Airline based priority flight sequencing

of aircraft arriving at an airport

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by

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to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Monday September 14, 2020 at 2:00 PM.

Student number:	4351487	
Project duration:	September 16, 2019 – September 14, 2020	
Thesis committee:	Dr. M.A. Mitici,	Delft University of Technology, Supervisor
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This thesis is confidential and cannot be made public until September 14, 2020.

TU Delft

knowledge & development centre
Mainport Schiphol

Preface

This thesis marks the final step in the path to obtaining the degree Master of Science in Aerospace Engineering. The thesis research is conducted in collaboration with the Knowledge & Development Centre (KDC) and the Air Transport & Operations department of the Delft University of Technology. It was a privilege and compliment to the academic basis of the TU Delft education to be able to conduct the research with some of the powerhouses of the Dutch commercial aviation field. Special thanks go out to Gerard Verschoor, Marc de Lange, Anne Fennema and Martin Dijkzeul at KLM for their assistance and feedback throughout the project.

I would like to express my gratitude towards the fellow students graduating at the KDC "Centre of Excellence", who were both academically as well as emotionally of great support during the many days working on the graduation project. My sincere thanks also go out to Ferdinand Dijkstra who provided guidance and expertise from his industry perspective. Ferdinand not only did so with a vast pool of knowledge, but also shared in his truly exceptional and inspirational passion for the aviation industry.

I would like to thank my daily supervisor, Dr. Mihaela Mitici, for her coaching, thoughtful feedback and level of detail which undoubtedly pushed the work to a higher level. It was a pleasure and great learning experience completing the thesis under your supervision. At last, I wish to thank Mike Zoutendijk from Delft University of Technology for his feedback and advice throughout the final months of the thesis.

R.M. Vervaat
Delft, September 1, 2020

Contents

List of Figures

List of Tables

Nomenclature

Greek Symbols

β_i	ATC delay for aircraft i	seconds
$\delta_{i,j}$	Landing sequence indicator variable between flight i and j	-
Δ_i^{LFV}	Loss of Future Value Delay cost function as a function of total flight delay TD_i	EUR/pax
γ_i	IPS cruise time adjustment (through speeding up/slowing down) for aircraft i	seconds
θ_i	IPS action indicator variable for flight i	-

Roman Symbols

Add_i	Maximum amount of time added by slowing down for flight i	seconds
ATA_i	Actual Time of Arrival of flight i	seconds
BT	Percentage of passengers considered 'Business Traveller'	%
C_i^{IPS}	IPS speed change fuel cost for flight i	EUR
C_i^{LFV}	Loss of Future Value for flight i	EUR
C_i^{loiter}	loiter fuel cost for flight i	EUR
C_i^{mc}	Cost of missed connections for flight i	EUR
C_i^{mc}	IPS action penalty cost for flight i	EUR
CF	Set of competitor flights	-
$\text{Cs}_{i;q}$	Additional transfer time above minimum for passenger q on flight i	seconds
d_i^{cr}	Cruise distance of flight i	meters
ETA_i	Estimated Time of Arrival of flight i	seconds
F	Set of flights to be scheduled	-
$\text{F}_i^{cr}(V_i^{IPS})$	cruise fuel burn for aircraft i under the IPS adjusted cruise speed (V_i^{IPS})	kg/sec
$\text{F}_i^{cr}(V_i^{nm})$	cruise fuel burn for aircraft i under the nominal cruise speed (V_i^{nm})	kg/sec
$\text{F}_i^{lt}(V^{loiter})$	Loiter fuel burn for aircraft i under the published loiter speed (V^{loiter})	kg/sec
i	ith scheduled flight to arrive at the airport	-
M	Large integer constant	-
m	amount of passengers in passenger set PAX_i	–
MF	Set of managed flights	-
n	amount of flights in set F	-
P^{AP}	Cost of issuing an IPS instruction to an aircraft	EUR/AC
P^{F}	Fuel price	EUR/kg

P^{mc}	Average cost of a misconnecting passenger	EUR/pax
PAX_i^{mc}	Set of passengers on board flight i who miss their airline guaranteed connection	-
PAX_i^{nc}	Set of passengers on board flight i with no onward connection	-
$pax_{i,q}$	passenger q on board of flight i	-
PAX_i	Set of passengers on board of flight i	-
Rec_i	Maximum amount of time recoverable through speeding up for flight i	seconds
$Sep_{i,j}$	Minimum time based separation when flight i lands before flight j	seconds
STA_i	Scheduled Time of Arrival of flight i	seconds
T_i^{IPS}	IPS adjusted cruise time for flight i	seconds
T_i^{NM}	Nominal cruise duration time for flight i	seconds
TD_i	Total flight delay of flight i	seconds
V_i^{eq}	Equivalent (specific range) cruise speed for flight i	knots
V_i^{IPS}	IPS adjusted cruise speed for flight i	knots
V_i^{MR}	Maximum range cruise speed for flight i	knots
V_i^{NM}	Nominal cruise speed for flight i	knots

List of Abbreviations

AAMS Aircraft Arrival Management System.

ACARS Aircraft Communication Addressing and Reporting System.

AFR ICAO airline designator for Air France.

ALP Aircraft Landing Problem.

AMAN Arrival MANager.

ANSP Air Navigation Service Provider.

AOC Airline Operations Centre.

AS&S Arrival Sequencing and Scheduling.

ATA Actual Time of Arrival.

ATC Air Traffic Control.

ATCo Air Traffic Controller.

ATFCM Air Traffic Flow and Capacity Management.

ATM Air Traffic Management.

BADA Base of Aircraft DAta.

BAW ICAO airline designator for British Airways.

BEE ICAO airline designator for Flybe.

CI Cost Index.

CPS Constrained Position Shifting.

DAL ICAO airline designator for Delta Air Lines.

ETA Estimated Time of Arrival.

EUROCONTROL European Organisation for the Safety of Air Navigation.

EZY ICAO airline designator for Easyjet.

FAA Federal Aviation Administration.

FCFS First-Come, First-Served.

FIR Flight Information Region.

FMC Flight Management Computer.

IAF Initial Approach Fix.

IATA International Air Transport Association.

ICAO International Civil Aviation Organization.

IPS Inbound Priority Sequencing.

KLM ICAO airline designator for KLM Royal Dutch Airlines.

KPI Key Performance Indicator.

LFV Loss of Future Value.

LH Long Haul.

LP Linear Programming.

MILP Mixed-Integer Linear Programming.

NextGen Next Generation Air Transportation System.

NOC missed connection.

OTP On-Time Performance.

PANS Procedures for Air Navigation Services.

RHC Receding Horizon Control.

SESAR Single European Sky ATM Research.

SH Short Haul.

SR Specific Range.

STA Scheduled Time of Arrival.

TMA Terminal Manoeuvring Area.

TRA ICAO airline designator for Transavia.

VLG ICAO airline designator for Vueling Airlines.

Introduction

Motivation and Relevance

Air travel has shown strong levels of growth through the past decades and continues to do so in recent years. Estimates by the International Air Transport Association (IATA) forecast that the amount of passengers carried by air will double by the year 2035 [1]. At the same time, the infrastructure shared by this increasing volume of air traffic is growing at a much slower pace, where growth is even possible[2]. These factors amongst others have meant that, as usage is nearing capacity in the limited airspace and infrastructure available, delays are becoming more frequent and severe. Mitigating measures such as tactical arrival planning (between 24 and 1 hours before landing) are being implemented to a limited extent, resulting in the arrival flow being erratic and arrival delay common (Soomer and Franx [2008]).

Hub airports, whose operations are designed to facilitate efficient connections between flights (thus planning minimal connecting times) are especially susceptible to the negative consequences that flight delays pose. The problem is made worse by the fact that Air Navigation Service Providers (ANSPs) often have little insight into the preferences and priorities of airlines (Verboon et al. [2016]). With this, the scheduling and routing provided to aircraft is oftentimes far from the most beneficial to the airline (Carr et al. [1998]).

Starting from these observations, this research project tasks itself with investigating a concept enabling airline operators to influence the arrival sequence at a destination airport according to airline priorities. The Inbound Priority Sequencing (IPS) algorithm derived in this research evaluates the control possibilities for a single airline operator solely during the en-route segment starting several hours before landing. Combined with arrival information on competitor traffic and a purposely developed cost model, the algorithm derives the most economically optimal scenario and provides speed advisories for affected aircraft in order to accomplish this scenario. A key point towards acceptance is amongst the aviation community is that the arrival process at the destination airport and equity considerations such as 'First-Come, First-Served' will remain untouched.

The research project makes the following contributions; we evaluate the effectiveness of a (priority-based) Arrival Sequencing and Scheduling procedure executed from the single-airline perspective. Building on the basis of previous research (Montlaur and Delgado [2017]), we investigate the benefits of Arrival Sequencing & Scheduling (tools) on individual flight and passenger metrics rather than total delay and other fleet wide, time based metrics. Finally, we add to limited body of literature concerning Arrival Sequencing and Scheduling (AS&S) solely executed in the en-route phase, in contrary to most AS&S research focusing on the Terminal Manoeuvring Area and extending from there. The research sheds light on effectiveness of the application of Inbound Priority Sequencing through En-route speed control in order to influence the ATC controlled arrival process downstream at the destination airport, without the necessity for ATC as the brokering party.

[1] IATA press release `https://www.iata.org/pressroom/pr/Pages/2018-10-24-02.aspx`

[2] `https://phys.org/news/2018-02-iata-chief-airport-expansion.html`

Research Questions, Aims and Objectives

The section below lays out the Research Questions, Aims/objectives and the Sub-goals related to these, that will be treated in the thesis research project.

Research Objective

The research objective of the proposed study is to *develop an algorithm to sequence and schedule aircraft arriving at a hub-airport accounting for priority criteria of individual aircraft and the airline such that aircraft arrival cost are optimised.* To achieve the aforementioned research objective the following sub-goals are formulated:

1. Define Problem scope and determine assumptions.
2. Redesign and tailor Arrival Sequencing and Scheduling algorithms for the airline controlled case.
3. Determine airline cost drivers and establish connecting passenger model.
4. Develop an Arrival Sequencing and Scheduling model.
5. Verify and validate model performance.
6. Trade-off the optimal choice of objective function(s).
7. Analyse a case study for KLM flights arriving into Amsterdam Airport Schiphol.

Research Aim

The aim of the research is to:

Meaningfully and effectively trade delays for passenger and/or commercial benefit. By means of coupling en-route (Airline) control onto the AMAN/arrival process (ATC) at the destination center.

Research Questions

The main research question to be answered in the thesis work is;

> **How can airline priority criteria for inbound sequencing be taken into account in order to minimise delay cost by adjusting arrival schedules in the tactical phase?**

In order to answer the research question a set of sub-questions is developed, which together answer the overarching research question.

1. How can flight prioritisation be achieved in the operational setting into a major European hub airport?
    - 1.1. What modelling technique is most suitable for Arrival Sequencing and Scheduling with (airline) priority criteria?
    - 1.2. What assumptions and constraints must be made to model Arrival Sequencing and Scheduling? (e.g. time recoverable in flight, modelling distance, possible control actions, etc.)
    - 1.3. Which measures of control do airline operators have on incoming flights?
2. What are the effects on airline cost of taking airline priority criteria into account during Arrival Sequencing and Scheduling?
    - 2.1. What improvements can be achieved over the current, "First-Come, First-Served" (FCFS), Arrival Sequencing and Scheduling practices?
    - 2.2. How does the choice of design parameters influence the model performance? (sensitivity analysis)

Structure of this Report

The report is structured as follows. Part I is a self-contained article on the Airline based priority flight sequencing concept as introduced above. Part II provides an extensive literature study on the same topic and has been previously graded under course code AE4020. Following this Appendices A through C provide supplemental matter on the research project. Appendix A provides a breakdown of the (BADA) fuel model used in the research project. Appendix B provides a graphical example of the IPS algorithm and is used to further exemplify the relationship between variables in the IPS model. Finally, Appendix C provides a breakdown of Arrival Sequencing & Scheduling Problem features found in historic publications on the topic.

I

Scientific Article

Airline based priority flight sequencing of aircraft arriving at an airport

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***Abstract*—This paper addresses the airline centred Arrival Sequencing and Scheduling problem aimed at the smart distribution of arrival delays, considering the explicit preferences from users. We consider the scenario in which actions are executed solely in the en-route phase with the available leeway present in the current ATM system. The arrival process at the destination centre alongside equity rules such as ”First-Come, First-Served” remain untouched. A Mixed-Integer Linear Programming approach is presented in order to evaluate the fleet wide impact of speed changes by individual aircraft in order to come to a global (airline specific) optimum. The approach presented is evaluated using operational data in the form of a case study of a large European hub-style carrier. Case study results indicate the ability to decrease delay related cost by over 15% through the more efficient distribution of delay times between aircraft. Overall aircraft timeliness in the case study for both the controlled airline as well as competing airlines shows a slight improvements of several seconds of average delay per aircraft. In addition, a number variations to the base model are presented, investigating a possible trade-off between model priorities.**

***Index Terms*—Arrival Sequencing and Scheduling, Airline Delay Cost Optimisation, Cruise Speed Variation, Integer Programming**

I. Introduction and motivation

Air travel has experienced strong levels of growth through the past decades and has continued to do so in recent years. Estimates by the International Air Transport Association (IATA) forecast that the amount of passengers carried by air is set to double by the year 2035 [1]. At the same time, the infrastructure shared by this increasing volume of air traffic is growing at a much slower pace, where growth is even possible[2]. These factors amongst others have meant that, as usage is nearing capacity in the limited airspace and infrastructure available, delays are becoming more frequent and severe. Mitigating measures such as tactical arrival planning (between 24 and 1 hours before landing) are being implemented to a limited extent, resulting in the arrival flow being erratic and arrival delay common [1].

Runways and the Terminal Manoeuvring Area (TMA) around airports are prime regions where this negative effect becomes evident [2]. Aircraft arriving at airport controlled airspace in rapid succession of one another, so-called *traffic bunches*, must be spaced out in order to satisfy Wake-Vortex separation constraints imposed for safety by the time they touch down on the runway. The phenomena where traffic (locally) exceeds capacity, as illustrated in figure 1, is a large contributor to the inefficiencies in the current Air Traffic Management (ATM) system. Although in the long term capacity upgrades may be necessary to cope with the rise in demand, improved planning and scheduling can present an important building block in the solution of the current capacity crunch experienced in and around airports.

Currently, the responsibility for dealing with most capacity shortages is delegated to Air Traffic Controllers for whom operational efficiency is but one of many priorities they are expected to uphold. As a result and in combination with the limited control actions individual controllers are set to work with, most Air Traffic Control (ATC) focused solutions include single sided speed and or route changes, neither of which are preferable to the end users [4]. When facing more severe capacity limitations or when flight demand is expected to exceed airport capacity for extended periods of time, Air traffic Control organisations such as EUROCONTROL and the FAA have introduced Air Traffic Flow and Capacity Management (ATFCM) measures such as ground holding programs to limit the inflow of aircraft. Such programs, where aircraft are delayed at the departure airfield or before entering the constrained airspace rarely present the optimal solution to the capacity problem and above all, smaller local delays are often not (fully) addressed by the larger coordinated efforts.

From an airline perspective not all flights are equally important and as such, it may very well be that an aircraft appearing at the radar boundary at a later time, which has previously incurred a delay or with a high number of connecting passengers, might be more economically interesting to land before an aircraft which, due to favourable winds, is now arriving at the border of the TMA before its scheduled arrival time.

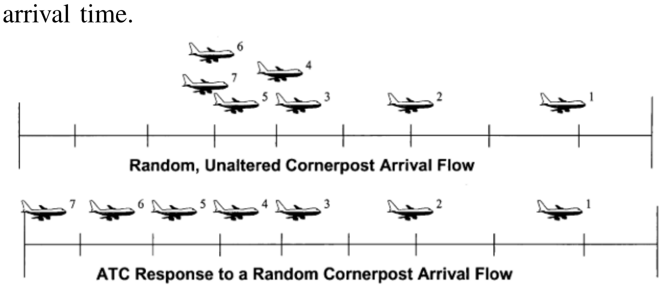

Fig. 1. Aircraft bunching before and after ATC intervention [3].

[1]IATA press release https://www.iata.org/pressroom/pr/Pages/2018-10-24-02.aspx

[2]https://phys.org/news/2018-02-iata-chief-airport-expansion.html

This leads to the idea and concept in this paper; we propose a single operator, airline-centred en-route Arrival Sequencing and Scheduling (AS&S) algorithm, which allows airlines to pre-impose speed changes within their own fleet in order to minimise factors such as mis-connecting passengers, fuel burn and other flight related cost for their own fleet.

By pre-imposing speed changes during the en-route segment, the operator can position their own flights in a more optimal (relative) arrival sequence, whilst at the same time better aligning the arriving flow of aircraft to the ATC controlled arrival management process at the destination airport. The Inbound Priority Sequencing (IPS) procedure as previously described operates within the operational leeway present in the current ATM system and most importantly relies solely on the control capabilities present for an aircraft operator without the necessity for ATC cooperation. This means that equity considerations such as the implementation of ”First-Come, First-Served” (FCFS) around airports are fully upheld, whilst simultaneously allowing the end user to tailor the solution towards their specific needs.

In this paper, we make the following contributions. First, we evaluate the effectiveness of a (priority-based) Arrival Sequencing and Scheduling procedure executed from the single-airline perspective. The airline is characterised by typical hub-carrier operations out of a large European hub airport with a significant segment of the overall traffic share. We build on the basis of previous research, which indicate that flight sequencing and scheduling might not have large effects on total delay or other fleet wide metrics that can warrant the impact of implementing AS&S tools, however zooming in to an individual flight or to passenger metrics, previous research has shown the benefits to have a more promising outlook [5].

Finally, we add to limited body of literature concerning Arrival Sequencing and Scheduling solely executed in the en-route phase, in contrary to most AS&S research focusing on the Terminal Manoeuvring Area and extending from there. The research sheds light on effectiveness of the application of Inbound Priority Sequencing through En-route speed control in order to influence the ATC controlled arrival process downstream at the destination airport.

The paper is structured as follows. Section II provides additional description of the scenario and operational context paving the way for further sections. The background is followed by a survey of previous work in Section III. Following this, Section IV introduces the Mixed-Integer Linear Programming (MILP) formulation of the Arrival Sequencing and Scheduling model, as well as the definition of airline priorities through the description of the cost function. Section V describes the case study used to evaluate the model after which Section VI presents the base model performance as well as several variations and a sensitivity analysis. In Section VII we present a short discussion. Finally, in VIII we conclude the research and reflect on the simulation results with suggestions for future research.

II. Background: The Nominal flight Process

Preparation for commercial flights commonly starts a number of hours before departure. Several interlinked processes need to occur leading up to the plane arriving at the gate for its flight. At this point passengers and cargo is loaded and, once the doors close, an aircraft enters a queue for taxi and take-off. Problems arising during any of the preparatory steps, or carrying over from previous aircraft rotations and in some cases congestion at the departure airfield can all lead to (initial) delays before the flight has even taken off and influence the timeliness of the downstream arrival process.

After take-off, an aircraft will interact with several Air Traffic Controllers (ATCo) and pass through a number of different types of airspace. Once levelled off, a flight has entered the cruise phase; cruise is typically the least restrictive flight phase for a commercial aircraft where an aircraft flies along pre-filed waypoints at speeds specified in the flightplan.

Aircraft manufacturers typically allow for performance tweaking by the end user through what is known as the cost index (CI). The cost index is a relative measure expressing the importance of time spent airborne versus (additional) fuel consumed and serves as a user input to the flight computers flying the aircraft. Variation in aircraft characteristics, as well as the user input in the form of the Cost Index influence the overall trajectory an aircraft will fly, including aspects such as the climb, cruise and descent profiles [6].

In the US, FAA[3] regulations specify that any speed changes larger than 10 knots or 5% (whichever is larger) need to be communicated to ATC, with similar schemes acting in European airspace [7]. This means that, within limits, flight crews retain some control over the speeds flown, which over the length of a typical cruise phase can have a noticeable impact on the arrival time.

Variations in (expected) wind and the possibility for (more) direct routing instructions by en-route ATC allow for further

[3] FAA Order JO 7110.65 [accessed 01-06-2020]

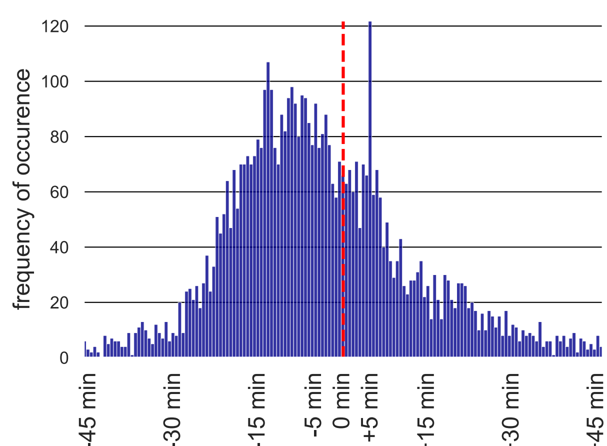

Fig. 2. Arrival delay variation observed in the test set.

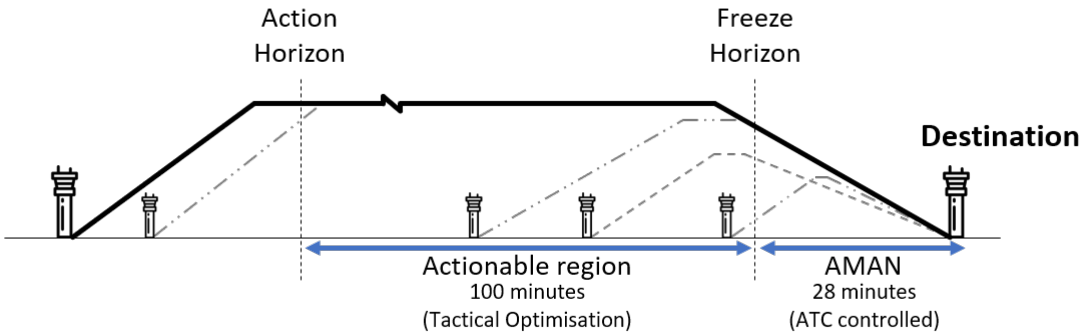

Fig. 3. Arrival optimisation regions overlaid with nominal flight paths.

variations in flight duration. In order to mitigate the impact of flight time variances airlines on airline scheduling, it is often chosen to build strategic buffers around flights when building an airline schedule [8]. These effects and the inherent airline preference for a flight to arrive (slightly) before schedule rather than after, results in the majority of all arrivals arriving before schedule. An illustration of this effect can be seen in Figure 2, derived from the test data considered in this research project.

The skew in the arrival delay distribution depicted in Figure 2 is the backbone of the situation this IPS concept leverages. Flights estimated to arrive early can choose to incur a small en-route delay with little negative consequence to the arrival time at the gate. Subsequently the virtual leeway created in the arrival queue can be exchanged by allowing a ”priority” aircraft with (significant) initial delay to make up some delays and arrive in the gap created by the other flights. Through this mechanism, a priority flight can in some occasions arrive before rather than behind the ”early arrivals” which leads to arrival delays being distributed more effective amongst the set arriving flights and in turn leading to an overall gain for the airline in question.

Finally, upon entering the airspace near the destination airport, Air Traffic Control assigns incoming aircraft to a landing runway and spaces individual aircraft apart such that minimum separation requirements are satisfied between successive arrivals. Aided by rules such as ”First-Come, First-Served” and confined by aircraft manoeuvring capabilities (e.g. speed limitations, rate of descent, etc.), ATC is tasked with safely passing all traffic through controlled airspace, whilst at the same time optimising the arriving flow of aircraft for each of the (commercial) stakeholders. In order to aid controllers in planning the arrival process, most commercial airports deploy Arrival MANagers (AMAN) visualising and planning out the arriving traffic flow according to rules such as ”First-Come, First-Served”.

III. Previous Work

Over the past decades, several research efforts have focused on formulating decision support tools and optimised arrival strategies for what is more commonly referred to as the aircraft landing problem (ALP). The aircraft landing problem is traditionally characterised as a decision problem with three components, namely sequencing, scheduling, and runway-assignment. From recent literature, Bennell et al. [9] provide an extensive overview of literature related to the aircraft landing problem. The following section highlights and extends from this literature through several recent or otherwise relevant papers for the formulation presented.

A majority of research around the ALP assumes the role of an (Extended) Arrival Manager, taking over some or all of the responsibilities of the destination ATCo and operating in the airspace directly encircling the destination airport. The algorithm presented in this research differs as it joins a handful of other researchers (e.g. [7], [10]) in examining the effects of tactical optimisation using en-route Control preconditioning the arrival flow **prior** the freeze horizon and destination air traffic control, leaving the destination centre’ arrival process and AMAN (largely) unaltered. See Figure 3 for a graphical representation of the active region of the proposed ALP and the ATC controlled freeze region.

ATC is often considered as the coordinating and executing party [4]. In contrast, Moertl et al. [11] and, Ren and Clarke [12] were able to demonstrate an operational concept for en-route sequencing and scheduling using airline control.

Commercially, ATH Group Inc, offers a software suite that analyses incoming traffic and re-times them in coordination with ATC such that they arrive ”in sequence for an optimal arrival flow.” [3]. Guzhva et al. [7] presents a benefit assessment of the aforementioned concept by the ATH group which they have dubbed the ”Aircraft Arrival Management System (AAMS)”. Considering the operations of the now defunct US-airways and a 1000nm action radius around Charlotte Douglas international airport in the USA, they observed an improvement (reduction) of around 5% in the aircraft dwell time in spite of compliance rate of only 6.5% of all arriving traffic.

Beasley et al. [13] notably expresses the ALP as a Mixed-Integer Linear Programming (MILP) problem and subsequently consider several variations from the single runway static case, to the multi-runway dynamic formulation [14],

[4]”En Route Speed Control Methods for Transferring Terminal Delay” - James Jones, David Lovell and Michael Ball, Presentation, 10th USA/Europe Air Traffic Management Research and Development Seminar, ATM, 2013

[15]. Since then, several authors have followed in formulating the ALP as a MILP ([1], [16]–[18]).

Both static and dynamic forms of the ALP have been presented in literature with the most dressed down problem formulation being the deterministic off-line optimisation (e.g. [13] and [19]). A commonly found solution to incorporate dynamic information or decrease computational times has been proposed in the form of a Receding Horizon Control (RHC) scheme ([20]). In the RHC scheme, the full problem is broken up into a set of smaller sub problems with some aircraft overlapping the specified optimisation windows. Each time the previous window has been solved and the next optimisation window is considered, scenario information can be updated with those aircraft overlapping and in subsequent optimisation windows benefiting from this increased scenario knowledge (see e.g. [21] and [22]).

When it comes to the objective of the ALP, several metrics have been used to express the performance mainly falling into one of two categories; Cost based metrics or Time based metrics. Time based metrics can be concerned with the maximised use of infrastructure such as in the minimisation of the time to land the last aircraft (minimal makespan) [23]. Samà et al. [18] choose to express the trade off between the minimal average delay all aircraft experience and the maximum individual delay a single aircraft encounters. [24] focus solely on the minimisation of deviation compared to the nominal arrival schedule. Variations proposed by [25] exclusively consider arriving later than scheduled in their objective, whilst [26] further discriminates the weighted delay time between different types of aircraft or if an aircraft is already airborne or not. Cook et al. [27] consider the delay metrics not on aircraft level, but break this down to a passenger specific metric by including the effects of flight delay on individual passenger (itineraries) and go as far as to consider the possibility of further accommodating any delayed passengers on subsequent flights, citing the large differences in impact when considering both flight versus passenger metrics.

Recent efforts by Montlaur and Delgado [5] highlight the strong non-linearity in airline delay cost with respect to delay time. Cook et al. [28] have presented an ongoing effort quantifying the cost of delay for airlines in the European context. For an airline, Cook et al. finds the main cost drivers in delay to be Fuel and Passenger cost, with passenger cost being both directly impacting cash (hard cost), as well as indirectly impacting cash through loss of future value (soft cost). [29], [30] and [31] all implement passenger cost in airline delay problem.

Fuel cost are commonly used to quantify the effects of flying faster versus arriving earlier at the destination or to express the time spent loitering [32]. Tools such as the Base of Aircraft DAta (BADA) developed and maintained by EUROCONTROL ([33]) have made performance calculations readily accessible to researchers for a wide range of the most prevalent aircraft types. More recently, concepts such as linear holding have been discussed in literature which leverage the fact that most commercial aircraft fly (slightly) faster than their most economical (from a fuel perspective) cruise speed in order to trade time spent airborne for additional fuel burn [34]. Furthermore, several concepts have been presented leveraging linear holding in order to delay aircraft at no additional (Fuel)cost [34]–[36]. This effort ties in with the push to include forms environmental performance indicators in proposed solutions through the correlation between fuel burn and (greenhouse gas) emissions [37].

Carr et al. [19] were one of the first to explicitly consider airline priorities in the decision making scope. This decision was in contrast to most earlier work which considered (average) delay time statistics as the primary measure of effectiveness. The work of Soomer and Franx [1] expand on the notion that delay cost are highly non-linear in time for airlines and introduced an Arrival Sequencing & Scheduling scheme in which airlines could submit their own cost functions, which would be scaled in order to to provide a "fair" trade-off between the individual airline stakeholders. The implementation of Soomer and Franx has the benefit that it allows for an airline to express the cost function without needing to share the exact "cost" of each flight with other stakeholders; information which is often quite sensitive for an airline. During simulations, Carr et al. [19] showed that using the preference of airlines could be implemented with little to no decrease in overall efficiency.

In the Aircraft Landing Problem, the most commonly modelled and virtually ubiquitous constraint is the wake-vortex separation between successive aircraft arrivals [9]. Finding similar levels of acceptance, constraints are placed, bounding the possible landing times for each aircraft, representing the presence of finite limits of aircraft performance; although sometimes formulated only single sided [38]. Balakrishnan and Chandran [23] introduce a constraint called Constrained Position Shifting (CPS), restricting each aircraft to land within a pre-determined number of positions from its place in the "First-Come, First-Served" arrival queue rather than the time advance or slow down achievable. Fairness and Equity are often a consideration in the ALP, with [39] going so far as to investigate the implementation of some forms of hard constraints enforcing various definitions of Fairness.

No single universally accepted solution has emerged and as such the topic remains of interest for research. For the project at hand, the strength and focus lie on the marriage between the ATM controlled arrival process and the Airline operator' fleet control capabilities aligned with its (commercial) priorities.

We consider and evaluate the en-route capabilities an airline has to adjust the entry times into the destination airport's airspace for its aircraft. The modelling approach couples arrival times right before entering the destination ATC controlled airspace and, simulates the response the ATM system has to the adjusted input. Whilst at the same time upholding and not altering safety and equity schemes (e.g. "First-Come, First Served") implemented by ATC in the destination airport's airspace. We evaluate the (commercial) impact of the ability for an airline to leverage the knowledge of surrounding traffic in the ATM system and the control leeway it has within only the aircraft in its own fleet.

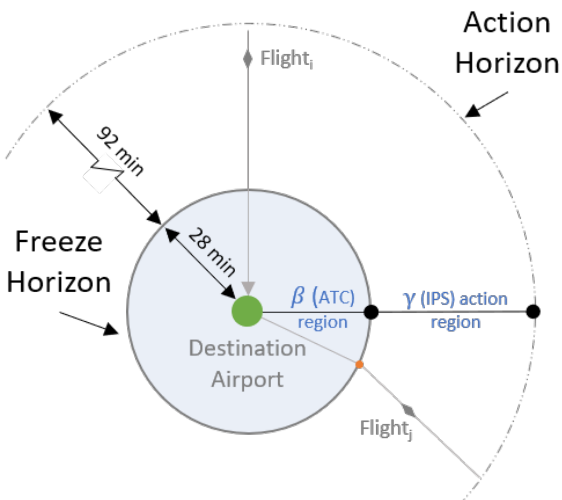

Fig. 4. Optimisation horizon overview in the IPS scheme.

IV. Modelling Approach - Methodology

This section describes the Inbound Priority Sequencing (IPS) algorithm and overall modelling framework used to determine the arrival Sequence and Times for a given set of flights. We first present the concept of operations for the IPS model after which we present the MILP formulation based on the single-runway formulation introduced by Beasley et al. [13]. Finally the section is closed off with a discussion of the most prevalent assumptions applied to the model.

A. Inbound Priority Sequencing (IPS) - concept of operations

In this paper we consider a variation to the Aircraft Landing Problem for aircraft landing on a single runway. Our variant is based on actions and control in the (en-route) actionable region before entering the destination airfield' ATC controlled Arrival Management (AMAN) process (see Fig. 3). Within the AMAN region, aircraft are landed by ATC in accordance to a so-called "First-come, First-Served" scheme based on their appearance time at the Freeze Boundary (freeze horizon, see Fig. 4). Finally, the window of control is limited to a single airline's fleet, simulating the single airline perspective. However, it should be noted that the airline considered has a majority stake in the inbound traffic share (e.g. a hub carrier at its home base).

The bound for the Action Horizon is set at two hours before nominal arrival at the destination airport and the ATC controlled arrival process starts at 28 minutes before the nominal arrival time, roughly when aircraft appear on the radar bound at the destination port [40]. In comparison to traditional distance based metrics, time-based boundaries account for the difference in aircraft performance characteristics (e.g. cruise speed, descent profiles, etc.). This means that depending on individual aircraft performance, the physical location (latitude, longitude, altitude) of the freeze and action horizon can differ. However, the time to destination is exactly at a set interval (e.g. [unobstructed] touchdown time - 28 minutes).

We assume flights to be controlled by IPS only within the actionable region and subsequently simulate ATC response according to a set of fixed flight handling rules (most notably "First-Come, First-Served") at the Freeze Horizon. Together this allows us to determine the adjusted arrival time up to the point of touchdown on the runway whilst accounting for IPS action in the actionable region. The reader should note that the problem is built up of two phases; the actionable region in which the (airline) control actions (γ) can be executed to alter arrival times at the freeze boundary, and the AMAN region in which (it is simulated how) ATC applies a "First-come, First-Served" scheme and spaces out (β) aircraft before landing in order to ensure separation between successive aircraft landings.

B. Mixed Integer Linear Programming formulation

In this section, a Mixed Integer Linear Programming (MILP) formulation of the model is given. First the variables and notation considered in the optimisation scheme are introduced, after which the priority based optimisation objective is presented, followed by the applied constraints.

1) Notation and Variables:

Flight sets:
Let F denote a set of flights to be scheduled, with flight $i \in F$, $1 \leq i \leq n$ being the ith scheduled flight to arrive at the airport. In addition, let MF denote the set of (controlled) managed flights such that $MF \subset F$, where $MF = \{i \in F \mid type$ is Managed$\}$ and, let CF denote the set of competitor flights such that $CF = F \setminus MF$

Passenger sets:
Let PAX_i denote the set of passengers on board of flight i, with $\text{pax}_{i;q} \in PAX_i, 1 \leq q \leq m$ being the qth passenger on board of flight i which contains m passengers.

Flight variables and parameters:

$\lvert n \rvert$:	Number of arriving flights in set F	
ETA_i :	Estimated landing time of flight i	$\forall\ i \in F$
STA_i :	Scheduled landing time of flight i	$\forall\ i \in F$
Rec_i :	Maximum amount of time recoverable through speeding up for flight i	$\forall\ i \in MF$
Add_i :	Maximum amount of time added by slowing down for flight i	$\forall\ i \in MF$
$Sep_{i,j}$:	Minimum time based separation when flight i lands before flight j	$\forall\ i, j \in F$
β_i :	Spacing delay time applied by ATC to flight i (after freeze horizon, Fig.4)	$\forall\ i \in F$
TD_i :	Total flight delay of flight i (see Fig. 6)	$\forall\ i \in F$
T_i^{nm} / V_i^{nm} :	Nominal cruise duration (time) and speed for flight i	$\forall\ i \in F$
T_i^{IPS}/ V_i^{IPS} :	IPS adjusted cruise duration (time) and speed for flight i	$\forall\ i \in F$
d_i^{cr} :	Cruise distance of flight i	$\forall\ i \in F$
P^F :	Fuel price in EUR/kg	

Passenger variables and parameters:

$\Delta_i^{\text{LFV}}{}_{(\text{TD})}$:	Loss of Future Value Delay cost function as a function of total flight delay TD_i (Fig. 6)
$Cs_{i;q}$:	Additional transfer time above minimum for passenger q on flight i; $\forall$ $\text{pax}_{i;q} \in PAX_i$
$F_i^x(V)$:	Fuel burn in kg/sec for aircraft i and flight condition x as a function of airspeed (V) (based on BADA 3.12 [33])
P^{mc} :	Average cost of a misconnecting passenger
BT :	% of passengers considered "Business traveller"
M :	Large integer constant

Decision variables:

γ_i : IPS cruise time adjustment for flight i (Fig. 4, IPS action region) $\quad \forall\ i \in MF$

$$\delta_{i,j} = \begin{cases} 1 & \text{If flight } i \text{ arrives at the bound earlier than flight } j \ (ETA_i + \gamma_i < ETA_j + \gamma_j) \\ 0 & \text{Otherwise} \end{cases} \qquad \forall\ i,j \in F$$

To start, the Actual Time of Arrival (ATA) of flight i is related through:

$$ATA_i = ETA_i + \gamma_i + \beta_i \qquad \forall\ i \in F \tag{1}$$

Aircraft are landed in a "First-Come, First-Served" manner according to the landing time estimate established at the freeze horizon (i.e. $ETA_i + \gamma_i$). When IPS is turned off, γ_i is zero for all aircraft. If no congestion exists (separation between aircraft ensured without intervention) the provided landing time estimate equals the Actual Time of Arrival (i.e. $\beta_i = 0$). However, if the time between successive arrivals is smaller than the required separation ($Sep_{i,j}$), ATC applies the minimal spacing delay (β) such that the inter arrival time is equal to the required separation between aircraft.

2) Objective function:
The objective for the IPS model is a reflection of the cost incurred by an airline for arriving flights. Each flight has different characteristics, such as the number of transfer passengers and their transfer times or, fuel efficiency of aircraft operating the specific flight. For this reason, the objective for the optimisation concerns the minimisation of the total delay cost and in addition, is limited to the cost for the reference airline only. The difference in flight value leads to relative priorities and a trade-off between delays for arriving flights.

The cost function considered in this paper consists of 4 components reflecting different aspects of the operation and is formulated as follows :

$$\min \sum_{i\ \in\ MF} \left(\underbrace{C_i^{loiter} + C_i^{IPS}}_{\text{Fuel Cost}} + \underbrace{C_i^{LFV} + C_i^{mc}}_{\text{Passenger Cost}} \right) \tag{2}$$

Fuel cost are split between the loiter fuel cost spent holding at low altitude in the airspace directly around the destination airport and the IPS fuel cost related to speeding up, or slowing the aircraft "en-route" in the actionable region through the IPS scheme. Passenger cost are related to the Actual time of Arrival and are subdivided into two components, the Loss of Future Value (LFV) related to passengers arriving at the hub and terminating their trip there and, the cost related to Missed Connections (mc) for passengers with onward connections. The following subsections will discuss the breakdown of each component in the objective function.

Loiter fuel cost
Loiter fuel cost are the fuel cost born as a result of above nominal fuel burn for holding near the destination due to ATC actions (β_i). Computing the fuel cost of loitering is achieved by converting the time spent loitering due to ATC (β_i) and relating this to the fuel burned and price of fuel. Equation 3 shows how the relationship is formed.

$$C_i^{loiter} = \beta_i \cdot F_i^{lt}(V_{loiter}) \cdot P^F \qquad \forall i \in MF \tag{3}$$

With F_i^{lt} representing the loiter fuel burn in kg/sec for aircraft i based on the BADA [33] total energy modelling approach under the published loiter speed (V_{loiter}).

IPS 'control' cost
IPS cost are those resulting from the increase or decrease in fuel cost resulting from IPS speed control actions undertaken during the cruise phase. The interesting component of IPS fuel cost lies in the concept of linear holding [36].

In order to illustrate, a unit of flight efficiency needs to be introduced, the specific range (SR). SR is defined as the distance that can be flown per unit of fuel (e.g. Kilometres/kg fuel). Figure 5 depicts the relationship between between Specific Range and cruise speed. The highest SR corresponds to the maximum range cruise speed (V_{MR}).

As introduced earlier, airlines typically fly their aircraft at a higher cost index (CI) and thus speeds in order to exchange fuel efficiency for time spent airborne. This higher "nominal

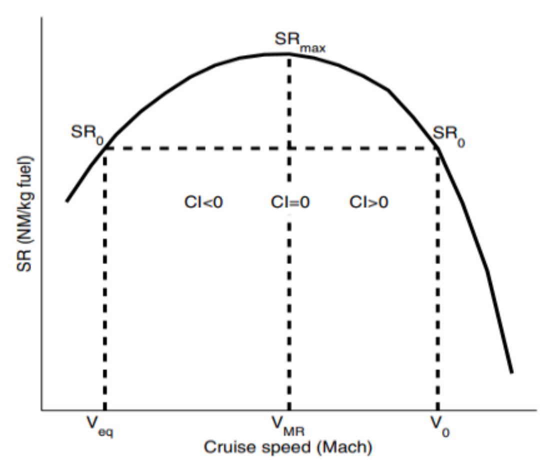

Fig. 5. Specific Range (SR) as a function of cruise speed [36].

cruise speed" (V0, Fig. 5) corresponds to a lower (sub optimal) SR. In the SR curves for most modern air transport aircraft, there exists an equivalent cruise speed (V_{eq}) such that the SR is equal to the SR at nominal cruise speed with $V_{eq} < V_0$. Any speed flown in between V_{eq} and V_0 nets a lower fuel burn during the cruise phase as compared to the nominal cruise speed. Any speed lower than V_{eq} or higher than V_0 results in additional fuel being consumed.

To quantify the impact of IPS actions, a comparison is drawn between the baseline "nominal cruise fuel" cost and the fuel cost for the cruise under the adjusted IPS scenario conditions (i.e. speeding up or slowing down). The following Equation shows the relationship we strive to evaluate:

$$\text{C}_i^{IPS} = [(\text{IPS Cruise Fuel}) - (\text{Nom. Cruise Fuel})] \cdot P^F \quad \forall i \in MF \tag{4}$$

The *nominal cruise fuel* can be calculated by multiplying the the the cruise length (expressed in time, T_i^{nm}) multiplied with the cruise fuel flow (kg/second) under the nominal cruise speed (V_i^{nm}); $F_i^{cr}(V_i^{nm})$. The cruise fuel flow, $F_i^{cr}(V)$, is evaluated using the BADA3 total energy model [33].

$$\text{Nom. Cruise Fuel [kg]} = T_i^{nm} \cdot F_i^{cr}(V_i^{nm}) \tag{5}$$

The expression for the *IPS Cruise fuel* becomes more complex (and non-linear) as both the cruise length (expressed in time) as well as the cruise speed are influenced by increasing or decreasing the cruise speed. The (IPS) decision variable (γ_i) indicates the additional time spent in the cruise phase due to speeding up or slowing down. Equation 6a and 6b relate the decision variable, γ_i, to the updated cruise time and speed. Throughout the application of IPS, cruise distance, d_i^{cr}, remains unchanged. IPS cruise fuel can henceforth be computed through Equation 6c.

$$\text{IPS adjust. cruise time} = T_i^{IPS} = T_i^{nm} + \gamma_i \tag{6a}$$

$$\text{IPS adjust. cruise speed} = V_i^{IPS} = \frac{d_i^{cr}}{T_i^{IPS}} = \frac{d_i^{cr}}{T_i^{nm} + \gamma_i} \tag{6b}$$

$$\text{IPS Cruise Fuel [kg]} = T_i^{IPS} \cdot F_i^{cr}(V_i^{IPS}) \tag{6c}$$

Filling in Equation 4 with the previously derived variables leads to the following expression 7a.

$$C_i^{IPS} = \left[(T_i^{IPS} \cdot F_i^{cr}(V_i^{IPS})) - (T_i^{nm} \cdot F_i^{cr}(V_i^{nm}))\right] \cdot P^F \quad \forall i \in MF \tag{7a}$$

Due to the inferred non-linearity in the of Equation 7a, a first order Taylor series approximation is applied to ensure compatibility with the proposed Linear Programming scheme. Due to the small margin of operation in the linearised variable (γ), linearisation errors remain marginal.

Loss of Future Value (LFV)

Loss of Future Value (LFV) quantifies the decreased likelihood of future business through the inconvenience caused by arrival delay to passengers with the hub airport as their final destination. Connecting passengers are not included in this category since arrival delay will either cause them have a shorter layover or miss their flight, the former without additional cost and the latter being encapsulated in the cost of a missed connection.

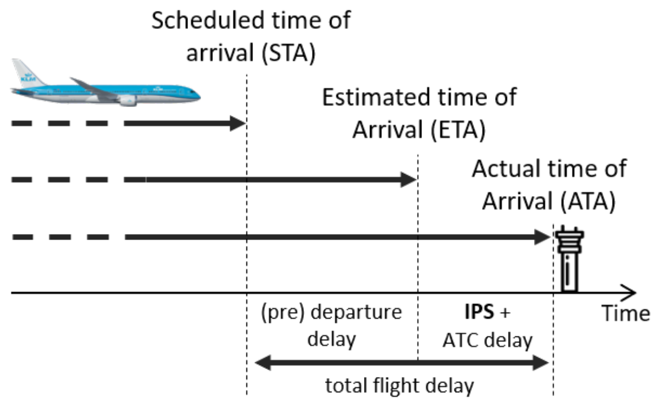

Fig. 6. Schematic overview of arrival timing

LFV is proportional to the delay compared to the scheduled time of arrival (STA), which is the agreed upon arrival time with the customer through the published schedule and therefore represents the customer expectation. Figure 6 depicts the traditional relationship between the STA, the Estimated Time of Arrival (ETA) and the Actual Time of Arrival (ATA). Total flight delay (TD) is defined as:

$$\text{Total flight delay}_i(TD_i) = ATA_i - STA_i \quad \forall\ i \in F \tag{8a}$$

$$TD_i = (ETA_i + \gamma_i + \beta_i) - STA_i \quad \forall\ i \in F \tag{8b}$$

Total flight delay can be further broken up into two segments (see Fig. 6) elaborated on below.

A. The difference between the Scheduled Time of Arrival (STA) and the Estimated Time of Arrival (ETA) or *"(pre) departure delay"*. (pre-)departure delay (as introduced in Section II) happens outside of the scope of IPS and is defined as any form of delay an aircraft encounters before entering the action horizon. Furthermore, it can be said that (pre-)departure delay is a characteristic of the input scenario used in the model, i.e. both STA and ETA are input variables defining the scenario.
B. The difference between the Estimated Time of Arrival (ETA) and the Actual Time of Arrival (ATA) or *"**IPS** + ATC delay"*. **IPS** + ATC delay form the core of the IPS optimisation and are embodied in the model through the decision variable, γ_i, for IPS actions and the modelling variable, β_i, representing the ATC delay.

Modelling the per flight cost attributed to Loss of Future value is achieved through first defining the "*Loss of Future Value Delay cost function*" ($\Delta_i^{LFV}(TD_i)$). The Loss of Future Value Delay cost function expresses the delay cost on a per passenger basis proportional to total flight delay experienced

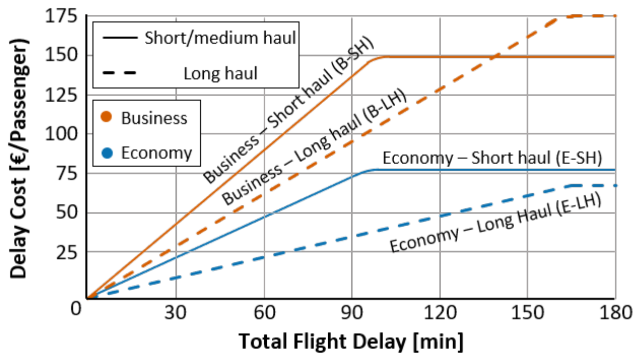

Fig. 7. Loss of Future Value delay cost function for a European Hub Carrier.

by the passenger and can be further broken up for passenger type and/or flight length.

A set of representative curves of which is shown in Figure 7. Depending on Flight length, either the dashed or solid LFV delay cost curves will be evaluated. That is;

$$\Delta_i^{LFV-B} = \begin{cases} \Delta_i^{LFV-B-SH} & \text{if } i \text{ is short/medium haul} \\ \Delta_i^{LFV-B-LH} & \text{if } i \text{ is long haul} \end{cases} \tag{9}$$

$$\Delta_i^{LFV-E} = \begin{cases} \Delta_i^{LFV-E-SH} & \text{if } i \text{ is short/medium haul} \\ \Delta_i^{LFV-E-LH} & \text{if } i \text{ is long haul} \end{cases} \tag{10}$$

Furthermore, a split of $BT\%$ Business travellers and $(1-BT)\%$ Economy passengers (different colours Figure 7) is assumed on every flight, for which their respective LFV delay function will be proportionally contributing (see Eq. 11a).

Equation 11 depicts Loss of Future Value cost on a per flight basis.

$$\Delta_i^{LFV}(TD_i) = BT \cdot \Delta_i^{LFV-B}(TD_i) + (1-BT)\cdot\Delta_i^{LFV-E}(TD_i) \tag{11a}$$

$$PAX_i^{nc} = \{pax_{i,q} \in PAX_i : Cs_{i,q} = \infty\} \tag{11b}$$

$$(\text{Flight LFV})_i = \Delta_i^{LFV}\left(\underbrace{[ETA_i - STA_i]}_{\text{(pre) departure delay}} + \underbrace{[\gamma_i + \beta i]}_{\text{IPS+ATC delay}}\right)\cdot|PAX_i^{nc}| \quad \forall i \in MF \tag{11c}$$

$$C_i^{LFV} = \max\left(\text{Flight LFV}_i, 0\right) \quad \forall i \in MF \tag{11d}$$

With PAX_i^{nc} referring to the set of passengers on board flight i with no onward connection. Equation 11d ensures that C_i^{LFV} will be at least zero, in other terms ensuring that no money is "earned" by arriving early.

Cost of missed connections (MC)

The cost of missed connections concerns the cost born by an airline as a result of a passenger missing their airline guaranteed connection. The cost of a missed connection is an assimilation of several costs including aspects such as accommodating a passenger on a future flight, providing refreshments during the delay, cash compensation claims and hotel cost if the delay last more than x hours. The cost fall in either of two categories; direct cash impact (hard cost) or loss of future value (soft cost). Within the IPS model, the cost of missed connections is modelled as a fixed constant regardless of connection type or recovery possibilities.

The cost of missed connections is a function of the amount of passengers who miss their connection as a result from the total encountered delay (TD_i or $[ETA_i - STA_i] + \gamma_i + \beta_i)$) times the average cost of a missed connection. Equation 12a expresses the flight based determination of the amount of missed connections . Subsequently, Equation 12b shows a breakdown of the cost function.

$$PAX_i^{mc} = \{pax_{i,q} \in PAX_i : Cs_{i,q} < (TD_i)\} \tag{12a}$$

$$C_i^{mc} = |PAX_i^{mc}| \cdot P_i^{mc} \qquad \forall i \in MF \tag{12b}$$

With PAX_i^{mc} referring to the set of passengers on board flight i with who do not make their onward connection and P_i^{mc} the average missed connection cost per passenger.

3) Constraints:

The section below outlines the set of constraints applied to the MILP model:

$$V_i^{IPS} \leq \max\left((1.05\cdot V_i^{nm}),(V_i^{nm}+10)\right) \quad \forall\ i \in MF \tag{13a}$$

$$V_i^{IPS} \geq \min\left((0.95\cdot V_i^{nm}),(V_i^{nm}-10)\right) \quad \forall\ i \in MF \tag{13b}$$

$$Rec_i \leq \gamma_i \leq Add_i \qquad \forall\ i \in MF \tag{14a}$$

$$\gamma_i = 0 \qquad \forall\ i \in CF \tag{14b}$$

$$\beta_i \geq 0 \qquad \forall\ i \in F \tag{15}$$

$$\delta_{i,j} + \delta_{j,i} = 1 \qquad \forall\ i \in F \tag{16}$$

$$(ETA_j + \gamma_j + \beta_j) \geq (ETA_i + \gamma_i + \beta_i) + Sep_{i,j} - M\delta_{j,i} \quad \forall\ i,j \in F \tag{17}$$

Equations 13a and 13b ensure that any speed changes applied to aircraft adhere to the set limits of a maximum of 5% or 10 knots of speed change (whichever is larger). Combined with Equations 6b and 6a, the limit case of Equation 13a (i.e. $\leq \rightarrow =$) is used to determine the maximum amount of En-Route time recoverable (Rec_i). Similarly, Equations 6b, 6a and the limit case for 13b (i.e. $\geq \rightarrow =$) form a system of equations which can be used to determine the maximum additional en-route time (Add_i).

Equation 14a bounds the possibility of the IPS algorithm to assign cruise time adjustments (speed-up or slow down, γ_i) larger than the upper bound or smaller than the lower bound corresponding to the allowed speed change and evaluated over the Actionable Region. Additionally, Equation 14b ensures competitor aircraft cannot be assigned any IPS action.

Equation 15 Ensures that ATC can only delay aircraft in order to guarantee adequate separation between successive landings and not advance them (speed them up).

Equation 16 ensures that either aircraft i lands before aircraft j or v.v. . The determination of δ itself is a function of the estimated arrival time ($ETA + \gamma$) and ensures "First-Come, First-Served" is upheld once an aircraft enter the Freeze Horizon.

Equation 17 represents the separation enforced between successive aircraft landings, not knowing the order of landing before the optimisation is commenced (but relating this through the delta variables). It is used to determine the ATC delay (β).

The term $(ETA_i + \gamma_i + \beta_i)$ is equivalent to ATA_i as introduced in Equation 1. For convenience, subsequent equations will refer to ATA_i.

There are two distinct cases for Equation 17:

a. If Aircraft i lands before Aircraft j; $\delta_{i,j} = 1$. Through Equation 16 this means that $\delta_{j,i}$ becomes 0, reducing Equation 17 to:

$$ATA_j \geq ATA_i + Sep_{i,j}, \tag{18}$$

ensuring separation is enforced.

b. If $\delta_{i,j} = 0$, then j lands before i and, from Equation 16, we have that $\delta_{j,i} = 1$. Therefore, Equation 17 becomes:

$$ATA_j \geq ATA_i + Sep_{i,j} - M, \tag{19}$$

i.e. ATA_j is larger or equal to some large negative constant, thereby ensuring that the constraint is effectively inactive.

C. Assumptions

Throughout the modelling process presented, several assumptions and simplifications are made. The following sections highlights a number of these as well as briefly mentioning possible implications.

- The formulation presented is deterministic, meaning all parameter values and scenario inputs are assumed to be known before running the algorithm. In practice this is not the case with among others arrival time and cost estimates evolving throughout time. Dynamic formulations can be considered and implemented through a rolling horizon scheme implementation of the model. In order to focus the investigative efforts, no deterministic effects were considered.
- The only capacity constraint in the system is runway capacity. In reality other considerations can be relevant such as available gate capacity or en-route capacity when determining the most efficient operation. To narrow the investigative scope it was chosen to focus solely on the effects of the runway capacity as the main arrival constraint.
- Single runway operations are considered in the model, noting that in most dual runway operations present in the scenario considered, runway assignment is dependant on aircraft arrival routing (Location of entry into airspace) significantly more than ATC operations. Corrective actions such as ATC ordered runway balancing are therefor not considered in the model.
- No spilled passenger recapturing possibilities are considered when determining the amount of missed connections. In reality some destinations offer the airline easier rebooking possibilities for passengers who miss their initial connection. As a result all missed connections are treated where the actual cost (or inconvenience) to the airline could vary. With integral knowledge of the further flight schedule, an implementing party could include a unique missed connection cost to each passenger or include recapture possibilities in the presented formulation.
- Aircraft, maintenance and crew limitations are not explicitly considered in the IPS formulation. In reality additional arrival time window limitations can be present as a result of these consideration, as well as additional (financial) incentives for certain arrival times. Where applicable,the formulation presented allows for these considerations to be added by the end user.
- Flight duration is calculated using nominal cruise speeds and wind patterns, with the distance based on the great circle distance between airports. In reality the end user has greater knowledge of filed flight plans and company routing. As a result the recoverable time calculation will be less precise than if this information would be present.

V. Case Study

In the following section a case study of KLM operations at Amsterdam Airport Schiphol is presented in order to evaluate and discuss model performance. Amsterdam Airport Schiphol is one of the world's busiest airports and, at the time of writing, ranks in the top five busiest airports within Europe by both amount of passengers as well as flight movements. Schiphol has 6 runways (see Figure 9) in varying directions necessary to with cope with the frequent variations in wind direction and speed encountered. Two runways at Schiphol, indicated by a cross, are only operated in a single direction. The airport itself handles over 600 scheduled arrivals per day, with significant portion (just over 50%) operated by the Dutch flag carrier KLM.

KLM is a traditional full service network airline operating a Hub-and-Spoke style network out of their home base Schiphol and has been quoted indicating over 70% of all passengers being connecting passengers[5]. KLM operates to over 65 countries and is part of the airline alliance Sky-Team. As part of the Hub-and-Spoke style network KLM (and partners) operate in a so-called wave structure concentrating arriving and departing flights in several compact windows throughout

[5]Tjalling Smit, SVP of Digital at Air France-KLM https://news.klm.com/social-airline-klm-connects-travellers-and-amsterdam-locals/

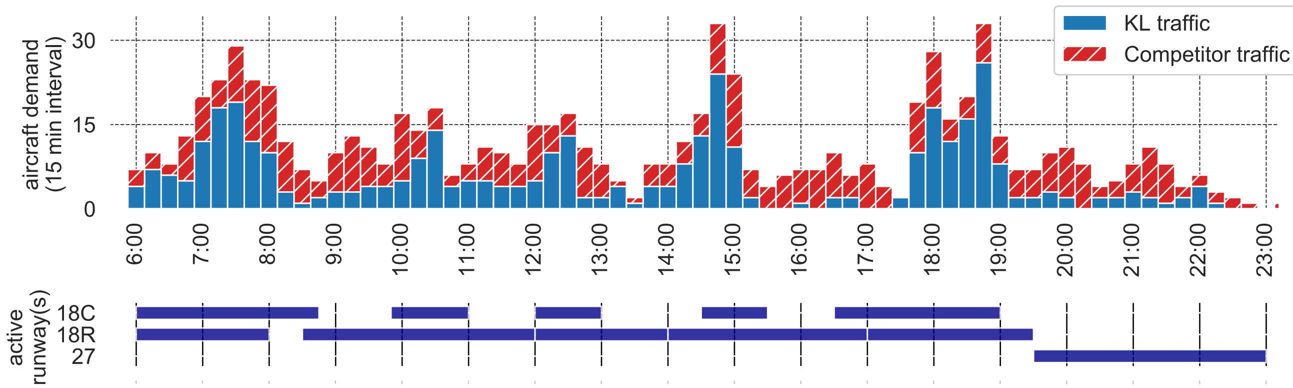

Fig. 8. Distribution of flight demand (top) throughout a day of operations and active arrival runways (bottom).

the day in order to minimise connection times for passengers (see Fig. 8). The mix of abundant connecting passengers, the presence of tight connections and relatively high overall traffic share (even higher than the 50% during peak waves) makes KLM' operations an ideal candidate for evaluation under the "Inbound Priority Sequencing" scheme.

A. Scenario description

The full scenario set considered consists of 10 (ten) days of operation throughout January of 2019. Both weekend and weekdays are included in the scenario and days range from 06:00 through to 23:00. Each day is broken up into several smaller scenarios corresponding to the (frequent) runway configuration changes at Schiphol. As a result, (sub-)scenarios range in absolute size from 35 aircraft to over 207 aircraft, although computational time remained in the same order of magnitude.

The 10 day flight set considered consists of 5514 scheduled flights, 51 distinct aircraft types and 258 destinations. In the data set just under 19% of all flights considered are under 500km, 67% are between 500km and 3500km and, the other 14% of flights are over 3500km. A majority of all arriving aircraft, 84%, fall into the medium ICAO wake vortex category. Of the remaining flights, 96% is considered heavy or more (super), with only a handful of flights falling into the light category. Notably, most heavy traffic is concentrated within the arrival waves.

One day of operation (25-01-2019) is depicted in Figure 8 with flight demand on top and the active runway(s) depicted below. In the bottom quadrant, both single runway operations (18R or 27), as well as multi-runway (18C + 18R) operations can be observed. For modelling purposes, the scenario was broken up for every distinct segment in which a runway was active. This means that the longest segment on the 25^{th} of January is runway 18R from 08:30 to 19:30 and the shortest 18C from 12:00-13:00. Although considered continuously in operation, even runway 18R had a number 10+ minute intervals without any flight demand, in which arrival streams could not possibly interact through the set IPS scheme.

Flight arrival information is extracted from historic arrival data recorded by Air Traffic Control The Netherlands (LVNL) and includes both schedule and operational arrival time information (e.g. STA and ETA), as well as information on the aircraft type and, airline operating the flight. Figure 8 shows clear demand peaks at several hour intervals coinciding with the concentrated arrival waves of hub operator KLM.

Figure 10 depicts the (pre-)departure delay present in the arrivals from 10 days worth of data in the data set upon entering the action horizon On average arrivals tend to touch down several minutes before their scheduled arrival time. Outliers (more than 45 minutes schedule deviation) exist with both early and late arrivals, with a relative higher occurrence of delayed aircraft. Aircraft with significant delays can present an interesting (moral) decision in the model, as some aircraft

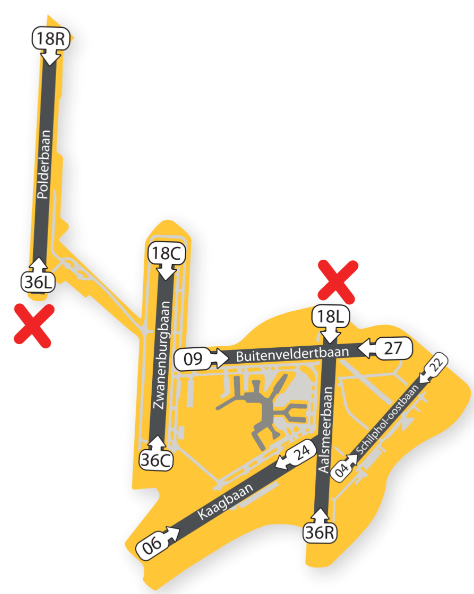

Fig. 9. Runway configuration of Schiphol airport [courtesy: Amsterdam Airport Schiphol].

delays are significant enough that no actions within the IPS model can decrease the cost function (in proportionally noticeable levels) for the affected flight and further delays come at a marginally low to no cost.

Jetfuel prices are set at €0.70EUR/kg and are estimated using the IATA Jet Fuel Price Monitor[6] and reference values presented by [28].

The entry window for which aircraft enter the actionable region (the action horizon) is set at two hours (120 min) before the Estimated Time of Arrival (ETA), with the freeze horizon (after which ATC takes control of the aircraft) starting at 28 minutes before ETA, roughly when an aircraft enters Dutch airspace. Speed control is limited to a maximum of 10 knots or 5% of the original speed, whichever is larger. The limits are chosen in order to stay within limits within which ATC does not need to be instructed of the speed change (e.g. FAA[7]), although concepts leveraging En-Route speed control with ATC cooperation have chose similar order of maginitude of speed changes (e.g. Guzhva et al. [7] ± 15 knots, Soomer and Franx [1] ± 5% or Averty et al. [41] ± 6%). The resulting window and speed change horizon allow for slightly over 4 minutes to be recovered over the full action window or just shy of 5 minutes of additional flight time.

Runway separation is modelled using assumed aircraft and airline specific approach speed charts combined ICAO wake-vortex separation standards[8] in order to convert the distance based separation minima into time based (dynamic) landing intervals. It was assumed that ATC ensured at least this level of throughput during congested times, which operational data extracted from the same data set supports is upheld in practice[9].

[6]https://www.iata.org/en/publications/economics/fuel-monitor/ [accessed 12-05-2020]

[7]FAA Order JO 7110.65 [accessed 01-06-2020]

[8]Procedures for air navigation services: Air Traffic Mangement (PANS 4444), ICAO 2016

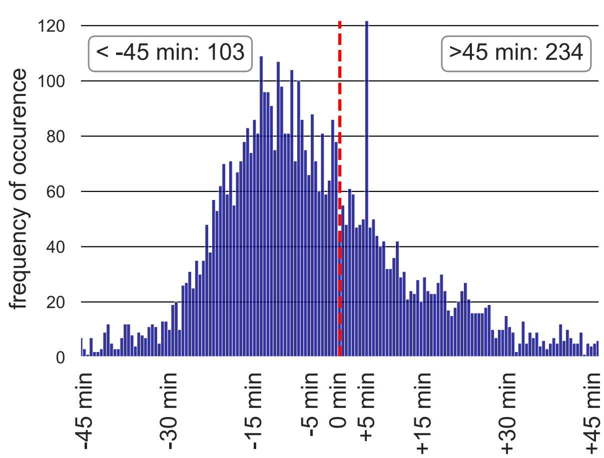

Fig. 10. (pre-)departure delay observed for flights arriving at Amsterdam Airport Schiphol during the test period.

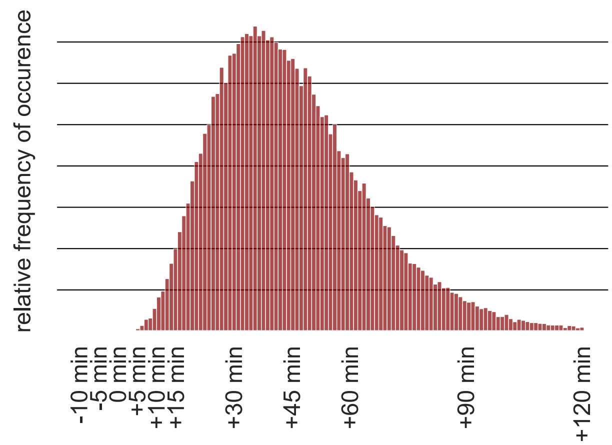

Fig. 11. Random Distribution representing onward passenger connection slack (above minimum connection times).

Planned passenger connection slack ($Cs_{i;q}$), also known as the time a passenger has between connecting flights above the minimum established connecting time, is modelled using distributed random sampling following input from airline sources to represent a wave style hub-carrier and [5]. A skewed gamma distribution (as depicted in Fig. 11) is used with a mean connection slack of 45 minutes on top of the minimum connection time. The style of connections ensures that most connections will occur within one connection wave at the hub airport. Different minimum connection times were upheld between different flight connections (e.g. European flight connecting to an Intercontinental flights vs. EU to EU connections). No other forms such as connections without baggage were considered. Exact passenger flows and related costs were not provided by the airline for confidentially reasons.

B. Delay cost parameters

Alongside scenario parameters, a handful of cost parameters further define the optimisation goal and with this the model behaviour. After experiencing arrival delay, passengers are less likely to return for future business. The relative reduction of future business or value this customer holds for the airline is encapsulated in the ”Loss of Future Value”. Loss of Future Value or LFV for short is included in the IPS optimisation in the form of a ”Loss of Future Value delay cost function” for different types of passenger types and flight lengths.

For the Case study presented, Figure 7 represents the Loss of Future Value delay cost function and is interpreted as follows. Depending on flight length either the solid or dashed lines are considered, both remaining lines will then be evaluated at the correct flight delay. Of the two curves, one for Business travellers and one for Economy passengers, a proportionality of 80% economy and 20% business travellers is assumed (i.e.

[9]Contact the author for additional information on the data set

$BT = 20\%$) reflecting the relative shares of passengers on board of each flight.

The maximum LFV per passenger is largely dependant on type of customer, with the loss of value for a business passenger (€150-€175) being roughly twice the value of a regular economy passenger(€75). These values in part follow from the logit passenger dissatisfaction function presented by [28] with values adjusted in coordination with airline partners to align with the proposed type of operation.

Passengers who miss their connections have a right to and, are generally provided with some forms of compensation depending on the type of delay experienced. For passengers with Amsterdam as their final destination this is encapsulated in the aforementioned (LFV) delay cost function. For (mis)connecting passengers this takes the form of the cost parameter P^{MC}.

In reality, the cost of a missed connection is partly dependant on the consequences this has for the onward journey of the affected passenger, i.e. if the passenger can be accommodated on a flight 90 minutes after the originally planned connection, the financial implications will be orders of magnitude less than if the passenger would need hotel accommodation and meal vouchers if their rebooked flight does not depart for several hours. Since exact passenger itineraries are not included in the case study, it was chosen to determine an average cost considering all types of missed connections (and implications) and proportionally attribute this equal to the relative frequency of occurrence. In collaboration with industry partners, the cost were estimated to be on average €139,-.

VI. Results

Section VI-A outlines the results of the IPS model using the Schiphol airport case study. Subsequently, VI-B presents a sensitivity analysis of the model for small parameter changes. Included in VI-C are a handful of alternative formulations to the base IPS model presenting a basis for discussion on possible priority trade-offs. Finally, VI-D draws a broader picture on model performance and elaborates on the results from several days worth of model simulation.

Scenarios are analysed using the CPLEX 12.9 commercial LP solver and run on a Dell notebook running a quad-core i7-8550U CPU with 16GB of ram. The data set is broken up according to runway usage as discussed in Section V-A, with a full day worth of operations being analysed in around 6-7 minutes. The focus of sections VI-A through VI-C will be one day worth of operations (Friday 25$^{\text{th}}$ of January, 2019) in order to present a deep dive into the model's behaviour.

A. Case Study results

Table I depicts the main performance indicators of the model before and after implementation of IPS as introduced in IV. The day of operations consists of 573 aircraft, 289 (50.4%) of which are KLM aircraft. Average arrival delay per aircraft in the IPS-off condition was -117 seconds (early arrival). The IPS-on case resulted in a average delay reduction of around 7 seconds with the IPS-ON average delay coming to -125 seconds arrival delay (early arrival) compared to scheduled times. The on time performance of all flights, defined as the percentage of flights with a delay less than or equal to 15 min or 900 seconds (Equation 20), increases slightly by 1.1% from 85% to 86.1%.

TABLE I
Comparison of model cost results for 25 January 2019. N = 573 aircraft

	IPS - OFF (baseline)	IPS - ON (ref. sol.)
OTP-15[a]	85.0 %	86.1%
IPS speed changes	N.A.	285
Misconnecting passengers	436	362
Add. delay related fuel cost	€7 050	-€35
Local passenger delay cost	€48 780	€41 697
Misconnect. passenger cost	€60 613	€50 327
Total Cost	**€116 431**	**€91 981**

a On-time performance within 15 min - percentage of flights with a delay less than or equal to 15 min.

$$\text{OTP-15} = \frac{1}{|n|}|\{flight_i \in F : (ATA_i - STA_i) \leq 900\}| \tag{20}$$

Case study results indicate just over €24 450,- can be saved within the day of operations, which constitutes around 20% of all delay cost incurred. 74 additional passengers make their connection (17% of all missed connections). The largest individual increase in successful connections is found on KLM758 arriving from Panama City which reduced the amount of missed connections by 12 passengers by arriving just over 7 minutes earlier than in the IPS off scheme. About half of the time gain was achieved through arriving in the queue before other KLM aircraft and thus receiving less ATC delay.

The largest cost reduction can be found in the cost related to misconnecting passengers which comprised of 42% (€10 286,-) of the total cost reduction resulting from the application of IPS. Fuel and Local passenger delay cost are tied in value as the model trades off the delay minutes (time) for additional fuel burn. The investments enabling the IPS solution can be seen in the 285 IPS speed changes issued which constitutes nearly 95% of all KLM aircraft in the day of operation.

The total delay-related costs between IPS-ON and IPS-OFF decrease by on average €84 for each KLM flight. Long haul flights perform almost twice as good in this respect when compared to short haul flights, €149 and €76 saved per flight respectively.

Delay related fuel cost decrease by over €7000,-. In fact, fuel costs decrease by a larger amount than the original delay related fuel cost for the IPS-OFF scenario. The root of this effect can be traced to the concept of Linear Holding and the above optimal fuel flow commercial aircraft nominally fly at (i.e. higher cost index, see [6]). By incurring forms of en-route delay, it is observed that aircraft fly closer to their fuel

TABLE II
FLIGHT REARRANGING THROUGH THE IPS ALGORITHM (SEE FIG. 12)

Callsign	STA	ATA (IPS-OFF)	ATA (IPS-ON)	difference: (IPS-ON) - (IPS-OFF)		
				Δ ATA	Δ Missed connections	Δ Total flight cost
EZY52ZA	12:35:00	12:29:19	12:29:19	00:00:00	N.A.	N.A.
KLM1182	12:45:00	12:30:43	12:32:18	00:01:35	0	-€29
KLM86N	12:35:00	12:32:07	12:33:42	00:01:35	0	-€44
KLM1870	12:15:00	12:33:31	12:30:54	-00:03:23	-5	-€1 351
KLM20H	12:35:00	12:35:01	12:35:01	00:00:00	0	0

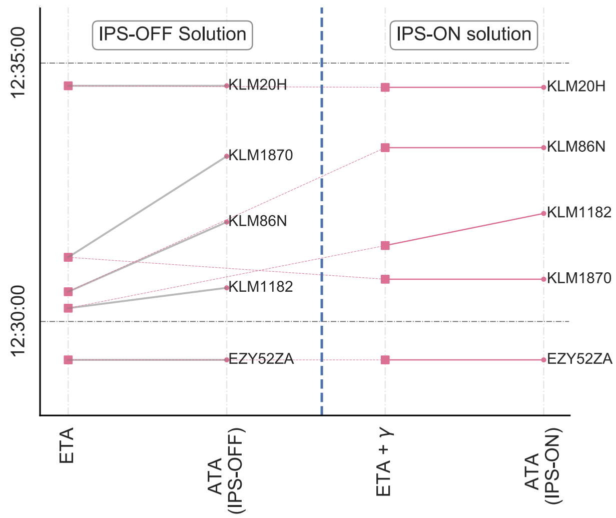

Fig. 12. Flight rearranging through the IPS algorithm (see Table II for exact values)

burn optimal airspeed (see Fig. 5). The fuel savings incurred through this phenomena are attributed to the 'delay related fuel cost' in the model evaluation as, the fuel burn savings earned are in the greater scheme exchanged for a delayed arrival at the destination.

It is important to note that passenger delay cost are determined in relation to schedule times. Significant (pre-) departure delays (i.e. the difference between ETA and STA) can result in delay situations from which a flight cannot (fully) recover. An example of this is KL1352, a Boeing 737-800 departing Moscow with a (pre-) departure delay of over 4 hours and 10 minutes. 150 seconds of arrival delay is saved, with a cost reduction of €50,-. However, the amount of missed connections modelled remains constant at 98% of all connecting passengers on board.

Example results for a small flight cluster

Figure 12 and Table II present a flight cluster observed during the deployment of the IPS model. First to briefly explain what is seen in the image. Left of the dotted centerline the IPS-off scenario is presented, with the right of the dotted line being the alternative reality with IPS-ON. Each horizontal line (and the attached markers) represents one aircraft in the scenario, with the horizontal (dashed) line crossing between scenarios indicating the En-route IPS actions (γ) applied to aircraft. Notably, competitor aircraft such as *EZY52ZA* have a γ of zero (seen as no slope crossing the center line).

To the left of the centerline (IPS-OFF) two columns can be identified. The leftmost, labelled ETA (square markers) indicates the Estimated arrival time if no other aircraft were around (unimpeded landing time) in the IPS-OFF reality. The second column from the left, labelled "ATA (IPS-OFF)" (circles) represents the Actual Time of Arrival after ATC intervenes and spaces out aircraft according to a FCFS scheme to ensure proper separation between successive arrivals. The steeper these connecting lines are, the more (ATC) delay is applied to aircraft. Through this logic it can be observed that *KLM20H* has no ATC delay (horizontal line), whilst *KLM1870* encounters the largest ATC delay.

To the right of the dotted centerline we observe the IPS-ON universe. The lines crossing the centerline, connecting the two sub-scenarios (IPS-OFF and IPS-ON) represent the en-route IPS actions (γ) applied. In this case, two aircraft (*KLM86N* and *KLM1182*) are slowed down and one aircraft (*KLM1870*) is sped up. Where necessary, aircraft are spaced out by ATC (second to last column ■ vs. rightmost column ●), although this time only *KLM1182* encounters any ATC delay.

KLM1182, *KLM86N* and *KLM1870* are said to arrive in a traffic bunch, with the ATC delay of one aircraft stacking on top of the ATC delay of preceding aircraft. By advancing *KLM1870* through the IPS scheme (γ) and simultaneously

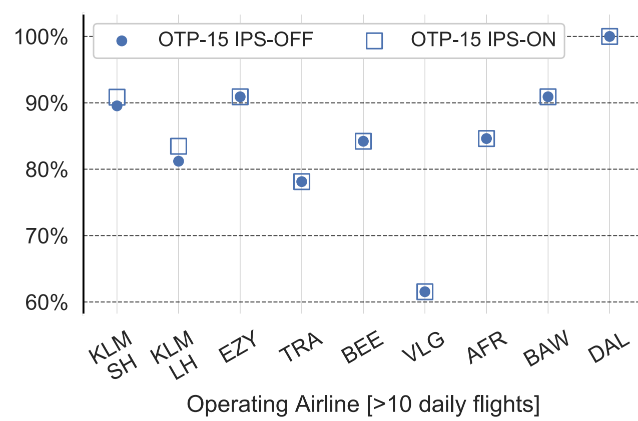

Fig. 13. On time performance within 15 minutes on 25-01-2019 before and after IPS implementation.

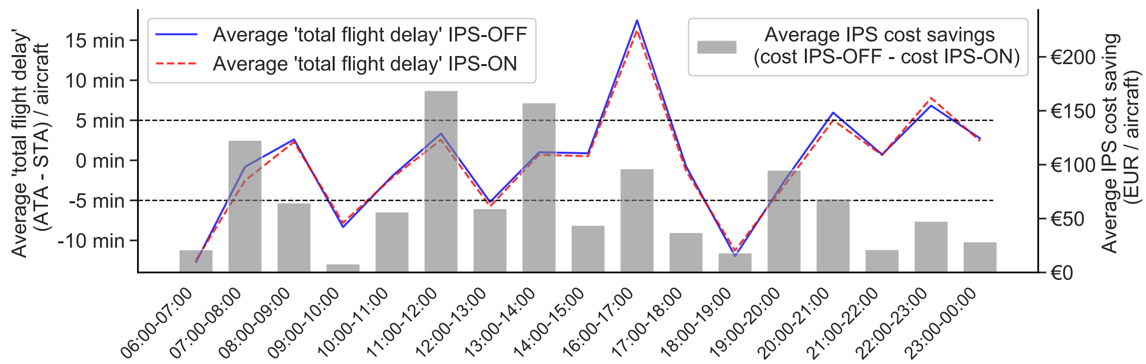

Fig. 14. Hourly Aircraft normalised average flight delay and aircraft normalised cost savings observed for KLM aircraft on the 25th of January.

delaying *KLM86N* and *KLM1182* delay is exchanged between aircraft within the traffic bunch, allowing *KLM1870* to touch down (Δ ATA) three and a half minutes earlier.

In Table II we can observe the difference in arrival times, misconnecting passengers and flight costs between IPS-OFF and IPS-ON. Firstly, it can be observed that most flights arrive earlier before their scheduled arrival time with only *KLM1870* arriving after. The greatest benefit is gained by *KLM1870* arriving 213 seconds earlier and with this saving 5 missed connections and €1351. Even though *KLM86N* and *KLM1182* receive en-route delays and now arrive after *KLM1870*, they still show a cost benefit by transferring ATC delay to the en-route sector.

Most flight bunches observed in the simulation set include between 5-8 aircraft and follow similar effects to the previously described example. A group of aircraft incurs a small delay in order to advance a single (although in some cases several) aircraft with (significant) (pre-)departure delay resulting in a overall cost reduction.

Figure 13 depicts the on time performance (OTP) within 15 minutes for the largest operators by number of flights on the 25^{th} of January. For KLM, the largest operator out of Schiphol, flights are further broken up by flight length; Short Haul (SH) $\leq$ 3500km and Long Haul (LH) $>$ 3500km. For operators other than KLM, the OTP-15 does not change between the IPS-OFF scenario and the IPS-ON scenario. For KLM a positive movement is observed both in the long haul fleet OTP-15 (+2.3%), as well as in the Short Haul fleet(+1.3%).

The lines in Figure 14 depict the aircraft average 'total flight delay' observed for KLM aircraft during each hour of the 25th of January. Both the IPS-ON as well as the IPS-OFF cases are presented. The bars in the same Figure represent the aircraft normalised IPS cost savings between implementing IPS (IPS-ON, dashed line) and the baseline IPS-OFF (dashed line) situation.

All hours show improvement with regards to cost after implementing IPS (positive grey bars). Interestingly, the largest cost savings do not coincide with the largest demand peaks seen in Figure 8, nor do they occur with when the average delay is the largest average flight delay (solid and dashed lines, Figure 14).

Throughout a majority of the hours of the day of operations, a small improvement in average flight delay between IPS-OFF and IPS-ON can be observed. For some hours (e.g.09:00-10:00 and 22:00-23:00), the opposite does occur with the IPS-OFF situation resulting in a greater average delay (i.e. dashed line above solid line), although notably a cost reduction still occurs. No (direct) correlation is observed between the two measures.

Figure 15 shows the relative frequency of speed changes in the IPS model. More aircraft are slowed down than advanced, with the algorithm more often than not opting to choose either the maximum or minimum allowable speed change.

B. Sensitivity analysis

In Tables III through VII we present a sensitivity analysis of a set of parameters defining the IPS-ON model evaluated on the 25^{th} of January. All solutions are compared with the reference (base) version of IPS-ON and, of importance to note, are expressed in the nominal cost values. 3 cost variations are introduced each with a relative increase and decrease of 10% compared to the nominal cost values. Furthermore, Table V

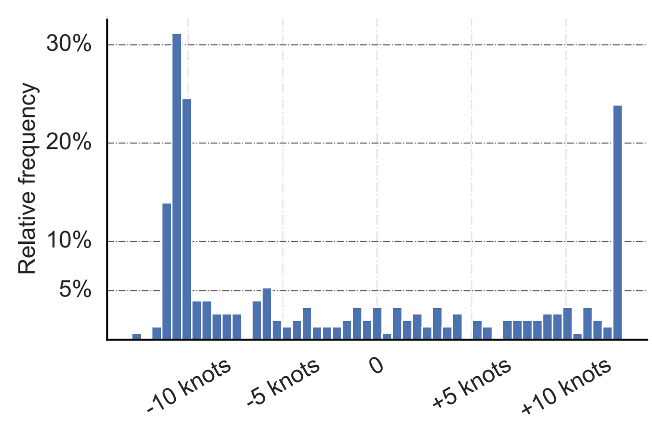

Fig. 15. Relative Frequency of en-route speed changes observed amongst IPS instructed aircraft on 25-01-2019.

TABLE III
SENSITIVITY ANALYSIS WITH RESPECT TO THE FUEL PRICE PARAMETER.
(EXPRESSED IN REFERENCE COST VALUES)

	IPS - ON (ref. sol.)	IPS - ON: P^f variation	
Fuel price (P^f) [Eur/kg]	**€0.70**	**€0.63 (90 %)**	**€0.77 (110 %)**
IPS speed changes	285	285	285
Misconnecting passengers	362	362	362
Add. delay related fuel cost	- €32	€36	-€86
Local passenger delay cost	€41 697	€41 674	€41 789
Misconnect. passenger cost	€50 327	€50 327	€50 327
Total Cost	**€91 981**	**€91 984**	**€91 986**

TABLE IV
SENSITIVITY ANALYSIS WITH RESPECT TO THE MISSED CONNECTION COST PARAMETER.
(EXPRESSED IN REFERENCE COST VALUES)

	IPS - ON (ref. sol.)	IPS - ON: P^{MC} variation	
Cost of missed conn. (P^{MC})	**€139**	**€125 (90 %)**	**€153 (110 %)**
IPS speed changes	285	286	286
Misconnecting passengers	362	362	362
Add. delay related fuel cost	- €32	€0	€1
Local passenger delay cost	€41 697	€41 697	€41 697
Misconnect. passenger cost	€50 327	€50 327	€50 327
Total Cost	**€91 981**	**€91 984**	**€91 984**

TABLE V
SENSITIVITY ANALYSIS WITH RESPECT TO THE ACTION HORIZON PARAMETER.
(EXPRESSED IN REFERENCE COST VALUES)

	IPS - ON (ref. sol.)	IPS - ON: Action hor. variation	
Action Horizon	**120 min**	**90 min**	**150 min**
IPS speed changes	285	285	286
Misconnecting passengers	362	367	357
Add. delay related fuel cost	- €32	€256	-€248
Local passenger delay cost	€41 697	€42 431	€41 320
Misconnect. passenger cost	€50 327	€51 022	€49 632
Total Cost	**€91 981**	**€93 666**	**€90 662**

TABLE VI
SENSITIVITY ANALYSIS WITH RESPECT TO THE LOSS OF FUTURE VALUE FUNCTION COST.
(EXPRESSED IN REFERENCE COST VALUES)

	IPS - ON (ref. sol.)	IPS - ON: LFV cost variation	
Loss of Future Value cost (Δ^{LFV})	**100 %**	**90 %**	**110 %**
IPS speed changes	285	285	286
Misconnecting passengers	362	362	362
Add. delay related fuel cost	- €32	-€86	€21
Local passenger delay cost	€41 697	€41 788	€41 678
Misconnect. passenger cost	€50 327	€50 327	€50 327
Total Cost	**€91 981**	**€91 985**	**€91 982**

TABLE VII
SENSITIVITY ANALYSIS WITH RESPECT TO SPEED CONTROL AUTHORITY.
(EXPRESSED IN REFERENCE COST VALUES)

	IPS - ON (ref. sol.)	IPS - ON: Speed change window variation	
Allowable Speed Change	**Nominal**[a]	**smaller**[b]	**larger**[c]
IPS speed changes	285	287	287
Misconnecting passengers	362	366	358
Add. delay related fuel cost	- €32	€69	-€251
Local passenger delay cost	€41 697	€42 398	€41 271
Misconnect. passenger cost	€50 327	€50 883	€49 771
Total Cost	**€91 981**	**€93 307**	**€90 747**

[a] : $\min\big((0.95 \cdot V_i^{nm}), (V_i^{nm} - 10)\big) \leq V_i^{IPS} \leq \max\big((1.05 \cdot V_i^{nm}), (V_i^{nm} + 10)\big)$
[b] : $\min\big((0.955 \cdot V_i^{nm}), (V_i^{nm} - 9)\big) \leq V_i^{IPS} \leq \max\big((1.045 \cdot V_i^{nm}), (V_i^{nm} + 9)\big)$
[c] : $\min\big((0.945 \cdot V_i^{nm}), (V_i^{nm} - 11)\big) \leq V_i^{IPS} \leq \max\big((1.055 \cdot V_i^{nm}), (V_i^{nm} + 11)\big)$

TABLE VIII
OPTIMISATION RESULTS FOR THE ADDITIONAL FORMULATIONS OF THE IPS MODEL.

	Evaluated IPS Model				
	IPS - ON (ref. sol.)	IPS - ON: AP	IPS - ON: MC	IPS - ON: HC	IPS - ON: DO
IPS speed changes	285	91	285	289	153
Misconnecting passengers	362	362	361	361	364
Add. delay related fuel cost	- €32	€2 549	€531	-€1 263	€3 813
Local passenger delay cost	€41 697	€42 709	€43 089	€49 077	€41 758
Misconnect. passenger cost	€50 327	€50 237	€50 188	€50 188	€50 605
Total Cost	**€91 981**	**€95 541**	**€93 764**	**€97 959**	**€96 132**

shows the effects of varying the optimisation window from the nominal 120 minutes by 30 minutes more or less. Table VII depicts the effects of allowing a relative 10% more speed authority as compared to nominal case of max(5%, +10 knots).

Most changes show marginal effects to the overall cost (<0.1% of total cost, expressed in reference cost values) and amount of missed connections. An additional (relative) 10% of speed control as depicted in Table VII does, however, show larger effects on the overall with changes in the order of 1.3%/1.4% of the total cost. Results suggest that the solution is predominantly sensitive to the effects of speed control authority and marginally to other parameters.

C. Additional formulations of the IPS model

Alongside the base formulation presented in earlier sections, a number of variations to the base model have been investigated that pose potential trade-offs to decision makers. The following section will elaborate on each of the four different variations considered and compare them to the reference (nominal) IPS-ON solution. Table VIII shows a table of the key performance indicators for each of the solutions and the respective change as compared to the nominal IPS-ON case.

Action penalty 'IPS - ON: AP'

The nominal formulation of the IPS model tries to optimise all possible gaps in the arrival queue. As a result, aircraft are instructed with speed changes, even when the gains are marginal. In some cases, decision makers would rather have that aircraft only be instructed for speed changes when possible gains are above a set threshold in order to minimise the amount of affected aircraft and with this the workload of pilots and the Operations Control Centre (OCC) of the airline, from where the effort is coordinated.

The IPS action indicator variable (θ_i, Eq. 21) is introduced and Equation 22 added to the objective function with a threshold value of €50,- set (P^{AP} = 50) for each aircraft which receives a speed change instruction (i.e. abs(γ) > 0).

$$\theta_i = \begin{cases} 1 & abs(\gamma_i) > 0 \\ 0 & \text{Otherwise} \end{cases} \qquad \forall\ i \in MF \quad (21)$$

$$C_i^{AP} = P^{AP} \cdot \theta_i \qquad \forall i \in MF \quad (22)$$

Analysing the results in Table VIII it can be noted that by instituting a penalty for each IPS command issued the amount of IPS commands issued can be reduced by 194 or 68%. At the same time, the solution cost rises by €3500,- or around 3.9% of the total cost. The main increase in cost is found in additional fuel cost. The amount of missed connections remains identical, presumably in part due to the fact that each missed connection saved is almost three times as valuable than the set action penalty (€139,- vs €50,-).

Hard cost only 'IPS - ON: HC'

In contrast to hard cost, soft cost are cost that are not instantly born or paid out by an airline, nor are they estimated with complete certainty. As a result, some reasoning exists to only focus only direct costs or the hard cost in the optimisation of an arrival delay problem. In order to adapt the cost function to reflect only hard cost, two changes are made. Firstly, P^{MC}, the cost of a missed connection, is reduced to €65,- reflecting only the direct compensation cost an airline has to pay for items such as hotel cost, flight re-booking or refreshments effectively removing the loss of future value portion of P^{MC}.

In addition, the "*Loss of Future Value Delay cost function*" ($\Delta_i^{LFV}(TD_i)$) seen in Figure 7 is set to 0 at all times for all passenger types, reflecting no loss of value for any amount of arrival delay. However, as per [29], a fictitious penalty of 1 cent / passenger minute of delay is added in order to ensure that a unique solution exists.

When optimising for hard cost only the amount of affected aircraft (IPS commands issued) remains largely the same (-4 / 1.4%). 1 Fewer missed connection is achieved and the overall fuel cost is reduced by around €1000,- as compared to the nominal IPS-ON case. Local passenger delay cost (or Loss of Future value) cost increase by 17.7% or around €7500,- as the soft LFV cost are no longer a objective in the objective function. The overall cost of the hard cost scenario evaluated under the nominal cost values is around €6000,- (6.5%) higher than the reference IPS-ON case. The increase of 6.5% is the highest cost increase in of the alternative formulations.

Minimum missed connections 'IPS - ON: MC'

Through interviews with airline representatives it became evident that in the current delay mitigation efforts a large focus is placed on minimising the amount of missed connections. These efforts, although not always (directly) economically viable, can help strengthen the image of an airline and provide less quantifiable benefits. As such, a model variation is set up, establishing the maximum possible number of missed connections without other economical barriers. To achieve this, noting that the cost of missed connections is directly proportional to the amount of missed connections, the objective for the optimisation is changed to:

$$min \sum_{i\ \in\ MF} (C_i^{mc})$$

Once again, a fictitious penalty of 1 cent / passenger minute of delay is added in order to ensure that a unique solution exists.

The missed connection minimised case results in a total cost increase of 1.9% (€2000,-) whilst achieving 2 less missed connections as compared to the nominal IPS-ON case. The amount of aircraft instructed with IPS commands is identical with both the fuel and local passenger delay cost increasing when compared with the reference case. No fewer than 361 missed connections can be achieved in the scenario without increasing either the speed control or optimisation window size. Both of which can be observed in the results presented in Section VI-B.

Only delaying aircraft 'IPS - ON: DO'

The final model variation is found in the form of only delaying aircraft. This means that the IPS control is only allowed to

TABLE IX
OVERVIEW OF RESULTS FROM TEN (10) SIMULATION DAYS.

	IPS-OFF			IPS-ON		
	Minimum (29/01)	Maximum (23/01)	Average (22/01 - 31/01)	Minimum (29/01)	Maximum (23/01)	Average (22/01 - 31/01)
IPS speed changes	-	-	-	292	294	283
Misconnecting passengers	62	2025	513	62	1819	795
delay related fuel cost	€8 787	€10 928	€9 273	- €361	- €1 587	-€700
Local passenger delay cost	€17 793	€104 468	€60 113	€13 675	€93 791	€53 217
Misconnect. passenger cost	€8 618	€281 475	€124 835	€4 170	€252 841	€110 519
Total Costs	**€35 197**	**€396 872**	**€194 222**	**€17 484**	**€345 045**	**€164 437**

impose delay (slow down commands), instituting that $\gamma_i \geq 0$. The condition stems from the fact that in some cases aircraft are already flying at the limit of their flight envelope or are instructed by ATC to fly below certain speeds. Although seemingly intuitive, slowing down does not always increase fuel efficiency (see Section IV-B2)

$$\gamma_i \geq 0 \qquad \forall i \in MF \tag{23}$$

With the decrease in control abilities (i.e. only delaying aircraft) the amount of aircraft for which IPS commands is issued reduces by 132 (-46%). Interestingly enough, the amount of missed connections increases by a mere two, with the total cost of the scenario increasing by just over €4000,- or 4.5%. The increase in cost stems largely from additional fuel burned with the Loss of future value for local passengers and the cost of missed connections increasing by a combined less than €500,-.

D. Ten day simulation

In the following section, results from ten days worth of simulations are presented following the results presented in earlier sections focusing on the 25^{th} of January 2019. The results are meant as to serve as a exploration of model performance under a broader variety of input scenarios.

Table IX tabulates aggregated results extracted from 10 days of simulation (including 25/01). A comparison is presented between the IPS-OFF baseline cost and the IPS-ON cost after subjecting the same input scenario to steering through the IPS algorithm. Three different columns are presented for each case (IPS-OFF and IPS-ON) indicated by the columns 'minimum', 'maximum' and 'average'.

The column named minimum (both for IPS-OFF and IPS-ON) indicates the results generated from the day of operations with the least benefit from the IPS model; this day corresponds to 29/01. Similarly, the column named maximum depicts the results from the day of operations within the 10 day data-set with the most amount of cost savings through applying the IPS algorithm; this day corresponds to 23/01. Finally the column named average presents the daily average over the full 10 day set of simulation.

The cost of the most expensive IPS-OFF observed day (23/01) is almost ten times the cost observed in the least expensive IPS-OFF day indicating a range of different delay scenarios present in the test set. On average, the IPS savings (total cost IPS-ON - total cost IPS-OFF) amount to around €30 000,-, with the largest share of the cost benefit found in a reduction of missed connections. The savings observed on 29/01 (the 'minimum' case) are around 1/3 of the of the most beneficial day in the test set, namely 23/01 ('maximum' column). Throughout the scenarios, the amount of IPS speed changes (commands issued) remained largely similar both in absolute amount as well as percentage of flights affected.

The amount of missed connections is seen to vary between 62 and 2025 depending on the day. Days with large amount of missed connections showed a relative high occurrence of flights in which more than 95% of all passenger missing their connection when compared to days with lower amounts of missed connections. The occurrence of large groups of missed connections on single flights often coincided with large (pre-) departure delays.

Finally, extrapolating the average benefit observed during the ten day set, an estimated 10 million euros can be saved on a annual basis by implementing the deterministic formulation presented.

VII. DISCUSSION

The observed and systemic (pre-)departure delay present in arriving aircraft translates into differences in the (economical) impact of additional arrival delay between individual aircraft. The proposed IPS algorithm is able to exploit these inherent differences and create value for end user expressed through the reduction of cost in the developed airline cost function. The results in the paper align with earlier work and indicate that little delay is dissipated from the overall system through the introduction of the IPS algorithm.

Within an airline the modelling results indicate there can be an (economical) incentive to participate in the decluttering (de-bunching) and better aligning of arriving flights at the destination centre. By including cooperative measures between several aircraft the algorithm is able to more effectively accommodate high priority aircraft by enabling opportunities (e.g. creating space in the arrival queue by delaying aircraft and leveraging bunching effects) greater than what would otherwise be possible when considering only the affected 'Priority' flight.

The alternative model formulations presented amongst the results highlight the room for trade-offs in the application of the IPS model. A clear example of this can be seen through the introduction of an action penalty 'IPS-ON: AP' significantly reducing the number of speed adjustment commands issued at the price of minor overall (economic) effectiveness. A further formulation in which only en-route delays are allowed 'IPS-ON: DO' stresses the possibility to create value without the explicit necessity for any flight to arrive earlier at the effected (destination) airspace, but rather exchange delays already present. The latter coming at the cost of a reduction in overall IPS cost effectiveness of around 25% when compared to the nominal IPS-ON case with full speed control.

Overall, the results indicate merit in the application of IPS and the ability of an airline to do so within the confines of limited en-route control without the necessity for ATC involvement. In practice, several complicating factors are still expected in the priority based arrival sequencing. Firstly, the accuracy of arrival predictions will continue to play a role in the effectiveness of the overall IPS model. Although currently assumed deterministic, flight arrival times are in reality (partially) stochastic and should be seen as a probability distribution becoming more accurate the closer aircraft get. Operationally the concept should include additional considerations on the probability of success when positioning aircraft in the arrival queue, possibly building additional buffers between aircraft to increase these success rates to ensure effectiveness under non-deterministic operations and ensure the optimal use of the available infrastructure.

Secondly, the estimates of economical impact presented in this paper are an indication for the effectiveness of IPS for a hub-style carrier. Exact numbers will be reliant on the specific end user implementing the concept and their style of operations. The IPS algorithm is designed to, but also reliant on, complimentary systems within the airline in order to effectively represent the complex and often heavily interlinked daily operation which are in term necessary to fully reflect the impact of delay on airline operations.

The results presented on passenger connections are modelled and not extracted from operational data which lead to some effects not fully being captured. Part of the strength of the IPS concepts lies in exploiting the inherent differences in commercial value between flights. Extremes in flight value caused in part, for instance, by groups travelling on the same itinerary can present interesting optimisation cases, but are not modelled and thus less "extreme" opportunities are present.

Finally, airlines are not reactive bodies, but rather constantly adjusting their actions to react to changes in network operations, weather and actions undertaken by other stakeholders, all resulting in flight cost estimates changing with some frequency. As a clear example of this behaviour, it can be expected that airlines will pro-actively start re-booking passengers when delays exceed a certain threshold, which in turn would present a new connection time for effected passengers and an updated cost function for the affected flight. As such, airline implemented solutions of the presented model would benefit being formulated as a dynamic problem for which the presented MILP formulation can serve as a basis for example when paired with a Receding Horizon Control (RHC) approach.

The IPS formulation as proposed finds its relevance as a near term implementable solution enabling priority based arrival Sequencing and all associated benefits, all be it only for carriers with a majority share in traffic. At the same time IPS serves as a stepping stone towards future aviation concepts priming users into assessing the strategic problem of fleet wide arrival sequencing and scheduling decisions.

VIII. Conclusion and further research

This paper addresses the airline centred Arrival Sequencing and Scheduling problem aimed at the reduction and smart distribution of arrival delays, considering the explicit preferences from users. We consider the scenario in which actions are executed solely in the en-route phase with the available leeway present in the current ATM system. The arrival process at the destination centre alongside equity rules such as "First-Come, First-Served" which the destination ANSP upholds remain untouched.

The problem is formulated as a mixed-integer linear program with constraints regarding the time based wake-vortex separation, en-route speed authority and runway capacity. We evaluate arrival time estimates when aircraft present themselves several hours out and derive the most optimal speed commands for aircraft from a single airline operator in order to influence and align arriving aircraft with the arrival traffic predicted at the destination centre.

The case of KLM and its hub airport Amsterdam Airport Schiphol is used to demonstrate the concept. It is shown through the case presented there exist (economic) incentives for airlines to participate in arrival sequencing and scheduling even with the limitations of en-route control before entering the destination centre. By pre-imposing delays, airlines can steer flights to arrive at positions and times in the (predicted) arrival queue which better align to the economic value of the greater airline operation, without the necessity for coordination with ATC organisations. This effect is furthermore enabled by the presence of flight bunching where the effect of small changes in arrival times can be leveraged to gain larger effects.

The model, algorithm and case study presented indicate the potential of airline centred, en-route arrival management to generate additional value in arrival delay situations. Still, future work should explore topics better studying the potential of the proposed concept. For instance, a rolling horizon scheme can be derived from the presented formulation in order to incorporate dynamic information and adjust speed commands accordingly. A non-deterministic approach should be investigated exploring the effects of variances in arrival times for incoming aircraft. Finally, explicit passenger itineraries could be considered alongside passenger (re-) allocation models to better model passenger cost which embodies the largest delay cost.

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II

Literature Review (Previously graded under AE4020)

1
Introduction

Air travel has presented strong levels of growth through the past decades and continues to do so in recent years. Estimates by the International Air Transport Association (IATA) forecast that the amount of passengers carried by air will double by the year 2035[1]. At the same time, the infrastructure shared by this increasing volume of air traffic is growing at a much slower pace, where growth is even possible[2]. These factors amongst others have meant that, as usage is nearing capacity in the limited airspace and infrastructure available, delays are becoming more frequent and severe.

Runways and the Terminal Manoeuvring Area (TMA) around airports are prime regions where this negative effect becomes evident [3] Aircraft arriving at airport controlled airspace in rapid succession of one another, so-called *traffic bunches*, must be spaced out in order to satisfy Wake-Vortex separation constraints by the time they touch down on the runway. The phenomena where traffic (locally) exceeds capacity, as illustrated in fig. 1.1, is a large contributor to the inefficiencies in the current Air Traffic Control (ATC) system.

Small changes in the arrival times of aircraft at the cornerpost of Airport Controlled Airspace can have have a large impact on the arrival time of aircraft at the gate. The latter being hugely important to aircraft operators and their customers. This leveraging effect, aggravated by the occurrence and severity of aircraft bunches, can cause delays which in turn are undesirable for all stakeholders involved.

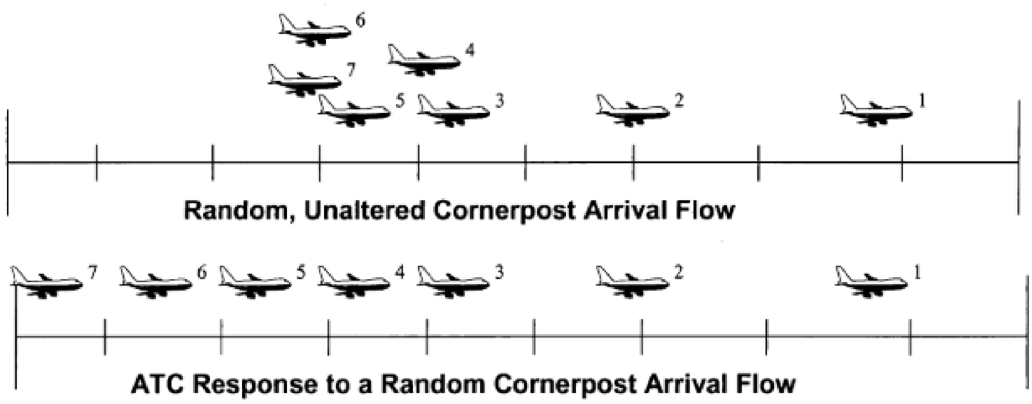


Figure 1.1: Example of aircraft bunching before and after ATC intervention.[Adapted from US patent 7-248-963]

[1]IATA press release `https://www.iata.org/pressroom/pr/Pages/2018-10-24-02.aspx` [accessed on 03-10-2019]
[2]`https://phys.org/news/2018-02-iata-chief-airport-expansion.html` [accessed on 10-01-2019]
[3]EUROCONTROL performance statistics, November 2019 `https://www.eurocontrol.int/our-data` [accessed on 09-01-2020].

Hub airports, whose operations are designed to facilitate efficient connections between flights (thus planning minimal connecting times) are especially susceptible to the negative consequences that flight delays pose. Delays oftentimes not only impact individual passenger' itineraries, but can have a knock on effect through a hub-airline's schedule lasting for many hours and flight cycles after the initial perturbation (AhmadBeygi et al. [2008]).

Air Navigation Service Providers (ANSPs) often have little insight into the preferences and priorities of airlines. With this, the scheduling and routing provided to aircraft is oftentimes far from the most beneficial to the airline (Carr et al. [1998]). From an airline perspective not all flights are equally important and as such, it may very well be that an aircraft appearing on radar at a later time, which has previously incurred a delay or with a high number of connecting passengers, might be more economically interesting to land before an aircraft which, due to favourable winds, is now arriving at the border of the Terminal Manoeuvring Area (TMA) before its scheduled arrival time (Verboon et al. [2016]).

The desire from airlines to express their interest in the (relative) sequence and landing times of aircraft has been formulated in a concept named Inbound Priority Sequencing (IPS). *IPS is designed to better serve airline objectives by optimising the timing and sequence of arriving aircraft at capacity constrained airports.*

Enabled by the advances in navigational technology and driven by the traffic growth, the IPS concept proposed in this paper focuses on the single operator, airline-centred En-Route Sequencing and Scheduling concept. This form of IPS will allow airlines to optimise and allocate delays within own their fleet in order to minimise factors such as mis-connecting passengers, fuel burn and other flight related cost.

Single Operator, airline centred IPS is a short term implementable stepping stone concept for future more advanced and Collaborative arrival techniques aimed at the reduction and smart distribution of arrival delays, considering the explicit preferences from users. Smarter use is to be made of the current resources in order to preserve the current level of service to air travellers, even under the levels of growth that is expected over the next years and decades.

The following paper is structured as follows; chapter 2 provides an overview of the relevant literature surrounding the Arrival Sequencing and Scheduling Problem and, the proposed IPS implementation in this paper. Following this, in **??**, the research plan coupled to this work is presented. The research plan contains a synopsis of the current literature gap, proposed research questions and objectives, and an overview of the proposed methodology. Finally, the work is rounded off with concluding remarks in **??**.

2

Literature Review

The following chapter provides a survey of literature surrounding the Arrival Sequencing and Scheduling Problem and, the proposed IPS implementation in this project In order to understand the coupled arrival problem, it is important to first present a proper overview of the individual components tackled in Aircraft Sequencing and Scheduling Problem, as well as previous research surrounding Arrival Management. Following this overview, an introduction into the specific goals and possible implementations of the ASP is given. Finally, a survey of literature around the Modelling Methods and Solution Techniques is presented.

Section 2.1 provides an overview of the aircraft planning process and within discusses the current practices coupled to a nominal flight execution. The case discussed surveys the practices surrounding nominal flights modelled around a European hub airport, paving the way for the future sections surrounding arrival management. Subsequently, section 2.2 presents an overview on the aircraft sequencing and scheduling problem. The section focuses on methods for the problem formulation and presents an overview of relevant sub-components within this formulation such as the Objectives, Constraints and Decision Variables. Section 2.3 dives deeper in possible goals and applications of the Aircraft Sequencing and Scheduling problem. Section 2.4 rounds of the survey of literature with a round up of commonly used modelling methods and solution techniques in the Aircraft Sequencing and Scheduling problem.

2.1. The Aircraft Planning Process

The following section is dedicated to providing the reader with an overview of how flights are planned and executed in the current ATC system. The section is not meant as an exhaustive survey, but to provide the reader with an overview of the main components and planning steps conducted throughout a nominal flight and, those aspects affected by the proposed IPS concept.

2.1.1. Flight Planning

A commercial flight commences with the filing of a flight plan. At its basis, a flight plan includes information on the origin and destination, as well as general information on the aircraft and entity executing the flight, with the addition of how much fuel is carried for the flight. Furthermore, a flight plan will list the planned route, speed and altitude, alongside how these might change along the route. This information is not fixed prior to departure and regularly alters several times depending on the operational environment of the specific day. Important considerations can be the current wind situation or factors such as en-route congestion (Altus [2009]). flight plans are filed to a regulatory body and serve as checks in order to assure flights meet set operational and regulatory requirements. Additionally, flight plans are essential for ATC organisations in order for them to effectively manage air traffic flows and assure safety for all airspace users.

In particular for commercial aircraft operators, flight plans are planned and (thoroughly) optimised entities. Flight plans are, however, not closed contracts. Both the aircraft operators, as well as Air Traffic Control entities can deviate from these plans for operational reasons. Flight plans are designed around set arrival times, which for busy/congested airports have been translated into "landing slots". Slots are landing time contracts which are designed to limit the flow of incoming aircraft and preemptively reduce the chance of congestion at busy airports. As of summer 2018 there are 177 fully slot controlled airports worldwide; a num-

ber which is expected to keep increasing for the foreseeable future [1].
Outside of the set way-points filed in a flight plan, commercial aircraft fly the most optimal (regulatory bounded) route. Most of the route calculations are performed by a Flight Management Computer (FMC), located on board of the majority of commercial aircraft. Operators retain some forms of control in this equation by specifying the so-called "Cost Index". Simply put, the cost index sets the relative importance of time versus the cost of fuel (Roberson [2007]). Low cost index values optimise fuel burn over time saving measures, whereas high(er) cost index values trade off extra fuel burn for shorter flight lengths. The use of Cost-Indices can present significant variations and spread to the flight profiles of affected flights (Rumler et al. [2010]). An illustration of how this phenomena impacts climbing flight is presented in fig. 2.1.

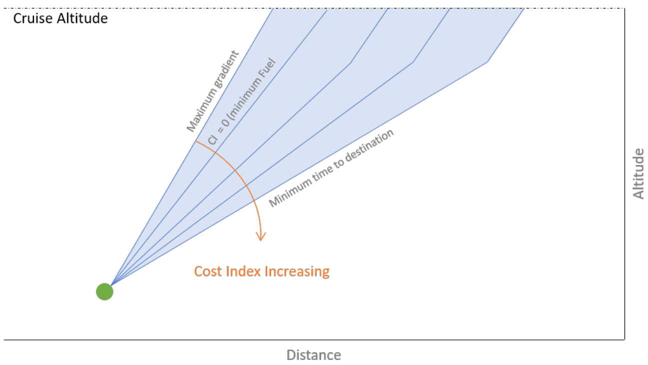


Figure 2.1: Effect of selected cost index on the climb performance. (Adapted from Roberson [2007])

2.1.2. Flight Execution and Monitoring

Once airborne and clear of the terminal airspace, ATC interference is minimal and the the flight is mainly undisturbed to fly its filed route through the different en-route ATC sectors. Congestion, adverse weather and sometimes even geopolitical disturbances can cause a flight to deviate from its filed flight plan. This is however, not the nominal situation. Flight crews, Aircraft Operators and ANSPs rely on flight plans combined with real time (tracking) information (e.g. ADS-B transmissions and radar tracking) in order to monitor and predict transit and ultimately arrival times.

For each of the stakeholders, reliable trajectory predictions enable efficient operations, which in an industry such as aviation is coupled with large cost reductions. Efforts from Cook [2015] have estimated the average cost of just one minute of airborne delay lays around €80,- to €100,- , with values for some larger aircraft reaching into several hundred Euros for just one minute of airborne delay.

The current stream of communication between Aircraft and Air Traffic Control makes use of vhf radio communication which is shared between all aircraft operating in a specified airspace. Exceptions do exist where communication between aircraft and ATC is conducted in a text based form with prescribed phrasing, although this is still an exception. An example of this is found in ocean clearing when crossing the North-Atlantic ocean. Communication between flight crews and Airline Operations Centre (AOC) is commonly performed through a digital data link. The well known example of this type of communication is the Aircraft Communication Addressing and Reporting System or ACARS (Moertl et al. [2009]).

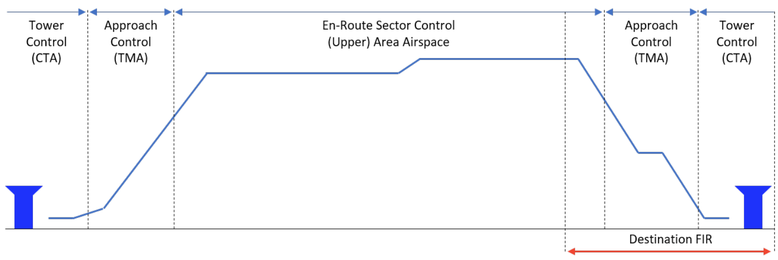


Figure 2.2: ATC control sections encountered during a nominal flight.

[1] A. Odoni, "The Airport Capacity Crunch", lecture notes, AE4446 Airport Operations, Delft University of Technology, March 2018

2.1.3. Aircraft Landing and Flight Completion

Around one to two hundred kilometres before arriving at the destination airport, aircraft begin descending and eventually start slowing down. Similar to departure, but in reverse, aircraft descend out of upper-area airspace into area airspace and eventually into the TMA and finally tower controlled airspace. Each step of the way the airspace becoming busier and as a consequence requiring more ATC intervention in order to assure proper separation between aircraft and, prime flights into a sequence in which they can be landed. The latter itself creating more opportunities for conflicts.

Part of the Sequencing and Scheduling of these aircraft can be done in transit directly before the aircraft enter the TMA airspace and are made possible through technological support tools such as the trajectory predictions discussed in section 2.1.2. Ultimately, the final stages of flight are often a source of significant part of the total delay a flight will encounter (Knorr et al. [2011]). Next to the commercial benefit of reduced delays for the operators, congestion is also a large contributor to the overall workload experienced by air traffic controllers and is marked as a prime (research) goal within both the SESAR [2] and the NextGen[3] research initiatives.

2.2. Problem Formulation

The following section is devoted to the principal problem formulation of the Aircraft Sequencing and Scheduling Problem (ASP). The Aircraft Sequencing and Scheduling Problem considers the inflow of aircraft as an unalterable fact and tries to deal with bringing the inflow of aircraft in a set distance to the runway in the most efficient and effective manner. The core of the ASP remains similar, regardless of the exact type of arrival sequencing considered or the problem scope defined. The former referring to the distinction between concepts such as (extended-)Arrival Managers, En-Route Sequencing and Scheduling tools, or the formulation around an Airline Based versus Airport focused tools. Through application of unique objectives, constraints and decision variables, the problem is tailored around the relevant application and scenario.

The section is structured as follows; after a general description of the problem, section 2.2.1 discusses a variety of time discretisation techniques applied in literature. section 2.2.2 subsequently focuses on the the objectives for optimisation in the ASP and following the goal description, section 2.2.3 discusses the constraints applied to the problem formulation. In support of the discussion presented in the following section, fig. C.1, fig. C.2 and fig. C.3 found in appendix C, contain overview tables of the main publications examined. In addition, the final paragraph of each sub-section contains summarising remarks and highlights the trend(s) observed in the surveyed papers and their respective sub-domain.

Airports in their role as the final link in the arrival chain of incoming flights, are limited in the capacity that they can offer. The capacity they offer is a function of many factors such as the physical number of runways, the amount of gates at an airport or, more soft aspects such as the number and skill level of airport staff. However diverse, these factors always result in a maximum number of flights able to be processed in a set time frame. The limitations in capacity offered mean that, in some cases, the capacity requested from airports can be exceeded by the capacity being offered and an imbalance is realised. Where this imbalance exists, actions need to be undertaken in order to balance the incoming flow of aircraft and deal with any backlog that has accumulated in the mean time. The (flow) balancing aspect of this problem is briefly touched upon in 2.3.1, but largely falls outside of the scope of this work.

Early efforts of the ASP were formulated for specific problem scenarios with limited possibilities for intercomparison. A first leap in this respect came when Beasley et al. [2000] not only published a set of results within their problem formulation, but also published the set of test scenarios of incoming traffic, the "OR-library". This database facilitated further research to compare model performance not only on personally developed test scenarios, but also on a base set of problems directly relatable between research efforts.

Pinol and Beasley [2006] and Furini et al. [2012] undertook efforts in their work further quantifying a formal formulation of the ASP; advancing efforts by Carr et al. [1998] and Beasley et al. [2000]. Generalising formulations allowed the ASP to become more widely applicable between scenarios whilst retaining similar mathematical formulations merely exchanging objectives and constraints. More recently, Ji et al. [2016] presents a full paper on this subject, noting that this generalisation can be of great importance in practical ATM implementations, which might need to switch in some regularity between different scheduling requirements and thus constraints.

[2] https://www.sesarju.eu/news-press/news/sesar-injects-%E2%82%AC19-billion-atm-research-avert-congestion-european-sky--343
[3] https://www.faa.gov/news/fact_sheets/news_story.cfm?newsId=19375

Figure 2.3 depicts the core of the breakdown of the ASP where all flights within a set radius around the terminal are considered; the eligibility horizon (outer Radius). Depending on the type of problem considered the, the region for this horizon is set, alongside the choice of what form of control is considered for each of the aircraft in the horizon (e.g. full of all aircraft vs. exclusively on ones' own fleet) (Zhang et al. [2020]).

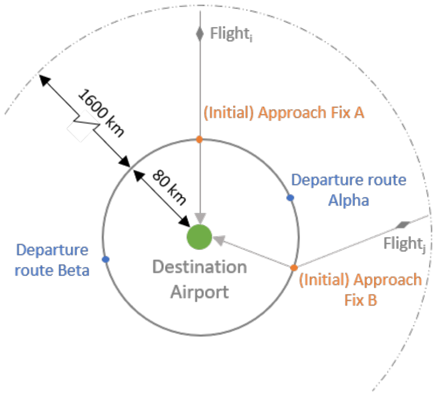


Figure 2.3: Top down view of the optimisation radii.
(Eligibility horizon (outer Radius) & freeze horizon (inner Radius)).

Within the outer radius (eligibility horizon) lies a second horizon, namely the freeze horizon. The freeze horizon (fig. 2.3) is a smaller region around the destination port in which no control actions can be applied to traffic. The freeze horizons models the final stages around the terminal, often between the initial approach fix and the destination runway, in which ATC vectors the traffic in a tight sequence and where the primary consideration is safety. Actions in this region are costly in their nature and are realised through relatively invasive measures and therefore not considered plausible for optimisation terms.

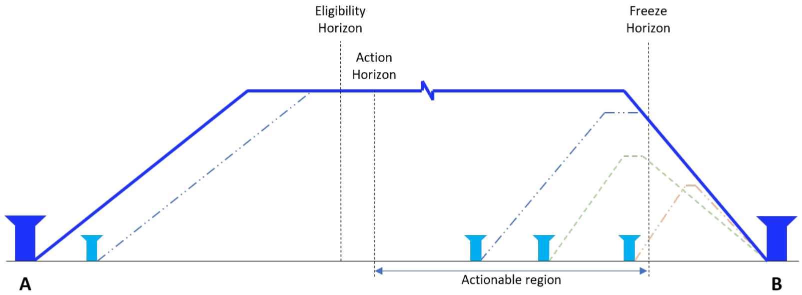


Figure 2.4: Aircraft Sequencing and Scheduling optimisation Region as viewed from the side.

Bounded by the eligibility and the freeze horizon lies the actionable region (see fig. 2.4), which forms the heart of the Aircraft Sequencing and Scheduling Problem. Within the Actionable region aircraft control is possible and aircraft are subject to optimisation. Depending on the size of the actionable region, not all aircraft are necessarily known at the start of the optimisation period. So called "pop-up Flights", depicted as dashed trajectories in fig. 2.4, are flights departing from airports within the eligibility horizon which appear for the first time at closer radii to the airport (Vanwelsenaere et al. [2018]).The larger the Eligibility horizon, the greater the control, but accordingly also the uncertainty in both trajectories, as well as the possibilities for disturbances such as the aforementioned pop-up flights.

2.2.1. Time Discretization

In the early 2000s the the problem started gaining more attention with several research efforts exploring different strategies on how to set up the ASP. For the different strategies, a major mode of distinction is found in the manner in which the problem is broken up in the time dimension. Figure 2.5, from the work of Bennell et al. [2011] presents an overview of how the timeframe is broken up between the different strategies. In guidance to the following section, fig. C.1 in appendix C illustrates the different optimisation strategies found within a cross-section of the papers surveyed in the literature review at hand, which can be used as a supplement to the overview presented in the following section.

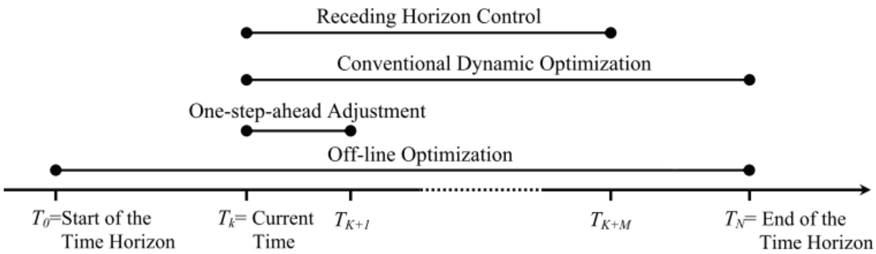


Figure 2.5: Different optimisation strategies (Bennell et al. [2011])

The earlier work by Psaraftis [1978] investigates both the static, as well as the dynamic form. The static form of the ASP is defined by the case in which all information is known at the start of the optimisation period. Conversely, the dynamic form allows for additional information to be added into the problem as time progresses (Samà et al. [2013]).
Beasley et al. [2000] and Carr et al. [1998] focused on the off-line optimisation in which the full set of information is known before the optimisation commences. Within this strategy, the information remains unchanged and the problem set is solved in one instance (D'Ariano et al. [2015]). A distinct sub-formulation within the "off-line optimisation" is presented in the form of the "One-step-ahead" strategy. The scope of the optimisation is confined to a specified time step. Within the aforementioned time step, the problem is solved in an analogous manner to the the off-line optimisation (Ernst et al. [1999]).

A more advanced adaptation of the previous concept is found in the Receding Horizon Control (RHC) concept (Samà et al. [2013]). Within the RHC, the problem set is broken up in several overlapping time instances called planning instances. The RHC, of which an overview is given in fig. 2.6, is defined by a fix horizon and a decision horizon. Aircraft within the fix horizon influence the solution set, but cannot be controlled directly. This "fixed" section of the airspace being introduced in order to model airspace in which control might no longer be feasible, such as the final approach stage before landing. Aircraft in the decision horizon by contrast, can be controlled and whose arrival times are subsequently optimised within the sub problem.

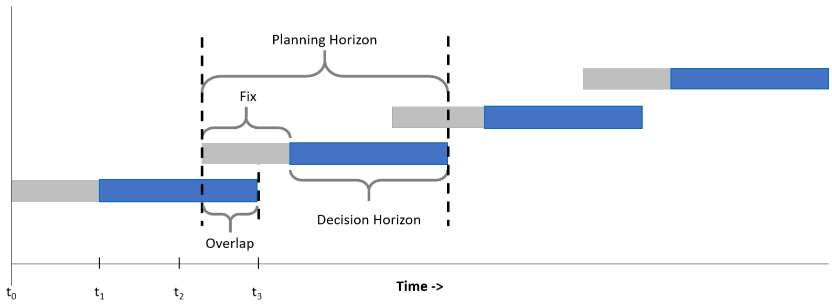


Figure 2.6: Receding Horizon Control scheme (adapted from Santos et al. [2017])

Once the sub-problem has been solved, the problem is marched forward one time step after which the optimisation is repeated. Between each of the optimisation steps, the possibility arises to update the information set to include new aircraft, as well as flights which might have altered (Hu and Chen [2005]). The inclusion of a region of overlap between the sub-problems allows for the RHC algorithm to account for optimisation of the edge cases.

Several parameters define the RHC concept, one of the most investigated of which being the length of the decision horizon. Atkin et al. [2006] presents an analysis of strategies for determining segment lengths in which scenario dependency is indicated on the outcome of the optimisation. Chen and Zhao [2012] investigate the effects of decision horizon length and indicate the adverse effects of (too) large control regimes. In addition, the percentage of overlap between optimisation regions is shown to have an effect on the overall performance both in solution quality, as well as the computational time required to reach this. Samà et al. [2013] discuss the relationship between planning horizon and decision horizon and, in their work, also discuss the trade-off between computational effort. In an effort to further improve solution performance and highlighting that within a problem set different "optimum" parameter values exist, Furini et al. [2015] discusses the process of dynamically determining the decision horizon length taking into account the inflow of aircraft over time.

Finally, Beasley et al. [2004] consider a system where deviations from the previous solution are penalised, as it is presented infeasible to have all agents under control change their actions every time the model presents a new solution. Adding solution changes as a penalty allows for faster computability when compared to the alternative of adding constraints to achieve similar bounds.

Concluding remarks

The predominant time discretisation form for the Aircraft Sequencing and Scheduling problem (ASP) found in surveyed literature (as also seen in fig. C.1 in appendix C) is the Off-Line Optimisation. The Off-Line optimisation strategy bounds the problem to a single traffic scenario on a predefined time instance in which the full set of information is known. This strategy is often preferred as it limits the variability in the problem when the research effort focuses on an investigation of different parameters, constraints or objectives related to the ASP.

The trend seen over the past years has been a shift from predominantly static problems into a larger focus on the dynamic form of the ASP (fig. C.1). The benefit of the dynamic form is often cited as being a closer modelling of ATM scenarios, in which new (solution changing) information appears as a regular occurrence, but which is oftentimes related to increased complexity and computational strain as well. Within the dynamic form, few have also considered cases where information does not only appear over time, but previously "known" information can also alter over time (see the outermost column fig. C.1).

Aiding in the resurgence of dynamic style problems is the introduction of the Receding Horizon Control Discretisation technique. First being published in relation to the ASP in 2005, the past years have seen it become a regular occurrence (fig. C.1). Within the surveyed selection of recent ASP publications, RHC and Conventional Dynamic Optimisation have almost become as frequently as the 'base' Off-Line Optimisation.

2.2.2. Objectives

Arrival Sequencing and Scheduling tries to optimise the timing and sequence of incoming aircraft in order to increase the efficiency of the overall process. This means that individual aircraft subject to the sequencing and scheduling outcome can experience different outcomes, both positive and negative, when different (global) optimisation goals are considered (**?**). It is therefor also of interest to differentiate between the global objective and individual flight and passenger based metrics.

In broad terms two categories of metrics can be used within the Aircraft Sequencing and Scheduling Problem (ASP); time based metrics and cost based metrics respectively. Although different on paper, most metrics can be transformed into the other form, facilitating forms of comparison between the individual aspects. In support of the following section, fig. C.2, found in appendix C, provides the reader with an overview the different objective functions treated in publications.

Time Based Metrics

Minimal Makespan

One of the primary metrics related to the limited availability of airport infrastructure is to maximise the possible utilisation obtained from this resource and, as such, minimising the time spent per landing aircraft. Minimising the landing time over an entire queue of landing aircraft corresponds with minimising the so-called makespan of the landing queue. Several researchers have devoted efforts investigating this concept, some notable examples can be found in the work of Balakrishnan and Chandran [2006], Beasley et al. [2004] and Salehipour et al. [2013] who have as goal to minimise the landing time of the last aircraft in the queue.

Deviation from Target Landing Time
In similar terms Rodríguez-Díaz et al. [2017], minimises the variance between actual landing times and the scheduled landing times in an effort to minimise the total schedule deviation introduced into the system. This objective, in contrast to the "delay only" scheme presented by Anagnostakis et al. [2001], this scheme penalises both early as well as delayed arrivals into an airport in equal terms. Soomer and Koole [2008] proposes a scheme in which early arrivals can compensate delays created elsewhere in the system. In the latter scheme, two minutes of delay could be compensated by two other aircraft arriving 60 seconds earlier.

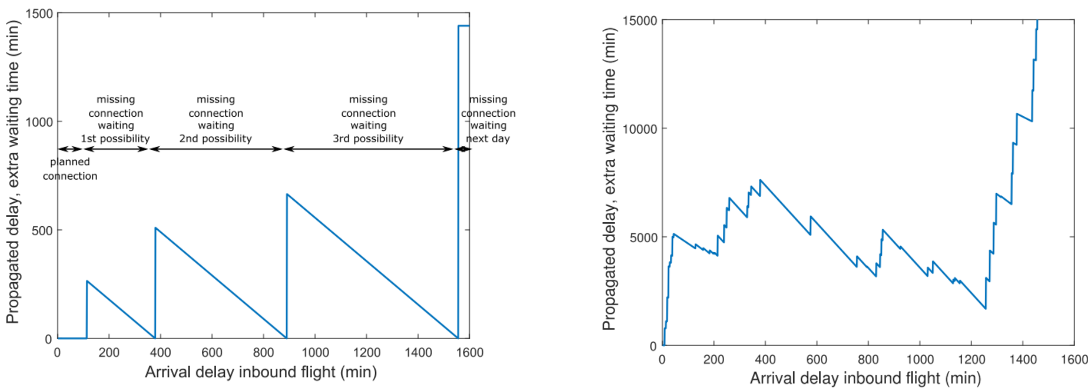
Not all types of delay should necessarily be considered equal. Considering the disproportionality in the cost between airborne delays and ground based delays, the former being a former being several times larger than the latter, stakeholders often prefer delaying ground based aircraft over those that are already airborne (Delgado and Prats [2014]). Bennell et al. [2017] and Hu and Chen [2005] consider a mixed-mode traffic scenario in which both departing aircraft, as well as arriving aircraft are considered simultaneously. The metric they implement discriminates between the two categories of aircraft in order to produce a more cost effective and environmentally strenuous solution.

Min/Max Delay Trade-Off
Samà et al. [2014] investigates the trade-off between individual aircraft' delay/deviation from scheduled arrival time and the the overall average throughout the population or a subset thereof. The goal in this objective form being to create a form of fairness for single operators and specific flights in a global scheme. This effect being important as it is often less impacting for an aircraft operator' operation to deal with several small(er) delays, than to deal with a single large delay and the possible reactionary delays set on by the strong aircraft and crew interdependencies between flights (Xu and Prats [2019]).

Priority Considerations
Ghoniem et al. [2014] and Furini et al. [2015] developed a weighted scheme allowing for different stakeholders to express their relative interest as priority indications onto a subset of aircraft or even individual flights. An example of this can be found in landing more polluting classes of aircraft before others or, a passenger based metric where the delay is not accrued per aircraft, but counted as a summation of total delay introduced over the entire passenger body. This second method, however, showed a tendency to prioritise larger aircraft over their smaller counterparts in a majority of the scenarios.

Other Time Based Constraints
Zhang et al. [2020] introduces a controller workload metric by relating the an aircraft spends inside an air traffic controller' airspace to the workload they are subjected to. Minimising the total time aircraft spend under the control of said controller is argued to be proportional with a decrease in controller workload.

Lastly, Jacquillat [2018] explicitly considers the downstream effects for not only aircraft in an airline' fleet, but also on individual, multi-legged, passenger itineraries. Montlaur and Delgado [2017] illustrate this effect through the figures depicted in fig. 2.7, where the impact of a set amount of inbound arrival delay can have varying effects on the total propagated passenger delay.



(a) One passenger connecting (Montlaur and Delgado [2017]).

(b) Several passengers connecting (Montlaur and Delgado [2017]).

Figure 2.7: Extra (passenger) delay due to missed connections.

Cost Based Metrics

Some forms of inefficiency or sub-optimality are not measurable in a time based metric, but are more suitably expressed in terms of a cost function. This cost function does not in all cases relate to a form of currency, but expresses the inconvenience cost of a solution. Most cost based functions are related to airline operations and behave in a non-linear manner (Montlaur and Delgado [2017]). Cook [2015] published an ongoing effort to quantify airline cost levels in a European context, but notes that these estimates show variance between individual carriers.

Fuel Cost

Fuel being one of the largest cost centres for most aviation operations, several efforts have been posted focussing on a Fuel Cost based metric. In these metrics, such as the scenario proposed by Lan et al. [2006], the penalties associated with a deviation from the scheduled arrival time are weighed up against the cost of flying faster. Flying faster in most every case results in an aircraft operating further away from its most optimal (in the fuel sense) cruise speed and/or altitude (Rumler et al. [2010]).

Passenger Cost

Carr et al. [2000], Soomer and Franx [2008] and Santos et al. [2017] develop a cost based objective revolving around passenger cost. Especially for Hub based operations most commonly found in the hub and spoke operations of legacy carriers, passenger cost becomes relevant and takes on significant values. Late arrivals can result in passengers missing their connecting flights, which in addition to the time based delays discussed in the previous sub-section, can result in addition cost for the airline in order to accommodate passengers on a competitors flight, the cost of hotel accommodation or in more regions of the world direct cash compensation. The EU261/2004 regulations implemented by the European Commission [4] and more recently the rules implemented by the Canadian Transportation Agency [5] are prime examples of legislation forcing airlines into compensation claims.

Cook et al. [2009], Soomer and Franx [2008] and Delgado et al. [2016] are amongst many to also consider so-called "Soft" cost for passengers in their objective functions. Soft cost are those cost related to the business retention of customers after the incurred inconvenience of a delay, or the cost associated with the loss of future value from this customer (Pilon et al. [2016]). An estimate and additional insight for the European case can be found in Cook [2015].

Environmental Cost

Lieder et al. [2015] and Delgado et al. [2016] define environmental cost functions considering aspects such as emissions of CO_2 and NO_x and, the emission of noise. These functions try to minimise the extra pollutants secreted by aircraft loitering and/or the extra fuel burn from flying non-optimised flight manoeuvres. Noise becomes especially relevant at low altitudes over (dense) living areas as occurs shortly before landing. Holding patterns are oftentimes not flown within these conditions (Klooster et al. [2008]).

Slots

Another way in which Aircraft Operators bear cost, especially at highly congested airports, is through (landing) slots. Landing slots are developed around in order to ration incoming traffic and distribute landing rights over time. Currently slots are distributed once on a per season basis with minimal changes in between [6]. Vossen and Ball [2006] develop a market based mechanism in which airlines can bid for their preferred landing slot on a per day basis. This added flexibility allows airlines to express the value a slot has for their operations (Schummer and Abizada [2017]). A goal of the optimisation is to introduce a form of fairness between the different players through the market value expressed for each slot (alteration).

Most research around the ASP focuses on a single objective type, which is, in some cases, traded off against a different objective in order to compare model behaviour. In a more recent effort by Samà et al. [2017] and Zhang et al. [2020] a trade-off between several criteria in the aircraft landing problem is presented. Additionally, in both the works from Samà et al. and Zhang et al., an effort has been made to define multi objective objective functions in search of a "good compromise" style solution. What objective is most relevant is largely dependant on the stakeholder consulted and as such the ideal solution is rarely black or white. Many interests are involved and goals are often (partially) conflicting with one another (Hong et al. [2017]).

[4] `https://europa.eu/youreurope/citizens/travel/passenger-rights/air/index_en.htm` [accessed on 10-01-2020]
[5] `https://otc-cta.gc.ca/eng/content/air-passenger-protection-regulations-finalized` [accessed on 10-01-2020]
[6] A. Odoni, "The Airport Capacity Crunch", lecture notes, AE4446 Airport Operations, Delft University of Technology, March 2018

Concluding remarks
When examining the trends observed from the surveyed papers on Arrival Sequencing and Scheduling (fig. C.2 in appendix C), the dominant Objective found pertains to Minimising the makespan of the arriving aircraft queue. This constraint is in fact, often the main driving factor for the investigation in the first place (capacity constraints at airfields).

Other time based metrics such as minimising the maximum delay or discriminating between arrival and departure delay find regular introduction in literature, although often in addition to the makespan measures. In more recent times, deviation from target landing time is frequently introduced in conjunction with cost based measures, likely since the former is often the basis on top of which the latter metric is based.

(Passenger) Cost functions or priority considerations are introduced with some regularity (fig. C.2). More frequently these measures are discussed in technical papers and trials at airlines/airports without disclosing full results in an academic paper.

Environmental objectives showed a small peak of interest halfway through the 2010s, but have not gained much attention from the ASP over time. Some papers citing that this is linked to the strong dependency between environmental cost and delay as a whole or in relation to fuel burn. Following the interest in environmental cost functions, fuel based cost functions have started gaining attention from the ASP. The latter remaining a frequent appearance in publications to date (fig. C.2).

The last trend seen in the objective functions of the ASP can be seen in the introduction of trade-off based optimisation schemes evaluating multiple objectives and their impact on the overall optimisation. Some authors going as far as to present an investigation into multi-objective optimisation.

2.2.3. Constraints

The base formulation of the ASP allows for several modes of differentiation. This, however, also means that without proper bounding and scoping, the model outcome might not fully align with the intended purpose or produce formulations which do not fully encompass the scenario under consideration. Constraints are the tools used to further define the scope of the model and produce the limits within which the individual agents operate. The subsection below provides a survey of the most prevalent forms found in literature. Figure C.3, found in appendix C provides a tabulised overview in support of the discussion found below.

Wake-Vortex Separation
The primary constraint placed on landing operations in the current ATC context is found in wake-vortex separation. Wake vortex separation is a measure to cope with the unpredictability in airspeed and wind direction direction caused by the disturbed atmosphere behind aircraft (Fahle et al. [2003]). The phenomenon itself is predominantly the result of physical effects induced by the pressure differences equalizing around the wingtips of aircraft as they "slice" through the air. Wake Vortex separation constraints, internationally defined by the International Civil Aviation Authority (ICAO), need to be respected between each successive arrival and with this, a minimum (aircraft pair dependant) spacing is introduced [7]. Wake vortex separation, in combination with the variance in size of aircraft arriving, is one of the leading considerations linked to the maximum (theoretical) throughput a runway can accommodate (D'Ariano et al. [2010] and Bennell et al. [2017]).

Bounded Arrival Time
Flights cannot stay airborne without bounds and as such in modelling attempts, the landing time is often set between an earliest and latest possible landing time. Physical, technical alongside operational constraints play a part in bounding the feasible set of arrival times and, together result in one most limiting constraint on the arrival bounds (Bennell et al. [2011]). Time constraints are predominantly treated as hard constraints which would need to be respected in all feasible solution scenarios.

Several implementations of the bounded arrival interval are found in literature. In the most inclusive form, Balakrishnan and Chandran [2010] bounds both the upper and lower limits of the arrival time as described in the previous paragraph. Rodríguez-Díaz et al. [2017] and Samà et al. [2017] choose to only impose boundaries on the lower bounds or earliest arrival times. They argue that the earliest arrival time, related to the amount of fuel carried or the physical limitations to the speed at which an aircraft can fly, imposes the most limiting case. Upper bounds, or latest arrival times, would not be reached due the nature of the optimisation goal and their omission would provide significant computational benefits.

[7] Procedures for air navigation services: Air Traffic Mangement (PANS 4444), ICAO 2016

Constrained Position Shifting

Constrained Position Shifting, or CPS for short, is a term describing the limitations posed on an aircraft's position in the optimised arrival queue relative to the initially defined position an aircraft had in the First-Come, First-Served sequence (Balakrishnan and Chandran [2010]). Initially introduced by Dear [1976] in order to (partially) limit the computational burden by reducing the feasible solution space, the CPS constraints was recognised to also model operational and fairness considerations. For instance, Ghoniem et al. [2014] introduces the CPS constraint citing operational considerations, where significant overtaking manoeuvres would simply be infeasible to execute due to the traffic density. In contrast to bounding the actual discrete number of aircraft that can be shifted within a queue, Mesgarpour et al. [2010] proposes a time bound scheme in which overtaking constraints are based around the the time advancement or set-back defined feasible for each flight. The maximum number of flights shifted within this scheme depends on the amount of overlapping arrival windows within the arrival queue.

In similar terms as the operational constraints on position shifting, Eun et al. [2010] presents a case in which route based overtaking restrictions are applied to aircraft arriving from the same arrival path and general direction. Zhang et al. [2007], with a similar logic, breaks up the incoming traffic per arrival route and considers each as a discrete optimisation problem, later to be combined.

Eun et al. [2010] and later Murça and Müller [2015] impose restrictions on the possible arrival time influence for aircraft. Each aircraft is assigned a discrete set of possible movements and arrival times corresponding to these path shortening or lengthening exercises. Murça and Müller [2015] discusses the development of a tool focused around the least invasive manners for overtaking or delaying, thus improving upon efficiency.

Minimum Turn Around Time

When viewed from an airline perspective, constraints pertaining to the (on-time) dispatch readiness of aircraft can be considered relevant. In this respect, Montlaur and Delgado [2017] and Delgado et al. [2016] build in constraints surrounding the minimum connection time for passengers and the minimum turn around time between aircraft rotation necessary to perform the ground handling in prior and post completion of each (commercial) flight.

Fairness and Equity

Fairness relates to the form of equity between stakeholders in a problem. In the context of the Aircraft Sequencing and Scheduling problem, this often relates to the "equitable" distribution of delay minutes between flights (Bennell et al. [2013]). For air traffic control organisations, fairness is often a criteria to which they have to oblige. Favouring a "fair" outcome over an outcome with the minimal level of delay is thereby preferred Soomer and Koole [2008]. From an airline perspective this fairness aspect is far less strict as in the free market environment, players are free to behave in the manner most effective to them (within, of course, the bounds of any laws and regulations).

For the Aircraft Sequencing and Scheduling problem, several implementations of fairness are possible, both in hard terms as a constraint, or as an (additional) objective in the optimisation problem. The former being discussed in section 2.2.2. In the constraint form fairness is first mentioned in the work of Carr et al. [1998], where airline priorities are considered, but abstract bounds on delay minutes are introduced in order to equalise the field. Soomer and Koole [2008] takes a different approach by only allowing actions of Airline A to influence aircraft from Airline A. A practical example of this constraint allowed for only swapping between arrival (or landing times) within one's own fleet. Another way to introduce fairness can be found in Samà et al. [2017] where the delay introduced into the system is set to be zero, thus meaning that any advancements of aircraft must be traded with delays to another.

Concluding remarks
Wake-Vortex separation is found to be one of the most influential factors in determining runway capacity, as a result the Wake-Vortex Separation constraint was found in every ASP paper surveyed during the presented literature review (fig. C.3 from appendix C).

Sharing the popularity of the Wake-Vortex constraint(s), a qualified majority of the papers on ASP implemented forms of Arrival Time Bounds for the aircraft scheduled to land (fig. C.3). The latter two constraints are often regarded as the basis used for modelling both macroscopic as well as microscopic formulations of the ASP to which other constraints are added depending on the exact extent of the modelling effort.

The earlier half of modelling efforts on the ASP tended to include Constraint Position Shifting (CPS) constraints on the maximum variance achievable within the arriving queue of aircraft (fig. C.3). Some efforts cite the reason related to the computational effort reductions, whilst others model this with the intent of better modelling realistic scenarios. At the same time, some research efforts chose to formulate the CPS constraints in the form of precedence constraints (FCFS, on a certain route) or route based overtaking constraints (see columns 3, 6 & 7 in fig. C.3). Both of which apply similar bounds on arriving traffic, but in search of different goals.

For fairness (column 6, fig. C.3), the precedence constraint is often the most discussed constraint. Although covered in earlier works, the inherent subjectivity of fairness meant that fairness and equity schemes have not shown regular occurrence within publications related to the ASP.

2.3. Setup of the Aircraft Sequencing and Scheduling Problem

Although similar in formulation, the Aircraft Sequencing and Scheduling Problem can be applied to a diverse set of scenarios each with distinct considerations, but ultimately serving a similar end goal. Between the different scenarios, a varying set of stakeholders can be affected and a distinct set of control actions can be undertaken. The following section presents an introduction into the different problem setups found within the broader scope of Aircraft Sequencing and Scheduling and builds further on the base formulation discussed in section 2.2.

Following a brief introduction, section 2.3.1 continues with a survey on the Sequencing and Scheduling problem within the TMA and elaborates on the benefits gained through this form of arrival sequencing. Following this, section 2.3.2 is devoted to En-Route Arrival Management, which encompasses both Ground-Based formulations as well as Cockpit-Based scenarios.

The Aircraft Sequencing and Scheduling Problem at its core tries to deal with the incoming flow of traffic to an airport in the most efficient way as to minimise the amount of delay/inefficiency introduced due to the (local) mismatch between inbound traffic and runway capacity. The problem can be adapted to focus on outgoing instead of incoming traffic, or in some cases mixed-mode operations where aircraft land and take-off using the same infrastructure and within the "same" sequence.

Sequencing and Scheduling of aircraft fixes two important aspects of an incoming traffic stream. The first aspect, sequencing, is an important input to arrival scheduling algorithms used by ANSPs. Many ANSPs choose to uphold relatively simple strategies such as "First-Come, First-Served" (FCFS) in order to treat traffic in an equitable manner. Scheduling, is in several ways dependant on the defined traffic sequence. Wake Vortex separation constraints defined by the International Civil Aviation Authority (ICAO) need to be respected between each successive arrival and with this, a minimum (aircraft pair dependant) spacing is introduced. At times where the traffic flow is not saturated, ATC retains the possibility to schedule traffic more freely and can, for instance, choose to speed up traffic at the start of a busy arrival period in order to gain more room at a later time instance or choose to implement advanced arrival strategies such as continuous descent approaches (Knorr et al. [2011]).

2.3.1. TMA and Airfield Arrival Management

The early days of arrival management, of which Arrival Sequencing and Scheduling is a sub-form, mainly dealt with the Terminal Manoeuvring Area (TMA) close to the destination airfield. This focus was a natural consequence of the limited congestion found during other stages of flight. With increased traffic came the need to efficiently and effectively react to the inflow of traffic. Starting at the base of the problem, the scope was bounded to that area that was directly congested; a natural bound formed where control passed from one air traffic control agent to another, the TMA (Carr et al. [2000]).

Benefits of Arrival Management can be expressed in several different forms. The most evident benefit can be found in the increased efficiency of operations; this meaning less time spent by aircraft loitering before they can land or spent queuing before they take-off (Carr et al. [1998]). The effects of this can be seen in the decrease of delays and delay related costs and is often posed as the major goal in the arrival optimisation program (Zhang et al. [2020]). However, the effects stretch beyond what is immediately apparent. Runway capacity is one of the large factors indirectly influenced by the efficiency of the arrival process and thus by arrival management (Balakrishnan and Chandran [2006]). A third benefit highlighted is found in the ATC workload, or more precisely, the reduction of ATC workload that more efficient (and thus with fewer interventions) arrival management has.

The (initial) focus of the TMA based Arrival Sequencing and Scheduling Problem resulted in a narrow problem formulation. Narrow in the context of the ASP referring not only to the physical distance limitations resulting from the defined scope, but also to the limited possibility for controllers to influence the further progress of flights. Controllers often resort to relatively inefficient control actions such as route extensions or holding patters in order to streamline traffic in the limited airspace available. These actions which not only extend the path of affected aircraft when compared to the nominal path, also result in more flight time in one of the least efficient flight regimes (low altitude and speed) (Bennell et al. [2013]). Limiting the scope of the problem to the TMA furthermore allows for a reduction of uncertainty coupled to the aircraft position and movement, both of which are often hard to predict over large time instances (in the order of hours) and present a distinct topic for investigation in and of itself (Scharl et al. [2006], Klooster et al. [2009] and later Tielrooij et al. [2015]). The scheduling algorithms proposed for TMA based Arrival Sequencing and Scheduling were no exception to these limitations and have to operate within the same constraints.

A possible mitigation of this limitation is found in the works of Clare and Richards [2011], Heidt et al. [2014] and Delgado et al. [2016], who define the scope of arriving (or departing) flights beyond the airborne segment by adding an optimisation of the ground based movements aircraft perform at the airfield. Taxi times are oftentimes hard to predict in an empirical manner; recent efforts with machine learning have yielded some forms of success, but have not yet matured to the case in which the method can be (easily) transferred between scenarios. Clare and Richards [2011] mention, that due to difficulties in estimating accurate taxi times, modelling approaches are often preferred. In some cases equally limiting, Santos et al. [2017] adds gate and stand availability as a further consideration to the optimisation process.

At the same time, large scale efforts are being launched under the umbrella of the SESAR research initiatives in order to investigate and develop concepts unifying the airspace bounds and, furthering cooperation between individual centre Arrival Management (AMAN) tools (Vanwelsenaere et al. [2018]). Cooperation between centres, especially in the highly decentralised nature of Europe, can allow for the implementation of Extended-Arrival Management tools which due to the larger scope of control and better intra-ATC-centre cooperation can deal with traffic more efficiently at the cost of individual centre control (Knorr et al. [2011]).

2.3.2. En-Route Arrival Management

Within the context of the proposed "IPS Arrival Sequencing and Scheduling" algorithm and with this the extended window of sequencing and scheduling, the En-Route segment becomes a vital link in the sequence of arrival management. In addition, similar to Extended Arrival Manager (E-AMAN) concepts, a large share of the proposed control actions find their greatest effect if executed within this en-route phase. Due to its significant role in the proposed concept, the following sub-section will elaborate on a subset of En-Route Arrival Management concepts. After a brief introductory paragraph, each of the concepts will be treated as a stand alone topic.

Considering the drawbacks and partial suboptimality of control actions within the Terminal Manoeuvring Area (TMA), researchers have sought solutions minimising route extensions and delays within this region and, in even more optimal situations, seeking to mitigate route extensions al together. A diverse set of concepts exist, leveraging different components of a flight other than the final stages within the TMA. Their goal is however, as elaborated upon previously, largely the same; decreasing delay cost by either mitigating or transferring delay. The results of these efforts can be broadly encompassed within the term En-Route Arrival Management which applies much of the core elements of the Aircraft Sequencing and Scheduling Problem on the En-Route sector.

Important to note is that although En-Route concepts can be viewed as a stand alone optimisation priming traffic for the TMA, it can also be argue that the benefits achieved (or lost) with almost any (en-route) arrival management concept pivot for a large part around the successful integration with arrival processes within the TMA[8]; efficient arrival management requires the coordination with downstream processes without which traffic bunching (see introduction) is virtually inevitable.

Arrival Metering / Required Time of Arrival

One of the better treated topics within en-route arrival management is the concept op Arrival Metering, or more simply stated striving towards coordinated and agreed upon arrival times at a specified point (often near the airfield). This 4D traffic management process coordinates traffic and allows further ATC sectors to vector in traffic to the runway in the most efficient manner without spending time decluttering traffic bunches (Dijkstra et al. [2011] and Thipphavong et al. [2011]).

An example of the possibilities achievable by implementing Arrival Metering tactics is demonstrated in the work from Nieuwenhuisen and de Gelder [2012] with the full scale traffic wide implementation of Continuous Descent Operations (CDO). These operations, as depicted in fig. 2.8, are more fuel efficient and environmentally less invasive than those currently implemented. The drawback of many of these systems is that more separation is needed between successive aircraft arrivals which, if implemented by holding or route extensions in final flight stages, can offset the benefits obtained by the CDO itself (Klooster et al. [2008] and Itoh et al. [2017]).

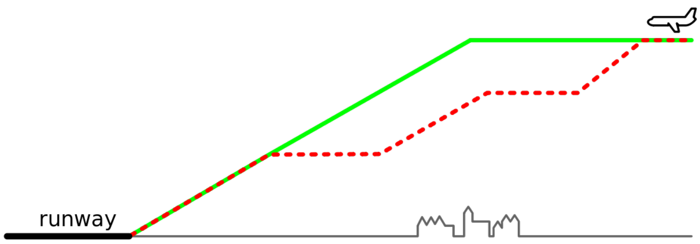


Figure 2.8: Graphical representation of Continuous Descent Operations (solid green) compared to conventional approaches (dashed red). [Adapted from [9]]

A different set of trials carried out by Ren and Clarke [2008] and later Moertl et al. [2009] applied the concept of arrival metering to the aerial operations of the United Parcel Service (UPS) fleet at Louisville, Kentucky in the United States. The operations of parcel giant UPS in Louisville are quite unique as they concern large volumes of traffic from one single airline at nighttime where interference from traffic other than their own operation is minimal. Both [Moertl et al., 2009] and [Ren and Clarke, 2008] experienced some forms of success by spacing out traffic before they reached set waypoints along the route into Louisville after which a large share of traffic was able to perform CDOs into the airfield, ultimately reducing delays and increasing fuel efficiency. An additional opportunity presented within the work of [Moertl et al., 2009] was that to influence not only the arrival times, but also the arrival sequence. This allowed flights where more sensitive on a time scale to be prioritised over others without sacrificing efficiency or requiring large control actions.

Although advanced applications such as integration with CDOs are possible through Arrival Metering, a more prevalent application is in the decongestion of airspace and runway queue's. In fact, some of the most impactful tools in the ATC toolkit of both EUROCONTROL, as well as the FAA are based around arrival metering. Ground delay programs (FAA) and ATFM departure slots (EUROCONTROL) calculate the inflow (or through-flow) of aircraft in a specified piece of airspace and ration the amount of arriving aircraft by delaying their take-off (Knorr et al. [2011]). An important aspect to note is that although both EUROCONTROL and the FAA calculate delay programs around Estimated Times of Arrival (ETAs) at the airspace boundary, they opt to relate ETAs back to departure times and subsequently enforce only the departure times (Delgado and Prats [2011]). This policy enables aircraft (operators) to partially negate the intended decongesting effects of ground delay programs by flying faster of different routes than previously filed in a flight plan and thus arriving earlier for their own benefit (Bilimoria [2016]). Additionally, enforcing departure times limits the application of more advanced tactics such as linear holding (discussed further in this chapter) to more efficiently cope with delays.

[8]"En Route Speed Control Methods for Transferring Terminal Delay" - James Jones, David Lovell and Michael Ball, presentation, 10th USA/Europe Air Traffic Management Research and Development Seminar, ATM, 2013

Studies have been performed into the Metering concept both in the simulation form, as well as with operational flight tests. During some flight test studies researchers encountered issues determining comparable days due to the large amount of changing environmental considerations. The study of Guzhva et al. [2014] is a great example of this.

Trapani et al. [2012] investigates several forms of arrival metering at progressively larger distances from the runway, after which the throughput performance is evaluated. In the simulation study presented, controller workload decreases with each progressive distance step (further away from the runway) that metering is applied to. Throughput itself does not increase with every step, but does (overall) show a positive trend with increasing metering steps. With all metering bounds activated up to 25nm distance, the throughput increased by over 30% compared to the un-metered concept.

Coppenbarger et al. [2004] takes a different approach to arrival metering and introduces a tool called the "En-Route Descent Advisor" (EDA) . EDA functions as a decision support tool to air traffic controllers in their realisation of Metering Times. The tool helps controllers not only deliver aircraft at their predetermined metering fix on time, but also mitigates aircraft conflicts along the planned trajectory.

Airservices Australia, the Australian ANSP, presents one of the largest scale real world applications of arrival metering of the past decade. In an effort to mitigate excessive holding during the early morning inbound peak into the curfew bound Sydney airport, long range flow control is applied to incoming flights (AirServices Australia [2007]). The ATM Long Range Optimal Flow Tool (ALOFT) starts working at a range of 1000 miles from Sydney, where speed control advisories are distributed to aircraft to ration the inflow and transfer delays. Through the use of ALOFT, Airservices estimates yearly fuel savings of around 1 million kg (Knorr et al. [2011]).

Interval Management

The aforementioned methods of Sequencing, Scheduling and Spacing rely up to a certain extent ground based centralised coordination and distribution to achieve the overarching goal. Although (fully) ground based solutions benefit from relatively cheap computing power and are located within the heart of the operation, these solutions oftentimes have less accurate information on the aircraft surroundings and intent than the flight itself (Ballin et al. [2002]). In addition to this, once aircraft are sequenced into an arrival chain, changes made to leading aircraft can impact several aircraft following, which in the ground based situation, all need to be informed and coordinated with independently. Based on this observation and enabled by the wide spread deployment of high precision aircraft information broadcasts such as Automatic Dependent Surveillance-Broadcast (ADS-B) , the concept of interval management was developed (Barmore et al. [2016]). Interval Management, as illustrated in fig. 2.9, delegates part of the coordinating task to individual aircraft. Each aircraft receives spacing instructions relative to a preceding aircraft, which means that any upstream disturbances are automatically corrected for by trailing aircraft (Hicok and Barmore [2016]).

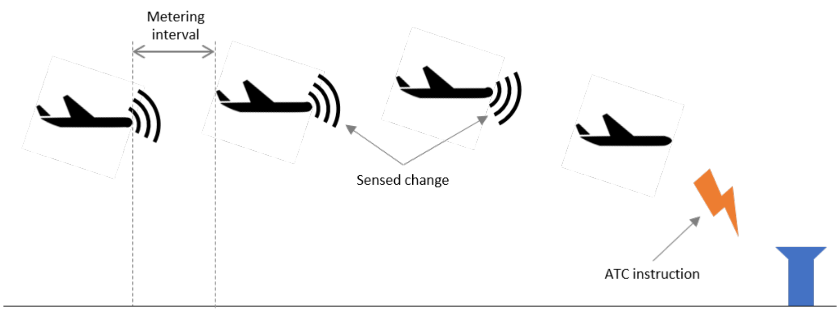


Figure 2.9: Graphical representation of Interval Metering.

The most prevalent forms of Interval Management is defined by a strategic ground based setup phase, followed by a tactical implementation from the flight deck. The resulting system allows for aircraft to be spaced closer to one-another and with greater consistence, all whilst upholding a greater level of safety than current practices (Penhallegon and Bone [2009]). Similar to metering concepts, Interval Management aims at reducing the in-efficiencies tied to the final stages of a flight by reducing the need for additional separating of aircraft by Terminal Air Traffic Controllers (Barmore et al. [2016]). For airports these inefficiencies reduce the overall capacity that they can offer, whilst on the airline side this leads to increased cost and a higher environmental footprint.

Operational trials held in cooperation with UPS in the work of Penhallegon et al. [2016] illustrated the potential of the concept in operation without large infrastructural changes or realising an increase to Pilot workload, nor that of Air Traffic Controllers.

The base concept of (flight-deck based) interval management lends itself to integration and merger with several other proposed traffic flow management concepts and further paves the way for higher en-route prediction accuracy. The latter especially being a stepping stone for many NextGen and SESAR concepts being proposed (Moertl and Pollack [2011]).

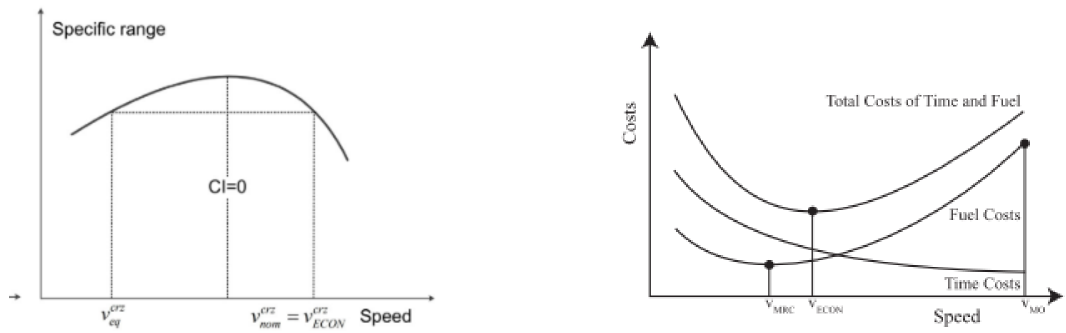
Linear Holding

Fewer delays in the aerospace system present the best-case scenario for all parties involved, however, in some scenarios delays are inevitable. An example of this is can be seen in the onset of adverse weather, which can severely limit capacity of an airfield [10]. As previously touched upon, capacity crunches, if known sufficiently in advance, are solved by imposing delays on aircraft prior to departure in a calculated measure to reduce the inflow of aircraft in a fuel efficient manner. Aircraft Operators, considering their commercial interest, are shown to regularly combat the imposed ground delays by “racing” to the destination airport as soon as the effected flight has departed (Evans and Lee [2016]). This “racing” towards the arrival airport has both an effect on the en-route fuel burn, but also on the congestion levels in the TMA at the destination and thus once again creates a situation with holding and delays.

Linear holding is a concept in which the delays necessary for the decongestion of terminal airspace at the destination are not (solely) applied to aircraft prior to departure, but (partially) transferred to the en-route segment of approaching aircraft in order to absorb delays at no addition fuel cost(Xu and Prats [2019]). The underlying concept on which this strategy relies is related to how aircraft operators execute most commercial flights.

Theoretical basis

The cost to own and operate an aircraft depend on a wide variety of different components, the predominant distinction being made between cost directly related to the operation of a flight and those cost indirectly related to the operation of a specified flight (Belobaba et al. [2015]). Within the cost related to directly operating an aircraft, fuel is the largest cost, followed by the cost of crew (of Aviation Policy and Plans [2016]). The nature of how both cost are accumulated, however, is quite different. Crew cost are driven by the flight length and show a proportionality to the duration of a flight. Fuel cost do not follow the same proportionality and can be considered as a convex function with an optimum slightly below the transonic region (Xu and Prats [2017]). An illustration of which can be seen in the Specific Range curves in fig. 2.10a, which depict the distance that can be travelled per unit of fuel burned as a function of the selected cruise speed.



(a) Specific Range as a function of airspeed Adapted from Knorr et al. [2011] .

(b) Cost curves for fuel and time related cost adapted from Rumler et al. [2010] .

Figure 2.10: Operating fuel consumption and cost for aircraft.

For an airline operating within a commercial framework, the ideal operating region is a balance between the aforementioned two cost curves. The balance between these two curves is depicted through fig. 2.10b and constitutes as a weighted compromise between the most time efficient and fuel efficient flight regimes (V_{econ}). Flying at the economical speed results in the lowest operating cost for the airline, but as illustrated, does not correspond to the the individually most time or fuel efficient cases. By leveraging the inefficiencies

[10] `https://www.eurocontrol.int/news/weather-responsible-third-delay` [accessed on 13-12-2019]

pre-calculated into flights by operators, the linear holding concept aims at flying at a speed which has an equivalent specific range as the undisturbed flight, but at a slower flight speed. Flying slower allows a flight to become airborne earlier than under the nominal ground delay program, allowing for less interference to the arrival time, as well as large benefits if the ground delay program is lifted during the cruise stage of the affected flight (Delgado and Prats [2011]). Within the specific context of the Aircraft Sequencing and Scheduling Problem, the linear holding concepts depict the flexibility possible within flight speed regimes without requiring additional fuel reserves to be carried.

Practical Implementations
Jones et al. [2013] develop a MILP model which issues speed advisories to aircraft arriving into a terminal around 500nm before entering the TMA. The speed advisories direct arrivals into a streamlined flow arriving at coordinated Arrival slots, and with this eliminating most of the terminal delay in favour of absorbing this delay in-flight. Even with modest compliance levels around 30%, over a third of the delay achieved within the system could be moved away from the TMA. Fuel burn savings examined during the modelling effort ranged upwards of 75kg per flight arrival.

After an initial feasibility study (Delgado and Prats [2011]), Delgado and Prats [2012] focus their effort around the effects of linear holding in the context of ground delay programs. by flying at a similar specific range, but lower absolute speed (V_{eq} vs. V_{econ} in fig. 2.10a) in stead of ground holding, Delgado and Prats manage to partially recover delays (in the order of several minutes) imposed by Air Traffic Flow Management (ATFM) measures without addition fuel. Xu and Prats [2019] extend on this concept by implementing more advanced measures and pre-planning steps to a simular concept. Xu and Prats manages to achieve the same order of magnitude with respect to delay recovery without additional fuel, but investigates the effects of extending this time range upwards of ten minutes for instances in which they allow additional fuel to be carried. The latter case stated to still remain cost effective to the airline operator.

In comparison to the earlier investigations presented in Delgado and Prats [2012], Delgado and Prats [2014] investigates the effects of linear holding when, most simply, only the cruise speed is adapted and no changes to flight level or path are considered. This being operationally more advantageous (ease of implementation), but at the same time yielding smaller benefits as well. Delgado and Prats [2014] further investigates the effects of sector length on the total time recoverable exemplifying the benefits to be gained if long-haul flights were to be included in stead of exclusively focusing on flights within a set radius with the total delay recoverable for the case-studies performed increasing in several-fold.

Not focusing on the context of Ground Delay Programs (GDPs),Jones et al. [2015] propose several modelling methods in order to leverage linear holding to transfer delay from the terminal area to the (more cost efficient) En-Route Airspace. In a full compliance scenario, Jones et al. managed to transfer on average just under 20% of all delays away from the TMA. In the more realistic scenario with aircraft non-compliance rates (to the instructed speed advisories) of up to 50%, the benefits, or transferred delay, remained at around 10%.

2.3.3. Airline-Based Arrival Sequencing and Scheduling

Most Aircraft Sequencing and Scheduling concepts revolve around the ATC stakeholder as the coordinating and executing party [11]. As the primary body designed to regulate air traffic and the stakeholder with the first hand overview of traffic this is not surprising. However, this distinction does come with some complications and limitations as well. The section below provides the reader with considerations around Airline-Based Arrival Sequencing and Scheduling with respect to ANSP focused models. The section continues by elaborating on a subset of airline-based Arrival Sequencing and Scheduling tools. The literature discussed under this umbrella earns its relevance due to the close relationship with the modelling view proposed in the subsequent research paper.

As a first limitation of ANSP based sequencing and scheduling, ATC organisations, as independent bodies, must uphold fairness and equity considerations in the traffic they manage and direct (Soomer and Koole [2008]). Taking into account priority considerations or commercial goals is oftentimes diabolically opposed from that objective, bounding the actions undertaken by ATC.
Secondly, as a result of ATC sector bounds, Air Traffic Controllers have a limited, and oftentimes non-optimal span of control over the aircraft arriving into/departing their sector (Knorr et al. [2011]). In order efficiently and effectively streamline traffic; optimisation strategies often span over several sectors. Within the ATM context this limits the optimal control actions to only larges scale, umbrella organisations such as the FAA in

[11] "En Route Speed Control Methods for Transferring Terminal Delay" - James Jones, David Lovell and Michael Ball, Presentation, 10th USA/Europe Air Traffic Management Research and Development Seminar, ATM, 2013

North-America and EUROCONTROL in Europe.
Finally, when it comes to the distribution of flight intent there are limited sharing capabilities between ATC organisations and Aircraft, let alone Aircraft Operators (Ballin et al. [2002]). The lack of long term intent sharing limits the possibilities for aircraft to apply advanced and collaborative arrival tactics and, sometimes even creates (speed up, to wait for longer) scenarios with increased inefficiency when compared to the the undisturbed base case (Verboon et al. [2016]).

Creative Solutions to the previously mentioned drawbacks, alongside the highly sensitive nature of the business value of flights has pushed an effort by Airline Operators to investigate the possibility for Arrival Sequencing and Scheduling within their own control (Baiada and Bowlin [2007]). The scenario of Airline-Based Sequencing and Scheduling being especially promising for airlines operating within a so-called hub-and-spoke model, in which flights and passenger itineraries are highly interconnected or, to operators who "own" a significant share of traffic into a single airport. Airline-Based Arrival Sequencing and Scheduling follows the same base formulation as that from the Air Traffic Control perspective. Leveraging the fact that Airlines have the possibility to instruct flight crews during the full duration of a flight, the airline-based setup focuses on the execution of smaller alterations of a longer time span as a more efficient alternative to the more drastic control actions single ATC sectors can undertake. Airlines, as the sole decision stakeholder in the problem, retain full control over the equity and fairness considerations when controlling their own fleet. The latter at the apparent drawback of only being able to instruct ones' own aircraft and not the other traffic with which the traffic needs to be shared. Finally, Airline-Based Control actions need to conform with the ATC bounds set around deviations from flight plans. For example, within the European Airspace only speed changes larger than 5% or 10 knots of the filed speed, whichever is larger, need to be reported (Guzhva et al. [2014]). Other and potentially larger control actions would be possible, but are subject to ATC compliance (Verboon et al. [2016]).

Several approaches considering airline control have been presented in literature, most notably in the work form Moertl et al. [2009] and Ren and Clarke [2008] during their trials at the Kentucky (USA) based Parcel giant UPS. The UPS trials showed the possibility for not only sequencing and scheduling of traffic, but in the trials performed by Moertl et al. [2009], also the possibility to prioritise certain traffic over other. The UPS case presented an interesting case, as the UPS traffic peak occurs during the dead of night into an airport which owes a majority share of traffic to the UPS cargo operations [12]. Competing/conflicting traffic is thereby limited to a minimum.

In 2010 and 2011, Moertl and Pollack [2011], continued the trials at UPS with a dedicated flight sequencing and scheduling tool called ABESS; which stands for "Airline Based En Route Sequencing and Spacing". Observations from the flight tests conducted during the testing period helped identify bottlenecks in the arrival sequencing process and helped quantify the arrival accuracy (as well as the limitations of this). Even with the limitations in aircraft trajectory accuracy in their 100 minute look ahead window, Moertl and Pollack was able to detect future conflicts and pre-sequence traffic in over three quarters of the all the scenarios.

Commercially, ATH Group Inc, offers a software suite that analyses incoming traffic at large, congested hub-airports and re-times them in conjunction with local ATC such that they arrive "in sequence for an optimal arrival flow."[13]. The tool, for which a patent has been awarded (Baiada and Bowlin [2007]), has been implemented most notably by Delta Airlines, at several airports under which their main hub airport and the busiest airport in the world when it comes to traffic movements; namely Atlanta Hartsfield-Jackson. Savings due to the tool are reported to be in excess of $8 million over a two year time period starting in 2008; comparable numbers have been presented by the ATH group for several hubs/airline partners since then [14].

More recently, Guzhva et al. [2014], validated some of the claims presented in the case of a single-airline Aircraft Arrival Management System (AAMS) based on the aforementioned Atilla tool offered by ATH group; once again aimed at the streamlined arrival of aircraft into a congested hub airport in order to reduce overall delays. Using speed control measures of ±15 knots, Guzhva et al. controlled aircraft belonging to the now defunct US-airways in a 1000nm range around Charlotte Douglas international airport in the USA. During their one year trial, they managed to evaluate both pre- and post-implementation scenarios citing an improvement (reduction) of around 5% in the aircraft dwell time, saving over 150 thousand kilograms of fuel in the optimised period. This all was achieved in spite of a compliance rate of only 6.5% of all arriving traffic.

[12] SDF Lousiville International, cumulative Airport traffic statistics November 2019 `https://4ab57t3vd0rl1ditwf19czdz-wpengine.netdna-ssl.com/wp-content/uploads/2020/01/Aviation-Stats-2019-11.pdf` [accessed on 20-01-2020].
[13] "Flights' flow gets innovative fix", Jeffrey Leib, `http://www.athgrp.com/Innovative.pdf` [Accessed on 19-11-2019].
[14] "NAS Congestion; Part I: Who's to Blame?" Journal of Air Traffic Control Winter 2017 [accessed on 07-01-2020]

2.4. Modelling Methods and Solution Techniques

The following section provides an overview of a variety of strategies for modelling and solving the Aircraft Sequencing and Scheduling Problem (ASP) in literature. The ASP enjoys attention from several fields of research; for example, the ASP is frequently covered as part of efforts from transport sciences and operation research, but also in computer science the topic finds frequent introduction (Bennell et al. [2013]). The diversity in fields covering the problem translates itself into a wide variety of methods being applied to the problem; some being more exotic than others. section 2.4.1 will provide an overview of the modelling techniques and section 2.4.2 treats a set of relevant Solution Algorithms.

2.4.1. Modelling Methods

Arrival Sequencing and Scheduling was first introduced introduced into broad literature by Dear [1976] and Psaraftis [1978]. Psaraftis presents a dynamic programming approach in order to tackle the Sequencing problem within a 50NM radius around the specified airport, where [Dear, 1976] introduces the notion of Constrained Position Shifting (CPS) as an integral design choice in the model. Later work by Carr et al. [1998] and Beasley et al. [2000] specified in more detail the base problem for the Arrival Sequencing and Scheduling Problem (ASP). The formulations presented in these works remain relevant to date and serve as the basis for much of the current work on the topic.

Fast Time Simulations

The fast time simulations in the work of Carr et al. [1998] used a proprietary sequencing and scheduling algorithm developed and presented by Erzberger [1995]. The real time scheduler developed by Erzberger assigned the most favourable runway to each landing aircraft and subsequently minimised the landing time such that delays within the sequence were minimised. The modelling method was chosen in order to facilitate fast computing times, but allowed for further iterations when time and computational burden allowed.

Mixed-Integer Linear Programming

Beasley et al. [2000] and Beasley et al. [2004] present the basis for the Mixed-Integer (Linear) Programming (MILP) approach to tacking the ASP. Formulation of the ASP as a MILP allows for relatively basic swapping and the addition of constraints and objectives without large adaptations of the complete model (Briskorn and Stolletz [2014]). The Aircraft Sequencing and Scheduling Problem is classified as a NP-Hard problem and with this the time (and computational effort) to produce solutions grows (near) exponentially with the size of the problem (Bennell et al. [2013]).

Job Shop Scheduling

Throughout the history of the problem, several authors have identified the similarities the Aircraft Sequencing and Scheduling problem shares with the Job Shop Scheduling problem (Bencheikh et al. [2009]). The Job Shop Scheduling problem itself being a well covered topic within operations research, this similarity allows for a great deal of research to be adapted to the job shop scheduling problem. Bennell et al. [2013] presents an overview of the similarities between the Job shop scheduling problem and the ASP; Each job in the Job Shop problem can be related to the landing of a single flight. The capacity of the system is modelled through the machines with the ready time corresponding to the Estimated Landing Times of aircraft. The time constraints on the landing of aircraft are represented by the starting time and latest completion time of the job. The (aircraft pair dependant) processing time models the required wake-vortex separation between aircraft landing.

An example of the analogy taken from the Job Shop Scheduling can be found in the application of the Alternative Graph formulation in which the base Job Shop Scheduling Problem is expanded to include alternative paths. The alternative Graph representation comprised of a set of fixed and flexible arcs adds the modelling possibility of aircraft to include holding patterns or make use of alternative arrival paths (Samà et al. [2017] and D'Ariano et al. [2010]).

Queueing Model

Similar lines can be drawn between queuing theory and the Aircraft Sequencing and Scheduling Problem as highlighted in the work of Bäuerle et al. [2006]. The special queuing model developed describes incoming aircraft as customers of different types with the separation time acting as the service time for each of the "customers". The incoming aircraft, whose arrival is modelled through a Poisson process, are handled by the service agents representing the runways in the problem.

Traveling Salesman Problem

The finally modelling methodology treated, is yet another which finds its origins in a classic optimisation problem, namely the travelling salesman problem (TSP). The TSP arises when a salesman is tasked with visiting a defined set of destination cities in the most efficient manner, thus minimising the distance travelled between the full set (Furini et al. [2012]). In the similar case with the Aircraft Sequencing Problem, the cities visited in the TSP are analogous with the aircraft to be landed and the intercity distance represents the aircraft pair dependant separation (Bennell et al. [2013]).

Concluding remarks
Throughout the surveyed history of the ASP, the most prevalent method found is the Mixed-Integer Linear Programming (MILP) approach (fig. C.4). The straightforward approach and large flexibility is often found to be a key factor in deciding on the approach. Several other unique methods have been introduced over time of the ASP, not all being as promising as initially expected and with this disappearing into the background after an initial introduction. For many of these modelling techniques, they are implemented in conjunction with MILP formulations in order to compare and contrast the performance and applicability.

Earlier approaches to solving the ASP implemented modelling methods formulated around Constrained Position Shifting (CPS); these methods often relied on CPS to limit the amount of solutions to be evaluated in order to keep the solutions to large scale instances computationally tractable. Additionally, several CPS based modelling methods are implemented in line with real-time applicable solutions.

In more recent times the Alternative Graph Formulation has been a recurring modelling theme within the ASP. The Alternative Graph Formulation is mainly driven by a subset of researchers, whom to date still extend on top of the same core model. The Alternative Graph Formulation has been compared to other modelling methods, but no decisive outcome on preferred outcome has been established to date.

2.4.2. Solution Algorithms

Several approaches exist to provide solutions to the Aircraft Sequencing and Scheduling Problem. Solution performance is not solely defined by the solution outcome itself, but also by the effort and speed with which the results are obtained. Considering the importance of these different aspects of the solution product, researchers have devoted significant effort into developing a variety of algorithms. The following subsection provides a survey of some of the main literature related to the solution algorithms found in the context of the ASP.

The Airport Runway Problem, as which the Aircraft Sequencing and Scheduling Problem is sometimes also referred to, enjoys attention from both the transport science branch, as well as the computer science field. This twofold of attention can be attributed to the fact that for many solutions, the computation time aspect is of great importance to the applicability of the solution; that is, (near) real time solution are in many cases more valuable than those with long(er) computation times. Implementations provided directly to air traffic controller are a case in which the "real-time" computation aspect can become a requirement Murça and Müller [2015].

Dynamic Programming
Dynamic programming, or DP for short, is an optimisation strategy in which previous partial solutions are leveraged in order to reduce computational effort and time for the full solution (Balakrishnan and Chandran [2010]). The iterative nature and sequential form of the Aircraft Sequencing and Scheduling Problem lends itself to improvements through solution architectures as dynamic programming (Bennell et al. [2011]). The first implementation of dynamic programming is found in the work of Psaraftis [1978], where partial solution sequences are merged rather than recomputed in full at every evaluation instance. Balakrishnan and Chandran have presented implementations of dynamic programming incorporating numerous different objective functions, investigated several different constraints (e.g. Constraint Position Shifting (CPS)) and, considered a handful of different scenarios ranging from large traffic simulations of real arrival flows to controlled small scale tests.

Branch-and-Bound
Similarly systematic solution approaches have also been applied to the ASP. Abela et al. [1993] and Beasley et al. [2001] use a Branch-and-Bound solution algorithm to solve their Linear Programming based models. Samà et al. [2013] compares an exact Branch-and-Bound based solution to the currently offered First-Come, First-Served algorithm in which the former presents a more robust solution over changing Estimates of Arrival time, than the latter. Eun et al. [2010] derives a strategy in which they use Langrangian Dual-Decomposition to significantly decrease the computation time when compared to more traditional Branch-and-Bound algorithms. Ernst et al. [1999] use a Branch-and-Bound approach, but further employs a heuristic search algorithm to speed up the evaluation of bounds. Sölveling and Clarke [2014] continues on this track and presents a

two-stage stochastic Branch-and-Bound algorithm in which aircraft are first sequenced and thereafter scheduled in the defined landing queue. Pre-processing regimes are introduced in the work of Ghoniem et al. [2014] in an attempt to decrease the size of the solution space and and increase the solution speed.

Branch-and-Price
Closely related to Branch-and-Bound, the Branch-and-Price algorithm forms a hybrid between the Branch-and-Bound algorithm and a column generation approach in which the problem size is (initially) restricted and expanded strategically. Wen [2005] is first to apply a column generation approach in the context of the ASP, later followed by Ghoniem and Farhadi [2015]. Ghoniem et al. [2015] presents a final investigation on the topic highlighting the computational benefit of the algorithm being upwards of 80% in certain cases when compared to traditional Branch-and-Bound approaches.

Ant Colony Optimisation
Continuing in the realm of heuristic solutions, Ant Colony Optimisation (ACO) is an algorithm in which, as the name implies, the natural solution searching movements of Ants are modelled. Ant Colony optimisation relies on the local search towards optima, after which the local optimum route is marked and prioritised as a starting point for the next solution path iteration (Xu [2017]). Bencheikh et al. [2011] illustrated possible applications on both the single runway, as well as the multi runway Aircraft Sequencing and Scheduling problem.

Genetic Algorithms
Furthermore inspired by nature, genetic algorithms are based around the phenomena of evolution. Solution instances are initially randomly generated and evaluated at each successive instance, after which the fittest solution instances of that generation are randomly crossed into a new population. The heuristic process is subsequently repeated until some forms of convergence are reached or other termination criteria are satisfied (Hu and Chen [2005]). Furthering their previous work, Hu and Di Paolo [2009] apply a genetic algorithm to both the single runway as well as the multi-runway case. In contrast to the random crossovers considered by Hu and Chen, Pinol and Beasley [2006] discusses an algorithm where the new population is a linear combination of the previous generation.

Other
Bencheikh et al. [2009] combines both the Ant Colony approach with a Genetic Algorithm. Using the Ant Colony Optimisation to generate a more favourable initial population, the Genetic Algorithm continues to a final solution. This strategy leverages the fact that the final outcome of the Genetic Algorithm is largely dependant on the initial population input.

Some algorithms do not fall within the aforementioned categories, but have presented feasible and comparable results nevertheless. For example, Erzberger and Itoh [2014] introduces a two stage algorithm optimising both the runway assignment and landing times, as well routing towards the Initial Approach Fix (IAF). Ji et al. [2016] discusses a Sequence Searching and Evaluation (SSE) algorithm after formulating the ASP as a constrained permutation-based problem. Finally, Rodríguez-Díaz et al. [2017] introduces a Simulated Annealing approach for a runway under mixed-mode operations.

Concluding remarks
The most popular Solution Algorithm found in the surveyed literature (fig. C.4 in appendix C) is Branch-And-Bound (or similarily the Branch-and-Price algorithm). The fact that B&B is the most prevalent solution algorithm, can for a part be tied into the large popularity of the MILP Modelling Technique. In addition to explicitly discussed Branch-and-Bound techniques, many of the commercial solver instances rely on the B&B technique to produce feasible (and ultimately optimal) solution instances.

In more recent times, heuristics have taken more of a centre stage as a solution technique. Heuristics are often compared with B&B or other exact methods whose computational time is (far) larger than that of the proposed heuristic. Heuristics, in being a non exact method show several different approaches with varying behaviour. Some are stronger in obtaining a relatively "good" solution in quick times, whilst other build up more slowly, but end up far closer near the end of the specified computational window. In the surveyed papers (fig. C.4), several main streams of heuristics (e.g. Simulated Annealing, Genetic Algorithms, etc.) can be identified, but due to the variance in performance, no one method has gained near universal levels of acceptance.

Both Heuristics as well as exact methods keep returning over time, showing the balance between research efforts into quick and good or slow and optimal solutions. Both remain relevant, but applications of each vary.

3
Conclusion of Literature Review

Air travel has presented strong levels of growth through the past decades and continues to do so in recent years. The growth of current infrastructure comes at ever increasing cost, if growth is even possible. Novel methods are to be introduced to not only close the capacity gap making use of the current state of infrastructure, but also introduce greater efficiency into the system. At the same time, airlines present an ever increasing desire for individual priorities to be taken into account during the the arrival process into airports, thus better serving the customer.

The goal of this project is to develop an Arrival Sequencing and Scheduling algorithm for the airline centric inbound priority case in order to decrease arrival cost. During the project, an algorithm will be developed in order to assist with the determination of control advisories within an airline's fleet and a model will be developed in order to simulate the traffic scenarios into the hub airport.

The paper at hand presents an overview of relevant literature from the field related to the Arrival Sequencing and Scheduling concept and is meant to provide a basis for the project execution which is to succeed this report. Several mathematical representations are presented to model the ASP, alongside a wide variety of solution methodologies. An overview of different goals and implementations is given and a group of variants on problem is discussed. A collection of constraints and scenarios has been touched upon throughout the literature survey and finally the objectives are discussed. Although much research has focused on the Aircraft Sequencing and Scheduling Problem, few efforts have considered the flight and passenger specific impact obtained through Arrival Sequencing and Scheduling. The aforementioned objective is oftentimes lost in optimisation efforts focused on dissipating delays and cost for the full body of incoming aircraft altogether, rather than that which can be obtained through a single aircraft. Tactical inbound flight prioritisation will be studied as a possibility to better serve the airline' and their customers where only limited impact can be had on global flight metrics.

The Thesis project will add to the body of knowledge by developing a Mixed-Integer Linear Programming (MILP) Arrival Sequencing and Scheduling model taking into account several operation considerations. The model will provide an investigation into the possibility for an airline centred approach to Sequencing and Scheduling inbound traffic into a hub style airport. Furthermore, the work will aid in closing the gap on passenger metrics in the Aircraft Sequencing and Scheduling Problem, alongside discussing the impact Inbound Priority Sequencing can have on the business value of flights. Finally, the work will evaluate several objectives and stakeholder interests and, discuss the possibility of a "good compromise" style solution.

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III

Supplemental Thesis Matter

A

Fuel Flow modelling - BADA 3

The following section presents an in-depth look into the modelling approach used to estimate fuel economy and the impact of loitering and/or IPS speed changes implemented in the proposed IPS model. The model is an adaptation from the "Base of Aircraft Data" (or BADA for short) and represents a validated set of aircraft performances under external input conditions [44].

The goal of the BADA model in the context of this paper is to achieve the following relationship;

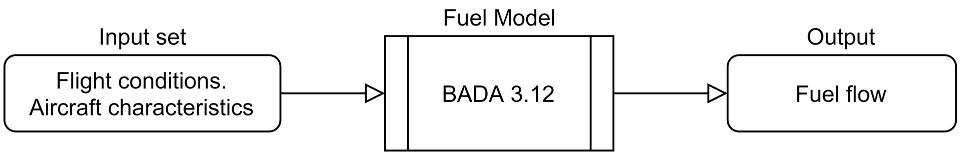

Figure A.1: In/Output relationship BADA modelling

The core of the BADA modelling approach is based on a total energy model equating the rate of work done by forces acting on the aircraft to the rate of increase in potential and kinetic energy. This relationship, depicted in Equation A.1, is simplified by the fact that under cruise and/or loiter conditions the aircraft is assumed to be in steady level flight (i.e. no accelerations and constant height).

$$(Thr - D) \cdot V_{TAS} = mg_0 \frac{dh}{dt} + mV_{TAS} \frac{dV_{TAS}}{dt} \tag{A.1}$$

Where:

Thr :	Thrust acting parallel to the aircraft velocity vector	$[Newtons]$
D :	Aerodynamic drag	$[Newtons]$
Thr :	Aircraft mass	$[kg]$
h :	Geodetic altitude	$[m]$
g_0 :	Gravitational acceleration	$[m/s^2]$
V_{TAS} :	True Airspeed	$[m/s]$
t :	Time	$[s]$
$\frac{d}{dt}$:	Time derivative	$[s^{-1}]$

Applying the steady flight assumption to Equation A.1, simplifies the relationship to Equation A.2c.

$$(Thr - D) \cdot V_{TAS} = mg_0(0) + mV_{TAS}(0) \tag{A.2a}$$

$$(Thr - D) \cdot V_{TAS} = 0 \tag{A.2b}$$

$$Thr = D \tag{A.2c}$$

Drag
Solving for drag can be done through Equation A.3.

$$D = \frac{C_D \cdot \rho \cdot V_{TAS}^2 S}{2} \tag{A.3}$$

Where:

C_D :	Drag coefficient	$[-]$
ρ :	Air density	$[kg/m^3]$
S :	Wing reference area	$[m^2]$

Countering the new unknown introduced in Equation A.3, Equation A.4 further expresses the drag coefficient in terms of the lift coefficient valid for nominal conditions (i.e. all except take-off, approach and landing). The lift coefficient is subsequently related to the aircraft state through Equation A.5c; rewriting the relationship Lift equals Weight, valid in steady flight.

$$C_D = C_{D0} + C_{D2} \cdot (C_L)^2 \tag{A.4}$$

$$Lift = Weight \tag{A.5a}$$

$$C_L \cdot \frac{1}{2} \rho V_{TAS}^2 S = m \cdot g_0 \tag{A.5b}$$

$$C_L = \frac{2 m g_0}{\rho V_{TAS}^2 S} \tag{A.5c}$$

Where:

C_{D0} :	Parasitic drag coefficient	$[-]$
C_{D2} :	Induced drag coefficient	$[-]$

Thrust
Reverting back to Equation A.2c, the drag side of the equation is now expressed in known entities. Next, thrust is rewritten in order to achieve a similar form. We start by expressing the total Thrust force to the thrust specific fuel consumption (η) as seen in Equation A.6a, valid during cruise (like) conditions.

$$Thr = \frac{F^{cr}}{\eta \cdot C_{fcr}} \tag{A.6a}$$

$$\eta = C_{f1} \cdot \left(1 + \frac{V_{TAS}/0.514444}{C_{f2}}\right) \tag{A.6b}$$

Where:

F^{cr} :	Fuel flow, cruise like conditions	$[kg/min]$
η :	thrust specific fuel consumption	$[kg/(min \cdot kN)]$
C^{fcr} :	cruise fuel flow correction coefficient	$[-]$
C_{f1} :	1^{st} thrust specific fuel consumption coefficient	$[kg/(min \cdot kN)]$
C_{f2} :	2^{nd} thrust specific fuel consumption coefficient	$[knots]$

Fuel Flow
Substituting Equations A.3 to A.6b in the original equation for steady level flight (Equation A.2c), we are are left with Equation A.7e. Further simplification of which is determined to be trivial for the modelling application at hand.

$$F^{cr} = C_{fcr} \cdot \eta \cdot Thr \tag{A.7a}$$

$$= C_{fcr} \cdot \eta \cdot D \tag{A.7b}$$

$$= C_{fcr} \cdot \left[C_{f1} \left(1 + \frac{V_{TAS}/0.51444}{C_{f2}} \right) \right] \cdot \frac{C_D \cdot \rho \cdot V_{TAS}^2 S}{2} \tag{A.7c}$$

$$= C_{fcr} \cdot \left[C_{f1} \left(1 + \frac{V_{TAS}/0.51444}{C_{f2}} \right) \right] \cdot \frac{(C_{D0} + C_{D2} \cdot (C_L)^2) \cdot \rho \cdot V_{TAS}^2 S}{2} \tag{A.7d}$$

$$= C_{fcr} \cdot \left[C_{f1} \left(1 + \frac{V_{TAS}/0.51444}{C_{f2}} \right) \right] \cdot \frac{\left(C_{D0} + C_{D2} \cdot \left(\frac{2mg_0}{\rho V_{TAS}^2 S} \right)^2 \right) \cdot \rho \cdot V_{TAS}^2 S}{2} \tag{A.7e}$$

Equation A.7e expresses the Fuel Flow (kg/min) of an aircraft i in terms of a set of aircraft coefficients and characteristics provided by BADA ($C_{f1}, C_{f2}, C_{fcr}, C_{D0}, C_{D2}$ & S) complemented by the flight conditions as the direct function input ($\rho(altitude), V_{TAS}, m$(aircraft mass)). Resulting in the flow diagram depicted in Figure A.1.

B

Schematics IPS Scheme

B.1. Nominal Arrival Process

The following appendix presents a visual guide to the different components of the IPS algorithm. The section is meant as a supplement to the formulation presented in Part I.

The visualisation revolves around a set of 5 aircraft, of which 3 aircraft are part of the controlled group, the blue flights (callsign BF-x). The other two flights, competitor aircraft (callsign CF-x), are not controllable by the IPS scheme. Figure B.2 presents the base case in which no IPS is applied.

Due to the close inter-arrival times between subsequent aircraft arrivals (time between aircraft arrivals on the ETA timeline), ATC intervention (β) is needed to space the aircraft out before they can safely land on the runway. The aircraft are landed in a "First-Come, First-Served" manner according to their broadcasted ETAs (i.e. $ETA_{BF-1} < ETA_{CF-1} < ... < ETA_{BF-3} \Rightarrow ATA_{BF-1} < ATA_{CF-1} < ... < ATA_{BF-3}$). Applying β is not a decision of the IPS algorithm.

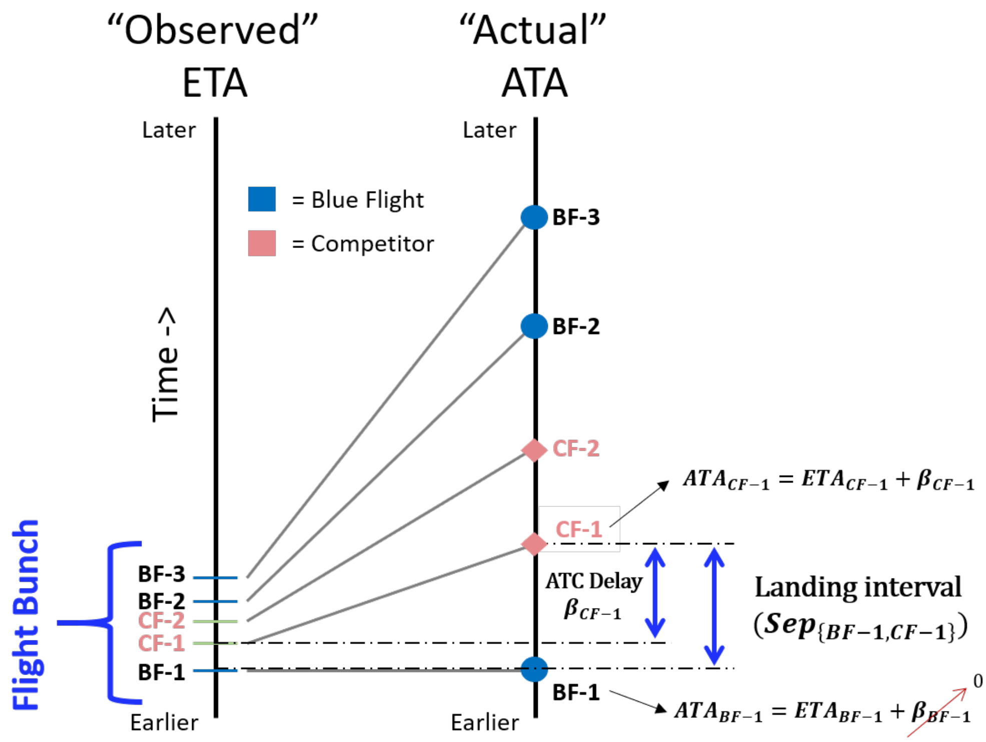

Figure B.1: Schematic overview of a regular unsteerded arrival process.

Some observations for the input case;

1. All aircraft except for 'BF-1' have some form of ATC delay in order to meet the minimal landing interval separation between aircraft.
2. The steepness of the (grey) lines between ETA and ATA visualize the amount of ATC (β) delay allocated to each aircraft.
3. The ATC delay of earlier aircraft (e.g. CF-1) is compounded for each following aircraft (e.g. CF-2 through BF-3).

B.2. IPS Steered Arrival process

The following scenario presents the case if IPS steering would be applied to the case as previously introduced. IPS is used to steer aircraft arrival on the ETA bound and influence the Arrival process. What IPS has done is rearrange the input times by applying some form of IPS steering (γ) and thus rearrange the landing sequence of which the effects are shown in Table B.1 (hence the name of the scheme Inbound Priority **Sequencing**)

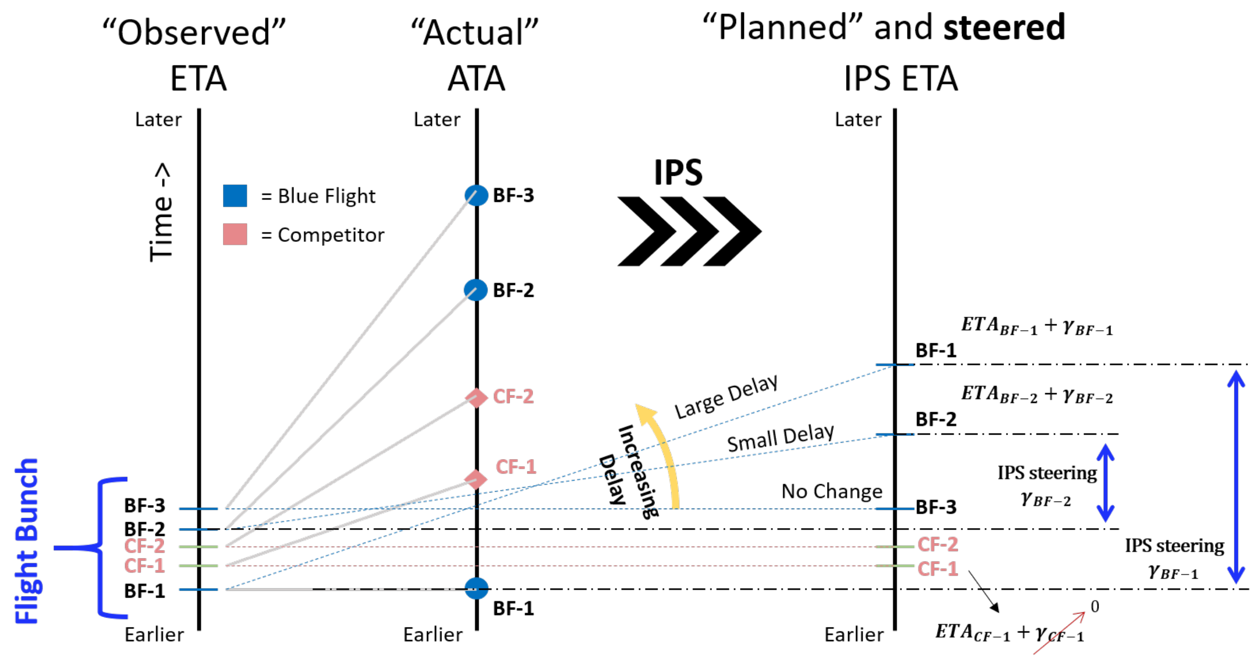

Figure B.2: Adjustments to the arrival sequence due to IPS input.

AC	Position Pre-IPS	Position Post IPS
BF-1	1	5
CF-1	2	1
CF-2	3	2
BF-2	4	4
BF-3	5	3

Table B.1: Position in arrival queue before and after IPS implementation

Some observations from the IPS altered input (IPS ETA);

1. The difference between the "Planned (non IPS) ETA" input and the "Planned and steered (IPS) ETA" is $\gamma_i \quad \forall i \in BF$
2. All competitor aircraft have unaltered times at the ETA bound (i.e. $\gamma = 0 \; \forall i \in CF$).
3. The steepness of dotted lines connecting the "Planned ETA" of each flight to the "planned and steered ETA" corresponds to the amount of IPS steering applied (γ).
4. Both Blue flights as well as Competitor Flights have shifted positions in the arrival queue even though only Blue flights have been addressed by the IPS algorithm.

B.3. IPS ATA calculation

Figure B.3 shows Actual landing times as a result of ATC spacing and the input of the IPS algorithm. In this scenario, all aircraft are impacted, however, for some the impact remains minimal, whilst others have a large effect in their eventual ATA. The rightmost section of the figure depicts a sample calculation of an ATA according to BF-2.

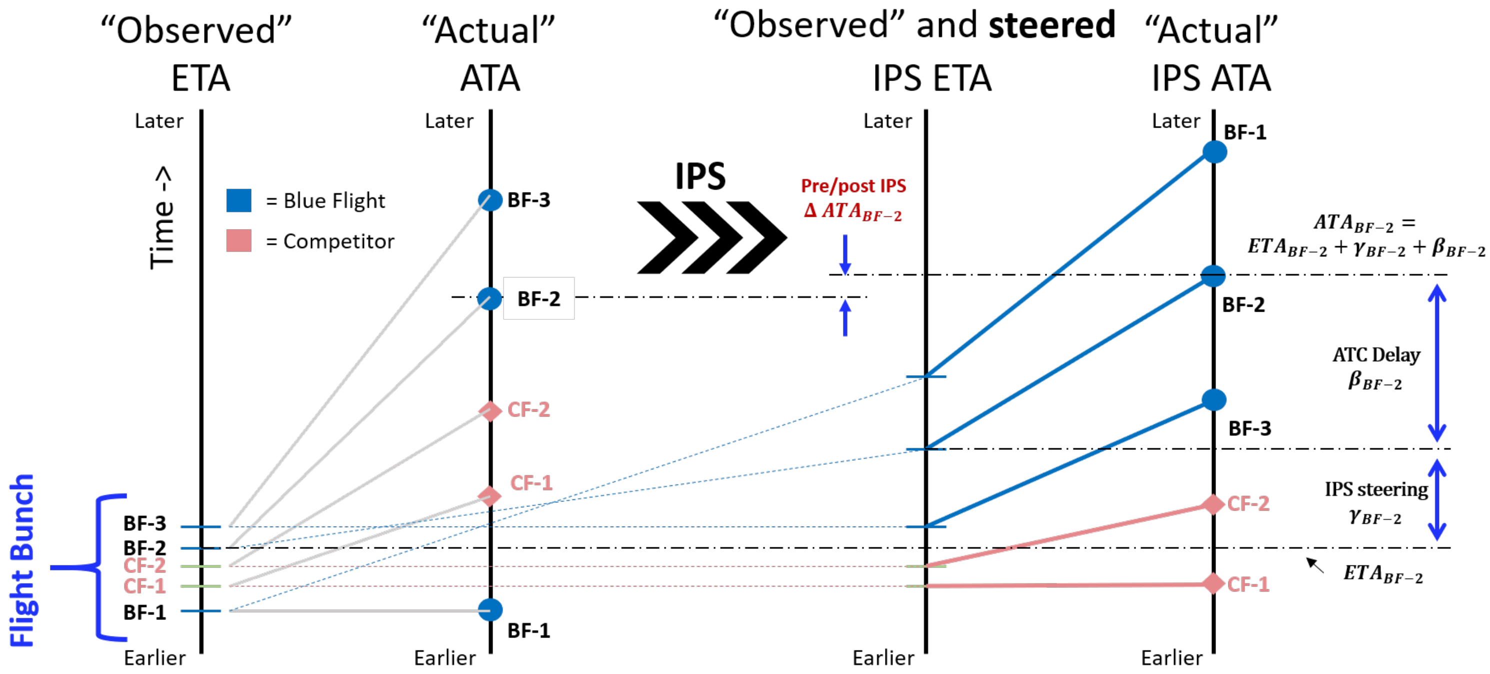

Figure B.3: Schematic overview of the IPS ATA and associated calculation.

Some observations from the IPS altered output (IPS ATA);

1. The ATA of any flight can be calculated through: $ATA_i = ETA_i + \gamma_i + \beta_i$
2. BF-1 and BF-3 have swapped locations in the arrival queue and as a result of FCFS will also touch down (land) in the updated order. (i.e. No overtaking can ever occur between ETA and ATA line pairs)
3. Although BF-2 went from a γ of zero in the ETA/ATA case to a positive, non-zero value in the IPS ETA/IPS ATA case, the net arrival time (ATA) remains largely similar (see Figure B.3). This implies that although γ increased, this was largely compensated by β decreasing.

B.4. IPS Advances and Push-back

The final comparison to make is to review the effects of IPS on the overall outcome of the scenario. Figure B.4 highlights the largest differences between the Pre-IPS and post-IPS arrival time (ATAs). The focus is set on the highest gain/cost examples (BF-1 and BF-3).

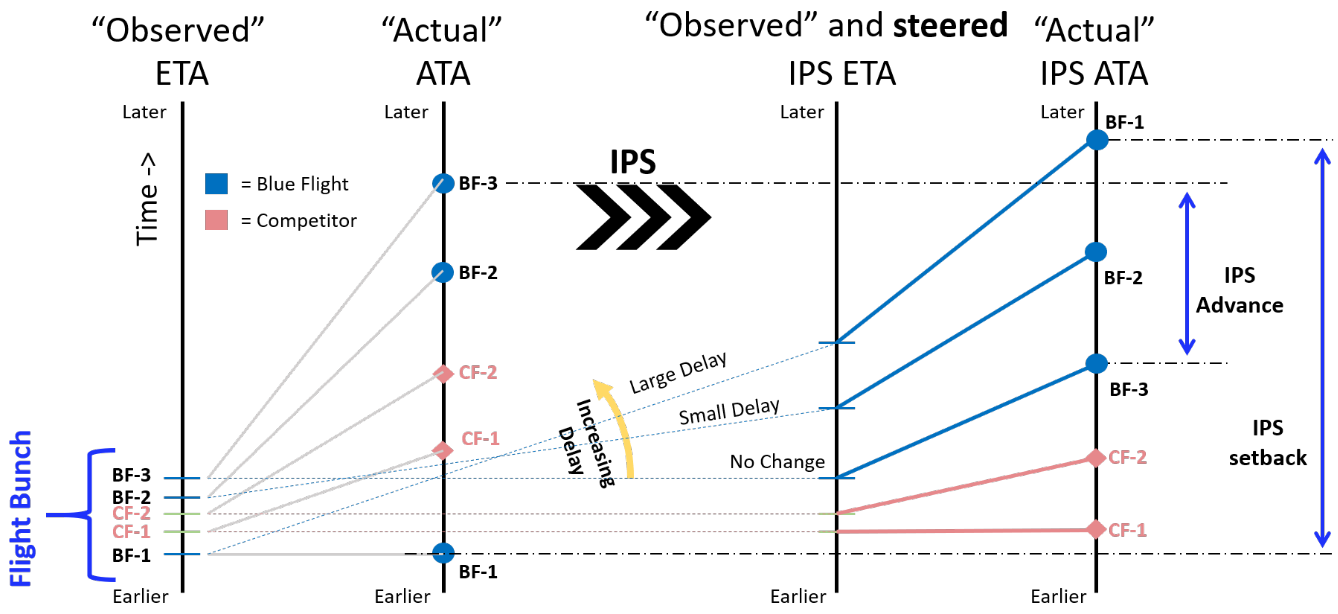

Figure B.4: Schematic overview of the IPS ATA gains and pains.

Some observations from the IPS altered output (IPS ATA);

1. BF-1 has the largest time loss when compared to the un-optimised (pre-IPS) scenario, BF-3 has the largest time gain when the same comparison is made.
2. The advances by BF-3 are not fully offset by the push-back of BF-3.
3. Although not directly altered, both competitor flights (CF-1 as well as CF-2) have an altered arrival time. Due to the constraint placed (Equation **??**), it has been ensured that all competitor flights will always have the same or better Actual Arrival Time (ATA) under the IPS scheme.
4. Although the outcome of these flights has changed, competitor flights are not part of the optimisation goal (see Equation **??**). The optimisation goal only includes Blue Flights, although can be constraint by Competitor flight outcomes.

C

Publication specific breakdown of Aircraft Sequencing and Scheduling Problem features

Publication	Optimization Strategy: Receding Horizon Control (RHC)	Optimization Strategy: Conventional Dynamic Optimisation	Optimization Strategy: One-step-ahead Adjustment	Optimization Strategy: Off-line Optimisation	Information Supply (✶ : Info appears, not altered; ⁎: Information changes over time)
Dear [1976]	-	◆	◆	-	Dynamic (✶)
Psaraftis [1978]	-	◆	-	-	Dynamic (✶)
Carr et al. [1998]	-	-	-	◆	Static
Carr et al. [2000]	-	-	-	◆	Static
Anagnostakis et al. [2001]	-	-	-	◆	Static
Fahle et al. [2003]	-	-	-	◆	Static
Beasley et al. [2004]	-	-	-	◆	Static
Hu and Chen [2005]	◆	-	-	-	Dynamic (⁎)
Balakrishnan and Chandran [2006]	-	-	◆	-	Static
Zhang et al. [2007]	-	-	◆	-	Static
Soomer and Koole [2008]	-	-	-	◆	Static
Soomer and Franx [2008]	-	-	-	◆	Static
Balakrishnan and Chandran [2010]	-	◆	-	-	Dynamic (✶)
D'Ariano et al. [2010]	-	-	-	◆	Static
Eun et al. [2010]	-	-	-	◆	Static
Salehipour et al. [2013]	-	-	-	◆	Static
Ghoniem et al. [2014]	-	-	-	◆	Static
Samà et al. [2014]	◆	-	-	-	Dynamic (✶)
Furini et al. [2015]	◆	-	-	-	Dynamic (✶)
Lieder et al. [2015]	◆	-	-	◆	Static / Dynamic (✶)
Murça and Müller [2015]	-	◆	-	-	Dynamic (✶)
Delgado et al. [2016]	-	◆	-	-	Dynamic (⁎)
Bennell et al. [2017]	◆	-	-	-	Static / Dynamic (✶)
Hong et al. [2017]	-	-	-	◆	Static
Montlaur and Delgado [2017]	-	◆	-	-	Dynamic (✶)
Rodríguez-Díaz et al. [2017]	-	-	-	◆	Static
Samà et al. [2017]	-	-	-	◆	Static
Santos et al. [2017]	◆	-	-	-	Dynamic (✶)
Zhang et al. [2020]	-	-	-	◆	Static

Figure C.1: Overview of Time Discretisation Schemes used in Publications on the Aircraft Sequencing and Scheduling Problem.

Publication	Time based				Cost Based			Miscellaneous	
	Min. Makespan	Deviation from Target Time	Arrival. Delay vs. Departure Delay	Min. Max. Delay	Passenger ✶ : Currency ✲: Time	Fuel	Env.	Priority ◆: Various ✶ : Queue #	Other ✶ : Trade-Off ✲: Oper. Cost
Dear [1976]	◆	-	-	-	-	-	-	-	-
Carr et al. [1998]	-	-	-	-	-	-	-	✶	-
Carr et al. [2000]	-	-	-	-	✶	-	-	✶	-
Anagnostakis et al. [2001]	◆	◆	◆	-	-	-	◆	-	-
Fahle et al. [2003]	-	✳	-	-	-	-	-	-	-
Beasley et al. [2004]	◆	✳	-	-	-	-	-	-	-
Hu and Chen [2005]	◆	-	◆	-	-	-	-	◆	-
Balakrishnan and Chandran [2006]	◆	-	-	◆	-	-	-	-	-
Zhang et al. [2007]	◆	◆	◆	◆	-	-	-	◆	✲
Soomer and Koole [2008]	◆	✳	-	-	-	-	-	-	✲
Soomer and Franx [2008]	-	◆	-	-	✶	-	-	◆	✲
Balakrishnan and Chandran [2010]	◆	-	-	◆	-	-	-	-	-
D'Ariano et al. [2010]	-	-	-	-	-	-	-	-	-
Eun et al. [2010]	◆	-	-	-	-	-	-	-	-
Mesgarpour et al. [2010]	-	-	-	-	-	-	-	-	-
Salehipour et al. [2013]	◆	◆	-	-	-	-	-	-	-
Ghoniem et al. [2014]	◆	-	-	-	-	-	-	◆	-
Samà et al. [2014]	◆	-	-	◆	-	-	- / ◆	-	-
Furini et al. [2015]	-	✳	◆	-	-	-	-	◆	-
Lieder et al. [2015]	◆	-	-	-	-	-	◆	-	-
Murça and Müller [2015]	◆	◆	-	-	-	-	-	-	-
Delgado et al. [2016]	-	-	-	-	✶ / ✲	◆	◆	-	-
Bennell et al. [2017]	◆	◆	◆	◆	-	◆	- / ◆	-	-
Hong et al. [2017]	◆	-	-	-	-	-	-	-	✶
Montlaur and Delgado [2017]	-	◆	-	◆	✲	◆	-	-	Reactionary Delays
Rodríguez-Díaz et al. [2017]	◆	(Late only)	-	-	-	-	-	-	-
Samà et al. [2017]	◆	-	-	◆	-	-	-	-	✶
Santos et al. [2017]	-	-	◆	-	✶	◆	-	-	-
Jacquillat [2018]	◆	◆	-	◆	✲	-	-	◆	✶
Zhang et al. [2020]	◆	◆	◆	◆	-	◆	-	-	✶ / ✲

Figure C.2: Overview of Objectives used in Publications on the Aircraft Sequencing and Scheduling Problem.

Publication	Wake-Vortex Separation	Bounded Arrival Time ✶ : Earliest only	CPS ◆: Position ✶ : Time-based	Discrete Time ◆: Route-Segments ✶ : Arrival Slots	MTT	Fairness and Equity ◆: Multiple Impl. ✶: Delay Time. ✲: Precedence Constraints	Other ✶: Route Overtaking
Dear [1976]	◆	-	◆	-	-	◆	-
Carr et al. [1998]	◆	-	-	-	-	✶	-
Carr et al. [2000]	◆	-	-	-	-	-	-
Anagnostakis et al. [2001]	◆	◆	-	-	-	◆	-
Fahle et al. [2003]	◆	◆	-	-	-	-	-
Beasley et al. [2004]	◆	-	-	-	-	-	-
Hu and Chen [2005]	◆	-	◆	-	-	-	-
Balakrishnan and Chandran [2006]	◆	◆	◆	◆	-	✲	✶
Zhang et al. [2007]	◆	◆	-	-	-	-	✶
Soomer and Koole [2008]	◆	◆	-	-	-	◆	-
Soomer and Franx [2008]	◆	◆	-	-	-	◆	-
Balakrishnan and Chandran [2010]	◆	◆	◆	-	-	✲	-
D'Ariano et al. [2010]	◆	◆	◆	◆	-	-	-
Eun et al. [2010]	◆	-	◆	◆	-	-	✶
Mesgarpour et al. [2010]	◆	◆	✶ / ◆	-	-	✲	-
Salehipour et al. [2013]	◆	◆	-	-	-	-	-
Ghoniem et al. [2014]	◆	◆	-	-	-	-	Fixed Sequence
Samà et al. [2014]	◆	◆	-	◆	-	-	-
Furini et al. [2015]	◆	◆	-	-	-	-	-
Lieder et al. [2015]	◆	◆	-	-	-	-	-
Murça and Müller [2015]	◆	◆	-	◆	-	-	-
Delgado et al. [2016]	◆	-	-	✶	◆	-	-
Bennell et al. [2017]	◆	◆	-	-	-	-	-
Hong et al. [2017]	◆	◆	◆	-	-	-	✶
Montlaur and Delgado [2017]	◆	-	-	-	◆	-	✶
Rodríguez-Díaz et al. [2017]	◆	✶	◆	-	-	-	-
Samà et al. [2017]	◆	✶	-	-	◆	-	-
Santos et al. [2017]	◆	◆	-	-	◆	-	Taxiway / Gate
Jacquillat [2018]	◆	◆	-	-	-	◆	-
Zhang et al. [2020]	◆	◆	-	-	-	-	-

CPS: Constrained Position Shifting, MTT: Minimum Turnaround Time

Figure C.3: Overview of Constraints used in Publications on the Aircraft Sequencing and Scheduling Problem.

Publication	Simulation (✶: Fast-Time)	MILP	JSSP	TSP	Other	B&B	DP	GA	Other
	Modelling Method					Solution Technique			
Dear [1976]	◆	-	-	-	CPS Based	-	◆	-	-
Psaraftis [1978]	-	-	(◆)	◆	CPS Based	-	◆	-	-
Carr et al. [1998]	✶	-	-	-	-	-	-	-	Real-Time Scheduler
Carr et al. [2000]	✶	-	-	-	-	-	-	-	Real-Time Scheduler
Anagnostakis et al. [2001]	-	-	-	-	◆	◆	-	-	-
Fahle et al. [2003]	-	◆	-	-	Satisfiability Prob.	-	-	-	Hill-Climbing / Simulated Annealing
Beasley et al. [2004]	-	◆	-	-	Displacement Prob.	-	-	◆	-
Hu and Chen [2005]	-	-	(◆)	◆	◆	-	-	◆	-
Balakrishnan and Chandran [2006]	-	-	-	-	◆ / CPS Based	-	◆	-	-
Soomer and Koole [2008]	-	◆	-	-	-	-	-	-	Local Search
Soomer and Franx [2008]	-	◆	-	-	-	-	-	-	Local Search
Balakrishnan and Chandran [2010]	◆	-	-	-	CPS Based	-	◆	-	-
D'Ariano et al. [2010]	-	-	◆	-	Alternative Graph	◆	-	-	Job/Arc Greedy Heuristic
Eun et al. [2010]	-	◆	-	-	-	◆	-	-	-
Salehipour et al. [2013]	-	◆	-	-	-	◆	-	-	Simulated Annealing
Ghoniem et al. [2014]	-	-	-	◆	-	-	-	-	Threshold-based Heuristic
Samà et al. [2014]	-	◆	-	-	Alternative Graph	◆	-	-	Tabu Search
Furini et al. [2015]	-	◆	-	-	-	◆	-	-	Tabu Search
Lieder et al. [2015]	-	◆	-	-	-	-	◆	-	Built In solver LP package
Murça and Müller [2015]	-	◆	-	-	Alternative Graph	-	-	-	Built In solver LP package
Delgado et al. [2016]	◆	-	-	-	Agent Based	-	-	-	-
Bennell et al. [2017]	-	-	-	-	◆	-	◆	-	Simulated Annealing Iterated Descent
Hong et al. [2017]	◆	◆	-	-	CPS Based	-	-	-	Custom algorithm / Built In solver LP package
Rodríguez-Díaz et al. [2017]	◆	-	-	-	-	-	-	◆	Simulated Annealing
Samà et al. [2017]	-	◆	◆	-	Alternative Graph	✶	-	-	-
Santos et al. [2017]	-	◆	-	-	-	-	-	-	Built In solver LP package
Zhang et al. [2020]	-	-	◆	-	-	-	-	-	Imperialist Competitive Algorithm Built In solver LP package

MILP: Mixed-Integer Linear Programming, JSSP: Job-Shop Scheduling Problem, TSP: Traveling Salesman Problem,
B&B: Branch-and-Bound, DP: Dynamic Programming, GA: Genetic Algorithm

Figure C.4: Overview of Modelling- and Solution Techniques used in Publications on the Aircraft Sequencing and Scheduling Problem.