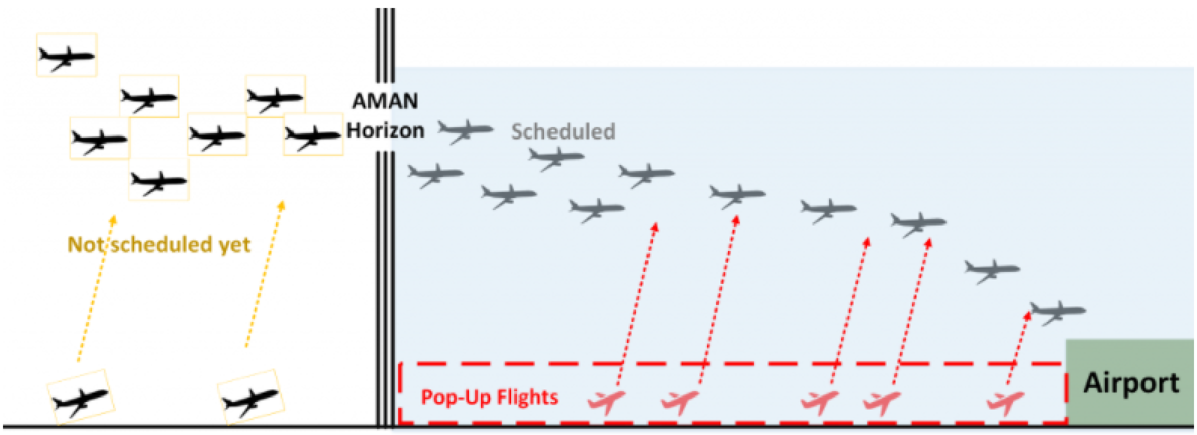

Figure 1.10: The problem of popup flights visualized [72]

1.7.2. Slot Coordination
Slots are used to regulate the amount of flights at airports. It gives permission for a flight operator to take-off or land at an airport on a particular day and particular time and is based on planned operation[2]. This permission is therefore something different from landing or take-off clearance received from ATC which is about the actual operation. There are three different levels indicating the degree of congestion at airports, being [2][14]:

Level 1 There is sufficient capacity to meet the demand. These type of airports are called 'non-coordinated';

Level 2 There may be certain periods in which demand reaches a capacity limit, but systematic delays are prevented due to a voluntary schedule-facilitation process. These type of airports are called 'schedules-facilitated';

Level 3 Without regulation demand would exceed the available capacity significantly. Therefore these type of airports are under slot control and are called 'coordinated airports'.

Schiphol is a level 3 airport and one of the most restricted airports in the world. Airport Coordination Netherlands (ACNL) is the slot coordinator in the Netherlands and monitors strictly the maximum amount of allowed flights (500,000). Also there are night restrictions which are strictly being monitored.[44]

If a flight operator gets a slot, it should make sure to obtain the so-called grandfather rights. These can be obtained by flying at least 80% of all planned flights and result in the ability to keep the slot. In case less than 80% is flown, there is the risk of losing the slot which then can be used by other flight operators [44].

1.8. Effect of delays on airlines

Although objectives of the ASP differ from each other, the core remains the same. That is, given an inflow of aircraft, trying to optimize this flow as efficient and effective as possible [75]. Minimizing delay is one objective. But to be able to do so, one has to first understand the concept of delay and the effects of delay. This is done by first briefly describing different types of delay in section 1.8.1. Then the way of dealing with delays within an airline is explained in section 1.8.2. Finally the costs related to delays are briefly touched upon in section 1.8.3.

1.8.1. Different Type of Delays

At the highest level there is the departure delay and the arrival delay. these are computed by subtracting the scheduled departure/arrival time from the actual time. The problem of this lies in the fact, it hides the cause of the delay. Therefore one can divide delays (or disruptions) into three main categories being [47]:

- Propagated disruptions or reactionary delays: Past delays propagate through the spatial-temporal network;
- Systematic disruptions: demand-capacity imbalance causes congestion (at the hub);
- Contingent disruptions: other inefficiencies like maintenance or late boarding.

In 2019 reactionary delays were the main type of delay (44.4%). For each minute of primary delay, the reactionary delay turned out to be 0.8 minutes [20]. This number is not available for the year 2020 in [21], most probably due to the impact of Covid. In fig. 1.11 a root delay causing reactionary delays on consecutive flights of a single airline is shown.

Also in 2019, the total en-route ATFM delay was 17.2 million minutes in the area of Eurocontrol and these minutes of delay affected 9.9% of all flights [21]. The average delay these 9.9% of flights experienced was 15.8 minutes [20]. 43.9% of the experienced en-route ATFM delays were caused by ATC capacity, 24.3% due to ATC staffing, 7.2% due to ATC Disruptions and 21.2% due to weather (the other 3.5% is miscellaneous) [20].

1.8.2. Disruption Management

Disruption in the airline operation can have various sources. It is the task of the Operation Control Center (OCC) to minimize the impact of those disruptions. This is mainly done via the following operations [68]:

1. Delaying flights. In fig. 1.11 this implies delaying the departure times of the light-gray colored flights;
2. Cancelling flights. Usually this is the last option left due to high costs;
3. Swapping resources. This can imply swapping aircraft and crews, but at coordinated airports slots can also be swapped;
4. Using reserved resources. A spare aircraft could replace another aircraft and crews on stand-by can take-over flights;
5. Deadheading and ferrying. Deadheading is crew that is taking a flight as a passenger in order to arrive at another airport. Ferrying is flying an empty aircraft. As with cancellation of flights, high costs are associated with these operations;
6. Speed controlling. Flight time is influenced by speed control. The two extremes are High Speed Flying (HSF) and Low Speed Flying (LSF);
7. Passenger reallocation.

Normally multiple recovery operations are used simultaneously. If the complexity of the disruption increases, the recovery problem is split in (1) aircraft recovery, (2) crew recovery, and (3) passenger recovery. These are then solved sequentially [68]. When using decision support or decision-making tools, it should provide solutions within one or two minutes [76].

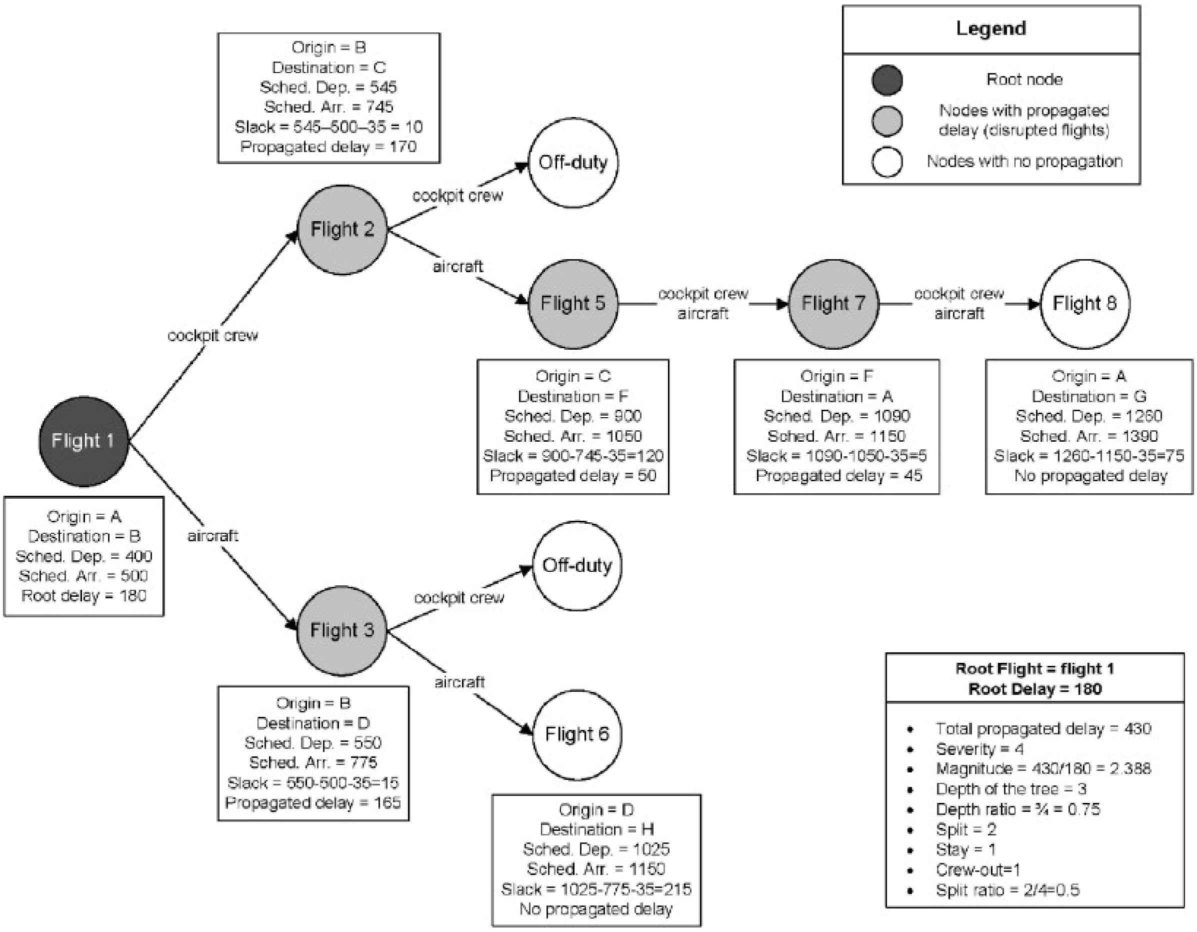

Figure 1.11: Visualization of a root delay causing reactionary delays [3]

1.8.3. Costs

Delay results in extra costs for airlines. These costs relate to passenger compensation or rebooking, but also the costs for additional fuel burn for example. Quantifying these costs can be hard as there is not only the direct impact, but also future revenue loss as passengers may not want to fly anymore with an airline if they had a delayed flight. These 'hidden' costs are called soft costs [16]. In total there are three types of delay costs [15]:

- hard costs: measurable such as additional fuel burn, passenger reallocation and passenger compensation;
- soft costs: loss of future revenue due to passenger dissatisfaction;
- internalized costs: borne by the passenger and not the airline. One can think of missing an appointment due to late arrival of a flight.

Andrew Cook has done quite some research on the topic of delay costs for airlines. He was one of the first investigating the hidden (soft) costs of delays in [16]. Also he established a reference list of the total cost of passenger delay based on the delay duration and aircraft type in [15]. These costs range from 10 euros for a 5-minute delay in a ATR 43 to 167,050 euros for a 5-hour delay in the Boeing 747. These costs also includes the European rules about passengers delay claims from [71]. Lastly, he established reference values for delay costs in [6]. The topics of [6] are:

- Fuel cost;
- Maintenance cost (per block hour);
- Fleet cost (per block-hour);
- Crew cost;
- Passenger cost (both hard and soft);
- Tactical delay cost;
- Strategic delay cost.

Unfortunately these reference values from [6] and [15] originate from 2015. One possible way to make them accurate is to correct for inflation. This however does not compensate for newer aircraft types or changed regulations about passenger delay compensation.

2

Existing Research

As already described in the introduction of section 1.1 the topic of this literature study falls under the Aircraft Sequencing & Scheduling Problem (ASP). This problem deals with the fact that there is a given incoming flow of aircraft that needs to be sequenced in an efficient and effective manner. In describing existing research in this field, two papers form the backbone. The first being [11] written by Julia A. Bennell where a comprehensive overview is given of different approaches to the problem from literature. The second is [36] written by Sana Ikli. The paper shows 'a focused review on the most relevant techniques in the recent literature on the RSP (Runway Scheduling Problem)'[36]. It continues where [11] stops (the year 2010). Also there is the master thesis of Robin Vervaat that investigated the deterministic case of optimizing arrival sequences by giving en-route speed restrictions. This thesis was performed in the year 2020 and its literature research is also used in this section. Furthermore his thesis will be elaborated extensively in section 2.3.2.

The ALP can be formulated as a Mixed Integer Program (MIP). Finding an exact solution however, can be time-consuming due to the fact the problem is NP-hard[11]. To come across this, several metaheuristic methods have been implemented. The current trend is that these metaheuristic methods are combined with mathematical programming, resulting in methods called matheuristics [36]. Heuristic methods are also in favor due to the dynamic nature of the problem. An optimal solution may not be optimal anymore when a new aircraft arrives at the boundary of the (simulation) horizon, for example. Lastly, in reality an exact method is not possible as there is always some form of stochastics involved.

The sections below are structured as follows. In section 2.1 common objectives in the field of the ASP are shown. This is followed by section 2.2 in which different modeling techniques and algorithms are discussed. Then in section 2.3 relevant actual research is shown. In its subsections the different application areas will be discussed.

2.1. Objectives

The objective of the Aircraft Sequencing & Scheduling Problem can be categorized into three main categories: optimization type, stakeholder type and area of optimization. Firstly the optimization type can be time based or cost based optimization. The stakeholder type is discriminated by the perspective of different stakeholders, being airports, air traffic controllers, airlines, and the government as described in [11]. Lastly the area of optimization can be either global or local optimization, which causes different positions for individual flights within the arrival sequence. In the remainder of this section several objectives from literature will be mentioned. If no source is given, it comes from [11], [36], or [75].

Minimize Makespan

[8] was one of the first addressing the ASP. In doing so, he also mentioned the objective of the minimization of the maximum landing time which comes down to minimize the time in the queue for a flight. Still, this objective is common in research as it maximizes the use of available resources at airports. Therefore, from the airport perspective the objective could be altered to maximize the (runway) throughput time. It is also mentioned in literature the workload for air traffic controllers is reduced by minimizing the makespan due to

the fact flights spend less time in the air.

(Weighted) deviation from scheduled arrival
There are different ways of incorporating deviations from scheduled arrival or departure times. One could for example minimize the total schedule deviation where early arrivals are penalized as well. However, for an airline not all flights are of equal importance. A flight with a lot of connecting passengers is more important compared to a flight with no or only a few connecting passengers. Therefore a weighted deviation from the schedule could be used.

Incorporate different stakeholders
Different stakeholders are involved in the arrival process such as the airlines, air traffic control, the airport, and even the government. All of these stakeholders have a different view on how the arrival sequence should look like. To include this in the ASP, bi- or multi-objectives could be used. One research that does this is [12] where the airline is included by minimizing the fuel costs, ATC is included by maximizing runway capacity, and the airport is included by maximizing punctuality. Then a weighted sum is taken to arrive at their solution.

Passenger cost
There are different ways of incorporating passenger costs. As explained already in section 1.8.3 there are different types of cost involved such as hard and soft costs. In literature the ASP is sometimes taken broader into disruption management where departing flights can be delayed in case of connecting passengers from a delayed arrival flight [64].

Fuel Cost
A major cost component for airlines is fuel. Therefore minimizing this, results in more profit or less delay costs. Often there is a trade-off to delay and fuel. Flying faster means catching in a delay, but burning more fuel. To overcome this problem, an objective of minimizing the total cost for an airline can be used where both fuel cost and delay cost is included. Along with minimizing fuel cost, the environment is also incorporated. Burning less fuel is beneficial for the environment.

Adherence to airline priorities within their own flights
Passenger and fuel cost are already mentioned, but there are more costs involved. Items to consider are for example the crew itineraries, but also the itineraries of the aircraft itself. Also given an arrival sequence and slots within this sequence for a particular airline, this airline could optimize the use of these slots by swapping flights.

Fairness among airlines
In aviation there is the principle of equity which means that no airline can be privileged over another airline. This is also the reason air traffic control mostly uses the FCFS principle. If however a slight deviation is possible in favor of the hub carrier of a particular airport, an objective could be to minimize the amount of position shifting within the arrival sequence. This is realized by Constrained Position Shifting (CPS) where it is only allowed to shift a maximum amount of places within the sequence.

Concluding remarks
The most profound objective in literature is the one of minimizing the makespan. In recent literature however, the objectives become more complicated by incorporating multiple aspects or stakeholders (multi-objectives). This results in a more allround-like solution. The downside however, is that the problem becomes NP-hard which is more difficult to solve.

2.2. Modeling Methods & Algorithms

This section is about the different modeling methods and algorithms used in the ASP. It is divided into an 'exact' solving part (section 2.2.1) and 'stochastic' part (section 2.2.2). However, some research does not fall necessarily in one of these two sections or incorporates both. section 2.2.3 is delegated to this other research.

2.2.1. Exact Methods & Algorithms

The most used exact methods in literature make use of MIP or Dynamic Programming (DP). However, constraint programming is also sometimes used and therefore mentioned in this section. The survey on the RSP of Ikli et al. ([36]) is used as a basis for this section.

Constraint Programming

In [25] Fahle et al. compare exact and heuristic methods that address the ASP. The methods are compared based on their quality, speed and flexibility. The problem formulation is based on the work of Beasley ([8]). They found out that constraint programming is very powerful, but by far the slowest method. Furthermore Francisco et al. found out in [18] that constraint programming results in high memory usage. Still they built a feasible application for the ASP. For the interested readers, Alligbol et al. performed a survey on constraint programming in ATM problems, including the ASP [5].

Dynamic Programming

DP is used in order to reduce the computational expense by taking into account previous partial solutions. Due to the nature of the ASP where estimate arrival times improve over time, or where popup flights interfere to an existing solution, DP can be used. Also in case of using CPS with a maximum amount of position shifts, DP is a feasible technique. The first time DP is used in literature was in 1978 where Psaraftis implements it for the ASP [60]. In recent literature DP is also used for multi-objective functions. In [12] this is the case for optimizing the arrival sequence where different stakeholders are included.

Mixed Integer Programming

MIP forms the backbone within the area of ASP. Beasley et al. in [8] is one of the most cited publications where a MIP approach is used in the context of ASP. This publication forms the basis for most publications that followed by extending the work, or by comparing new methods with this baseline MIP formulation.

2.2.2. Stochastic Methods & Algorithms

According to [36] before 2010 genetic algorithms were used the most. In more recent literature Tabu search and simulated annealing took over the genetic algorithms.

Algorithms inspired by nature

In literature the use of genetic algorithms and ant colony optimization can be found. Both are inspired by nature. The former refers to the subject of evolution or 'survival of the fittest', where randomly generated solutions are generated and evaluated in each successive instance [75]. The latter refers to the natural searching movements of ants [75]. Sometimes both approaches are combined. Bencheikh et al. for example [10] use the ant colony optimization to generate an initial solution. Then the genetic algorithm takes over and continues to find a final solution.

Tabu search

Furini et al. use a MIP and a Tabu search for the ASP [26]. The Tabu search method finds a solution by a permutation in the set of aircraft. Finding a neighborhood solution is then obtained by either a swap move or a shift move. The former refers to swapping the position of two aircraft, and the latter refers to moving an aircraft to a new position.

Variable neighborhood search

Variable Neighborhood Search (VNS) is often used in vehicle or personnel scheduling. It is robust, simple, and the algorithm is easy to implement [58]. In [58] Ouyang and Xu present a VNS for scheduling aircraft in a multi-runway terminal area. Compared to results using other algorithms (among which genetic algorithm) VNS can find better solutions within less time.

Simulated annealing

Simulated annealing is also sometimes used in literature. Rodriguez-Diaz et al. for example apply it to the ASP in [62]. By means of swapping aircraft positions, candidate solutions are found. They use the principle of CPS. For a large maximum allowed number of position sifts, their simulated annealing algorithm can improve up to 30% compared to real data [36]. Hybrid methods are also possible. For example by combining simulated annealing with iterated local search to escape from local optima [29].

2.2.3. Other Methods

Besides the aforementioned methods, three other methods are worth mentioning, being agent based modeling, machine learning and dynamic scheduling. Especially the latter is an interesting area of research as it includes uncertainties in the ASP.

Agent Based Modeling

When including different stakeholders Agent Based modeling (ABM) can be used to let negotiate these different stakeholders. Especially when implementing CDM principles, ABM can be used. In [54] this is done in combination with the usage of stochastic approaches in the CASSIOPEIA project. Focused on reducing costs and airline delays in the context of E-AMAN and hub operations, [17] published an ABM model. The output of their model is based on samples of random variables with unknown distributions. Therefore statistical analysis is required to consolidate the simulation results.

Machine Learning

One of the latest developments is using machine learning or the ASP. Ikli et al. applied for example machine learning techniques to the aircraft landing problem in [35]. Their approach fills in the gap caused by MIP approaches for large sample sizes regarding computation times. Reinforcement learning is also sometimes used according to [36]. This includes aircraft representing 'agents' and available positions correspond to 'states'. Actions are to delay aircraft whereas rewards are minimizing the delay encountered.

Dynamic scheduling

Most of the work in literature regarding the ASP deals with a static case which means all information about all flights in known beforehand. However, in reality this is of course not the case as various types of uncertainties exist. In [39] Xiao-Peng et al. propose an evolutionary approach, being addressing the ASP dynamically. This is done by decomposing the problem into a sequence of smaller sub-problems. In most literature this subdividing is realized by making use of Receding Horizon Control (RHC). These sub-problems are then however static. Therefore [39] makes use of a Dynamic Sequence Searching and Evaluation (DSSE). When solving the sub-problems, the DSSE makes use of the Estimation of Distribution Algorithm (EDA). Then a distance-based exponential probability model is used to calculate the assigned landing times for each flight. Although not explicitly mentioned, this research incorporates 'popup' flights as the DSSE will re-iterate to come up with a solution if a new aircraft enters the TMA. This can be seen in fig. 2.1. However, this research has a limited action horizon. This is done as the uncertainties of the estimate landing times of the aircraft will then be lower compared to the estimated landing time during cruise.

Another research concerning dynamic scheduling is that of [31] where Hong et al. implemented a two-stage stochastic method based on swarm optimization. The first stage makes decisions for uncertain parameters under incomplete information. The second stage then performs the remaining decisions after the uncertain parameters are known. The results show their approach is less conservative compared to deterministic approaches, however for real-life applications the computation time is too large. Also they did not include speed changes for aircraft which are therefore suggest for further research. Liu et al. build on this work in [49]. They realized there is very limited information available about probability distributions of aircraft arrival times. Therefore they relieve the assumption of exactly knowing these distributions. Their conclusion is similar to [49], being their approach takes a significant amount of computational effort.

2.3. Relevant Research And Its Applications

With all the different objectives and existing methods and algorithms, one can have a look to the area of application of the Aircraft Sequencing and Scheduling Problem. The first subsection (section 2.3.1) is delegated to popup flights. This is followed by section 2.3.2 about using speed restrictions to determine an arrival sequence from an airline's perspective. Then research in the field of airline delay management will be discussed in section 2.3.3. Last but not least the interesting area of incorporating uncertainties in determining an arrival sequence is shown in section 2.3.4.

2.3.1. Popup flights

As already mentioned in section 1.7.1 popup flights cause challenges for ATC. Literature about these flights are rare, but luckily one paper was found. Vanwelsenaere investigated the effect of popup flights within the

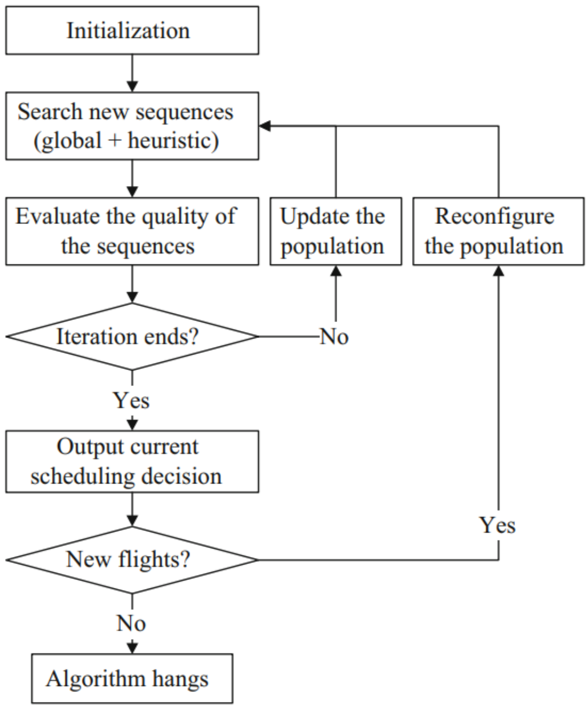

Figure 2.1: Flowchart of the DSSE [39]

horizon of E-AMAN [74]. He first found out that under AMAN 1.8% of all flights are popup flights at Schiphol. With E-AMAN this increases to 10.8%. Using simulations in the open source ATM simulator BlueSky Vanwelsenaere then found out that popup flights have a significant effect on the stability of the arrival sequence and delay costs. Also the workload of ATC and the flight crew is increased. During these simulations a baseline scheduler was compared with a pre-departure scheduler. It turned out that pre-planning a popup flight within an arrival sequence is beneficial for ATC and crew workload, but the actual take-off time cannot deteriorate more than two minutes from the Target Take-off Time (TTOT). If the deterioration is larger than these two minutes, it turns out to be more beneficial to only plan a popup flight in the arrival sequence once airborne. These results are similar to the ones coming from a NASA study [70] about the equivalent of E-AMAN in the USA: Multi-Center Traffic Management Advisor (McTMA). The results of Vanwelsenaere hold for peak periods. Off-peak periods have not been investigated.

2.3.2. Arrival Sequencing Using Speed Restrictions from an airline's perspective

Most research done about the topic of speed restrictions concerns the trade-off between making up a delay versus additional fuel burn or by moving the ground delay problem to the air in order to relieve resources on the ground. Two papers are however found with the exact same topic as this proposed thesis. The first paper [48] is written by Dr. Reinhard Lernbeiss who is both an engineer as an airline captain, resulting in both theoretical and practical knowledge. It must be said the idea of his research is not worked out on an academic level, which may come due to the fact it is a conceptual paper. Still, his work will be discussed as the global method could be used to extend upon. The second paper is written by Robin Vervaat as a master thesis at Delft University of Technology [75]. Both papers optimize flight speeds during the cruise phase in order to arrive in a sequenced manner at the IAF, where the sequence is optimized from an airline's perspective to optimize the arrival costs ([48]) or to prevent congestion, reduce costs and maximize profit ([75]).

Lernbeiss

Lernbeiss' research is based on the prevailing situation that the OCC decides to speed up flights in case of passengers with critical connections. This however happens without evaluating the overall costs like extra fuel burn. Furthermore, it can result in an even worse traffic bunch at the IAF. The objective function is shown in eq. (2.1) where C is the sum of all costs. The first part of the equation ($f_{Flight;PAX;Ticketprice}(t_{Flight;PAX})$) is a negative yield cost function that is time-dependent. it includes the ticket price of a passenger (PAX) on a certain flight. The time dependence comes from connecting passengers, reflecting possible opportunity costs in case of delays. The second part ($f_{Flight;PAX;Cost}(t_{Flight;PAX})$) deals with the cost for a missed connection or connecting a passenger to a next flight. The final part ($f_{Flight;Costs}(t_{Flight})$ deals with the operating cost of the aircraft depending on the cruise speed and arrival time. Unfortunately the paper does not discuss the algorithms and functions behind the mentioned cost functions. It only states that some cost functions are dependent on each other.

$$C = \sum_{Flights}\sum_{PAX} f_{Flight;PAX;Ticketprice}(t_{Flight;PAX}) + \sum_{Flights}\sum_{PAX} f_{Flight;PAX;Cost}(t_{Flight;PAX}) + \sum_{Aircraft} f_{Flight;Costs}(t_{Flight}) \tag{2.1}$$

The optimization method itself is not mentioned, only that it is 'a simple method to find the minimum cost or maximum profit varying the speed of all aircraft'[48]. Due to the fact the sum of all (cost) functions is nonlinear, several iterations are performed to get results. Still, in some cases it is not possible to obtain a solution. This is then due to the fact of finding a local optimum instead of the global optimum. The objective function is visualized in fig. 2.2 where the local optima also can be seen.

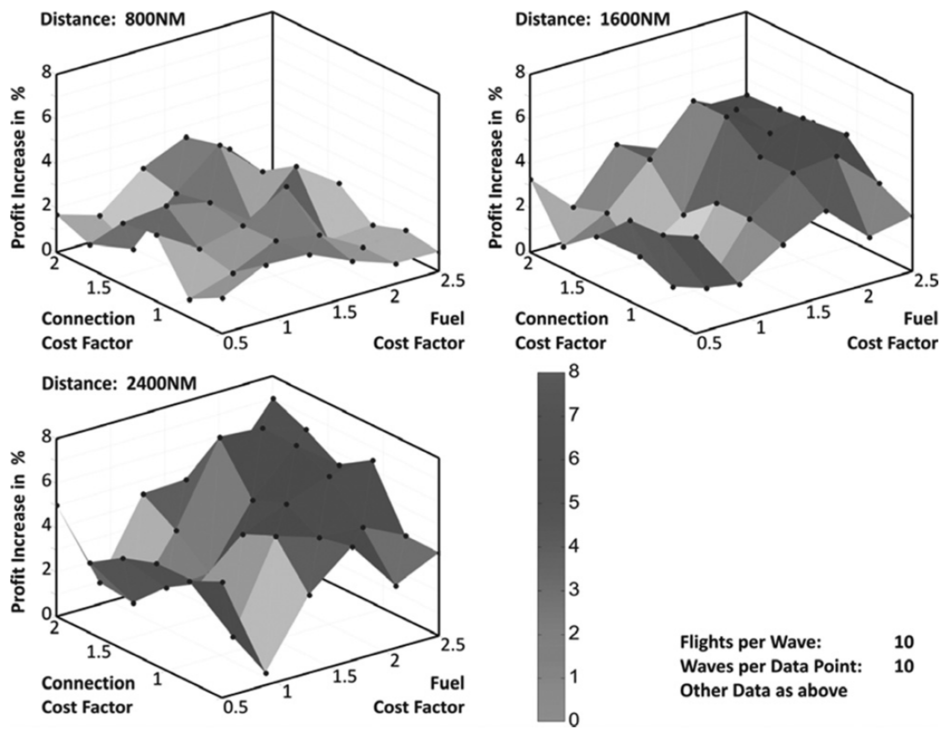

Figure 2.2: Results of Lernbeiss including profit increase, connection cost factor and fuel costs at different distances from the destination [48]

To simplify the model Lernbeiss uses randomly chosen load factors between distinct limits and uses an identical fleet of aircraft. Furthermore, no individual passenger itineraries are taken into account. The same holds for taking into account crew and tail number itineraries.

Vervaat

The research of Vervaat originates from the demand-capacity imbalance resulting in local traffic bunches. Currently air traffic control takes measurements to debunch, but this is not necessarily optimal from an airline's perspective. Therefore Vervaat proposes the 'single operator, airline-centered en-route Arrival Sequencing and Scheduling' (AS&S) algorithm. The algorithm acts on the cruise phase of flights. When approaching the IAF, ATC will still use the FCFS algorithm. Therefore the proposed solution does not violate the equity concept.

In fig. 2.3 one can see the two different horizons for the Inbound Priority Sequencing (IPS). Close to the airport up to 28 minutes before landing there is the freeze horizon in which ATC applies the FCFS principle. Then there is the second region denoted as the action region in which an airline can give flights speed restrictions.

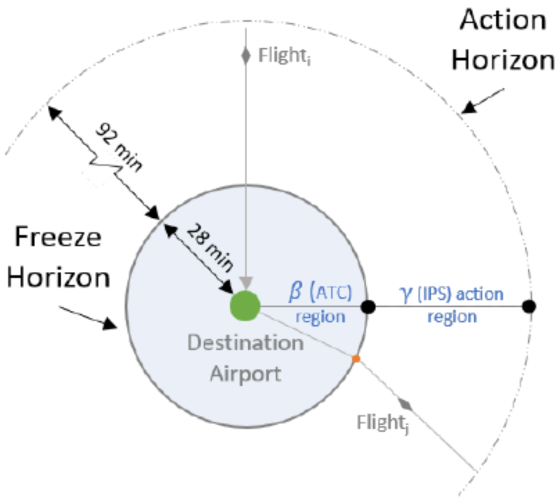

Figure 2.3: Different optimization horizons of Vervaat [75]

The objective function is shown in eq. (2.2). The objective is to minimize the total delay cost for an airline. It is split up into a fuel part and passenger part. The fuel part is split up into the cost of fuel spending in holdings (C_i^{loiter}) within the freeze horizon and IPS fuel costs related to increase or decrease the cruising speed within the action horizon (C_i^{IPS}). The passenger cost component is also split up in two part, the first being the Loss of Future Value (C_i^{LFV}) for passengers ending their trip at the hub and the related costs to missed connections (C_i^{mc}).

$$\min \sum_{i \in MF} (\underbrace{C_i^{\text{loiter}} + C_i^{IPS}}_{\text{Fuel Cost}} + \underbrace{C_i^{LFV} + C_i^{mc}}_{\text{Passenger Cost}}) \tag{2.2}$$

The Loss of Future Value is calculated by means of a simplified linear function and the cost of missed connection has only one fixed value where in reality this is not the case. No distinction between hard and soft costs are made for example and in reality every city pair comes with its own costs. Then there are the assumptions. The formulation of Vervaat is deterministic, hence all parameters are known beforehand. Furthermore, the only capacity constraint taken into account at the hub is the runway capacity. Also, no rebooking of passengers is considered which would influence the cost of a missed connection. Next, aircraft, crew and maintenance limitations are not considered. Last but not least the flight duration is calculated using great circle distance between departure and arrival in combination with wind data.

During a case study of KLM it became clear the model reduces the total delay cost with roughly 20% with respect to a baseline model which does not have the IPS. The cost for missed connections has the largest portion of the cost savings (42%). Caution should be taken as these missed connection costs were fixed. In reality this number may therefore differ. Furthermore (as already mentioned with the assumptions) the model uses deterministic values, in reality the arrival time predictions are stochastic which also may influence the results. Also, airlines will act proactively in reality, meaning they will start rebooking passengers in an early stage. As the presented model is static, this new information is not taken into account.

Knowledge and Development Center Schiphol

Besides the papers of Lernbeiss and Vervaat, industry has also done research on the ASP. Knowledge and Development Center Schiphol (KDC), for example, did a research and case study on Inbound Priority Sequencing (IPS) based on airline priorities [40]. In fig. 2.4 one can see the scope of their research which they performed in collaboration with KLM. KLM was allowed to have control over flights until approaching the

IAFs where LVNL took over control. The controlling measures consist out of seven building blocks from which the first three can be realized by KLM flow control and the rest by interaction between KLM flow control and LVNL:

1. KLM Arrival Planning: This is the core of the IPS where all information that is available to KLM is used to provide insights into the expected bunching and arrival runways. Deciding on which flights to prioritize is based on this building block;
2. In-flight direct routing: To shorten routes the flight crew or flow control can ask to fly so-called 'directs';
3. Speed management: By deviating from the reference (cruise) speed, a flight can potentially avoid (additional) delay. Aircraft are allowed to deviate from their filed flight plan speeds with 10 KTS or 5% without notifying ATC;
4. Priority indication: An airline creates awareness to air traffic control which individual flights are more important;
5. Speed intent sharing: This building block differs from 3 as the speed intents deviate more than 10 KTS or 5%, hence ATC should be notified;
6. Preview LVNL-planning: In case an airline is able to see a preview of the inbound planning ATC uses, it can decide to take actions like changing speed, swappping slots, etc;
7. Extended planning horizon: Here the inbound planning horizon is extended to include other ATC centers.

After performing a case study it was found the flight time reduction potential is about 3 to 5 minutes. During this study the equity principle was not considered, therefore this should be taken into account for future research.

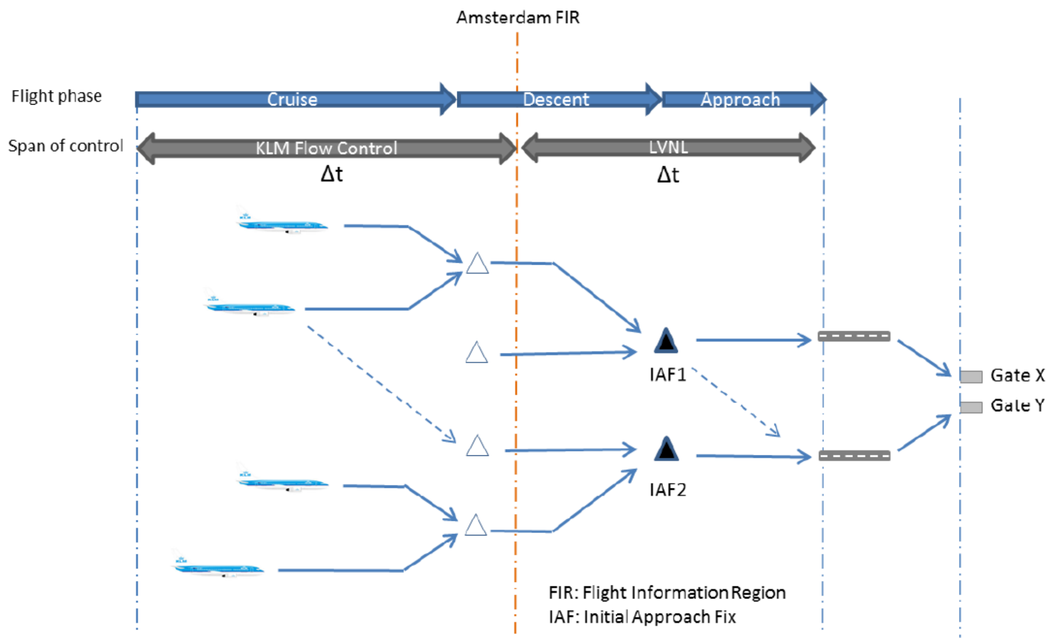

Figure 2.4: Scope of the IPS report of KDC [40]

ATH Group

Currently there is already a solution on the market for the ASP from an airline perspective: $Attila^{TM}$ [28]. It is based on three milestones, being monitoring, evaluating, and correcting. Estimated times of arrival are calculated and combined with the availability of resources such as availability of gates or ground crew. Based on this info flight crews will receive speed restrictions in order to arrive 'just-in-time'. In fig. 2.5 the Attila process is shown.

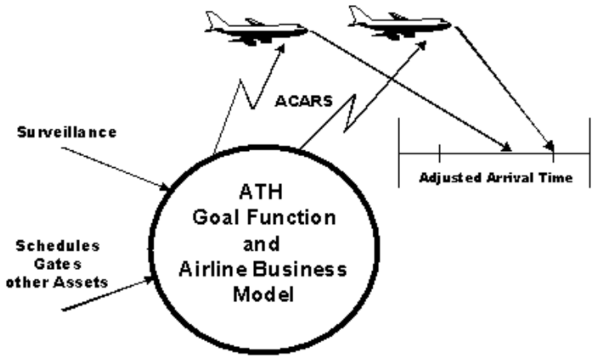

Figure 2.5: The Attila process [28]

2.3.3. Airline Delay Management

In literature another area of interest is the airline delay management problem. Given the fact there are delays, is it beneficial for a hub carrier to delay a subsequent flight. For the ASP this is too broad, but this problem deals with connecting passengers which is part of this literature study. Therefore some aspects of research on this problem could be used in this thesis.

In [64] Santos et al. created an innovative linear programming approach taking into account fuel cost, and passenger hard & soft costs. They apply a RHC for fast computational times and to guarantee the linearity of the model. The objective of the model is to minimize the total additional delay management solution costs for an airline. Local passengers are distinguished from connecting passengers. The passenger arrival delay cost is calculated by multiplying a monotonically increasing cost function with the affected passengers. Connecting passengers are exempted for this cost calculation as long as they can catch their connection. In case their connection is missed the cost is calculated by multiplying the delay cost of moving a passenger to a subsequent flight with the amount of passengers making the same connection. Finally, the cost of departure delay only entails passenger inconvenience due to late arrival at their destination. In the model no crew or aircraft itineraries are taken into account. Also the seat availability of subsequent flights in case of a missed connection is not taken into account. The latter due to the significant complification factor of the problem. During a case study with Kenia Airways it turned out a reduction of 29% of the delay costs was possible and the amount of missed connections decreased by more than 90%. For this research passenger itineraries were known. However, sometimes this is not known. To overcome this data gap Jacquillat used a statistical learning method to predict these passenger itineraries [38].

The same author also made a literature review together with Hassan and Vink about airline disruption management [30]. They found there are two main trends in recent literature. The first being recent literature is more in favor of an integrated approach, meaning including crew and passenger itineraries in the aircraft recovery problem. The second trend is adding more functionalities to better approximate reality. One should think of including multiple aircraft fleets, explicitly adding passenger itineraries, or control the cruise speed of aircraft. Here the link with recent literature from the ASP can easily be made, as the second trend is also visible there.

2.3.4. Scheduling with chance constraints in E-AMAN

In the field of E-AMAN interesting research has been carried out where an arrival sequence is determined based on chance constraints. These chance constraints take into account that the Estimated Time Over (ETO) the IAF has some uncertainties, especially when the look ahead time is over 2 hours as is the case with E-AMAN. Khassiba et al. performed several researches on this topic using two-stage stochastic programming. Two of these will be discussed here. In the first research a single IAF and runway is taken into account for determining an optimal arrival sequence [42]. In the first stage of the stochastic model target times over the IAF are given to flights where it is assumed actual times deviate randomly from the target times, where the probability distribution is known. The objective is to minimize the landing sequence length. In the second stage of the model it is assumed the actual times over the IAF are known and landing times are determined. The objective of this stage is to minimize a time deviation cost function. Within the second research Khassiba et al. continue with the former research by including multiple IAFs for a single runway and by including popup flights [43]. In the context of this literature study, especially the first part is of interest. Therefore this stage will be discussed in more detail.

The target sequence over the IAF equals the target sequence for landing. However, due to the uncertainties in the actual times over the IAF the actual sequence can differ from the target sequence. Also separation constraints (time based) over the IAF can be violated due to the uncertainties involved. To model this, probability constraints are included that express the acceptable rate of separation violations. As the time horizon is chosen to be 2-3 hours, it is assumed any sequence is feasible. However, to fulfill the equity concept or fairness among flights there are the time window constraints that prevent the situation in which aircraft are extensively delayed (especially delaying popup flights on the ground).

The chance constraints are incorporated into the mixed integer model by means of eq. (2.3). x_i is the TTO the IAF for flight i. w_i is the random variable representing the deviation from the TTO. $\underline{S}^I$ represents the minimal time separation over the IAF and M^I_{ij} are big-M constants. δ_{ij} represents two aircraft behind each other. it equals 1 if aircraft i is directly behind aircraft j. Else it equals 0. α represents the percentage of no separation loss over the IAF. Finally A is the set of aircraft.

$$\mathbb{P}\left(x_j + \omega_j \geq x_i + \omega_i + \underline{S}^I - M^{I\alpha}_{ij}(1-\delta_{ij})\right) \geq \alpha, (i,j) \in A \times A, i \neq j \tag{2.3}$$

In [42] it is proven that eq. (2.3) can be made a linear deterministic constraint if w_i is a independent and identically distributed random variable for all aircraft. It is also proven that using the latter in combination with $\alpha > 0.5$, eq. (2.3) can replace deterministic separation constraints.

Follow-up research: [43]
In principle the above described method remains the same in the follow-up research. it is only extended with multiple IAFs and popup flights. The former is extended to a decision of assigning one of the IAFs to flights which is out of the scope of this literature study. The latter however, is of interest. Each popup flight (called on-ground aircraft in the research paper) gets a TTOT. It is then assumed these TTOTs are not affected by uncertainties. This is an important assumption, as [74] found out that if the TTOT deviates more than two minutes, the planned sequence will be disrupted. The TTOT lies within a time window of 15 minutes. Based on the TTOT the flight time to the IAF is calculated. One would expect this sequence to be the other way around: based on a TTO the IAF, a TTOT is calculated. It is not mentioned in the research why this is not the case.

3

Conclusions on Existing research

This literature review is about the topic of Aircraft Sequencing and Scheduling from an airline perspective. As the airline perspective is not necessarily common in research, other research objectives have been reviewed as well. The most common approach in the field of Aircraft Sequencing and Scheduling is to have a deterministic integer programming method. However, the actual environment in reality is dynamic and has uncertainties that play a role. Also there are many stakeholders involved ranging from the airlines to the airport operator or from the government to the ground handlers. Combining these factors, future research should try to increase the level of realism. This is in line with the conclusion of [53]

Looking specifically at the Aircraft Sequencing and Scheduling Problem (ASP) from an airline perspective, only little research has focussed solely on optimizing the arrival sequencing during the en-route phase of flights. Let alone, including popup flights in their research. Most research that focuses on the en-route phase is in the context of Extended Arrival Managers (E-AMAN) where the objective is biased for Air Traffic Control (ATC) purposes. Think of maximizing the runway throughput, minimizing the makespan or minimizing the workload for ATC.

Regarding methods used on the ASP from airline perspective, deterministic linear programming is solely used. Due to the fact the cost function is often non-linear, it is tried to linearize the problem. Looking a bit broader, by including airline delay management, dynamic scheduling is proposed by including rolling horizon schemes. To the best knowledge of the author, stochastic modeling or including uncertainties are not yet covered, although this is the case regarding (Extended) Arrival Manager models for the use of ATC.

Besides including uncertainties in the ASP from an airline perspective, the cost function used in the objective is also an area of interest. To decrease the computational expense, these cost functions only include a limited amount of detail. If one looks for example at passenger costs, a missed connection results in a fixed cost instead of looking at the specific city pair or how much it will cost to rebook the passenger on a next flight.

4

Thesis Proposal

This chapter is about the thesis proposal. The research objective and research questions will be addressed first. Then the proposed approach on how to achieve this is presented briefly.

4.1. Research Objective

The proposed master thesis consists out of one main research objective and three sub-objectives or sub-goals. To start with the main objective:

> “The research objective is to create an optimal arrival traffic sequence at the Initial Approach Fixes from an airline perspective, by developing and testing a dynamic and stochastic decision support/making tool for the use of a network airline.”

To achieve this objective, three sub goals have been defined:

1. Extend the cost function used in current research with crew and aircraft itineraries;
2. Come up with a methodology for including chance constraints in a deterministic model to make the model probabilistic or stochastic;
3. Come up with a methodology to include a rolling horizon into the decision support/making tool in order to make the model dynamic instead of static.

4.2. Research Questions

The main research question is:

> “How can an arrival sequence be altered in the tactical phase in favor of a network airline in order to minimize additional delay cost?”

Sub-questions have been defined, to help to answer this main question. These sub questions can be seen below.

1. What method or technique for the optimization can be used best in the context of the research?
2. What input data is needed?
3. How should the equity principle be included?
4. Is it possible to apply the findings of this research to a (real time) decision support/making tool for the use of a network airline?
    (a) How should the outcome look like?
    (b) What is the maximum allowed processing time?
    (c) Does the tool result in mitigation of arrival congestions over the initial approach fixes?
    (d) Does the tool provide better solutions than existing tools that are used by a network airline?

4.3. Approach

In order to achieve the main and sub objectives it is chosen to change the static and deterministic model of Vervaat ([75]) and Lernbeiss ([48]) into a dynamic and stochastic model by including a rolling horizon and by including chance constraints respectively. The idea of the rolling horizon originates from Santos et al. ([64]) whereas the idea of the chance constraints originate from Khassiba et al. ([42])"[32]. All of these researches have been discussed in this literature report.

The first step is to identify all data sources and acquire their data. Differentiation can be made between data needed for a statistical analysis to come up with a probability distribution on the ETO an IAF and data needed to be used in the actual model such as position information or the number of connecting passengers on board. The data will be gathered from past research in combination with the usage of data coming from KLM Royal Dutch Airlines. The latter being the industry partner of this thesis. A last source will be the public domain in which historical flight position data can be gathered. After this step the second sub-research questions will be answered on what input data to use.

After having collected the necessary data, a statistical analysis will be performed in order to determine a probability distribution on the ETO IAFs. This will be done by comparing the ETO with the ATO the IAF. For airborne flights the ETO will be taken when they enter the action horizon. For popup flights on the other hand the ETO will be calculated back based on the scheduled arrival time. Then the probability distribution will be determined based on different time intervals. Off-peak periods will be compared with peak arrival and departure times. Chances are high the found probability distributions are in the form of a log, power, or Poisson distribution. However, to be able to include a chance constraint in a deterministic model, the function should be normally distributed ([42]).

With the established probability distributions one can move towards developing the actual model. Based on previous research, the model of Vervaat ([75]) and Lernbeiss ([48]) can be rewritten in order to incorporate a rolling horizon and the chance constraints. Although the idea of the rolling horizon originates from [64], the implementation will be different. The idea is namely to recalculate the sequence each time a new aircraft enters the action horizon of the model or if a departure flight at the hub gets an updated TOBT. The latter has to do with the connecting passengers. If their connecting flight is delayed, their incoming flight does not necessarily has to end in front of the sequence.

During recalculation of the sequence the previous solution is taken into account by including constrained position or time (to be determined) shifting. This makes sure aircraft that had already a target position (ETO the IAF) will remain in that position or will be shifted by a predetermined maximum amount of positions or time.

The equity principle is included in the model by not 'touching' traffic other than the traffic of the network airline. Flights belonging to the network airline are free to move around in the sequence as long as the other traffic will not receive (additional) delay compared to the FCFS sequence.

For verification purposes the chance constraints should have a 'on/off' button in order to compare it with the deterministic case. The same holds for the equity principle. It is expected the traffic will be sequenced more densely if the chance constraints are turned off and that the sequence will be more optimal for the network airline if the equity principle will be switched off. After this step it should be possible to answer the sub research question about if it is possible to convert the model into a decision support or making tool.

The final step is to validate the model by means of a case study with the KLM. This industry partner has also mentioned it would be possible to test or trial the model during real operation. For the latter the model should be converted into a decision support or making tool for the use of dispatchers at KLM. If this turns out to be feasible, the final research question can be answered, which is if the tool provides better solutions than existing tools. With this, now all sub-research questions can be answered and an answer can be given to the main research question.

III

Supporting work

1
Fuel Model

Within the IPS module fuel has a major stake in the outcome of the optimal sequence. For the largest part it has to do with the amount of fuel spent from entering the action horizon until reaching the IAF. Then there is the smaller part in case of spending time in a holding. Therefore it is necessary to accurately predict the amount of fuel. In literature there are several performance models such as BADA or OpenAp [55, 69]. The problem with these models is that it is open source and is not allowed to be used commercially, which was prohibitive for using BADA during this thesis. To come around this, a new fuel model had to be created.

The sole purpose of this fuel model is to predict the fuel consumption for flights in the case study of the IPS model. As one could do an entire thesis solely on creating an accurate fuel model, it was decided to create a model in which the order of magnitude is correct. Therefore the applied methods are rudimentary in order to obtain results in a relatively short period of time.

1.1. Method

For creating the fuel model actual aircraft fuel data is used from 190,000 flights, spread over 12 aircraft subtypes (e.g. Airbus A330-200 vs Airbus A330-300). Each flight consists out of 50-100 data points. All the data points per aircraft subtype are separated in their corresponding flight phase: climb, cruise, and descent. To separate the different phases of flight, the requirements for the data points are listed in table 1.1, as well as the applied method to obtain the outcome of the model. For the climb and descent phase the mean of all data points per aircraft subtype are taken, whereas 3D polynomial quadratic regression is applied to the cruise phase. These methods are simply to apply and have therefore been chosen.

Flight Phase	Determination criteria		Applied Method
	ft/min	FL	
Climb	≥ 500	-	Mean
Cruise	> -500, < 500	≥ 200	3D Polynomial quadratic regression
Descent	≤ -500	-	Mean

Table 1.1: Flight phase determination criteria and applied methods

For the climb and descent phase a single fuel flow in mass per time is outputted. For the cruise phase the fuel flow also depends on the flown True Airspeed (TAS) and altitude. The reason this flight phase is more detailed has to do with the fact the IPS model will be used most of the time for flights that are in their cruise phase. Only popup flights will have a climb phase or intercontinental flights when experiencing a step climb. The descent phase is then used for descending towards the published IAF altitude.

1.2. Results

For proprietary reasons the exact results of the fuel model cannot be shown. However to give an indication of the order of magnitude, Figure 1.1 is added in which the fuel data points and the resulting fuel model output looks like. The model is validated by checking the output with actual fuel consumption of individual flights.

During this comparison it turned out the mean difference is around 10%, indicating the order of magnitude is correct.

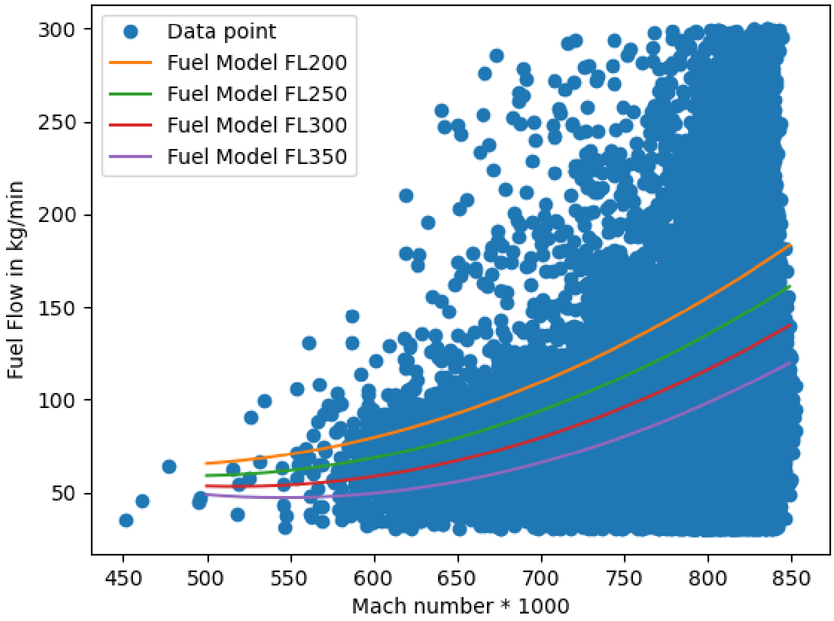

Figure 1.1: Fuel flow model output for the Airbus A330-200

2

Real-time Shadow Running of Decision Support Tool

To validate the proposed Inbound Priority (IPS) model, a live shadow run has been performed using a converted version of the IPS model. This appendix describes the set-up of the shadow run in Section 2.1. Then the results that followed from the shadow run will be shown in Section 2.2, after which a discussion will take place in Section 2.3. Last but not least a conclusion will be drawn and recommendations will be mentioned in Section 2.4.

2.1. Shadow run set-up

This section describes the set-up of the shadow run, by mentioning the data sources used and the conversion of the IPS model to a decision support tool for the use of an airline.
The shadow run took place in week 41 and 42 of 2022 and consisted out of sequencing traffic during the Westerly morning arrival wave over SUGOL.

2.1.1. Data Sources

The following data sources have been used for the live shadow run:

Flight Radar 24
Flight Radar 24 is used for live aircraft positions, in combination with their estimated landing times.

iLabs data dump
From Air Traffic Control the Netherlands (LVNL) an innovation Labs (iLabs) data dump was obtained containing flight messages from the Network Manager of EuroControl. The data dump originate from 2019 (precovid) and is used to calculate the average time it takes from SUGOL to touch down.

Operational Flight Information Schiphol
From the operational flight information of Schiphol, Collaborative Decision-Making (CDM) data is obtained. From this data the Estimated Landing Time is retrieved for arriving flights.

Airline database
Data was obtained from an airline regarding fuel consumption, flight plans, and passenger cost data.

2.1.2. Converting IPS Model

The difficulty of converting the IPS model from the model used for the case study to a decision support tool comes from connecting live data sources to the model. Also the data originating from these data sources has to be converted in order for the model to work properly. The three main calculation components are (I) calculating the estimated time over the IAF, (II) calculating the feasible window and corresponding fuel usages, and (III) calculating the total passenger cost as a function of arrival time.

I. Calculating estimated time over SUGOL
The data dump obtained from LVNL is used to calculate the time it takes from the IAF SUGOL to touch down. The reason for this being the fact flights have a publically available estimated landing time, but no estimated IAF time. Therefore from the estimated landing time it is calculated backward what the time over the IAF is. In table 2.1 one can see the results per landing runway, including the standard deviation. The data entails the entire month of September 2019.

Runway	Number of data points	Time to touchdown *min:sec*	Standard Deviation *min:sec*
06	393	11:18	2:10
18C	740	12:35	1:49
18R	1021	12:03	1:50
22	58	14:16	2:03
27	174	16:14	2:11
36C	263	14:45	2:20
36R	349	14:08	2:24

Table 2.1: Time from SUGOL to touch down per runway based on iLabs data

II. Calculating feasible window and fuel consumption
It was decided flights are only allowed to slow down with respect to their planned cost index. A cost index table shows the time and fuel gains or losses for each aircraft subtype per flown cost index with respect to the standard planned cost index. The table is also dependent on the time that will be flown with a new cost index to express the fuel and time gains or losses. As this table has time and cost index intervals, intermediate times and cost indexes are linearly interpolated.
To calculate the actual time and fuel gains or losses, the planned cost index is always compared to cost index zero. The time gains or losses are then added to the estimated time over SUGOL to come to the feasible time window.
A fundamental difference compared to the case study regarding the fuel consumption is that in the case study the total fuel consumption per flight is calculated from the moment a flight enters the action horizon. In the live shadow run on the other hand, the difference in fuel usage compared to the planned cost index is calculated.

III. Calculating passenger cost
A database containing passenger cost data was obtained. The cost within this database is interpolated, by means of quadratic polynomial interpolation.

2.1.3. Input Parameters

In table 2.2 the input values are listed for the live shadow run. The passenger delay related inputs are dependent on the specific individual passenger itineraries. Also they are now dependent on the specific individual passenger itineraries.

Input Parameter	Unit	Value
IAF_{ALT}	[*ft*]	10,000
IAF_{SPD}	[*kcas*]	230
IAF_{SEP}	[*sec*]	139 (26 flights per hour)
MCT	[*sec*]	variable
PMC	[*eur/pax*]	variable
PF	[*eur/kg*]	1.12
$EIBT_{offset}$:	[*sec*]	Airline values used in combination with iLabs values
RAD	[*nm*]	free to choose based on Flight Radar 24
M	[-]	1e7
$CCTOT_{airports}$	[-]	not included
t_i^{taxi}	[*sec*]	-
P_{TOD}	[*eur/min*]	-
P_{TTO}	[*eur/min*]	1
C_{thr}	[*eur*]	500

Table 2.2: Input parameters for the case study

2.2. Results

The shadow running of the IPS decision support tool took place in the mornings of 14, 15 and 17 October from 04:00 until 04:30 UTC. During this time interval the first popup flights depart from the UK, resulting in a mix of popup flights and intercontinental flights. After each run Flight Radar 24 is played back to find out the actual times over SUGOL. Only intercontinental/long haul flights have been sequenced. Popup flights were only taken into account once airborne, meaning no CCTOTs have been issued. The reason being to start small. The actual results will not be shown for proprietary reasons. Instead, the global findings will be stated.

In total 51 flights have been included in the shadow running of which 27 flights belonged to the controllable flights set. Of these 27 flights, 11 flights should have been re-sequenced according to the IPS model. The calculated target time over SUGOL resulted in a five-minute delay in the most extreme case. In some cases a delayed flight was delayed even more, although this resulted in additional passenger costs. By extra delaying however, the fuel savings were higher compared to the additional passenger costs, resulting in a net cost saving.

One aspect of the shadow running was to validate the model input, especially the estimated times over SUGOL. It turned out these estimates have an average deviation of 2.7 minutes based on 17 flights that are played back afterward to see the actual time over SUGOL. For flights that had accurate positions in Flight Radar 24 the estimate could be off by 5 minutes. This includes the error of the estimated landing time based on Flight Radar 24 and Schiphol data, and the backward calculation from touch down towards SUGOL. Flights that did not have accurate positions (their position is extrapolated from the last known accurate position) turned out to have deviations as large as 30 minutes.

2.3. Discussion

Although the shadow running is performed on a small set of intercontinental flights, the obtained results can already be used to give a first impression on the possibilities of the IPS model in the form of a decision support tool.

Given the input data, the model performs well. In all runs the model itself turned out to be feasible, and global cost savings were achieved. However, the estimated times over SUGOL turned out to be too inaccurate for a live run in which flights will adhere to the IPS model. To explain this, in some cases the feasible window over the IAF is as small as 5 minutes. If in that case the estimated time is 5 minutes off, the outcome of the IPS model could imply a pilot has to delay in flight by 10 minutes in reality which would be infeasible.

Another point for discussion is the deviation of the estimated time over SUGOL and the actual time. In all but one case the deviation was positive, meaning that the actual time turned out to be later than the estimated time. One of the reasons could be the interference of air traffic control that delays flight on purpose in order to be sequenced over SUGOL.

During the shadow running it was tried to give popup flights CCTOTs, however no (accurate) data was available regarding their estimated/target off block times. Furthermore they could only be sequenced roughly 10 minutes after they were airborne, as only then an estimated landing time was available.

2.4. Conclusion & Recommendations

It can be concluded the IPS model itself can help an airline in reducing their overall cost by sequencing their flights during (their last part of) the en route phase. However more accurate input data is needed in order for the model to be used by the operation control center. The most important input parameter that needs to be more accurate is the estimated time over the IAF for all flights. Before getting to this point however, the tool could be of use to sequence an airline's flights between themselves, without having a look at other traffic. Individual airline flights could send their estimated times of the IAF or waypoint along the Dutch FIR boundary from their flight management computer to the ground. Then the IPS model will not give individual waypoint target times, but the sequence in which the airline's flights should enter the FIR boundary or IAF. Also more accurate input data is needed from popup flights in order to be taken into account for sequencing them.

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