Arrival Time Management in Real Weather Conditions

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Abstract—**Dynamic in-flight trajectory optimization provides airports, air traffic control, and airlines with significant operational flexibility. This concept offers various optimization opportunities to meet the sustainability requirements of air transport, enhancing economic and ecological efficiency, and ensuring safety. One promising approach involves regulating aircraft arrival rates to balance the demand-capacity in the airport's approach sector.**

When extending this approach, particularly for long-haul flights, arrival times are controlled hours before landing. However, the effectiveness of these control measures and their impact on arrival times depend heavily on flight performance and the unpredictable influence of weather conditions.

In our study, we analyzed more than 5,000 realistic and physically possible arrival times of 23 long-haul flights destined for Singapore Changi Airport extracted during a peak hour. Each flight is manipulated in speed, route, and starting time of manipulation and is modeled in different weather scenarios. Therewith, we extracted an optimal time frame for a significant speed adjustment and acceptable weather-induced uncertainty.

As weather-induced uncertainty in arrival times grows over time, we recommend implementing speed or route control measures approximately four hours in advance. For control periods exceeding five hours, the uncertainty stemming from poorly predictable weather often outweighs the impact of speed adjustments on arrival times. Consequently, control measures over such extended durations are advisable only when assuming homogeneous weather conditions.

Keywords—**Arrival Time Management, Air Traffic Flow Management, Aircraft Trajectory Optimization, Flight Performance, Weather Impact**

I. Introduction

In the framework of an efficient Air Traffic Management (ATM), there is a conflict of interest between the objectives of single Airspace Users (AUs) and the objectives of ATM as a system. Specifically, in the vicinity of airports, trajectories resembling the aircraft AUs aim, strike a balance between punctuality, fuel efficiency, and flexibility. In addition to facilitating that AU's trajectory as much as possible, the Air Navigation Service Provider (ANSP) at the arrival airport also aims to expedite the trajectories of the other AUs. The latter calls for making the best possible use of the capacity for departing and arriving aircraft.

For this reason, at large airports, ANSPs aim to balance the demand with the available landing capacity by scheduling aircraft arrival times by short-term adjustments of inbound trajectories [1]. Therefore, the Air Traffic Flow Management (ATFM) has been established for a proper demand-capacity balancing at both local and global levels [2], [3]. One instrument of ATFM in the airport vicinity is the Arrival Manager (AMAN) [4]. AMAN maximizes all AUs' arrival trajectories within the confines of the arrival airport [5]. From an AU's perspective, however, deviations from these optimal trajectories should be minimal. For example, minor speed adjustments or path adaptions over a long flight segment induce less inefficiency than significant short-term trajectory changes [6].

The International Civil Aviation Organization (ICAO) specifies two components of aircraft arrival management: flow-based controls and time-based tactical controls [7]. The take-off time of arrivals at their departure airports is estimated in flow-based control methods to balance traffic needs and airspace or airport capacity per time window. By managing time-spacing among incoming aircraft, an AMAN manages synchronized arrival traffic [8].

For the balance between traffic demand and airport capacity, trajectories should be controlled as early as possible to achieve a large impact on Expected Time of Arrival (ETA) with small changes in fuel flow. Therefore, the aircraft sequencing should be shifted from the Terminal Manoeuvring Area (TMA) to the neighboring en-route airspace. For example, an extended AMAN controls aircraft arrivals within a radius of 500 NM around the airport [9]. In 2018, the concept of Long-Range Air Traffic Flow Management (LR-ATFM) was assessed within the Asia-Pacific (APAC) region. This assessment aimed to enhance demand capacity management by extending the current time horizon, thus supplementing existing regional ATFM initiatives.

However, for efficient, extended Arrival Management, accurate forecasting of the ETA at the airport and of the ANSPs capacity are engaged to alter the trajectories at certain horizons. In the framework of the so-called LR-ATFM concept, ATM-specific innovations as well as advancements in communication technology have been invented to influence aircraft trajectory at considerably longer time scales [10].

Although many entities are busy predicting and planning the arrival and departure management as best they can, the actual operations sometimes differ from what was intended. For instance, system-inherent uncertainties (such as reactionary delays), external factor disturbances (such as the weather at the airport) or the effects of changing wind conditions during the flight, flight interruptions (such as cancellations), the use of alternative airports, or airspace activities (such as decreased sector capacity or temporarily activated restricted areas) challenge the airport operations [6].

Weather-induced uncertainties in the prediction of the ETA increase with increasing time horizon, resulting in a maximum Remaining Flight Time (RFT) for efficient trajectory control. On the other hand, the earlier (and thus longer) speed adjustments are executed, the more efficient they are. This conflict gives rise to the following research questions for this paper:

1) At what RFT is the influence of a speed adjustment on ETA greater than the influence of weather?
2) Up to what RFT is the influence of speed adjustment on ETA still significant?

To answer the questions, 23 long-haul flights F_i arriving at Singapore Changi Airport (WSSS) on a busy day in a peak period were simulated in five distinct weather scenarios and manipulated at various time points with different speed settings. From the bunch of resulting ETA at the 170 NM radius around WSSS, different weather-induced speed-induced effects on the ETA of flight with specific tracks could be extracted. Note, in this study, ETA always refers to the estimated time of arrival at the 170 NM radius around WSSS.

II. State of the Art

A. Air Traffic Flow Management

In Europe, the implementation of ATFM activities is overseen by a centralized network manager under EUROCONTROL's jurisdiction [11]. A critical aspect of Air Traffic Control (ATC) in Europe involves the allocation of departure slots and the determination of Calculated Take Off Time (CTOT) values [11], [12]. In contrast, traffic management strategies like ground delay programs and rerouting are predominantly utilized in the United States [13], [14]. Meanwhile, in Asia, regional associations of Air Traffic Flow Management Unit (ATFMU)s have been established to enhance traffic flow coordination. Examples include the Multi-Nodal ATFM concept in the APAC region [15] and the Northeast Asia Regional ATFM Harmonization Group (NARAHG) [16].

However, efficiently managing the increasing traffic volumes necessitates the development and implementation of advanced ATC concepts. For example, a consequent implementation of Trajectory-Based Operations (TBO)s [6], [17], [18], a dynamic Demand Capacity Balancing (DCB) [19], and enhanced data exchange among responsible authorities [20].

B. Aircraft Performance Calculation

When considering an aircraft's six degrees of freedom, an aircraft motion model needs to address at least six nonlinear first-order differential equations of motion. In this context, it's essential to account for acceleration forces at each discrete time step and calculate all the forces acting on the aircraft. This is a formidable challenge that not many studies are willing to tackle. For example, the impact of atmospheric conditions (particularly, wind speed, wind direction, and temperature) on the integration of the equations of motion, is often neglected. The General Aircraft Modelling Environment (GAME), developed by Eurocontrol, is a kinematic-only performance model [21] that can be used for air transport research but not for optimization purposes.

Commercial performance data and tools of aircraft manufacturers (e.g., Performance Engineering Program (PEP) [22] are probably the most efficient aircraft performance calculation methods, however not publicly available. Additionally, third-party commercial tools for modeling aircraft performance, (e.g., the PIANO software [23]) can rarely be expanded or supplemented. Often not all parameters are made transparent.

A noteworthy development in this area is the open-source flight performance model called OpenAP, created by Sun et al. [24]. OpenAP is designed for jet engine aircraft types and derives lift-to-drag ratios and thrust values from historical Automatic Dependent Surveillance - Broadcast (ADS-B) data and a few Flight Operational DAta (FODA) sets. This open-source approach offers a valuable alternative to commercial products and provides the flexibility for further development and modular integration into other models. Specifically, tools for trajectory optimization that calculate target functions for controlled variables can leverage the thrust and drag module of OpenAP. However, a missing engine model and a missing consideration of stability and controllability (i.e., the flight attitude) reduce the degrees of freedom for optimizing aircraft trajectories with this model

The Sophisticated Aircraft Performance Model (SOPHIA) tool has been developed at TU Dresden and is solving the equations of motion every second, which involves calculating ground and airspeeds, as well as distances while taking dynamic weather information into account. SOPHIA primarily relies on fundamental physical principles and incorporates all relevant acceleration forces. The methods it employs are detailed in [25]. In some details, SOPHIA relies on the open-source flight performance model OpenAP [24] for coefficients that cannot be determined without aircraft-specific aerodynamic parameters, such as the drag polar and the maximum attainable thrust concerning altitude and speed. In the case of modeling a historical trajectory, each second, SOPHIA compares the current speed and altitude with the target speed and altitude and adjusts the lift coefficient to achieve the historical target values in the subsequent time step [26]. Missing information is controlled with a Proportional–Integral–Derivative (PID) controller [27]. When optimizing a trajectory, SOPHIA computes target values for speed and altitude based on the optimization target function (analytical or numerical) [26].

C. Extended AMAN Operations

Theoretical investigations in an extended AMAN operation within a radius of 500 NM around the airport, yield a transfer of delay of up to 20 % from the TMA to the cruising phase of aircraft through speed adjustments [9], [28]–[30]. However, those theoretical studies investigating the potential of arrival time prediction have not sufficiently considered flight performance (i.e. impact on fuel flow) or meteorological data (i.e. changes in wind speed and wind direction). In contrast, these studies have typically supplied the optimizer with probability density functions for actual arrival times. Consequently, the scope for ground speed adjustments may be constrained, as factors such as wind speed, wind direction, maximum Mach number, and stall speed need to be considered. Additionally, these studies have often overlooked efficiency concerns, including fuel efficiency.

Rosenow et al. [6] provided insights into the efficiency of LR-ATFM, taking into account the impact of flight performance for each long-haul flight. Furthermore, potential alternative routes from historical ADS-B data have been extracted and the most fuel-efficient scenario among all available options has been selected. Consequently, discrete arrival times for 26 long-haul flights arriving at WSSS airport within a single peak hour have been considered. Thereby, a maximum capacity constraint of 20 flight movements (including short-haul, medium-haul, and long-haul flights) occurring simultaneously in the approach sector has been allowed. For the first time, [6] considered only realistic ETA from modeled flights in real weather conditions. However, the impact of the weather conditions and the uncertainty due to unpredictable changes in weather conditions over long time periods was not considered. Hence, the robustness of the ETA could not be quantified. This research gap is going to be closed in the current study.

III. Methodology

A. Data preparation and Scenario Setup

To analyze the impact of weather, time, and amount of speed adjustments on the ETA for an efficient LR-ATFM, the real flight should be modeled. Therefore, a data set containing ADS-B information from flights to WSSS during the summer flight schedule period between April and September 2019 is used. In order to reduce the data points for each recorded flight, a Ramer-Douglas-Peucker (RDP) algorithm is employed [31]. The RDP algorithm is applied with a tolerance parameter of $\epsilon = 0.5$ [6]. This helps in simplifying the flight data while retaining essential information for subsequent analysis and modeling.

In this study, we focus on extended AMAN operations only active in the cruising phase of a flight (as defined in the LR-ATFM concept). Therefore, the position of the Top of Descent (TOD) as the transition point between the en-route and descent phases is considered and regarded as the latest possible time T_l where speed adjustment or an alternative route is possible. Hence, we define an approach sector (red circle in Figure 2) the boundary of which the flights reach TOD on average. Therefore, for each individual flight F_i, a mean TOD is calculated using historical data [6]. On average, the calculated TOD was 170 NM before WSSS. The most frequently observed flight time in the descent phase (i.e., within the approach sector) is around 35 minutes, although higher flight times are possible for holdings or inefficient arrival routes [6]. Hence, the ETA at 170 NM was modeled and analyzed.

Finally, a set of 23 long-haul flights F_i arriving within a peak period (between 3.00 p.m. and 6.00 p.m.) on a busy weekday (5th April 2019) at WSSS has been extracted from the historical data. The scenario has been chosen because, in addition to the long-haul flights, a high number of short and medium-haul arrivals occur at WSSS. Therewith, we ensure a high base utilization in the approach sector [6].

Not only do speed adjustments lead to a different ETAs, but also the choice of a different lateral route at a specific T_l. For three T_l, alternative routes have been extracted from the historical data (as described in detail in [6]) and considered in the analyses of ETA.

B. Flight performance modeling with speed adjustments considering different weather conditions

For investigating the trade-off between weather-induced uncertainty on the ETA and the speed-induced possibility for adjusting the ETA of an individual flight, 23 long-haul flights F_i (described by Flight ID, aircraft type, origin, Scheduled Time of Departure (STD), speed profile, altitude profile, and lateral route) to WSSS were modeled in five different weather scenarios k:

$$W_k, \text{for } k \in \{r, 1, .., 4\}. \tag{1}$$

One of those weather scenarios has been defined as a reference weather scenario W_r because it represents a typical weather condition for Singapore. Other weather scenarios $W_{1...4}$ represent a mixture of typical times of the day and year.

For the simulation of trajectory controls, each flight is subjected to seven different speed adjustments in terms of factors V_j of Mach number a [-]

$$\Delta V_j, \text{for } j \in \{0.95, 0.99, 1.01, 1.02, 1.03, 1.04, 1.05\} \tag{2}$$

According to ICAO [32] speed changes up to Mach 0.02 were performed in the field tests, performed between Singapore and Auckland in 2017. In this theoretical case study, extreme speed changes up to plus/minus $5\,\%$ have been considered to find maximal deviations in ETA, although the changes would have to be approved by the ATC. Additionally, a scenario V_r represents each flight with a typical aircraft-specific cruising speed. Thereby, aircraft type-specific and weather-specific flight performance limits are considered. These limits refer on the one hand to the stall speed v_{stall}, which represents an equilibrium in the vertical direction for a given mass, and on the other hand to the Mach_{max} which is tabulated in aircraft characteristics (see also Figure 1). Each speed adjustment has started at seven different points in time T_l with $\Delta T_l = 30$ min

$$T_l, \text{for } l \in \{11\text{a.m.}, 11.30\text{a.m.}, ..., 2\text{p.m.}\}. \tag{3}$$

Furthermore, at certain times T_l, alternative routes might be possible, again manipulating the arrival time. For this reason, alternative historical routes R_m were extracted and assigned to corresponding times T_l and RFT. In scenarios $S_{Ti,Rm}$, the flight performance along the alternative routes was modeled and additionally subjected to all speed adjustments.

Following the definitions in 1 to 3, the ETA of each individual flight depends on

$$\mathrm{ETA}(F_i, W_k, V_j, T_l, R_m) \tag{4}$$

and

$$\mathrm{ETA}(F_i, W_r, V_r) \tag{5}$$

represents the reference scenario in a reference weather without speed adjustments. The expected dependencies and the variables on ETA are also shown in the fishbone diagram 1.

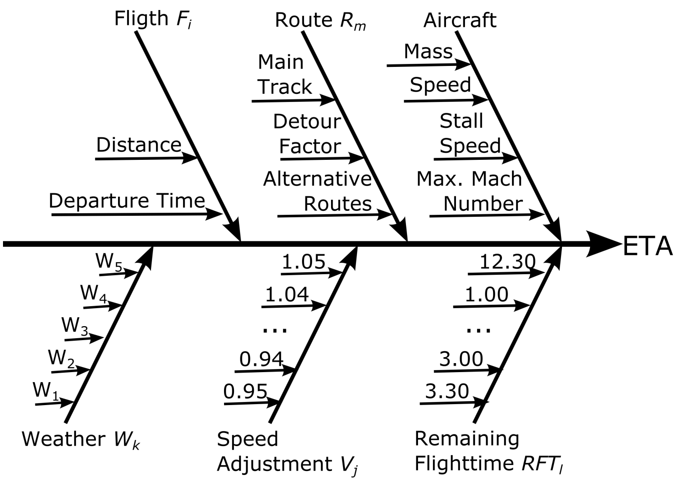

Figure 1. Expected dependencies on the ETA approximately 170 NM before arriving in WSSS.

C. Aircraft Performance Model SOPHIA

The aircraft performance model SOPHIA [26], [33], [34] is used for calculating ETA and the impact of weather, speed, and route on the arrival time manipulation. Note, that calculating the flight performance of each manipulation ensures that only physically possible trajectories are considered in the optimization of the arrival time. SOPHIA, validated for 16 different aircraft types, calculates and optimizes physically feasible 4-D aircraft trajectories [33], [34]. Unlike other aircraft performance models, SOPHIA employs an analytical solution for the equations of motion, with the exception of the drag polar, which is approximated using the OpenAP model [24].

What sets SOPHIA apart is its incorporation of acceleration and inertia forces, managed by a PID controller on a per-time-step basis, controlling true airspeed and utilizing the lift coefficient as a regulatory variable. The controller's parameters are tailored to specific aircraft types. The behavior of different aircraft types, as modeled by SOPHIA, has been demonstrated in previous work [25], [35].

For modeling real flight performance SOPHIA utilizes e.g. ADS-B data to access crucial parameters like cruising altitude and true airspeed. To adjust the trajectory, target functions for speed, path, and altitude are employed, which are then controlled by a PID controller to achieve the desired speed and altitude. It's important to note that flight performance modeling is highly sensitive to aircraft mass, a parameter not included in ADS-B data. To address this, we consider three major components: the Operational Empty Weight (OEM), payload calculations (using an 83 % seat load factor with passenger and luggage weights), and fuel load estimation (including contingency and holding fuel). These components ensure comprehensive mass considerations for accurate modeling [34].

SOPHIA contains a combustion chamber model to quantify the emissions as products of complete combustion (e.g. CO_2, H_2O and SO_2) and incomplete combustion (e.g. NO_x, HC, CO and black carbon) and to quantify the fuel burn.

For each flight F_i, each T_l is assigned to one of 14 RFT_m classes (see Figure2). Finally, for each RFT_m class, the effect of the speed adjustment on the ETA, compared to ETA in the reference scenario (V_r, W_r)

$$\mathrm{ETA}(F_i, V_r, W_r) - \mathrm{ETA}(F_i, V_j, W_k) \tag{6}$$

is calculated and statistically evaluated.

For research question 1, the scatter of the results due to different weather scenarios

$$\langle \mathrm{ETA}(F_i, V_j, W_k) \rangle_{W_k} \text{for } V_j = \text{const.} \tag{7}$$

was investigated.

For research question 2, the results were averaged over all weather scenarios W_k

$$\langle \mathrm{ETA}(F_i, V_j) \rangle_{W_k} \tag{8}$$

and analysed for each RFT_m. Here, speed adjustments were assigned as "significant" using the ICAO definition of at least one minute per flight hour [32].

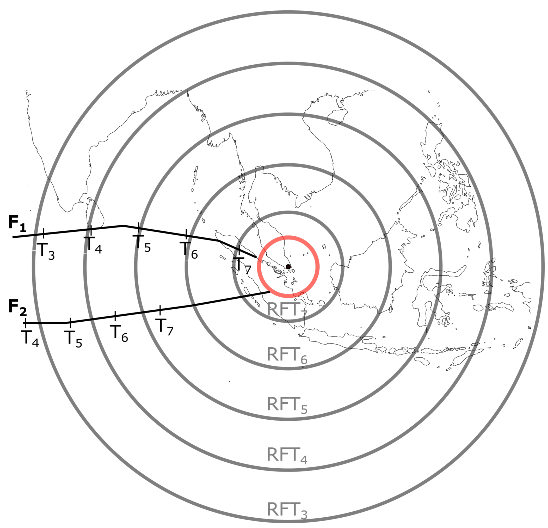

Figure 2. Example of two flights F_1 and F_2 (black lines) with destination WSSS (black dot), which are assigned to different classes of remaining flight time RFT_m (grey circles) due to their distance to WSSS at times T_l (black ticks). Furthermore, the WSSS approach sector is indicated by a red circle (ETA).

Figure 3 gives an impression on the modeled long-haul flights F_i to WSSS in the reference weather scenario. The flights cover different distances (with a different potential for adjusting the ETA) and two different main tracks (westbound and eastbound) to WSSS (black and blue).

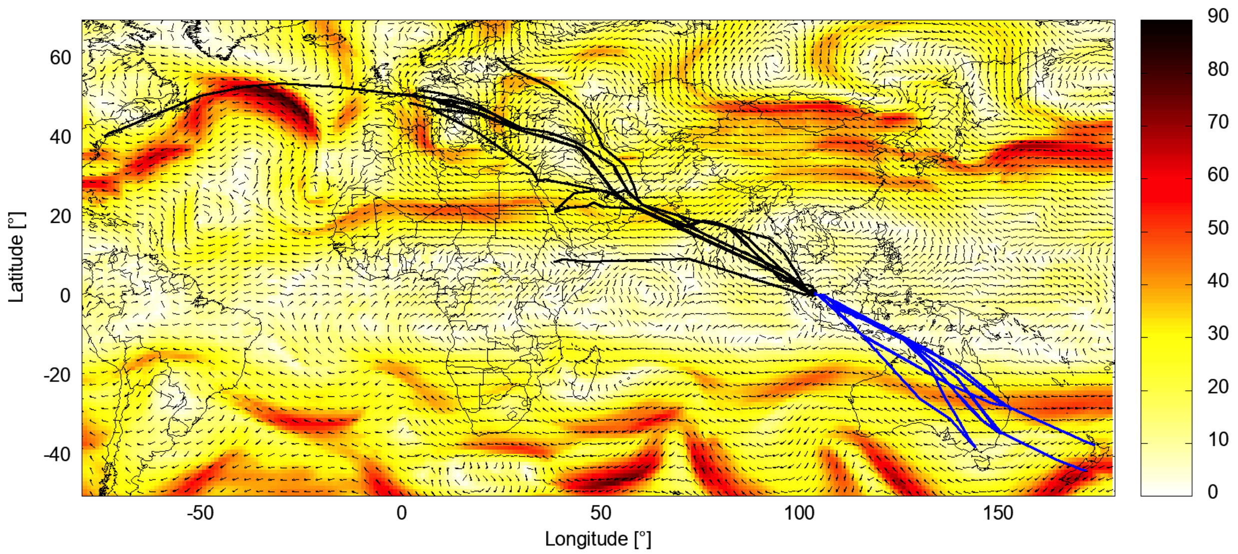

Figure 3. Scenario of investigation. 23 long-haul flights to WSSS covering different distances and tracks, westbound (blue) and eastbound (black).

D. Route Adjustments

The activities of an extended AMAN can include more than speed adjustments. At certain times T_l, alternative routes R_i might additionally be available, again manipulating the arrival time. For this reason, alternative historical routes were extracted and assigned to corresponding times T_l and RFT. In scenarios $S_{Ti,Ri}$, the flight performance along the alternative routes was modeled and additionally subjected to all speed adjustments. Figure 4 gives an example of three different routes of an A330 flight QTR946 from Doha International Airport (OTHH) to WSSS. Note, depending on the aircraft distance to WSSS at time T_l more or less alternative routes are available. For T_l=11 a.m. at least one alternative route was available for 23 flights. At T_l 12.30 p.m. 11 flights still had the possibility to change the route. At T_l 2 p.m. an alternative route was available for only a single flight QTR946.

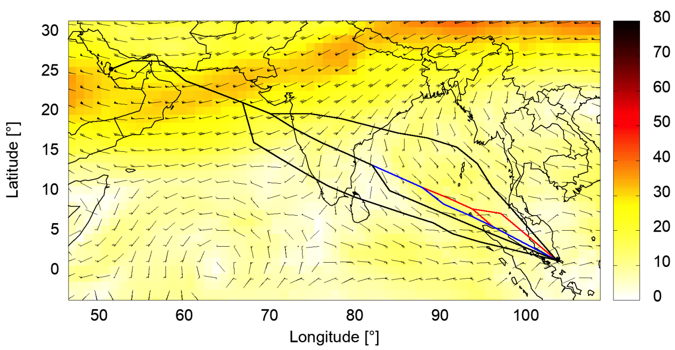

Figure 4. Example of different lateral routes for A330 flight QTR946 from OTHH to WSSS. Several route changes from T_l= 11:00 a.m. (black), T_l= 12:30 p.m. (blue), and T_l= 2:00 p.m. (red) and their effect on ETA are modeled.

IV. Results

A. Impact of speed adjustments of a single flight at different times on ETA

The potential of speed adjustments under different weather conditions is exemplified on an A330 flight from Brisbane Airport (YBBN) to WSSS with a mean flight time of eight hours (Figure 5). Starting the speed manipulation seven hours in advance (i.e., at the Top of Climb (TOC)) enables manipulation of the ETA of more than one hour. When manipulating the speed only during the last three hours of the cruise phase, the ETA can be shifted by approximately seven minutes (see Figure 5), which is still significant according to [36]. Following Figure 5, the impact of the weather on ETA cannot be denied. For example, in weather w_3 (grey dots), the speed adjustments are far less effective, compared to weather w_1 (dark blue dots). Note, that weather w_4 represents the reference weather data set.

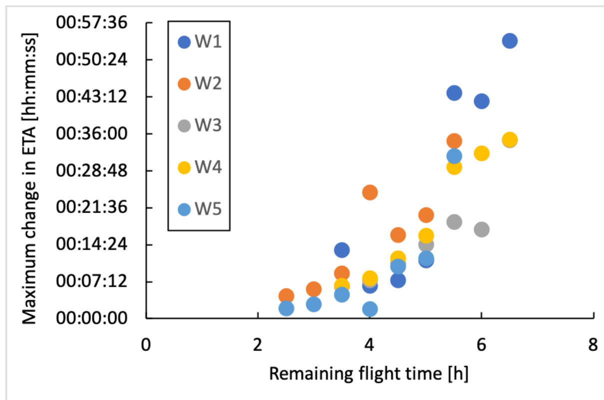

Figure 5. Maximum possible change in ETA of an example flight from YBBN to WSSS. Colors denote different weather data sets. Weather w_4 denotes the reference weather conditions.

This example flight shows that uncertainties in the weather forecast for the next seven hours cause uncertainty in the arrival time forecast of about 30 minutes, whereby the arrival time can be manipulated by about one hour. Three hours before arrival, on the other hand, the arrival time can be predicted to be within about seven minutes. At the same time, the arrival time of this single flight can be influenced by at least 7 minutes.

B. *Impact of speed adjustments of all flights on ETA in the reference weather scenario*

If we now extend the view from the single flight to all 23 flights, the influence of the RFT and the speed manipulation on the ETA increases surprisingly, although in Figure 6 initially only the results in the reference weather w_4 are shown. Here, for each flight, the maximum change in ETA is shown as a function of the RFT at which a speed adjustment was implemented. Now, six hours before arrival, changes in arrival time of almost two hours are possible. One hour before the arrival time, the margin is about 15 minutes. A distinction is made between westbound and eastbound flights. Obviously, in this weather, many hours before arrival, ETAs of westbound flights could be manipulated much more by speed adjustments than ETAs of eastbound flights. A few hours before arrival, the manipulations of eastbound flights were significantly more effective. This can be explained by the wind situation in the reference weather around WSSS (see Figure 3). While eastbound flights were confronted with headwinds at far distance and tailwinds near WSSS, westbound flights were confronted with tailwinds at far distance and headwinds near WSSS.

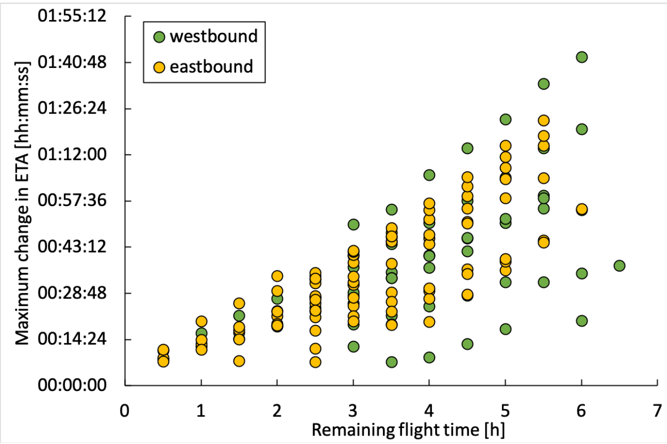

Figure 6. Maximum possible changes in ETA as function of RFT, when starting the speed adjustment V_j. 23 long-haul flights to WSSS are modeled in the reference weather scenario w_4. Colors distinguish between westbound flights (yellow) and eastbound flights (green).

C. *Weather-averaged impact of speed adjustments of all flights on ETA*

If we now additionally consider the influence of the weather, the speed adjustment, and the time of the speed adjustment on the ETA, things become quite confusing. Therefore, we have averaged the maximum changes of the ETAs due to speed adjustment over all flights and statically evaluated them over all weather scenarios and show in Figure 7 mean, maximum, and minimum of the ETA variation due to speed adjustment. Considering five weather data sets and 23 flights, the change in ETA does not increase significantly (compared to Figure 6 in the reference weather). It follows that the variations due to the individual flights (well seen in Figure 6) partially compensate for the variations due to the weather (see Figure 5 and Figure 8). Again, the arrival time six hours before arrival can be manipulated by almost two hours. The difference between eastbound and westbound flights averaged over all flights in a RFT is also surprisingly small.

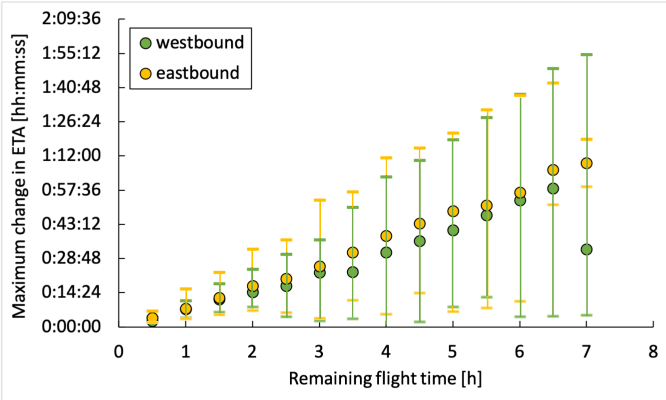

Figure 7. Weather-induced variations (minimum, maximum, and mean) in ETA manipulated by speed adjustments, which started at different times. Here, the maximum change in ETA due to speed adjustments is statistically analyzed. Colors distinguish between westbound flights (yellow) and eastbound flights (green).

D. *Weather impact on ETA on all flights*

Finally, we want to analyze the sole influence of weather on ETA without the influence of speed manipulation as a function of the RFT at which the flights were at a similar distance from WSSS in the respective weather. For this, Figure 8 shows the change in ETA between the weather-related earliest and latest arrivals of each flight as a function of the RFT. At the RFT, the compared flights F_i were at a similar distance from WSSS. The influence of the weather on the ETA is of the same order of magnitude as the influence of the speed manipulation. Assuming unknown weather and no speed control intervention, the arrival of the flight six hours before arrival can be predicted with an accuracy of 2.5 hours. Two hours before arrival, this security only amounts to a maximum of 45 minutes. It can be concluded that control actions more than four hours prior to arrival should only be considered due to weather-related uncertainties of nearly 1 hour if either the weather can be predicted with sufficient accuracy or intensive changes in control actions are possible during the remaining flight time.

E. *Impact of alternative routes on ETA*

In addition to speed adjustments, changes in the lateral route can also lead to an efficient control capability of the ETA in the long term. It is expected to have a particularly

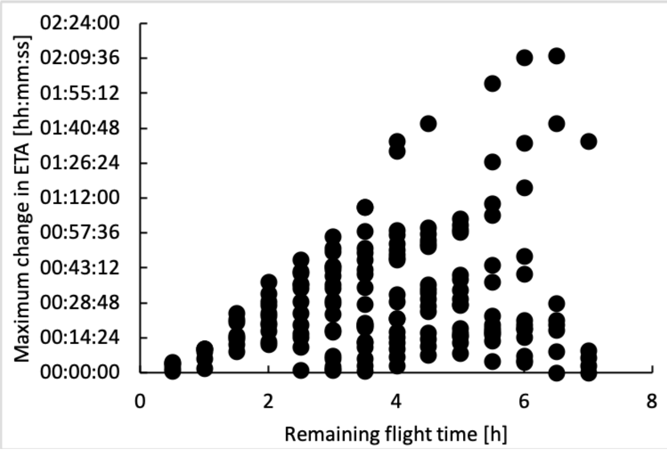

Figure 8. Weather-induced differences in ETA per flight F_i. The speed (Mach) of each flight F_i was reduced to $V_{i,j} = 0.95$ from a certain time (x-axis). The differences between the earliest and latest ETA of each flight F_i are shown.

high influence of weather. Let us start with the analysis of the weather impact on the change of ETA by choosing alternative routes starting from certain time points T_l, without considering speed adjustments. Figure 9 shows a relatively balanced dispersion of ETA by alternative routes in positive and negative directions. Due to the variance in wind speed and direction of the different weather scenarios, eight hours prior to arrival, route changes can delay the ETA by up to three hours and accelerate it by up to two hours. The smaller RFT, the less likely it is that an alternative route can be chosen. Therefore, two hours before arrival, all 23 flights on average can only delay or accelerate the ETA by 30 minutes. Since no speed adjustment is considered in this analysis, it can be concluded from Figure 9 that all negative, i.e. "premature" values also have a positive impact on fuel consumption.

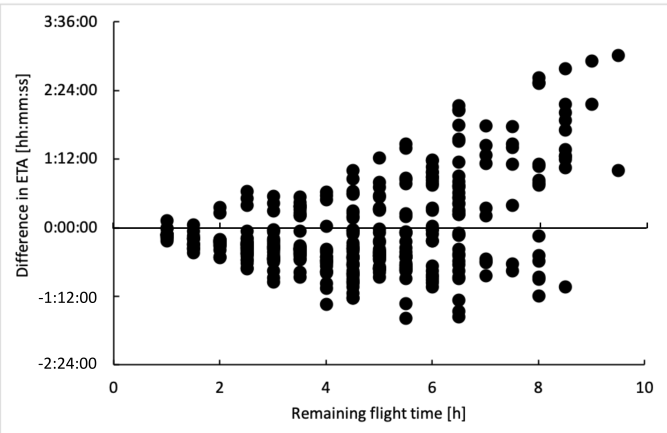

Figure 9. Differences in ETA between different routes per each flight as a function of RFT considering all weather scenarios. Here, the differences are only caused by different routes, not by speed adjustments. Although the choice of alternative routes was only possible at three different flight times T_l, those times T_l are assigned to all classes of RFT.

Speed can also be adjusted on alternative routes. Maximum differences in ETA per flight between the filed route and the alternative route, as well as between "accelerating" and "decelerating" weather scenarios show in Figure 10 an extreme impact of the combination of both control mechanisms for the extended AMAN. Extreme values of three to four hours with a route and speed adjustment approximately six hours before arrival could be modeled.

Compared to Figure 9, however, the effects of combining both control options compensate each other on average, so that on average the ETA is only shifted by about one hour.

This again clearly illustrates the challenge of this extended AMAN operation: with long time horizons of more than four to five hours, the weather-induced, unpredictable uncertainty outweighs the advantage of speed adaptation.

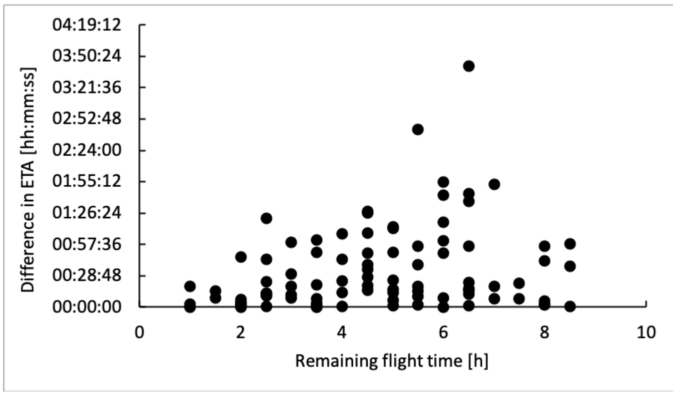

Figure 10. Maximum weather-induced differences in ETA between the originally filed and an alternative route. Differences are shown per flight and as a function of the RFT at which the alternative route could start at the earliest.

Aside from speed modifications, lateral route variations may be an option for controlling the arrival time after the aircraft is in the air. The impact of this option on fuel use relies on the weather conditions for minor deviations from the initially stated route. The longer the detour, the more likely increased fuel usage and the possibility of shifting the arrival time at the approach sector. Even one hour before arrival at least a single alternative route could be identified for most of the flights.

V. Conclusions

The research questions of this study were to identify the optimal time frame before arrival for an effective extended AMAN operation (or LR-ATFM). In addition to providing a sufficient duration of effect of speed manipulations on ETA, we wanted to quantify the uncertainty that poorly predictable weather conditions create and contrast it with the increasing efficiency of the long duration of effect of speed adjustments. We evaluated only physically possible aircraft type-specific speed adjustments and their influence on trajectories under the most heterogeneous weather conditions possible.

Assuming a successful weather prediction of two to four hours (either by reports of aircraft flying ahead or by numerical weather prediction models) we advise starting with a LR-ATFM about four hours in advance. For RFTs greater than five hours, the uncertainty due to poorly predictable weather often exceeds the influence of speed adjustment on

ETA. Control measures over such long periods are therefore only recommended if homogeneous weather conditions can be assumed. Therewith, research question 1 is answered.

If further route adjustments are allowed and possible, we advise preferring this option one to two hours before the TOD, because on average, the positive effect of alternative routes is not remarkably increasing with RFT.

A positive finding of our investigations was that significant changes in arrival time are possible even for short RFTs of about one hour. One minute per flight hour required by ICAO was exceeded in all scenarios. So we can increase our speed adjustment requirements to at least five minutes of flexibility in arrival time per flight hour. Therewith, research question 2 is answered as well.

The relatively weak influence of flight direction in combination with velocity adjustments on the ETA was amazing. Here, the undoubtedly strong effects of individual flights are already averaged out when considering only 23 flights and 5 weather scenarios.

The advantage of this method of controlling the arrival time in the approach sector is a low organizational effort since speed adjustments during cruise flight of maximum plus/minus 5 % or 0.01 Mach are allowed without ATC clearance [18], i.e. without a significant impact on the controller's taskload. Greater speed adjustments, however, are possible at any times during cruise, but subject to ATC instructions. It follows that the procedure could meet with less resistance from ATC than from airspace users, who have to expect high costs in the event of delays and additional fuel consumption.

Unlike its predecessor [34], this study did not consider the effect on fuel consumption but focused on realistic prediction of arrival times. Next, we will transform the weather-related uncertainties in the ETA into distribution functions and hand them over to an optimizer together with the multitude of modeled speed-related arrival times to achieve minimum-cost solutions for the LR-ATFM concept.

In this study, only realistic trajectories with realistic, physically possible, aircraft-specific fuel capacities were calculated. However, it was neglected whether the additional fuel (for speed adaptation) would have been covered by contingency fuel or by realistic amounts of extra fuel. This will need to be addressed in our future analyses.

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