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Evaluation of Time-window Trajectories with respect to Fuel Consumption and Arrival Time

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Evaluation of Time-window Trajectories
with respect to Fuel Consumption and Arrival Time

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List of Acronyms

A-FMS	Augmented Flight Management System
ACC	Area Control Centre
AHP	Analytic Hierarchy Process
ANSP	Air Navigation Service Provider
APM	Aircraft Performance Model
ATC	Air Traffic Control
ATCFM	Air Traffic Control Flow Management
ATCO	Air Traffic Control Operator
ATM	Air Traffic Management
ATS	Air Traffic Services
BADA	Base of Aircraft Data
CASSIOPEIA	Complex Adaptive Systems for Optimization of Performance in ATM
CATS	Contract-based Air Transportation System
CDM	Collaborative Decision-Making
CDR	Conditional Routes
CDU	Command Display Unit
CMA	China Meteorological Administration
CoO	Contract of Objectives
DDR	Demand Data Repository
DET	Deterministic
ECAC	European Civil Aviation Conference
ECMWF	European Centre for Medium-Range Weather Forecasts
EWF	Ensemble Weather Forecasts
FEI	Flight Efficiency Initiative
FMS	Flight Management System
FUA	Flexible Use of Airspace
GHP	Ground Holding Problem
IFPS	Initial Flight Plan Processing System
IFR	Instrument Flight Rules
INF	Infinite
ISA	Instantaneous Self Assessment of Workload
IQR	Interquartile Range

KPI	Key Performance Indicator
MIN	Minimum
NEST	Network Strategic Modelling Tool
NM	Nautical Mile
NMOC	Network Manager Operations Centre
OF	Objective Function
PROB	Probabilistic
pTP	Probabilistic Trajectory Predictor
R&D	Research & Development
RT	Radio Telephony
SA	Sensitivity Analysis
STCA	Short-Term Conflict Alerts
SWIM	System-Wide Information System
TIGGE	The International Grand Global Ensemble
TLX	Task Load Index
TP	Trajectory Predictor
TW	Time-window
WP	Waypoint

Part A:
MSc Thesis Paper

Evaluation of Time-window Trajectories with respect to Fuel Consumption and Arrival Time

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ABSTRACT

The flight planning process is an extensive and long process to direct and maintain a high level of operations within the airspace. As air traffic demand grows year after year, it's worthwhile to optimise the European air traffic system further. One way of optimising the system, is by creating optimal flight schedules that solve for demand-capacity imbalances. These schedules require an evaluation with respect to punctuality and fuel consumption in the tactical phase. For this article, an air traffic model has been developed in BlueSky to simulate air traffic while taking the variance of wind and delay into account. Subsequently, the performance of several optimised schedules will be assessed and compared with respect to wind, speed changes, punctuality and fuel consumption.

1. Introduction

Air traffic has grown significantly over the last decades and there are strong indications that a growth will continue in the near future. The growth can be measured over various KPI's such as the number of flights and passengers. By 2017, a record number of flights was reached of 10.6 million [16]. In 2019, a record was set at 2.43 billion passengers arriving in Europe which is a 32.3% increase with respect to 2014 [1]. When air traffic is observed over the last decade, it is noticed that the number of IFR flights remained fairly constant. This occurred despite economic downturns and high oil prices. It is over the period of 1988 to 2008 where air traffic has doubled in numbers [16]. When these trends are projected on the near future, it's expected that the number of flights increases to 16.2 million by 2040. This corresponds with an increase of 53% on the number of flights and an annualised growth of 1.9%.

The growth and prospects are favourable for the market, but there are downsides as well. More traffic and a higher utilisation of the airspace will undoubtedly lead to increases in the size and number of delays. There are calls not only from regulators, but also from airlines to optimise European airspace [2]. One of the main concerns remains the punctuality of aircraft. In 2018, an aircraft experienced on average a delay of 1.83 minutes. Despite the challenges, the European Commission set the ambition on reducing the delay to 0.9 minutes within several years [9].

Not only the punctuality is an issue, but the propagation of delays over the system raises concerns as well. These delays and the handling of them can create a considerable amount of additional costs. An aircraft with 'long' airborne delays can reach costs of up to 287 Euros per minute [8]. To attend these matters, several concepts and approaches have been developed to improve this system [17]. One of these ideas resulted in the Contract of Objectives (CoO) concept [3]. The CoO is an ATM concept which is developed and assessed within the CATS project by EUROCONTROL. The CoO acts as an operational link between all air navigation actors (airlines, airports and ANSPs) and represents a commitment between and for all the actors involved. These commitments are based on well-defined, shared and agreed objectives [6][7]. An alternative name for a CoO is time-window (TW). These objectives are set at delivering a particular aircraft within temporal and spatial intervals. These TWs are defined for transfer of responsibility areas such as between two Area Control Centres (ACCs). The sizes of the TWs are influenced by factors such as runway capacity, congestion, aircraft performance and others. These TWs provide aircraft a greater ability to absorb delays and hastes without complications. The underlying goal is to improve the punctuality of the system. These TWs are used to develop optimised schedules that solve for demand-capacity imbalances [4][7][21]. Thus, the need arises to compare and assess these schedules.

This paper will make an assessment of TW-schedules with respect to punctuality and fuel consumption while incorporating wind. These schedules are simulated in BlueSky, an open-source air traffic simulator [20][19]. For these simulations, a plugin is developed to mimic the behaviour of aircraft who adhere to TWs. BlueSky will also rely on BADA3 to estimate the fuel consumption [15][14][18]. A plugin will rely on ensemble weather forecasting to incorporate the wind [12]. A comparison and evaluation of these schedules will be done on single trajectories and on entire sets.

2. Augmented Flight Management System

This section explains the principles behind the Augmented Flight Management System (A-FMS) and the Fuel Consumption plugin. The logic of the A-FMS is shown in

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Section 2.1. The constraints and limitations are discussed in Section 2.2. The input to the A-FMS is presented in Section 2.3. The output of the A-FMS is shown in Section 2.4. And Section 2.5 elaborates on the Fuel Consumption plugin.

2.1. Logic of the A-FMS

To simulate the behaviour of TW with aircraft, a Flight Management System (FMS) with TW functionality has been developed. This FMS is called: the Augmented Flight Management System (A-FMS). The A-FMS does not replace BlueSky's FMS, but enhances it and is limited to sending speed instructions only. This means that this plug-in should not provide instructions when BlueSky's FMS is sending speed instructions as well. This holds for cases such as climbs and descents as BlueSky's FMS will be active during these periods. To prevent interference between the two systems, the A-FMS should be active during limited flight level changes only.

The purpose of the A-FMS is to simulate the behaviour of TW functionality for air traffic. This is achieved by simulating the speed changes of an aircraft which flies on a TW based flight plan. To achieve this, the A-FMS takes two main considerations into account;

1. The aircraft complies to the flight plan as much as possible.
2. The aircraft flies on cruise speed when the A-FMS is active.

To adhere to the first condition, the flight plan has to be interpreted as speed requirements. A set of variables is necessary to calculate these speed limits such as the current position of the aircraft and the details of the subsequent waypoint with an active TW. Using these variables, it's possible to calculate a minimum and maximum velocity for the aircraft such that the waypoint can be reached within the TW. A schematic illustration of this method is shown in Figure 1. In Figure 1 the horizontal axis represents the distance d on the path of the aircraft. A point on the horizontal axis represents a longitude, latitude and altitude. The vertical axis represents the time axis. The current position of the aircraft is marked as point AC and two waypoints on the path of the aircraft are marked as WPx and WPy. Point AC is associated with a single point on the path and the current time (t_current). In this example, WPx is an active waypoint with an associated TW. The waypoint is represented with a vertical line as the location of the waypoint is the same, but a range of arrival times is allowed as well. The waypoint is associated with an earliest arrival time (t_earliest) and latest arrival time (t_latest). Using these arrival times, the minimum (v_{min}) and maximum speed (v_{max}) of the aircraft are calculated such that the TW will be adhered to. Equations 1 and 2 show how these speeds are calculated. The distance to the next waypoint (Δd) is defined in meters and the remaining time in seconds.

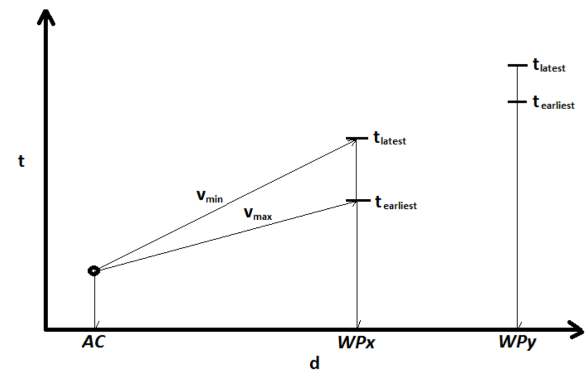

Figure 1: Graphical representation of the aircraft's trajectory

$$v_{min} = \frac{\Delta d}{t_{latest} - t_{current}} \quad (1)$$

$$v_{max} = \frac{\Delta d}{t_{earliest} - t_{current}} \quad (2)$$

When the current speed of the aircraft lies outside the range of the minimum and maximum speed, then a speed adjustment is necessary. If the speed isn't changed, then the aircraft will continue on its current speed and violate the TW when it reaches the active waypoint. The speed input will depend on the current speed of the aircraft. If the current speed is lower than the minimum speed, then the speed will be increased to the minimum speed. If the current speed is higher than the maximum speed, then the speed will be decreased to the maximum speed.

The second condition can only be applied when the aircraft is initially projected to adhere to the TW of the waypoint. This basically means that there is some slack available in the execution of its flight plan. In such cases, the aircraft will be instructed to fly at cruise speed. It is assumed that it's beneficial for the aircraft to fly for as long as possible at cruise speed if the aircraft is still able to reach the TW. If for example the flight plan is too strict, too lenient or the aircraft experiences a delay during its flight, then this can impede the aircraft's ability to fly at cruise speed. These examples can force the aircraft to fly at a different speed from its cruise speed or reduce the amount of time the aircraft can fly at cruise speed.

The A-FMS will send a speed instruction at specific positions and occasions. These are described by the following two conditions:

1. The aircraft has reached a waypoint.
2. An interval of 60 seconds have passed.

Every time an aircraft meets one or both of these conditions, the A-FMS will be triggered. The A-FMS will then evaluate the current conditions and send an appropriate speed instruction if necessary. When either the speed changes remain small or when the vertical speed is too high, the A-FMS will refrain from sending speed instructions. Whenever an aircraft reaches a new waypoint, the interval timer is reset as well.

2.2. Activation of the A-FMS

The FMS of BlueSky regulates aircraft attributes such as the trajectory, speed and attitude. As the A-FMS focuses solely on speed adjustments, the A-FMS should refrain from sending speed instructions when the FMS is doing so. This includes events such as climbs, descents and user input. Figure 2 shows the position of the A-FMS within a simulation when the A-FMS is active and functioning. Also, there are two controls in place to prevent interference with the FMS.

Figure 2 shows a flowchart of the simulation model. For a simulation, at least one aircraft has to be spawned. The aircraft relies on trajectory data to spawn it on the right coordinates and altitude. The aircraft data is then stored and processed by BlueSky internally. Aircraft data which are used to monitor the performance of the aircraft are stored outside of BlueSky in logs. The simulation then checks whether it should continue to the next timestep or end the simulation. This check is based on landing every aircraft in the set of flights. When the simulation isn't finished, the next timestep will be entered. To go to the next timestep, the A-FMS has to generate its output first. The A-FMS relies on trajectory, cruise speed and aircraft data to produce speed instructions. These speed instructions are then sent to the FMS along with trajectory and aircraft data. Also, user input such as speed and altitude commands are processed by the FMS. This leads to the FMS generating output to control and manoeuvre the aircraft. The simulation is then ready to go to the next timestep and update every aircraft with their respective FMS output. New aircraft originate from the trajectory data as every flight has to be flown. The updated data are then stored in logs again and the simulation checks whether the it should continue. When every aircraft has landed, the simulation ends.

The first control mechanism is the activation and deactivation of the A-FMS. The A-FMS can be turned on and off at every waypoint. This allows the user to use the A-FMS only during specific segments of the trajectory. The application of this control is to let the aircraft climb to its cruise altitude first. When the aircraft is close to reaching this altitude, the A-FMS will be turned on. The aircraft will then resume its flight until the end of its cruise phase where the A-FMS is deactivated. The FMS can then control the aircraft into its descent without interference.

The second control mechanism is a monitor on the vertical speed. When a speed adjustment has been generated, then the vertical speed will be inspected. If it exceeds 2.5 *m/s*, then the speed change is discarded. This allows the aircraft to change its cruise altitude without interference from the A-FMS. These two controls force the A-FMS to be used during the cruise phase only with limited altitude changes.

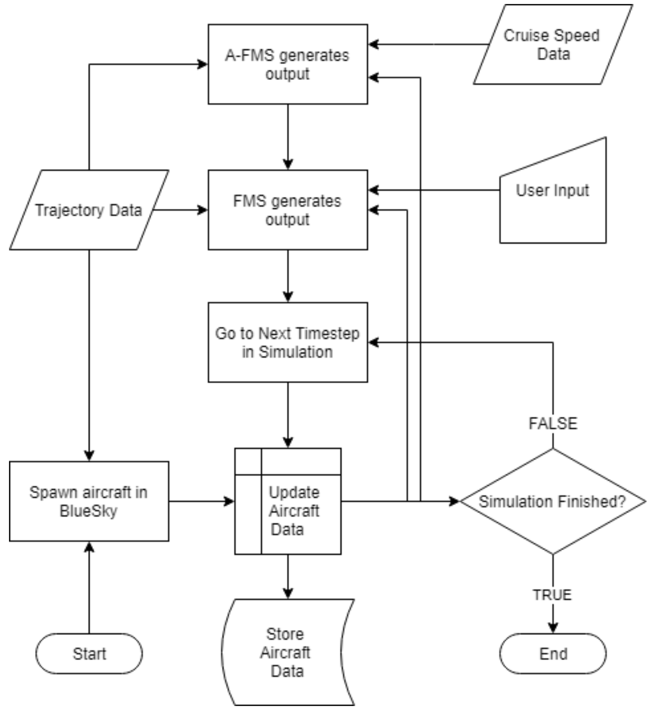

Figure 2: Flowchart of a simulation within BlueSky

2.3. Input of the A-FMS

The A-FMS has several requirements to function properly. These inputs are shown as a flowchart in Figure 2 as well. The A-FMS has to be able to request for aircraft data from the internal memory. Beside a connection to the internal memory, the A-FMS requires two sets of data to function. These data-sets are:

1. A set of trajectories with TW functionality.
2. A cruise speed for every trajectory and/or aircraft type.

A flight plan based on TWs allows an aircraft to fly at its desired speed if the opportunity arises. This flight speed should, in practice, be the speed incurring the lowest costs which can include the costs due to fuel consumption, delays, maintenance, and others. As this kind of information is hard to obtain for each aircraft type in varying situations, the cruise speed will be determined by the costs of the fuel consumption only. Henceforth, the cruise speed is determined by the most fuel efficient speed the aircraft can fly at.

BlueSky relies on Base of Aircraft Data 3.6 (BADA3) for the performance of aircraft. This data-set contains performance metrics for the most commonly used aircraft types. These metrics include data such as the specific fuel consumption and the flight envelope. The data-set contains a cruise speed as well which is the most fuel efficient speed of the aircraft. However, this only holds for a specific section of the flight levels the aircraft can fly at. If the aircraft

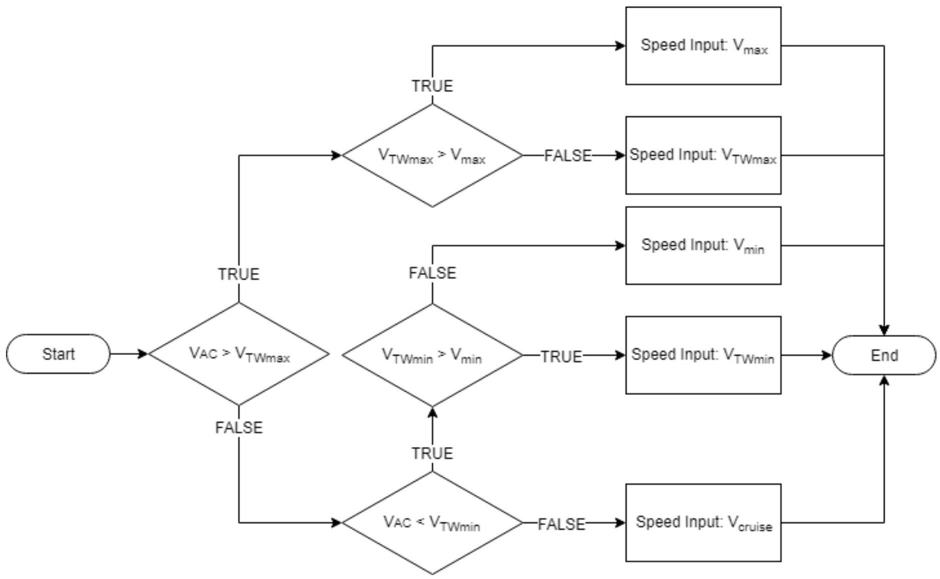

Figure 3: Flowchart of the generation of the speed input by the A-FMS

deviates from this section, then the most fuel efficient speed changes as well.

The importance of finding this speed lies with the fact that the aircraft will be delayed. This will force the aircraft to fly at a higher speed to catch up with its delay and to stay within its intended TW. The penalty for the delay will therefore lead to a higher fuel consumption and thus costs. However, if the cruise speed is for example identified to be lower than the most fuel efficient speed, then the increase in fuel consumption can not propagate properly. In this example, a flight with an initial delay will use less fuel than a flight without a delay even if it flies at a higher speed. The change in fuel consumption will therefore have to be explained by various reasons which complicates the analysis even further. It's therefore important to associate the lowest cost case with the flight plan which is executed best. This is achieved by setting the most fuel efficient speed equal to the cruise speed. If a deviation occurs from this speed for various reasons, higher costs on the fuel consumption of the flight will be incurred.

The most fuel efficient speed can be defined as the speed of an aircraft where the lowest amount of fuel is consumed over its flown distance. To find this speed, a set of aircraft has been flown in BlueSky at the same flight level over the same distance with small increments in speed. The fuel consumption of these aircraft are then compared to each other to identify the speed that consumed the least amount of fuel. This speed varies by aircraft type and by altitude. This information is then stored in 'Cruise Speed Data' as depicted in Figure 2.

It has to be noted that this way of obtaining the most fuel efficient speeds for various aircraft types does have a down-side. The obtained speeds can differ significantly from the actual fuel efficient speeds of those aircraft. This has been reported before in other research [22]. Unfortunately, BlueSky doesn't have the capabilities to work with BADA4 yet which has an improved accuracy and realism.

2.4. Output of the A-FMS

Whenever an aircraft reaches a new waypoint or an interval of sixty seconds has passed, a trigger is sent to the A-FMS. The A-FMS responds to the trigger by generating a speed input for that aircraft. To obtain that input, the following information has to be known first;

1. The speed limits of the aircraft.
2. The speed limits to reach the TW.
3. The preferred cruise speed of the aircraft.

The first set of aircraft specifications is known by using the BADA3 data-set. This data-set contains a detailed description of the aircraft's performance in various conditions. BlueSky is able to provide this information whenever it's necessary. The second set of variables is found by using Equation 1 and 2. The last variable is obtained from the cruise speed data-set.

When the necessary information is obtained and calculated, then the logical process to determine the speed input is started. A schematic overview of this process is presented in Figure 3. As can be seen, the flowchart starts on the left-side and the first logical operator looks whether the current speed of the aircraft (V_{AC}) exceeds the maximum speed to reach the TW (V_{TWmax}). If this holds true, then V_{TWmax} is evaluated against the maximum speed of the aircraft (V_{max}). If the former is higher, then the speed input has to be limited to V_{max} as the aircraft can't exceed that speed. If the latter is higher, then V_{TWmax} can be reached and that becomes the speed input. When these speed input have been generated, the process ends. In the case of V_{AC} being lower than V_{TWmax}, the V_{AC} will be evaluated against the minimum speed to reach the TW (V_{TWmin}). If V_{AC} is equal or bigger than V_{TWmin}, then the speed input becomes the cruise speed (V_{cruise}) as there is slack available in the flight-plan. If V_{AC} is lower than V_{TWmin}, then another evaluation is made. Similar to the top part of the flowchart, the V_{TWmin} is checked with the minimum speed of the aircraft (V_{min}). If V_{TWmin} is bigger than V_{min}, then V_{TWmin} is attainable and that speed becomes the speed input. If this evaluation doesn't hold true, then the speed input becomes V_{min} because this is the lowest speed that can be reached by the aircraft. After the speed input has been generated, the process is ended.

Subsequently, two inspections are held. The first one is an evaluation on the vertical speed of the aircraft. If this speed exceeds 2.5 *m/s*, then the speed input is discarded. The objective of this evaluation is to make sure that the A-FMS doesn't input any speed commands during significant altitude changes. The second inspection is on the magnitude of the speed change. If the difference between the speed input itself and the current speed of the aircraft is smaller than 0.5 *m/s*, then the speed input is discarded as well. This evaluation is set in place to prevent the A-FMS from cluttering the FMS with unnecessary, small speed commands. If the speed input has passed both evaluations, then the speed input is sent to BlueSky's FMS and the command is executed.

2.5. Fuel Consumption Plugin

The fuel consumption is calculated using a BADA3 plug-in made available in BlueSky. BADA3 contains a set of data with very specific performance metrics on aircraft and engines. This data-set is used to simulate the behaviour and performance of the aircraft. The aircraft spawns with a starting weight corresponding to the maximum take-off weight of the aircraft type at the start of the cruise. During flight, the aircraft will lose a mass equivalent to the fuel burned by the engines. By calculating the difference between the weight of the aircraft at the start and end of the cruise, the fuel consumption can be estimated.

3. Ensemble Weather Forecast Implementation

To model the wind into the simulation, a previously developed plug-in for Ensemble Weather Forecasts (EWF) is used. This plug-in has been developed to incorporate wind and its variability into the simulation. To model this aspect into BlueSky, the plug-in relies on TIGGE for its wind-data. TIGGE is a data-set which consists of ensemble forecast data from eleven global numerical weather prediction centres since October 2006. Its data can be accessed through data archive portals such as ECMWF and CMA [5][13]. By using short-term forecast data from TIGGE, the wind and its variability can be simulated in BlueSky. This will improve the realism of the flight-plans which are to be evaluated. Figure 4 and Figure 5 are an example of an ensemble of a TIGGE data-set.

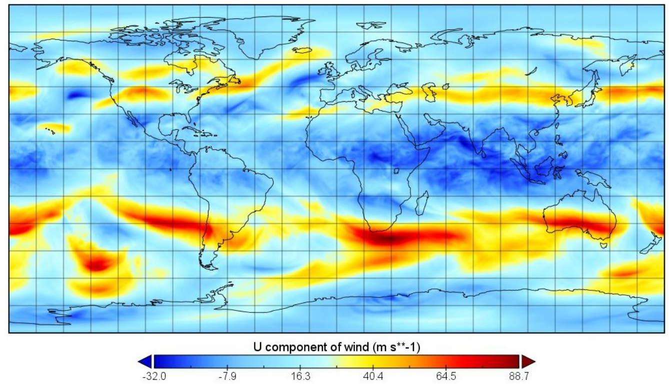

Figure 4: The U component of a selected wind field

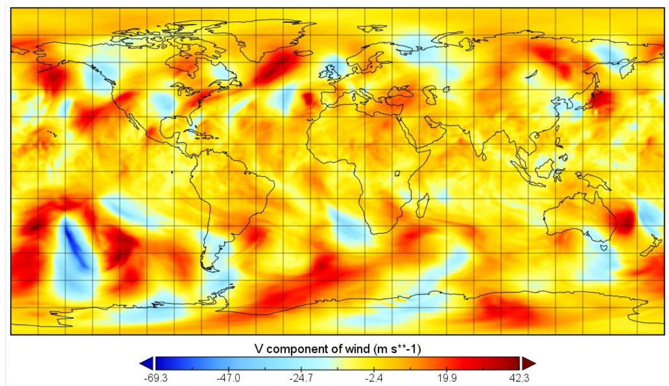

Figure 5: The V component of a selected wind field

The plug-in relies on a specific data-set of TIGGE. It's not only important to assess the magnitude and direction of the weather forecast, but also its uncertainty. To take this uncertainty into account, the plug-in relies on perturbed forecasts. There are two factors that decrease forecast accuracy with increasing forecast lead-times. These factors are the uncertainties in the initial conditions and the necessary approximations for the numerical model. An ensemble forecast is a set of different realisations of a single forecast. This set consists of 50 realisations and one control forecast. Each of these realisations is generated with perturbations on the initial conditions and at each model integration. These perturbations are used to represent the uncertainties in the chosen method and analysis [11][10].

The flight-plans which are used for the simulations are taken from the DDR2 database. These flight-plans are based on historical flights, primarily within Europe. From this database, information such as waypoints along a trajectory, arrival times, aircraft type and flight levels have been collected. If these flight-plans are used to simulate their trajectory, then the wind has indirectly been taken into account. The arrival times of the aircraft in those flight-plans are the result of not only the performance of the aircraft, but other factors such as wind and traffic as well. Therefore, the wind can't been loaded into BlueSky directly to re-enact the flight. An additional requirement on selecting the right ensemble is that a minimum lead-time of at least 24 hours has to be used.

When a data-set with the right lead-time has been retrieved, the plug-in loads only the variation of the wind into BlueSky. The first step for this process is to calculate the average wind at every measurement point for all N ensembles which is shown in Equation 3. The second step is the subtraction of the average wind from every corresponding measurement point as depicted in Equation 4.

$$\overline{W}_j = \sum_{i=1}^{N} \frac{W_{i,j}}{N} \; \forall \; i \in ensemble, j \in (lat, long, alt) \quad (3)$$

$$\Delta W_{i,j} = W_{i,j} - \overline{W}_j \; \forall \; i \in ensemble, j \in (lat, long, alt) \quad (4)$$

During a simulation, the variation of the wind is added onto the velocity of the aircraft (V^{ac}). This step is described in Equation 5. The trajectories can then be run on each ensemble to assess the effects while keeping the flight-plans unchanged.

$$V_i^{ac} = V^{ac} + \Delta W_i \; \forall \; i \in ensemble \quad (5)$$

4. Simulation Set-up

The simulations require additional set-up to generate results. Section 4.1 explains the set-up of the trajectory. Section 4.2 discusses the position of the time-window. And Section 4.3 presents the selection of the set of delays for a simulation.

4.1. Trajectory Creation

The trajectories for these simulations rely on EUROCONTROL's DDR2 database which contains various information from actual flights. This database provides the positional data and flight levels to shape the trajectory. These data-points are then used to create waypoints where an aircraft has to fly over. The arrival times on these waypoints are used to expand with their respective TW.

4.2. Shape of the TW

There are several ways to define the TW from the arrival time. For these simulations, there are 2 positions defined. A schematic representation of these positions is shown in Figure 6. 'Spawn Point 1' indicates the position where the TW is defined from the edge of the TW. The arrival times from the trajectories coincide with the earliest available opportunity within the TW. 'Spawn Point 2' is positioned at the middle-point of the TW. The arrival times of the trajectories are then widened by half the TW's size in both directions.

4.3. Flight Delays

The simulations look at the effect of flight delays on the flight plan of a trajectory. This is achieved by creating an off-set from the departure time for the aircraft with every run. The aircraft always departs from the same position as the no-delay case. The arrival times are selected from the database and are therefore identical with every scenario of a trajectory. The off-set that is added to the departure time is as large as the delay itself. The following set of delays have been selected to run every trajectory with; *0*, *180*, *300*, *600*, *900*, *1200*, *1500*, and *1800* seconds.

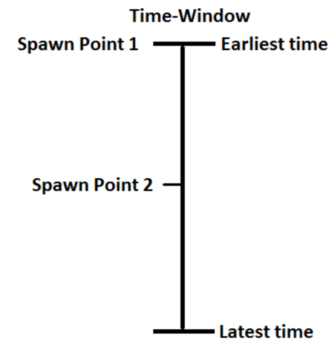

Figure 6: Schematic overview of spawn points within a TW

4.4. Flight Schedules

The simulations are used to compare flight schedules based on time-windows amongst each other. For the analysis, up to 4 of these schedules will be simulated and compared per set of flights. These schedules are the minimum (*MIN*), deterministic (*DET*), probabilistic (*PROB*), and infinite (*INF*) schedules. The *MIN*-schedule holds a small TW of 1 minute for every flight. On the other hand, the *INF*-schedule holds a very large TW of 60 minutes. These schedules are used to show the effects of such extreme TWs. The *DET*- and *PROB*-schedules are developed and optimised schedules with different approaches [7]. This leads to these schedules having varying TWs by flights. The analysis will focus on comparing the results of entire schedules with each other.

5. Definition of Metrics

The simulations lead to a vast amount of information and data. This section presents and defines the metrics which are used for analysing the results. Section 5.1 looks at the metric with respect to the wind and its implementation. Section 5.2 analyses the metric on speed changes. Section 5.3 examines the metrics on punctuality. And Section 5.4 looks at the metric on fuel consumption.

5.1. Wind

When an aircraft flies during the simulation, it will encounter the projected wind field. Over its trajectory, the wind strength is measured at every waypoint. This leads to a wind measurement at every waypoint for each of the 50 ensembles and for every delay. Figure 7 shows the North and East velocity components of those measurements on the trajectory of Flight BER717E. Every dot in this plot represents a different ensemble and the colour indicates a different delay. The

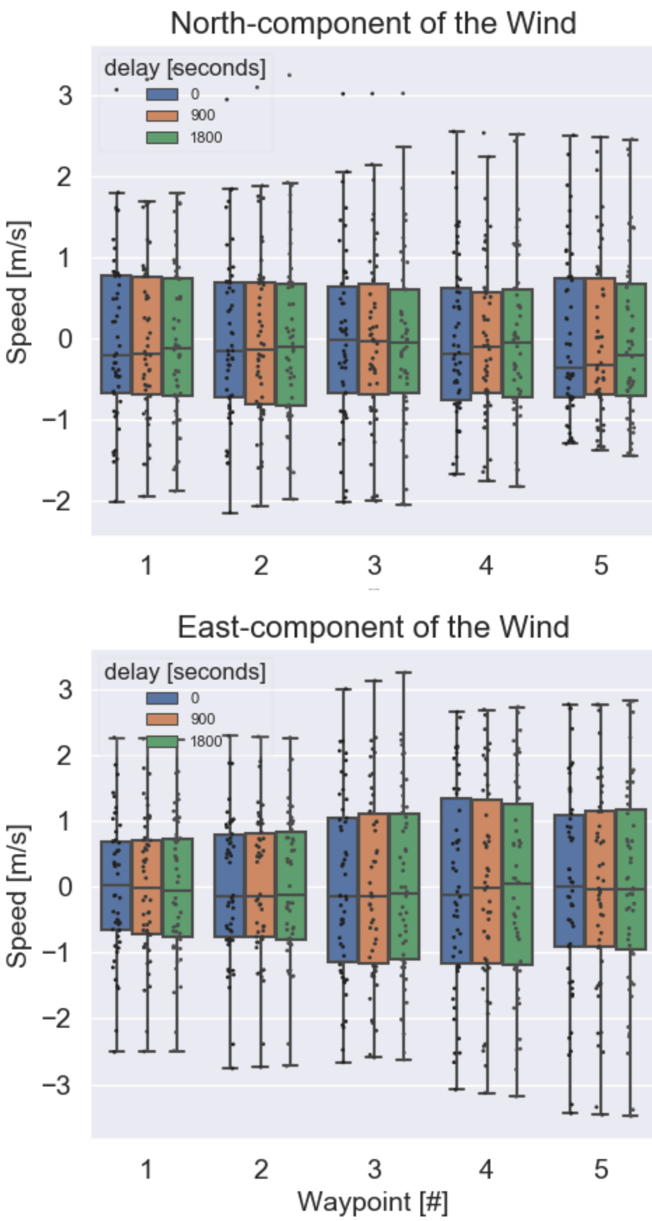

Figure 7: Wind - BER717E

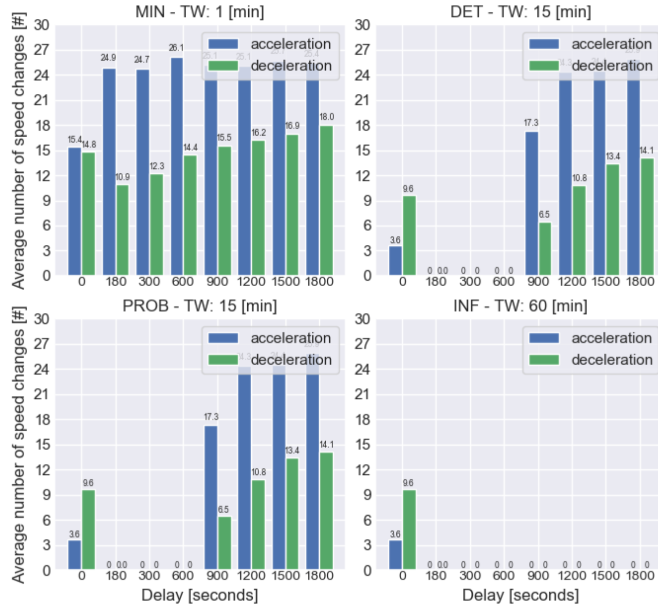

Figure 8: Speed changes - CCA931

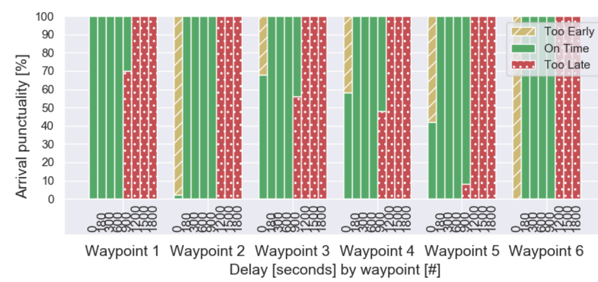

Figure 9: Punctuality - [DET] AFR234H

figure provides a snapshot on the magnitude of the wind on a selected trajectory. Also, the variations in wind strength between ensembles and between delays are shown.

5.2. Speed Changes

Another metric to evaluate the performance of a flight is to look at the number of speed changes. A higher number of speed changes will task the pilots with a higher work-load and increase the fuel consumption. It's therefore preferable to reduce the number of speed changes. The speed instructions from the A-FMS are compared with the previous speed instruction. If these differ, then the speed instruction is tallied in either one of these two categories; accelerations or decelerations. This process is repeated for every ensemble of a flight and for every schedule. This results in an average speed change per ensemble that can be compared between different schedules. Such a figure provides an indication on the amount and kind of speed changes for every schedule. Figure 8 shows this metric for Flight CCA931. As can be seen, the *MIN*-schedule requires relatively a lot of accelerations and decelerations. The *DET*- and *PROB*-schedule have an identical result as the TW's are of the same size. Note that there are several flights which don't require any speed changes even though they are delayed. These flights are able to fly the entire trajectory on cruise speed. The *INF*-schedule requires the least amount of speed changes.

5.3. Punctuality

To interpret the results with respect to punctuality, three types of figures can be produced. The first type deals with the punctuality on a per schedule and waypoint basis. The second type compares the punctuality for a single flight between schedules. And the third type looks at an overall punctuality assessment for all flights between schedules.

An example of a figure of the first type is shown in Figure 9. This figure shows the punctuality of a set of aircraft with various delays at each waypoint. The waypoints are shown

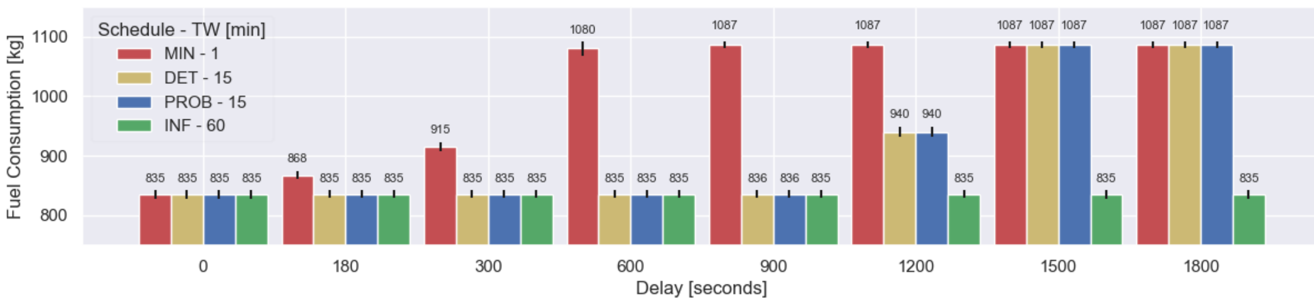

Figure 10: Fuel Consumption - DLH08W

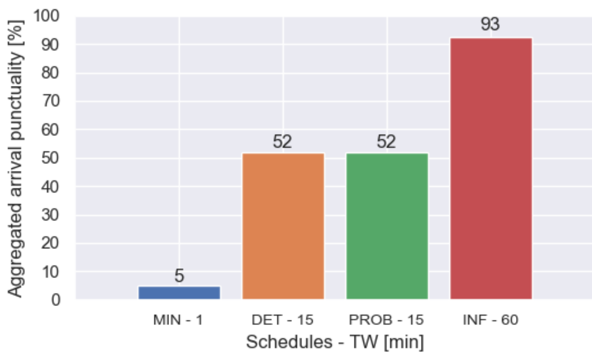

Figure 11: Punctuality - AFR234H

on the x-axis along with the delay of the aircraft in seconds. The punctuality is shown on the y-axis as a bar between zero and a hundred per cent where the sum of all the ensembles corresponds with 100%. A yellow, striped bar indicates an arrival ahead of the prescribed TW, a green bar an arrival within the designated TW and a red, dotted bar a deferred arrival. The size of the bars indicate the percentage of flights that belong to each category. If a bar consists completely of a single category, then that means that the change in wind between ensembles has no significant impact on the punctuality. This kind of figure can be produced for every type of schedule which the flight has flown on. Figure 9 shows this type for Flight AFR234H on the *DET*-schedule.

The second type of figure for Flight AFR234H is shown in Figure 11. The schedules are displayed along with their respective TW's on the x-axis. The score for the aggregated arrival punctuality is shown on the y-axis. The score is calculated using Equation 6 where d_i stands for the distance between the current and previous waypoint. $WP_i^{on-time}$ stands for the on time performance as shown in Figure 9, D stands for the distance over the entire trajectory and N_{delays} for the number of delays.

$$Score = \sum_{i=1}^{N} \frac{d_i \cdot WP_i^{on-time}}{DN_{delays}} \ \forall\ i \in (waypoint, delay) \quad (6)$$

An example of the third type is shown in Figure 12. This type shows an aggregated analysis of a set of 20 flights. The

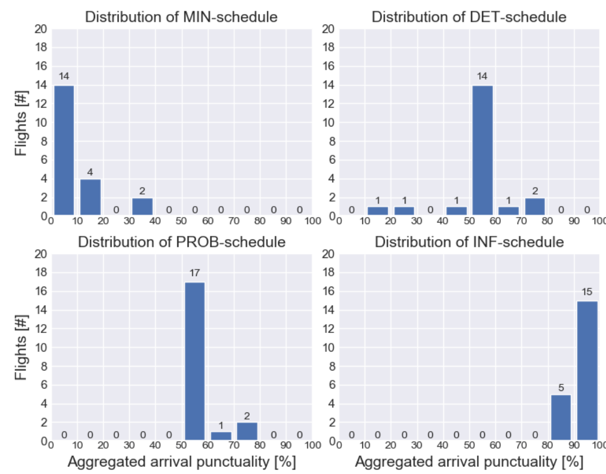

Figure 12: Punctuality - Set of 20 Flights

score is calculated with Equation 6 for every flight. Every score is then tallied in intervals of 10% by schedule. The resulting figure provides an overview on the punctuality assessment by each schedule.

5.4. Fuel Consumption

The results of the simulations provide an estimation on the fuel consumption of an aircraft. Every aircraft will try to fly at its most fuel-efficient speed for as long as possible. An aircraft that encounters a delay won't necessarily consume more fuel, unless it violates the prescribed TW. This behaviour will force the aircraft to consume more fuel if it wants to improve its punctuality. The fuel consumption for Flight DLH08W is shown in Figure 10. The figure shows the average fuel consumption for every schedule and delay over all 50 ensembles. The black lines indicate the standard deviation of the fuel consumption. Figure 10 shows that a small delay already leads to higher fuel consumption for the *MIN*-schedule. The larger the delay becomes, the more fuel is consumed until a ceiling is reached. A similar pattern is found for the *DET*- and *PROB*-schedule albeit at larger delays. This figure also implies that both of these schedules use the same TW as the fuel consumption are identical. The delays can lead to a change in the wind pattern and indirectly affect the fuel consumption as well. However, the *INF*-schedule holds the same fuel consumption for every delay. This indicates that the wind changes over time have a relatively small influence on the fuel consumption over the trajectory.

6. Results of Set I

The analysis in this chapter is focused on a set of flights from EUROCONTROL's DDR2 database. This set of flights uses 'Spawn Point 1' which is depicted in Figure 6 to define the TW. Also, for this set, 4 schedules with varying TWs will be tested. These schedules are the *MIN*-, *DET*-, *PROB*- and *INF*-schedules. The *MIN*-schedule will always use 1 minute as the size of its TW. Likewise, the *INF*-schedule will always use 60 minutes for the size of its TW. The *DET*-schedule uses a deterministic approach to optimise the size of the TW for the entire set. Similarly, the *PROB*-schedule uses a probabilistic approach to optimise the size of the TW. This leads to a varying TW size by flight for these schedules. From this set, several flights will be analysed into more depth; Flight AZA1572 in Chapter 6.1, Flight TAP1015 in Chapter 6.2, Flight BEL7PC in Chapter 6.3 and Flight EXS79G in Chapter 6.4. An aggregated analysis on the entire set of flights is performed in Chapter 6.5.

6.1. Flight AZA1572

Flight AZA1572 is flown in an Airbus A320. The aircraft departs from Alghero–Fertilia Airport (LIEA). The destination is set at Leonardo da Vinci International Airport (LIRF). The aircraft departs at 05h40m and the cruise is flown over a distance of 41.9 NM with 2 waypoints. The *DET*-schedule uses a TW of 4 minutes and the *PROB*-schedule uses a TW of 15 minutes.

Wind - AZA1572

Figure 13 shows the wind over trajectory AZA1572 for every ensemble. The average of the North-component of the wind vector lies near zero and most differences between ensembles are small. Even though the average remains near zero with increasing delays, the shape of the boxplot does change slightly. A similar pattern can be found for the East-component of the wind despite the outliers. Overall, the wind is comparable across various delays despite the slight changes over time.

Speed Changes - AZA1572

The aircraft experiences accelerations and decelerations over the trajectory. These speed changes are shown for every schedule in Figure 15. The aircraft in the *MIN*-schedule faces the most speed changes where a great majority of them consist of accelerations. Decelerations are only present in the case without delay. When a delay is introduced, the aircraft accelerates to catch up. As the cruise is rather short and the TW is small, the aircraft accelerates until the end of the cruise. The *DET*-, *PROB* and *INF*-schedule enjoy the benefit of a larger TW. These schedules show no speed changes for various delays as long as its smaller than the size of the TW. These aircraft are able to fly the entire trajectory using their preferred cruise speed.

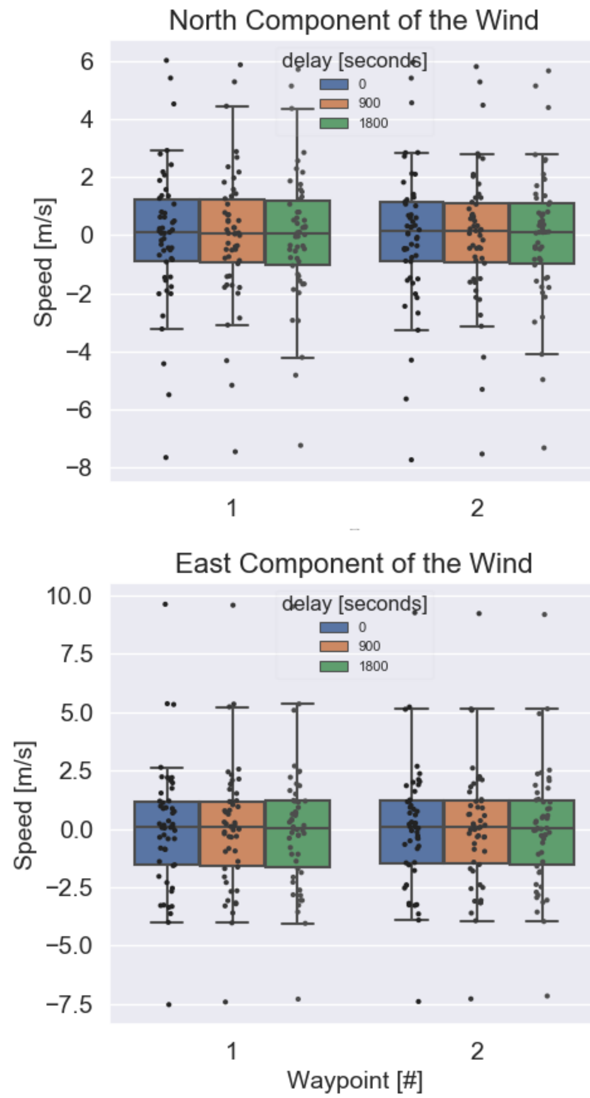

Figure 13: Wind - AZA1572

Punctuality - AZA1572

Figure 16 provides a comparison in punctuality between the schedules. It can be seen that the *MIN*-schedule has the lowest punctuality of 1%. The *DET*-schedule reached a punctuality of 13% and the *PROB*-schedule 50%. The *INF*-schedule attained the highest punctuality at 86%. As expected, the punctuality increases as the TW increases.

Fuel Consumption - AZA1572

The fuel consumption for this trajectory is presented in Figure 14. The lowest amount of fuel consumed over this trajectory is 230 kg as shown in every schedule without a delay. The highest fuel consumption is 249 kg. When an aircraft experiences a delay which is larger than the TW, the fuel consumption reaches this maximum value. This behaviour is caused by the short cruise and is consistent for the various schedules and delays.

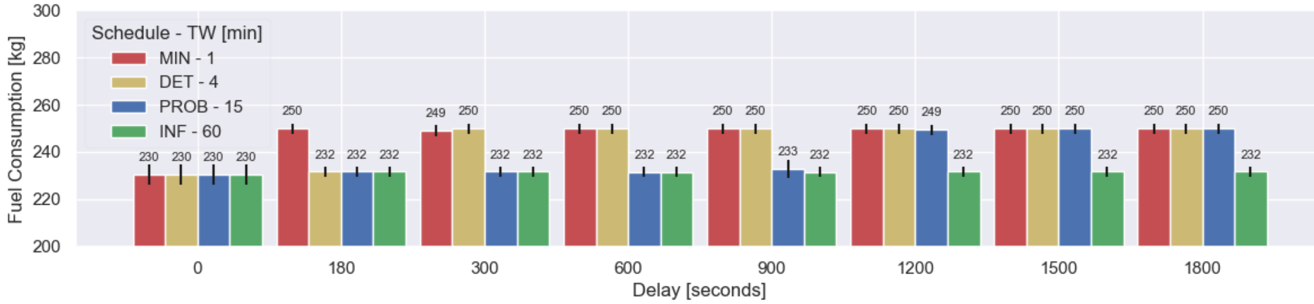

Figure 14: Fuel consumption - AZA1572

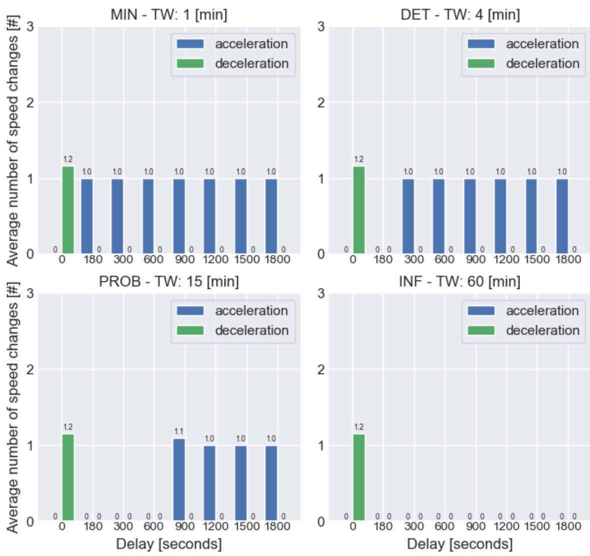

Figure 15: Speed changes - AZA1572

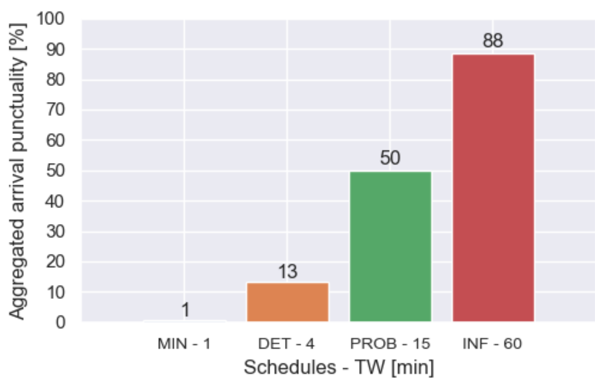

Figure 16: Punctuality - AZA1572

6.2. Flight TAP1015

This flight is flown with an Embraer ERJ145. The aircraft departs from Madrid (LEMD) and arrives at Lisbon (LPPT). It is therefore a relatively short flight and only has two waypoints. The aircraft departs at 13h15m and its cruise is flown over a distance of 165.4 NM. The *DET*-schedule uses a TW of 1 minute and the *PROB*-schedule a TW of 15 minutes.

Wind - TAP1015

From Figure 17 it can be concluded that the wind changes over the increasing delays. Not only the inter-quartile range (IQR) changes, but the median moves as well for both components of the wind. In the case of the North-component, two different processes are observed. At the first waypoint, the IQR moves deeper into the positive field of the y-axis which indicates a stronger and positive direction when delays are introduced. The second waypoint shows the same median over increasing delays, but a wider IQR. This indicates a higher spread in the North-component of the wind between the ensembles when the delay increases. The East-component of the wind shows a similar trend between both waypoints. The IQR moves into the negative field of the y-axis. This implies that the East-component of the wind moves towards a stronger and negative direction when delays are introduced.

Speed Changes - TAP1015

The speed changes of the aircraft are shown in Figure 18. As both TWs for the *MIN*- and *DET*-schedule are 1 minute wide, the schedules produce identical results with respect to speed changes. The plots show accelerations and decelerations up to a delay of 300 seconds. This indicates that the aircraft are able to catch up with their delay of up to 300 seconds. Delays which exceed 300 seconds are only caught up partially. This conclusion is confirmed by Figure 19 which shows a detailed breakdown on the punctuality of the *DET*- and *PROB*-schedule by waypoint. An aircraft with a delay of 300 seconds, following the *DET*-schedule, is able to arrive at the last waypoint on time. The *PROB*-schedule shows little to no accelerations for delays up to 600 seconds. A delay of 900 seconds corresponds with the width of the TW and forces the aircraft to start on the edge of the TW. Due to the effect of the wind, this can lead to a mixture of accelerations and decelerations. Delays of 1200 seconds and larger show identical behaviour. Figure 21 also shows that aircraft with 1200 seconds of delay, following the *PROB*-schedule, are able to arrive on time at their destination. Aircraft with larger delays are unable to catch up entirely. The *INF*-schedule has the largest TW and has no speed changes with increasing delays. Only the aircraft without a delay has some speed changes as the aircraft starts the cruise on the edge of the TW. Although the A-FMS doesn't take the wind

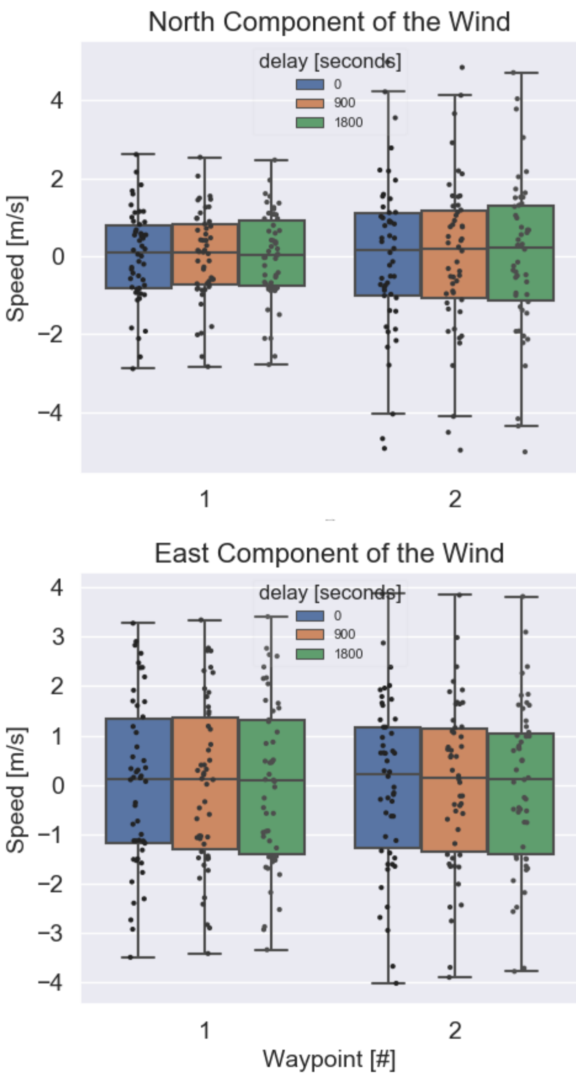

Figure 17: Wind - TAP1015

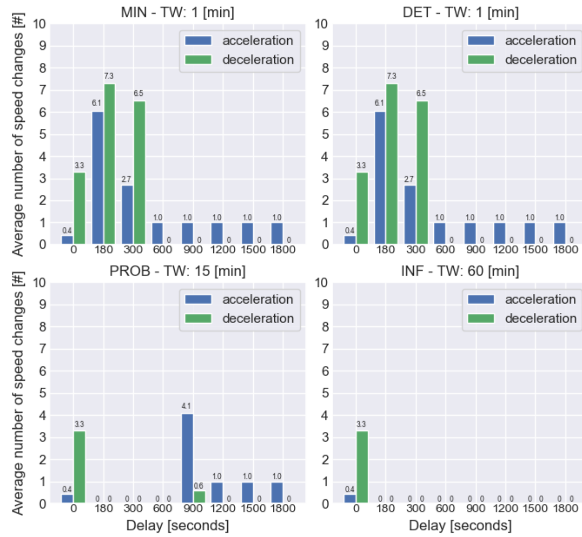

Figure 18: Speed changes - TAP1015

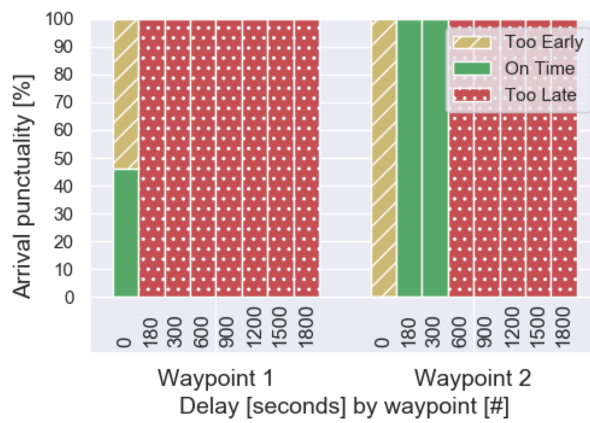

Figure 19: Punctuality - [DET] TAP1015

into account, it will still try to account for these deviations as best as possible. However, the instructions will carry a delay on its response which force the A-FMS to send subsequent instructions as shown in Figure 18.

Punctuality - TAP1015

The punctuality assessment for this flight is shown in Figure 22. As the *MIN*- and *DET*-schedule use 1 minute as their size for their TW, the punctuality assessment becomes identical. The scoring for these schedules is set at 15% as the aircraft is only able to catch up with small delays at the last waypoint. The *PROB*-schedule holds a much higher punctuality at 57%. This is due to the bigger TW and the ability to catch up with delays of up to 1200 seconds at the final waypoint. The *INF*-schedule is able to achieve a score of 90%. The cause for such a high score is the sheer size of the TW. At this point, the score is restricted due to an early arrival when the aircraft has no delay.

Fuel Consumption - TAP1015

Figure 20 presents the various fuel consumption by schedule and delay. It's observed that the lowest fuel consumption occurs when the aircraft has no delay. This amounts to 437 kg and can be explained by the deceleration of the aircraft. The highest fuel consumption is set at 470 kg and occurs when the entire cruise is flown at maximum speed. The *MIN*- and *DET*-schedule have a similar fuel consumption as both of their TW's are 1 minute. The fuel consumption for these schedules increases steadily up to the ceiling with increasing delays. The *PROB*-schedule holds the same fuel consumption until a delay of 1200 seconds or greater has been encountered. From this delay onward, the fuel consumption increases towards the maximum value. The delay of 1500 seconds shows a smaller value than the delay of 1200 seconds and 1800 seconds. This discrepancy is caused by an instability in the A-FMS which leads to a delayed acceleration of the aircraft. This means that the aircraft flies longer on its desired cruise speed than intended and is able to conserve its fuel despite the delay.

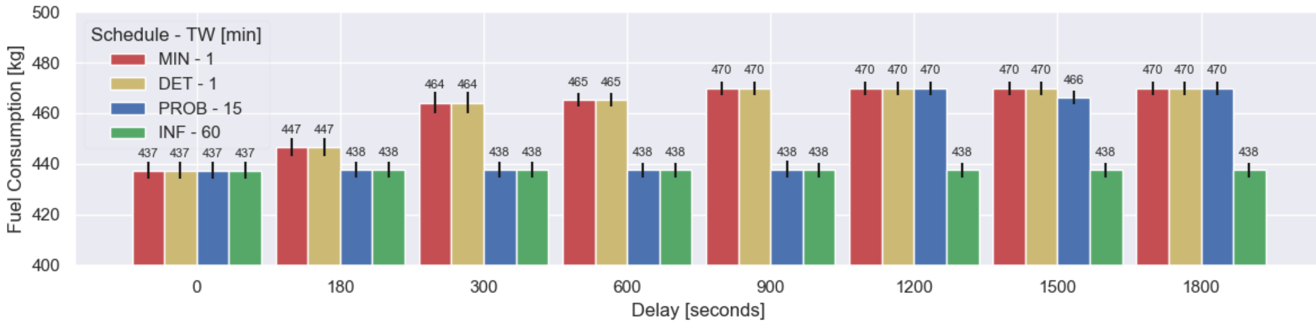

Figure 20: Fuel consumption - TAP1015

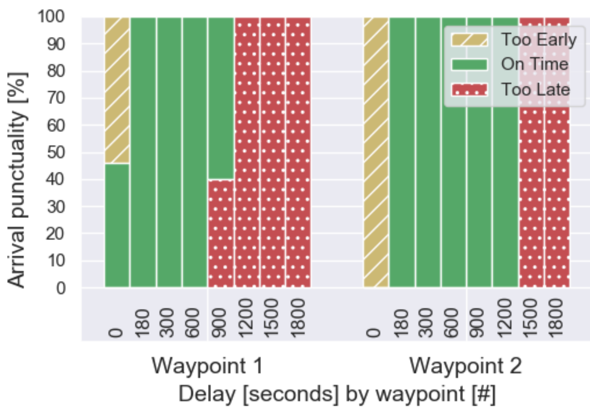

Figure 21: Punctuality - [PROB] TAP1015

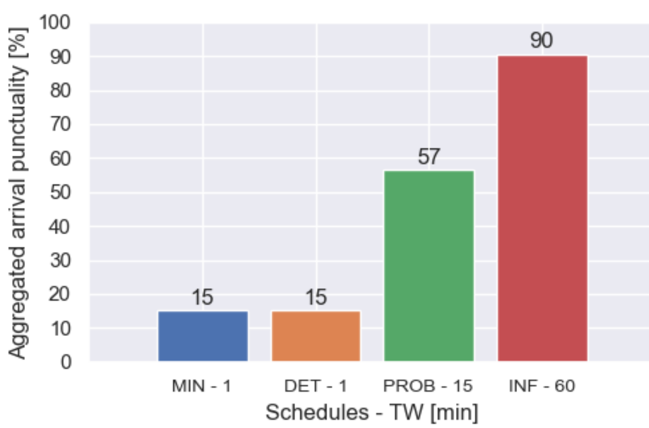

Figure 22: Punctuality - TAP1015

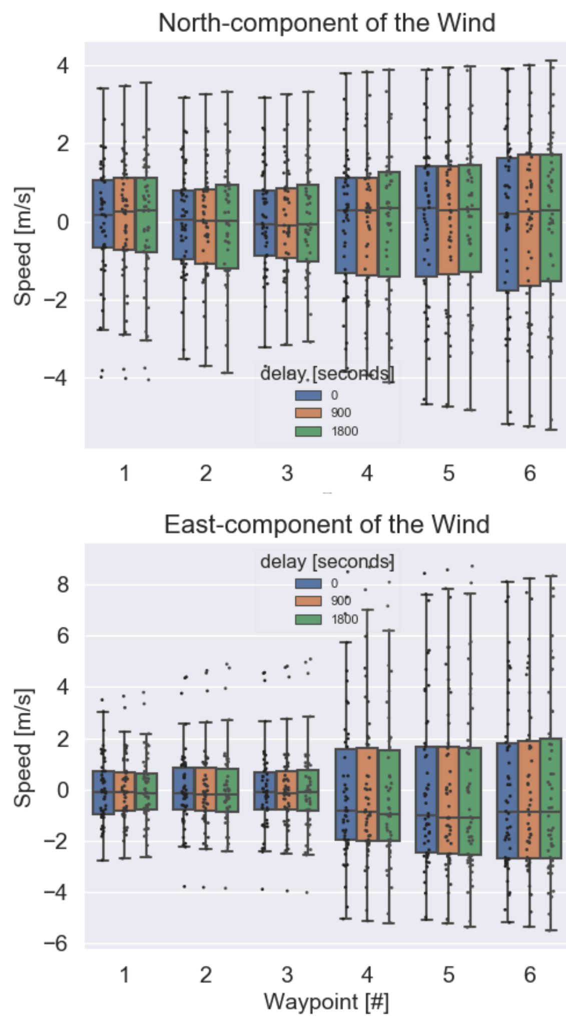

Figure 23: Wind - BEL7PC

6.3. Flight BEL7PC

Flight BEL7PC is flown in an Airbus A319. The flight departs from Brussels Airport (EBBR) at 14h49m and arrives at Milan Linate Airport (LIML). The cruise is flown over a distance of 163.7 NM and the trajectory has 6 waypoints. Both the *DET*- and *PROB*-schedule use a TW of 15 minutes.

Wind - BEL7PC

The magnitude of the wind over this trajectory is shown in Figure 23. The North-component of the wind shows an increasing IQR over the waypoints. This indicates that the ensembles have a larger variability amongst each other. The shape of the boxplot also changes over delays. A general trend can be observed where the minima and maxima of the boxplot move towards extremer values. This indicates a sharper contrast between ensembles. The median stays fairly consistent over the delays. The East-component of the wind shows a different trend. When the wind is inspected from waypoint 1 to 3, it can be determined that the wind stays relatively constant with increasing delays. The magnitude of the wind fluctuates mostly between -1 and 1 m/s. The median doesn't change and the IQR shows only slight changes. From waypoint 4 onward, the IQR increases significantly in size. This implies that there is a much bigger variance between ensembles and the strength of the wind increases. The IQR remains nearly constant with increasing delays. For waypoint 4 and 5, the median moves very slightly while for waypoint 6 it stays constant.

Speed Changes - BEL7PC

The speed changes for this flight are shown in Figure 24. As the aircraft starts at an edge of the TW, there are both accelerations and decelerations present for the case without delay. It can be seen that the *MIN*-schedule has a big spike in speed changes when a delay of 180 seconds is introduced. This is caused by the small size of the TW and a strong tailwind. When the aircraft enters back into its TW, the aircraft will be instructed to fly at its cruise speed. If the aircraft is still near the edge of the TW, then the tailwind drifts the aircraft out of the TW. The A-FMS will notice this drift and instruct a small deceleration to correct for it. As the wind isn't taken into account by the A-FMS, the deceleration might not be sufficient for strong tailwinds. The A-FMS will then reissue small decelerations until the aircraft stays within the TW. The *DET*- and *PROB*-schedule display an identical response from the A-FMS as the TW is 15 minutes for both schedules. There are no instructions from the A-FMS until a delay of 900 seconds is introduced which corresponds with the size of the TW. At a delay of 900 seconds, the aircraft starts at the edge of the TW and a mixture of accelerations and decelerations are generated. Subsequent greater delays than 900 seconds only generate a single acceleration to minimise the delay. The *INF*-schedule generates no instructions when a delay is introduced as expected.

Punctuality - BEL7PC

Figure 25 displays the punctuality on a per schedule basis. The *MIN*-schedule scores exceptionally low at 5%. This is caused by the strong tailwind which forces the aircraft to arrive too early at the final waypoint for the no-delay case. The *DET*- and *PROB*-schedule score the same at 52%. The *INF*-schedule scores a 90%. Just like the *MIN*-schedule, the other three schedules are negatively impacted on their score due to early arrivals as well.

Fuel Consumption - BEL7PC

The fuel consumption for this trajectory is displayed in Figure 26. The minimum fuel consumption for this flight is set at 672 kg and is reached by every schedule without a delay. This is caused by the decelerations due to the tailwind which allows the aircraft to save even more fuel. The *MIN*-schedule reaches the maximum fuel consumption of 740 kg when a delay of 600 seconds or greater is introduced. This indicates that the schedule is able to catch up with delays of up to 300 seconds. The *DET*- and *PROB*-schedule behave similarly with respect to their fuel consumption. They reach

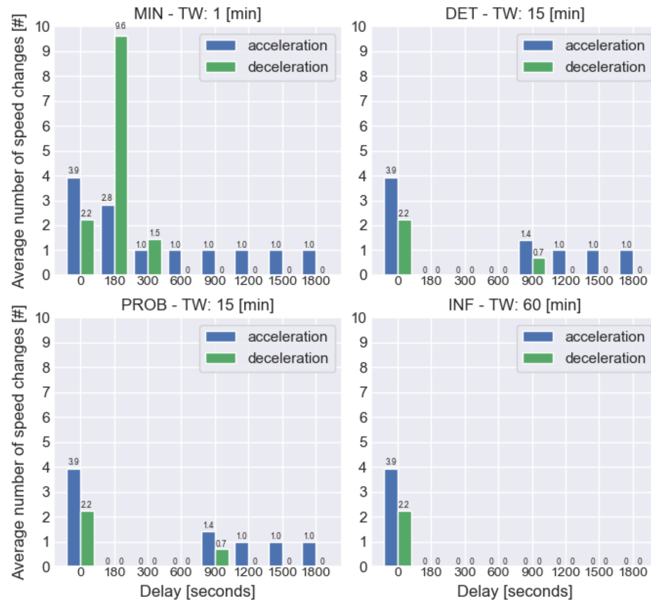

Figure 24: Speed changes - BEL7PC

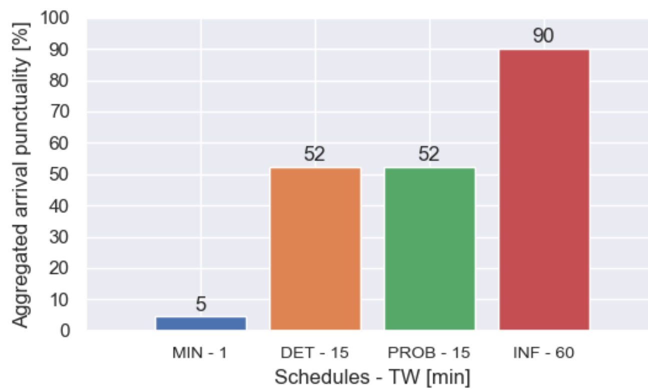

Figure 25: Punctuality - BEL7PC

the maximum fuel consumption from 1500 seconds onward. Aircraft with 1500 or 1800 seconds of delay are unable to catch up. The *INF*-schedule holds the same fuel consumption for every delay beyond the no-delay case.

6.4. Flight EXS79G

A Boeing 737-300 is used for Flight EXS79G. The aircraft departs from Leeds Bradford Airport (EGNM) at 13h30m. The destination for this flight is Madeira Airport (LPMA). The length of the cruise is set at 710.5 NM and the trajectory has 8 waypoints. Both the *DET*- and *PROB*-schedule use a TW of 15 minutes.

Wind - EXS79G

The wind distribution between ensembles is shown in Figure 27. The North-component of the wind shows a significant amount of wind of up to 1.5 or -1.5 m/s within the IQR. This strength stays relatively constant over the first 7 waypoints of the trajectory with some movements of the minima and maxima. The last waypoint shows an overall in-

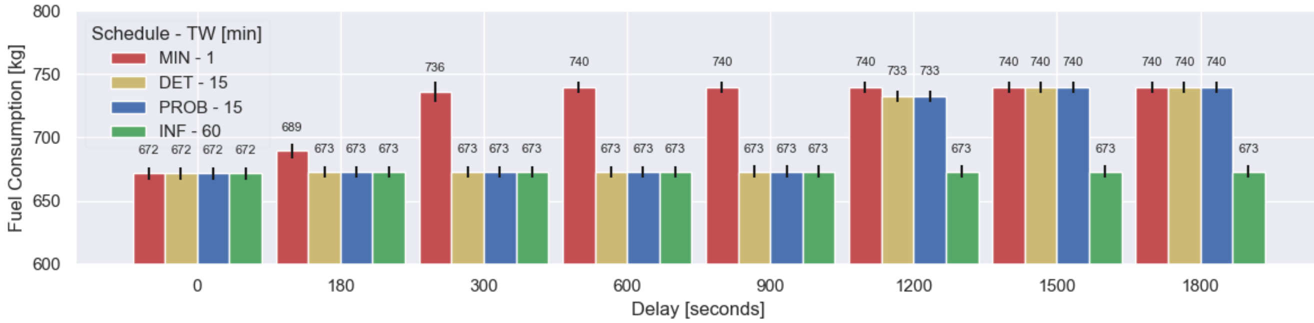

Figure 26: Fuel consumption - BEL7PC

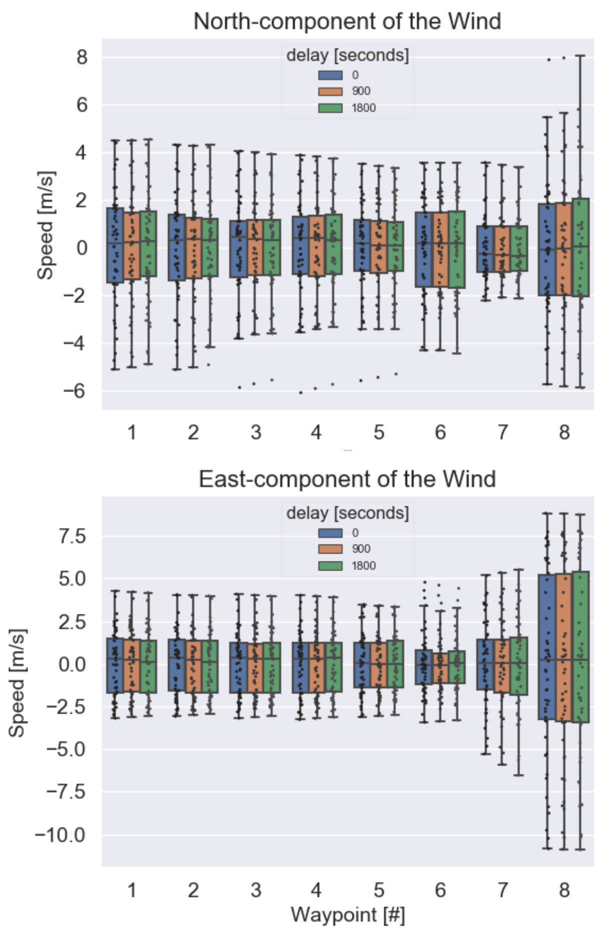

Figure 27: Wind - EXS79G

crease in strength with strong outliers. The East-component of the wind shows a similar trend. The first 6 waypoints have an IQR between 1.5 and -1.5 m/s. However, the minima show a much smaller strength in comparison to the North-component. The seventh and eight waypoint show much stronger minima and maxima. The IQR range of the eight waypoint spans from 5 to -3 m/s which is a larger span than the entire boxplots of previous waypoints. The wind at this waypoint varies much by ensemble and is able to reach speeds of 9 to -10 m/s. As the average is subtracted from every wind measurement, this can be an indication of strong wind fore-

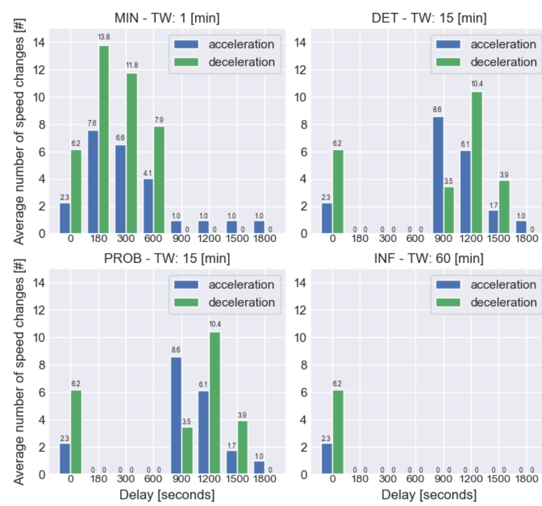

Figure 28: Speed changes - EXS79G

casts. Small perturbations in the measurement can therefore lead to large differences.

Speed Changes - EXS79G

The speed changes for Flight EXS79G are displayed in Figure 28. The number of speed changes over this flight is noteworthy. For the *MIN*-schedule, the number of speed changes are very high up to and including a delay of 900 seconds. As the distance of the cruise is over 700 NM long, it's plausible for an aircraft to catch up with considerable delays. However, this is achieved by accelerating the aircraft early on in the flight and decelerating when the aircraft enters into its TW. This shouldn't lead to the number of speed changes as presented in Figure 29. The detailed punctuality of the *MIN*-schedule is shown in Figure 30. It can be concluded that aircraft with delays of up to 600 seconds arrive too early at their final destination despite their initial delay. Moreover, most of these aircraft arrive on time at waypoint 7. This indicates that the aircraft is pushed ahead of the TW due to a tailwind. The A-FMS will generate subsequent decelerations to still match the TW. However, as the wind is strong at the end of the trajectory as indicated by Figure 27, the A-FMS is unable to sufficiently decelerate the aircraft to match the TW. This behaviour holds for the other schedules as well

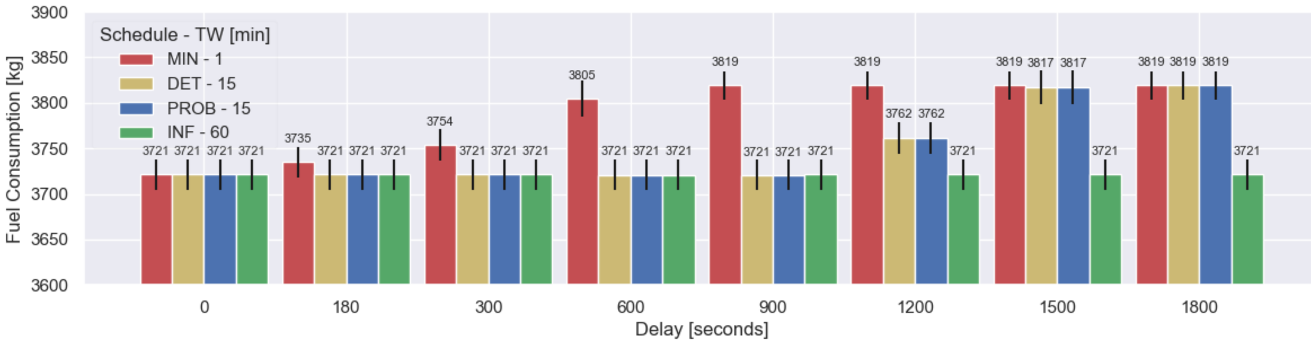

Figure 29: Fuel consumption - EXS79G

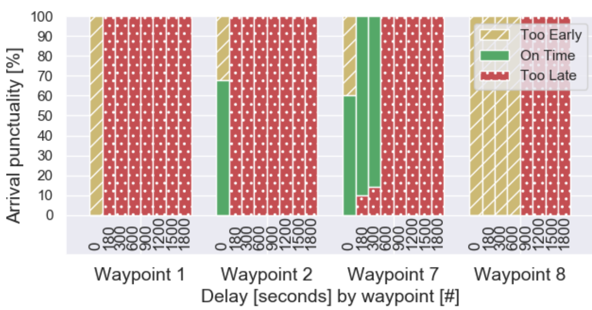

Figure 30: Punctuality - [MIN] EXS79G

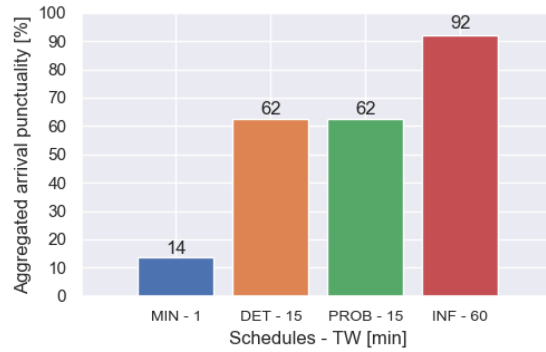

Figure 31: Punctuality - EXS79G

except for the *INF*-schedule. The TW of the *INF*-schedule is large enough to avoid any speed changes from the A-FMS when the aircraft is delayed. Only when the aircraft has to be instructed near the edge of a TW will the speed input of the A-FMS become cluttered due to a strong tailwind.

Punctuality - EXS79G

The punctuality for Flight EXS79G is assessed in Figure 31. The *MIN*-schedule reached a score of 14%. This is caused by the tailwind over this trajectory which forces the aircraft to arrive too early at their destination despite being able to match the TW. The *DET*- and *PROB*-schedule reached the score of 62%. This score is achieved by a wider TW and the ability of the aircraft to catch up with significant amount of delays. This ability is brought about by the tailwind and the length of the trajectory. The score of these schedules is bound by the aircraft's ability to match TW's at intermediate waypoints. The *INF*-schedule is able to attain a score of 92%. The score is exceptionally high already, but could be further improved if the aircraft was able to decelerate more effectively in the case without a delay.

Fuel Consumption - EXS79G

The fuel consumption for Flight EXS79G is shown in Figure 29. The minimum fuel consumption is achieved by every aircraft as long as it doesn't start outside the TW. The *MIN*-schedule shows an increasing fuel consumption with flight delay until a ceiling is reached. The maximum fuel consumption of 3819 kg is reached from delays of 900 seconds or larger. The *DET*- and *PROB*-schedule show no increase in fuel consumption until delays of 1200 seconds are introduced. At a delay of 1500 seconds the fuel consumption is a little short of reaching the ceiling. When delays of 1800 seconds are introduced, these schedules will reach this maximum. The *INF*-schedule shows no changes in the fuel consumption and is able to hold on to the minimum fuel usage across every delay.

6.5. Aggregated analysis of Set I

This set of flights consists of 45 flights and each one departed from 'Spawn Point 1' as depicted in Figure 6. The flights are categorised by their duration in Table 1 and by their distance in Table 2. The duration indicates the time segment planned for the cruise of a flight. The distance indicates the distance covered during the cruise according to the flight plan.

Table 1
Set I by duration of the cruise phase

Duration [min]	Number of Flights
0 - 30	21
30 - 60	11
60 - 90	2
90 - 120	5
120 - 150	2
150+	4
Total Flights	45

Table 2
Set I by distance of the cruise phase

Distance [NM]	Number of Flights
0 - 250	22
250 - 500	9
500 - 1000	9
1000 - 1500	2
1500 - 2000	-
2000+	3
Total Flights	45

An important outcome of the results is the effect of the TW size for the no-delay cases. As can be concluded from the previous chapters, the behaviour of the aircraft within flights and between schedules is very similar to the *MIN*-schedule regardless of the TW size. This is caused by the fact that the aircraft is only allowed to arrive later, but not earlier. Any tailwind that pushes the aircraft to arrive earlier will force the A-FMS to decelerate the aircraft to arrive later. A TW will therefore only benefit the aircraft in the case of delays. The larger the TW becomes, the more delay can be caught up with.

Punctuality

The punctuality by schedule is shown in Figure 32. As can be seen, the *MIN*-schedule scores the worst of all the schedules and the *INF*-schedule the best. These conclusions are rather straightforward due to the TW sizes used by these schedules. The *DET*- and *PROB*-schedule use a varying size by trajectory. The *DET*-schedule has a great majority of their flights in the bracket of 50 to 60%. The other flights are distributed among the remaining brackets in the range of 10 to 80%. The *PROB*-schedule has most of the flights in the 50 to 60% bracket as well. However, more flights fall into this bracket and the remaining flights are distributed in the range of 40 to 80%. This indicates that the *PROB*-schedule outperforms the *DET*-schedule with respect to punctuality.

Fuel Consumption

The fuel consumption between the schedules is compared in Table 3. As expected, a constriction on the width of a TW leads to an increase in fuel consumption. The biggest increase in fuel consumption is reached by the *MIN*-schedule with an increase of 1.15%. The *PROB*-schedule outperforms the *DET*-schedule by a very small margin of 0.02%.

Table 3
Fuel consumption by schedule of Set I

MIN	*DET*	*PROB*	*INF*
1709223 kg +1.15%	1697717 kg +0.47%	1697508 kg +0.45%	1689853 kg —

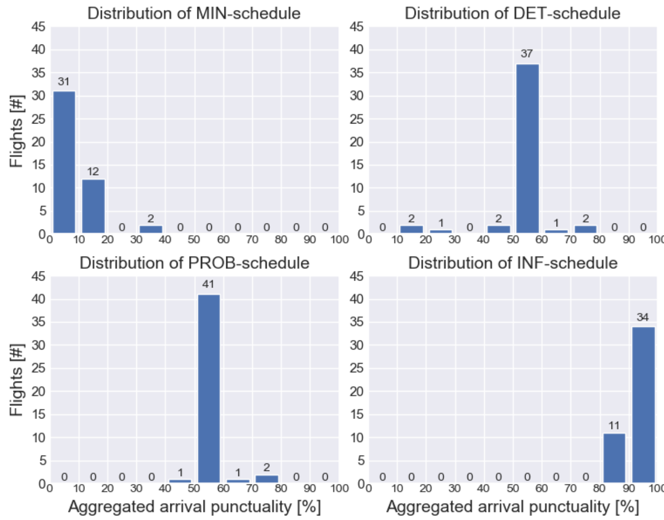

Figure 32: The punctuality assessment by schedule of Set I

7. Results of Set II

The analysis in this chapter is focused on a set of flights from EUROCONTROL's DDR2 database where the destination is set on Munich Airport (EDDM). This set of flights uses 'Spawn Point 2' as depicted in Figure 6 to define the TW. Three schedules with different TW's will be tested. These schedules are the *MIN*-, *DET*- and *INF*-schedules. The *MIN*-schedule will always use 1 minute as the size of its TW. Likewise, the *INF*-schedule will always use 60 minutes for the size of its TW. The *DET*-schedule uses a deterministic approach to optimise the size of the TW for the entire set. This leads to a varying TW size by flight for the *DET*-schedule. From this set, several flights will be analysed into more depth; Flight DLH2557 in Chapter 7.1, Flight IBE31DD in Chapter 7.2 and Flight SAS4759 in Chapter 7.3. An aggregated analysis on the entire set of flights is performed in Chapter 7.4.

7.1. Flight DLH2557

Flight DLH2557 is flown using an Airbus A321. The aircraft departs from Tbilisi International Airport (UGTB) at 01h49m. The destination for this flight is Munich Airport (EDDM).The length of the cruise is set at 1058.0 NM and the trajectory has 15 waypoints. The *DET*-schedule uses a TW of 1 minute.

Wind - DLH2557

The wind on this trajectory for odd numbered waypoints is shown in Figure 33. The North-component of the wind shows that the size of the IQR varies slightly over the waypoints. The minima and maxima change significantly in magnitude between the waypoints which indicates that the variation differs. This is in contrast to the small differences between delays. The East-component of the wind shows larger magnitudes on its IQR, minima and maxima. The minima and maxima up to waypoint 9 show a large deviation from the IQR as well. This indicates a high variance between the

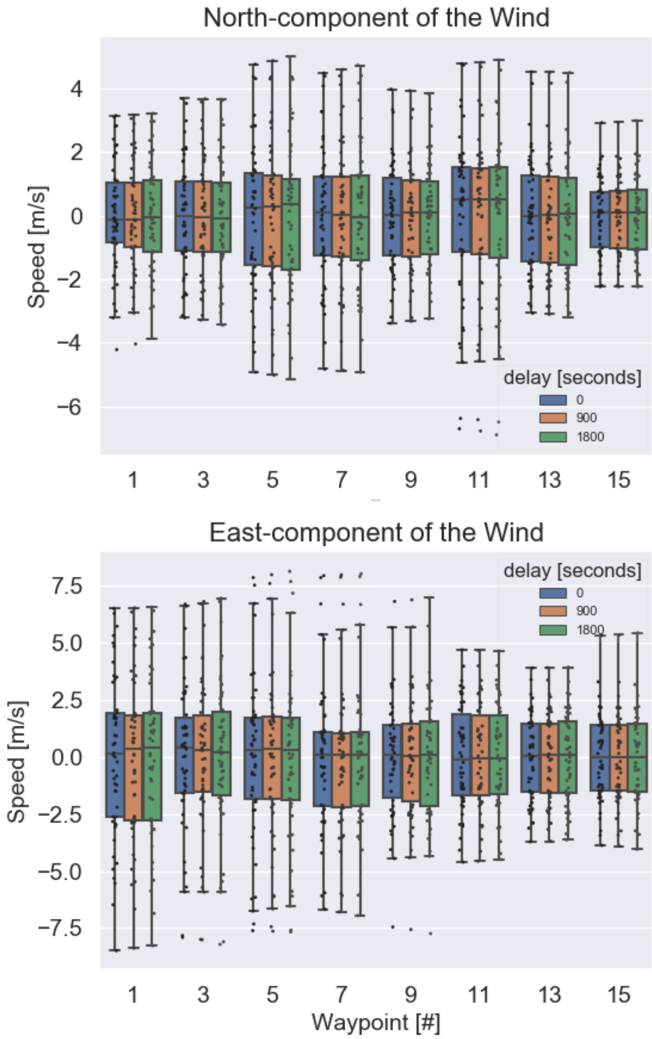

Figure 33: Wind - DLH2557

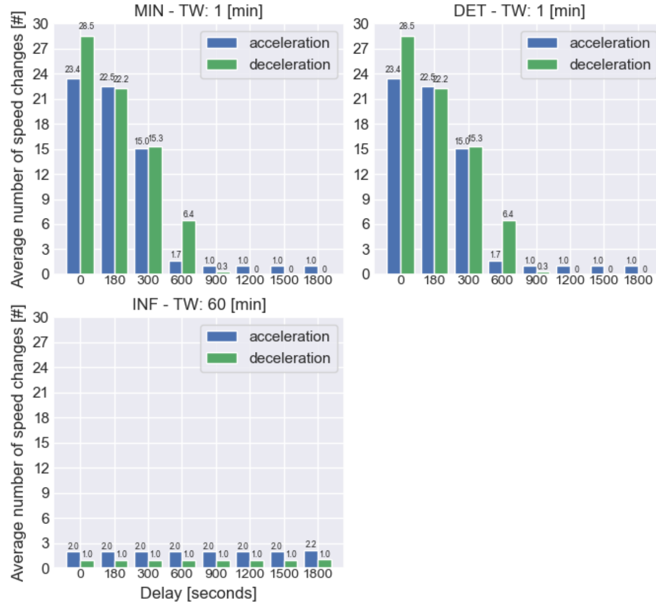

Figure 34: Speed changes - DLH2557

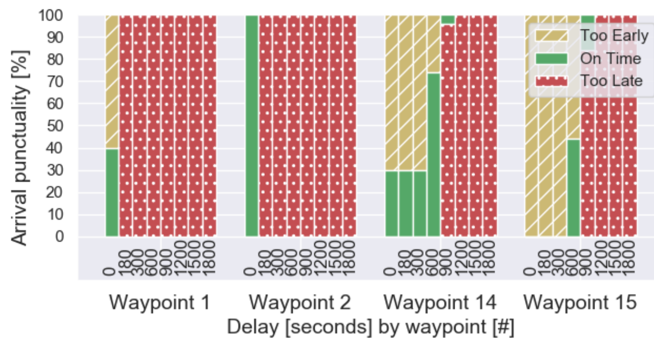

Figure 35: Punctuality - [MIN] DLH2557

ensembles. From waypoint 11 onward, the outliers, minima and maxima are situated closer to the IQR which leads to a more consistent forecast.

Speed Changes - DLH2557

The speed changes for Flight DLH2557 are shown in Figure 34. As the *DET*-schedule uses the same TW as the *MIN*-schedule, the results will therefore be identical. The high number of speed changes is notable, especially for the no delay case. A detailed punctuality assessment for the *MIN*-schedule is shown in Figure 35 for the first two and last two waypoints. The figure shows that for delays of up to 300 seconds, the flight will arrive too early at its destination. This indicates that a tailwind is present which couldn't be accounted for by the A-FMS. This can be attributed to the size of the TW as it's only 1 minute wide. The A-FMS will therefore send subsequent messages to try to stay within the TW. As the delay increases, the A-FMS sends less decelerations as well. The *INF*-schedule shows the least number of speed changes as the TW is very large. The speed changes that do show up are necessary as even flights with the largest delay don't start outside the TW.

Punctuality - DLH2557

The punctuality assessment of Flight DLH2557 is shown in Figure 37. The *MIN*- and *DET*-schedule show the same low punctuality score. This can be attributed to the small size of their TW. The *INF*-schedule obtained the highest punctuality score possible. This is ascribed to the large size and the position of the TW. The flight is therefore able to absorb significant delays and (strong) tailwinds while adhering to the TW.

Fuel Consumption - DLH2557

Figure 36 shows the fuel consumption of Flight DLH2557. As the size of the TW is of equal size between the *MIN*- and *DET*-schedules, the fuel consumption are identical as well. It can be seen that the lowest fuel consumption is set at 6436 kg. This is achieved by the entire *INF*-schedule and every aircraft without a delay. When a delay is introduced, the fuel consumption increases to a maximum of 6528 kg. This occurs from a delay of 900 seconds or larger. Figure 35 shows

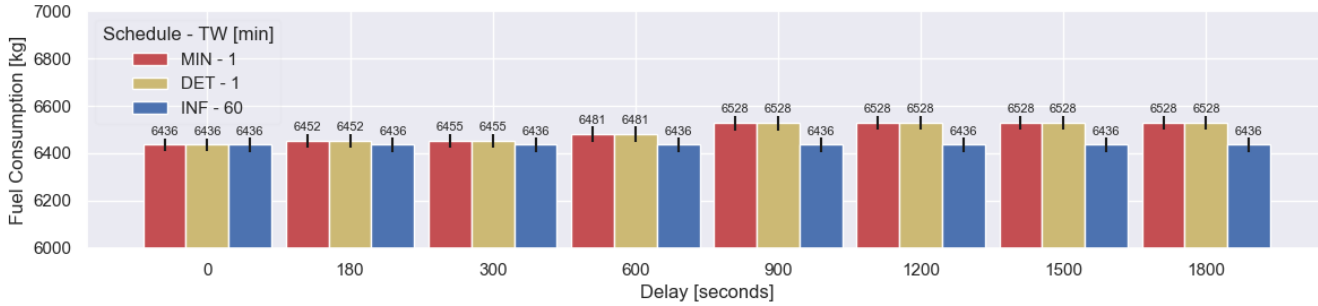

Figure 36: Fuel consumption - DLH2557

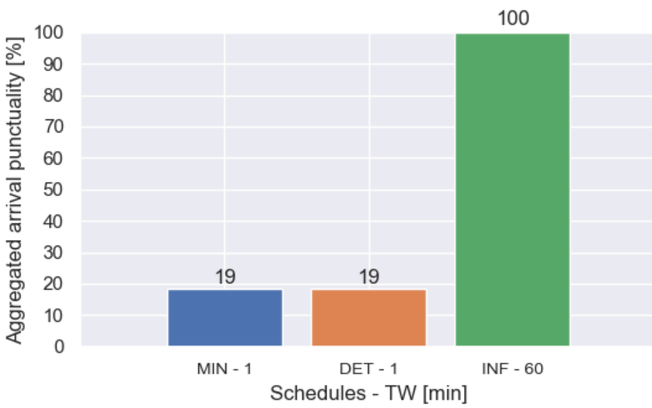

Figure 37: Punctuality - DLH2557

that delays of 900 seconds don't, in most cases, arrive on-time at their final waypoint. This implies that the aircraft flies the entire trajectory at maximum speed. Hence, the figure shows no difference in fuel consumption with larger delays while having an improved punctuality.

7.2. Flight IBE31DD

An Airbus A319 is used for the execution of Flight IBE31DD. The trajectory consists of 23 waypoints over a distance of 460.0 NM. The aircraft departs from Madrid–Barajas Airport (LEMD) at 18h11m and arrives at Munich Airport (EDDM). The *DET*-schedule uses a TW of 5 minutes.

Wind - IBE31DD

The velocities of the wind at every 3rd and final waypoint are shown in Figure 38. The North-component of the wind shows a large size for its IQR along with large magnitudes for its minima and maxima. This indicates a high variance between ensembles which could be the result of a strong wind. With respect to delays, the wind remains rather consistent. The East-component of the wind shows a similar trend of high variance and large magnitudes. However, the variance lowers as the aircraft moves further along the trajectory. And like the North-component, the wind shows a strong similarity at a waypoint even when delays are introduced.

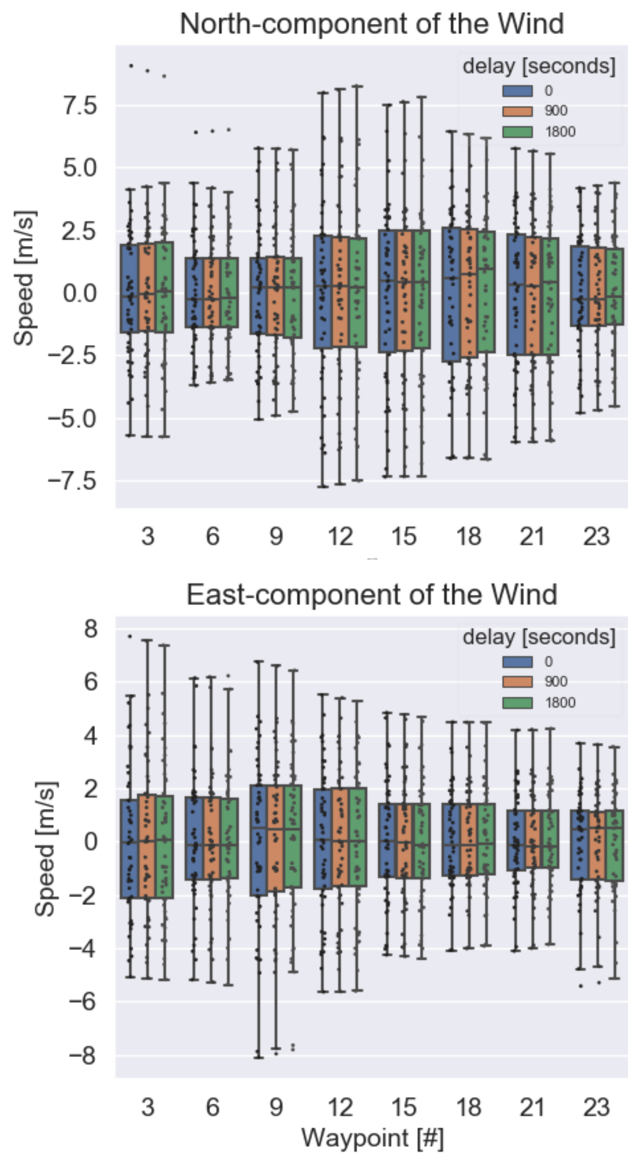

Figure 38: Wind - IBE31DD

Speed Changes - IBE31DD

The speed changes on this trajectory are shown in Figure 40. The *MIN*-schedule shows an expected behaviour. As the aircraft only has a TW of 1 minute, the A-FMS will

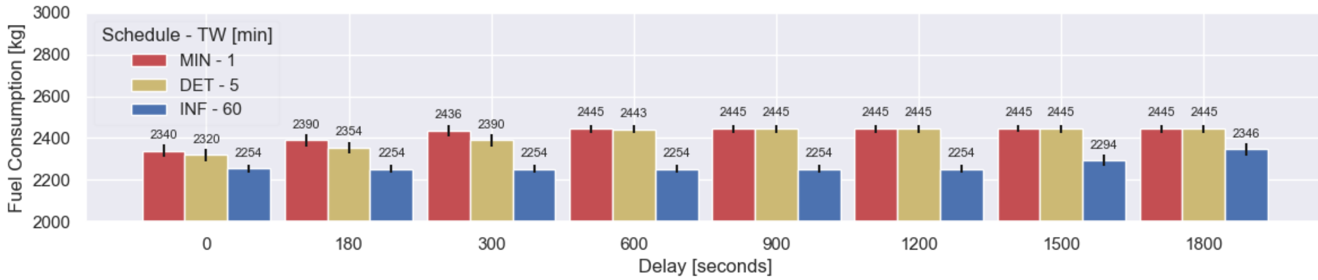

Figure 39: Fuel consumption - IBE31DD

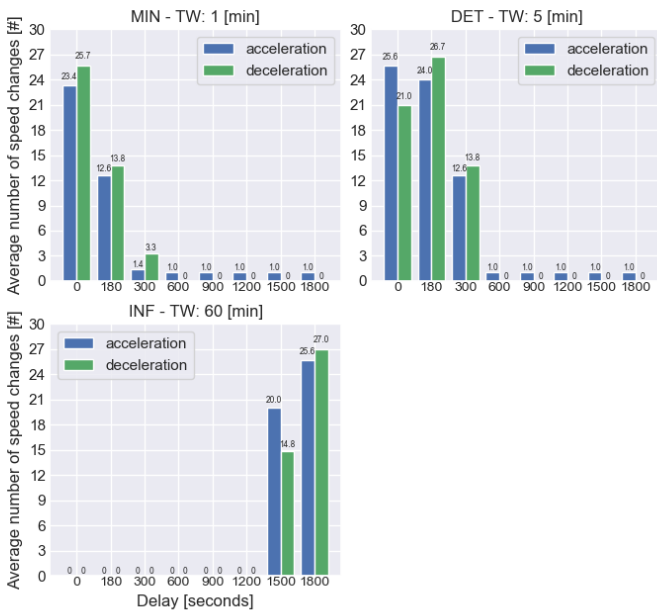

Figure 40: Speed changes - IBE31DD

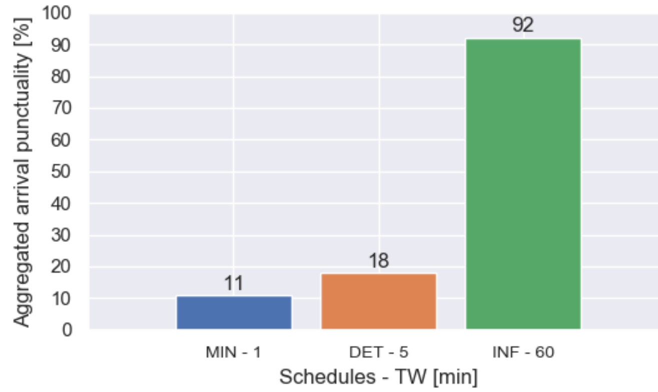

Figure 41: Punctuality - IBE31DD

need a lot of corrections to keep the aircraft within it. Note that the A-FMS sends both accelerations and decelerations to stay within the TW. As a delay is introduced and the delay increases, the number of speed changes are reduced. The *DET*-schedule shows a similar trend. Despite having a significantly larger TW, the aircraft requires a similar amount of speed changes to adhere to it. As the aircraft is subject to a strong wind while being near the edge of a TW, the aircraft will undergo a series of accelerations and decelerations. The aircraft will accelerate to get back into the TW and then decelerate to the cruise speed after meeting the TW. Since there is a higher number of waypoints than usual, the process will repeat itself more often. The *INF*-schedule shows the same behaviour when a delay is introduced where the aircraft reaches the edge of the TW. This happens at delays of 1500 and 1800 seconds.

Punctuality - IBE31DD

The punctuality of this trajectory is shown in Figure 41. As expected, the *MIN*-schedule scores the worst at 11%. This score can be attributed to the combination of strong wind and the small size of the TW. As the TW increases in size, the ability of the aircraft to deal with the wind improves. The *DET*-schedule obtains a punctuality score of 18%. The *INF*-schedule scores the highest at 92%.

Fuel Consumption - IBE31DD

The fuel consumption on Flight IBE31DD is presented in Figure 39. The minimum fuel consumption is set at 2254 kg and is achieved only by the *INF*-schedule up to delays of 1500 seconds. Delays of 1500 seconds or larger correlate with an increase in fuel consumption. The *MIN*-schedule uses 2340 kg of fuel without a delay. When a delay is introduced, the fuel consumption increases up to a maximum of 2445 kg. A similar pattern is observed with the *DET*-schedule. The lowest fuel consumption for this schedule is set at 2320 kg. As the delay increases, the fuel consumption increases as well.

7.3. Flight SAS4759

Flight SAS4759 is carried out by a Boeing 737-800. The trajectory contains 22 waypoints over a distance of 445.1 NM. The aircraft departs at 11h00m from Oslo Airport (ENGM) and arrives at Munich Airport (EDDM). The *DET*-schedule uses a TW of 5 minutes.

Wind - SAS4759

Figure 42 shows the wind over Flight SAS4759 at every 3rd waypoint. The North-component of the wind shows a wind of moderate strength along with a varying IQR. Not only does the IQR vary significantly between waypoints, but

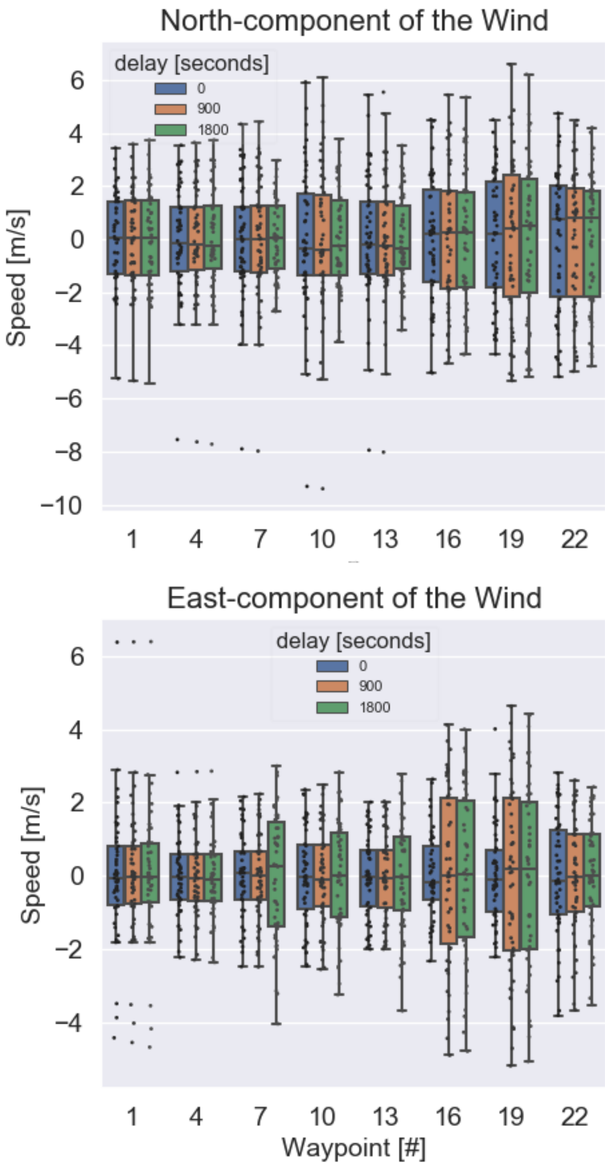

Figure 42: Wind - SAS4759

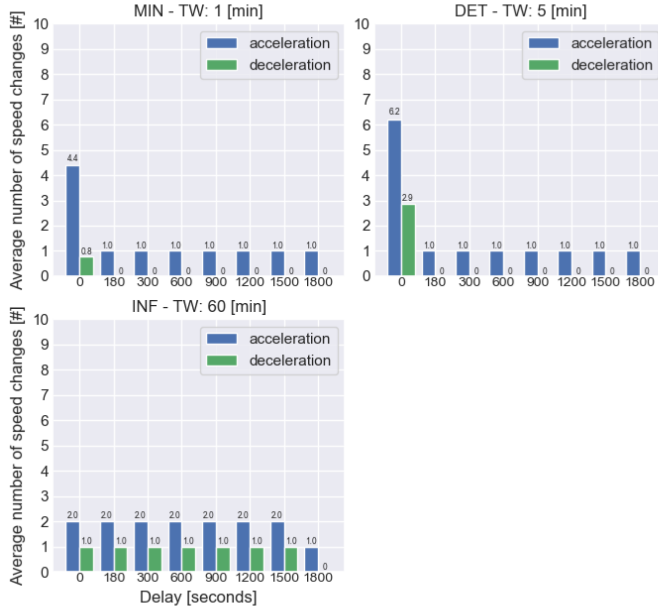

Figure 43: Speed changes - SAS4759

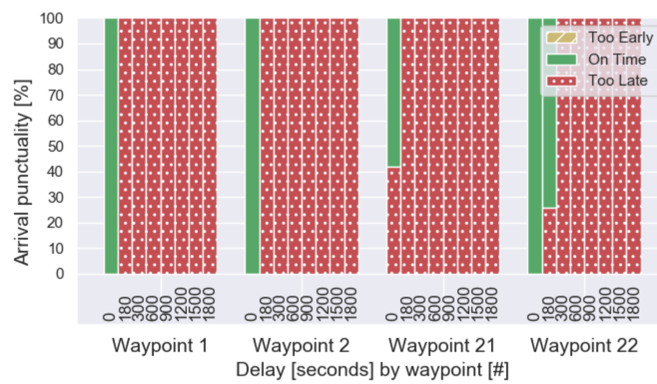

Figure 44: Punctuality - [DET] SAS4759

there are some slight changes over delays as well. The East-component of the wind shows a similar behaviour. The velocities are of the same order as the North-component, but with the presence of much stronger deviations. Waypoint 16 and 19 come across as the extremities on this trajectory. This indicates that aircraft who experience delays are subject to not only stronger winds, but also a different direction as well.

Speed Changes - SAS4759

The speed changes of this aircraft are shown in Figure 43. As can be seen, the *INF*-schedule has several speed changes despite having such a large TW. This is due to the fact that the trajectory has 3 flight level changes on its trajectory. Two of them increase the altitude and one of them decreases the altitude. A flight level change forces the A-FMS to calculate and instruct a new cruise speed for the aircraft. The *MIN*-schedule shows that when there is no delay, a set of mostly accelerations is instructed by the A-FMS. When a delay is encountered regardless of the size, only a single acceleration is instructed. This indicates that the schedule has little slack available and that a delay becomes hard to catch up with. In the case of the *DET*-schedule, the delay of 180 seconds forces the aircraft to start just outside of the TW and to catch up with at least 30 seconds. Figure 44 shows the detailed punctuality of this schedule for the first and last waypoints. As can be seen, over a quarter of the flights still arrive too late at the final waypoint.

Punctuality - SAS4759

The punctuality scores of Flight SAS4759 are shown in Figure 46. As expected, the *MIN*-schedule scores the worst at 2%. The combination of a small TW and a lack of slack in the schedule, contribute to the exceptionally low score. The *DET*-schedule scores 11% for its punctuality which can be attributed to the increased size of the TW. The *INF*-schedule scores the highest at 88%.

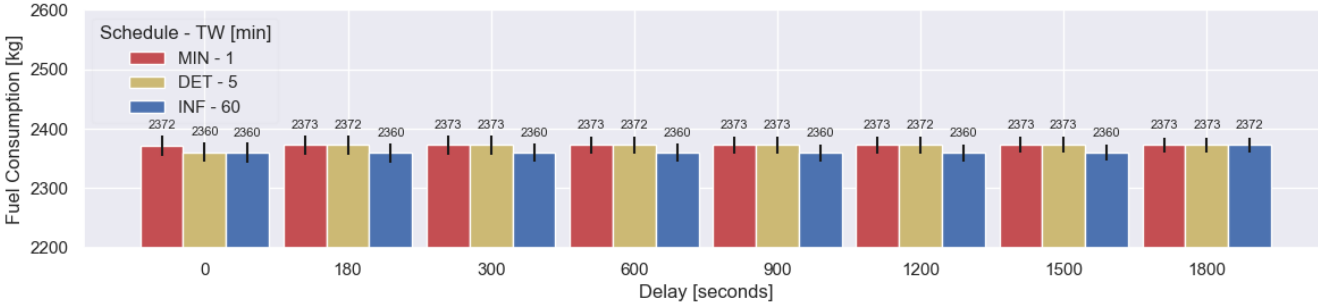

Figure 45: Fuel consumption - SAS4759

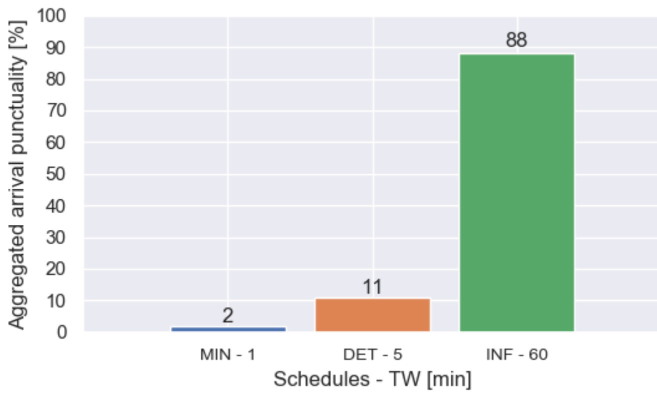

Figure 46: Punctuality - SAS4759

Fuel Consumption - SAS4759

The fuel consumption by the aircraft on this trajectory is shown in Figure 45. The minimum fuel consumption is set at 2360 kg and is only achieved by the *INF*-schedule with delays of up to 1800 seconds. The maximum fuel consumption is set at 2373 kg and is already reached when the aircraft is near the edge of its TW. This implies that the schedule hasn't much slack available and will result in a poor ability to catch up with delay. As can be seen, the *MIN*-schedule without delay already consumes 2372 kg of fuel. The *DET*-schedule with 180 seconds of delay departs just outside the TW and has to catch up with at least 30 seconds of delay. As shown in Figure 44, the aircraft is only able to catch up at the final waypoint. On such trajectories, the aircraft will rely predominantly on its TW to deal with delays.

7.4. Aggregated analysis of Set II

This set of flights consists of 30 flights and uses 'Spawn Point 2' which is depicted in Figure 6 as a reference for their TW. In contrast to flights that use 'Spawn Point 1', these flights are able to deal with winds better. This results from the fact that the TW expands in both directions and hence provides more leeway. Especially tailwinds can be taken better advantage of. The down-side is that only half the TW is made available to absorb delays. This becomes most notable when the aircraft has very little room to catch up with delays. The flights are categorised by their duration in Table 4 and by their distance in Table 5. The duration indicates the time segment planned for the cruise of a flight. The distance indicates the distance covered during the cruise according to the flight plan.

Table 4
Set II by duration of the cruise phase

Duration [min]	Number of Flights
0 - 30	2
30 - 60	6
60 - 90	11
90 - 120	5
120 - 150	5
150+	1
Total Flights	30

Table 5
Set II by distance of the cruise phase

Distance [NM]	Number of Flights
0 - 250	-
250 - 500	11
500 - 1000	12
1000 - 1500	7
1500 - 2000	-
2000+	-
Total Flights	30

Punctuality

The punctuality scores by schedule are shown in Figure 47. Most of the flights of the *MIN*-schedule reside in the category with the worst score. This result is attributed to the small size of the TW which stands in contrast to the *INF*-schedule whose scores belong to the best categories. Note that even in the *INF*-schedule, one of the trajectories scores between 40 and 50%. This indicates that a trajectory is invariant with respect to the TW. The *DET*-schedule shows, as expected, a score which lies between these two extremes. The score is distributed between 0 and 60% and shows significant improvement when compared with the *MIN*-schedule.

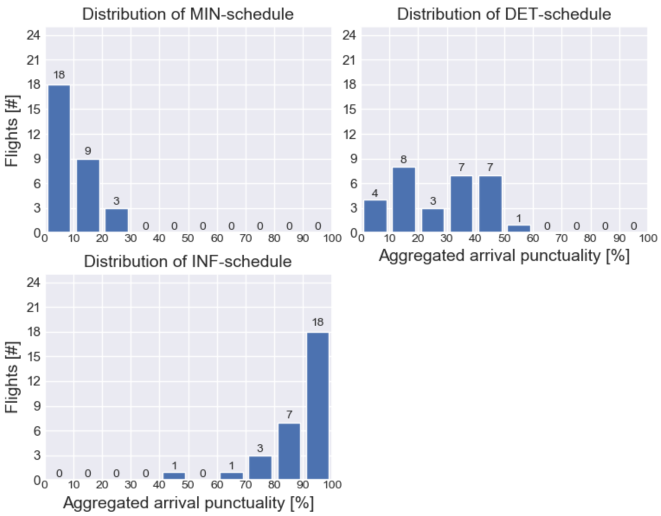

Figure 47: The punctuality assessment by schedule of Set II

Fuel Consumption

The fuel consumption between the schedules is compared in Table 6. The *MIN*-schedule uses overall the most amount of fuel. When compared to the *INF*-schedule, the fuel consumption is increased by 1.56%. The *DET*-schedule consumes less fuel than the *MIN*-schedule, but more than the *INF*-schedule. The difference is estimated to be 1.36% more than the *INF*-schedule. As anticipated, a larger TW correlates with a lower fuel consumption.

Table 6
Fuel consumption by schedule of Set II

MIN	*DET*	*INF*
978644 kg +1.56%	976758 kg +1.36%	963648 kg —

8. Sensitivity Analysis

A sensitivity analysis has been performed on the trajectories of Set I and Set II. This is done by simulating the same flights under the same conditions with the exception of the wind. The magnitude of the wind is tripled for these simulations. The trajectories and sets with the tripled wind will be prefixed by 'SA' (Sensitivity Analysis). Chapter 8.1 looks at this effect on Flight SA-AZA1572 and Chapter 8.2 at the effect on entire sets.

8.1. Flight SA-AZA1572

Flight SA-AZA1572 is executed on the same conditions as Flight AZA1572 with the exception of the wind. In the following sections, these flights will be compared to look at the effect of tripling the wind on the metrics. Chapter 6.1 provides further detailed information on this flight.

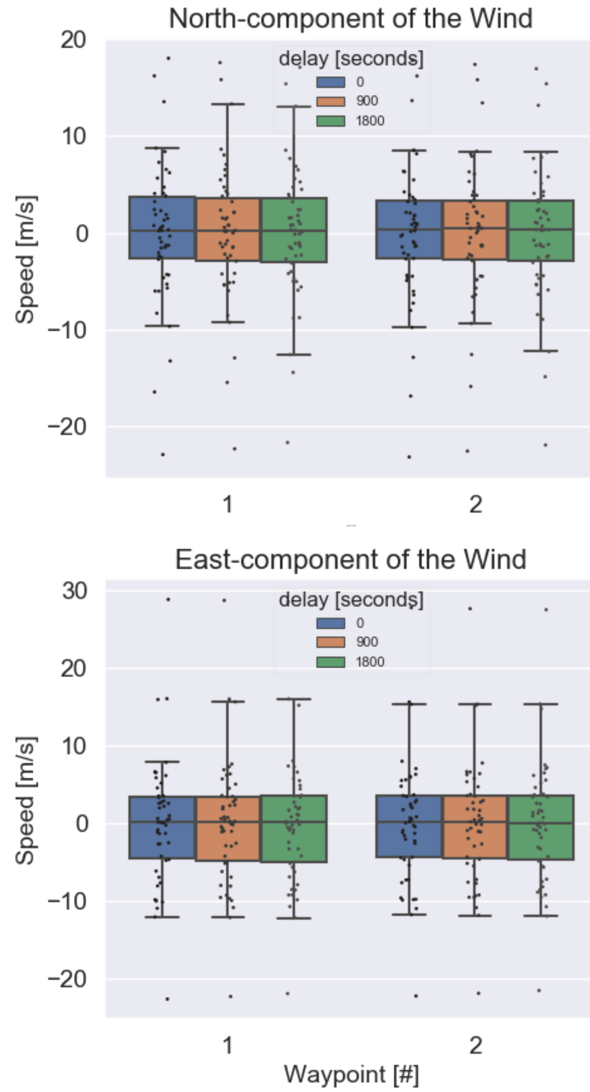

Figure 48: Wind - SA-AZA1572

Wind - SA-AZA1572

Figure 48 shows the wind at the waypoints of Flight AZA1572. When compared with Figure 13, it can be confirmed that the magnitude of the wind has indeed tripled at those waypoints. As expected, the shape of the box plots still remains identical between both simulations. This indicates that the variance hasn't changed and the wind has been implemented as intended.

Speed Changes - SA-AZA1572

Figure 50 presents the speed changes on this trajectory. When compared with Figure 15, it's observed that the decelerations significantly increase in number. This is caused by the A-FMS when it tries to deal with a tailwind. The A-FMS doesn't incorporate the wind in its calculations, but it will send instructions when the aircraft arrives too early. If the initial deceleration isn't sufficient, then subsequent decelerations will be instructed until the aircraft arrives within the TW. If the strength of the wind increases, then this process will require more instructions as shown in this figure. The

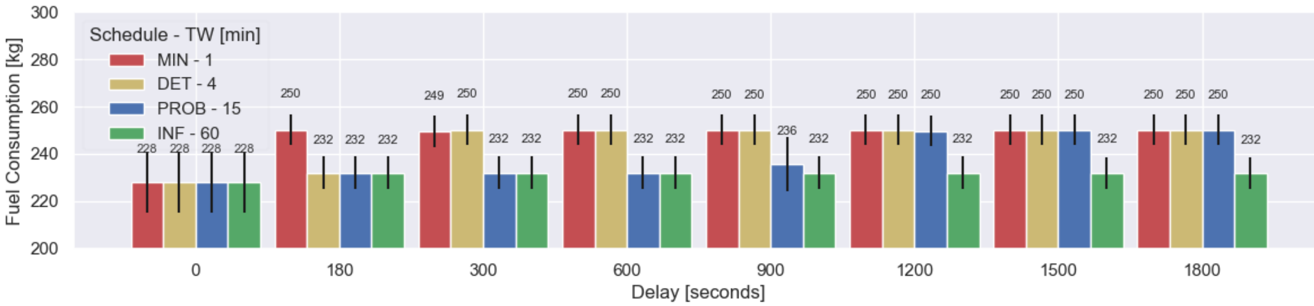

Figure 49: Fuel consumption - SA-AZA1572

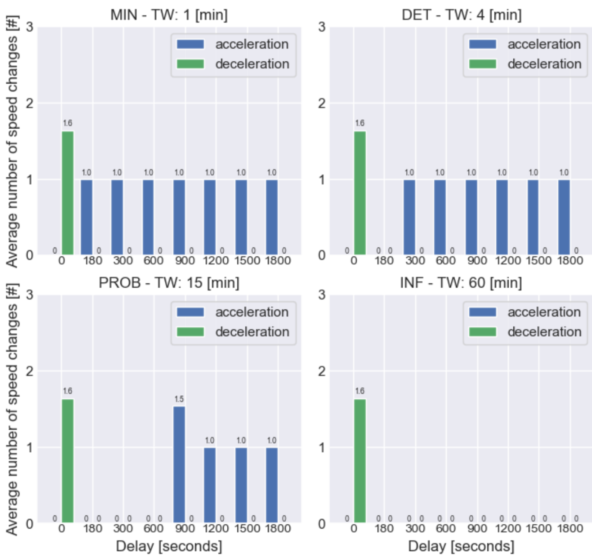

Figure 50: Speed changes - SA-AZA1572

PROB-schedule with a delay of 900 seconds requires more instructions as well. This is caused by the TW of the aircraft which is equal to the delay. The aircraft will therefore fly at the edge of the TW. Stronger winds will lead to more and larger drifts out of the TW. Hence, the A-FMS will send more instructions to deal with them.

Punctuality - SA-AZA1572

The punctuality scores for Flight AZA1572 and Flight SA-AZA1572 are shown in Table 7. As can be seen, the increase in the magnitude of the wind improves the punctuality score of this flight. This can be caused by the fact that the aircraft's ability to catch up with delay improves significantly for ensembles with tailwind. Cases where the aircraft can't catch up, become available now. If these ensembles outnumber the ones that worsen the aircraft's ability to catch up with delay, then the overall score improves.

Fuel Consumption - SA-AZA1572

The fuel consumption of Flight SA-AZA1572 is shown in Figure 49. As can be seen, most of the average fuel consumption remain similar to the ones of Flight AZA1572 as shown in Figure 16. This is in contrast to the standard deviation which has significantly increased. As expected, due to the increase in the strength of the wind, the minima are reduced and the maxima are increased for Flight SA-AZA1572. Table 8 provides a detailed overview on a comparison between the minimum and maximum fuel consumption. The percentile changes are provided for various schedules and delays.

Table 7
Punctuality - AZA1572 & SA-AZA1572

Flight	*MIN*	*DET*	*PROB*	*INF*
AZA1572	1 %	13 %	50 %	88 %
SA-AZA1572	1 %	15 %	51 %	89 %
	-	+2 %	+1 %	+1 %

Table 8
Fuel consumption - SA-AZA1572

Schedule	Delay	SA min	SA max
MIN	0 s	-16.3%	+6.1%
MIN	180 s	-5.1%	+5.3%
DET	180 s	-5.8%	+5.3%
DET	300 s	-5.1%	+5.3%
PROB	900 s	-5.8%	+5.3%
PROB	1200 s	-5.1%	+5.3%
INF	0 s	-16.3%	+6.2%
INF	1800 s	-5.8%	+4.9%

8.2. Aggregated Analysis

The aggregated analysis consists of 2 parts. The first part discusses the punctuality and the second part examines the fuel consumption.

Punctuality

The aggregated arrival punctuality of SA Set I is shown in Figure 51. If the scores are compared with the punctuality of Set I in Figure 32, then several differences stand out. The *MIN*-schedule shows a worse performance as 3 more flights fall into the worst bracket. The *DET*- and *PROB*-schedule show a very similar score. The *INF*-schedule shows a sig-

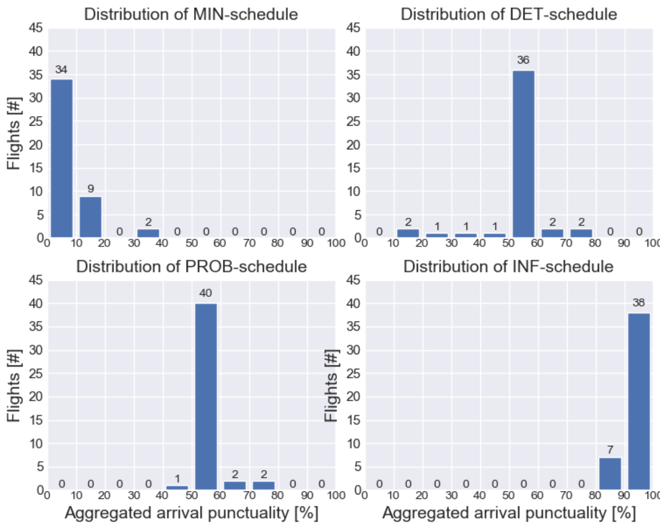

Figure 51: Punctuality - SA Set I

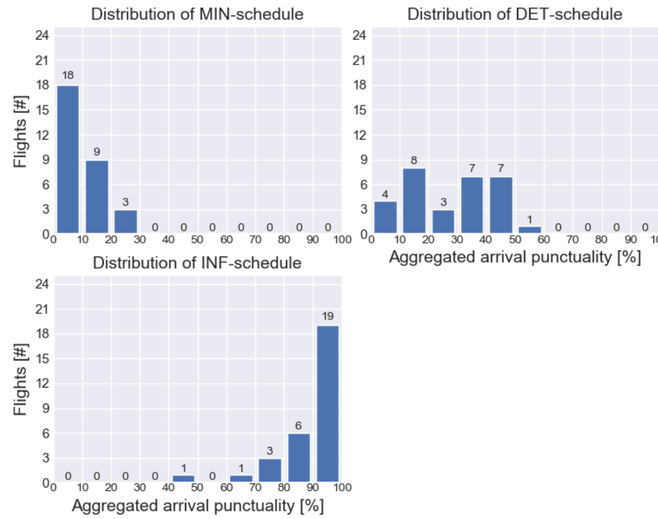

Figure 52: Punctuality - SA Set II

Table 9
Fuel consumption by schedule and wind per set

Set	*MIN*	*DET*	*PROB*	*INF*
Set I	1709223 kg	1697717 kg	1697508 kg	1689853 kg
SA Set I	1710812 kg	1699378 kg	1699173 kg	1691013 kg
	+0.09%	+0.10%	+0.10%	+0.07%
Set II	978644 kg	976758 kg	963648 kg	
SA Set II	979487 kg	977644 kg	964649 kg	
	+0.09%	+0.09%	+0.10%	

nificant improvement as 4 more flights fall into the best category.

Figure 52 shows the aggregated arrival punctuality of SA Set II. As can be seen, the *MIN*- and *DET*-schedule obtained the same scores as their counterparts of Set II as shown in Figure 47. The *INF*-schedule shows a very slight increase in performance of its punctuality.

These punctuality scores provide a general impression of the effects of wind on the schedule. SA Set I shows that stronger winds can affect the punctuality of some schedules such as the *MIN*- and *INF*-schedules. This is in contrast with SA Set II which shows very little to no changes in punctuality to the increase in wind.

Fuel Consumption

The fuel consumption of both sets have been compared and are displayed in Table 9. These results show that the differences in fuel consumption over entire sets become very small. The largest difference results in a 0.10% increase in fuel. These small changes are attributed to the way the wind is incorporated into a simulation. As only the variance of the wind is used for a simulation, the average wind strength will lie near zero. Multiplying the magnitude of a wind with an average around zero, still leads to very small differences.

9. Recommendations

The method used in this article provides an objective approach to compare various schedules based on time-windows. Several steps can be taken to improve this approach further. The current fuel consumption plug-in relies on BADA3 for its fuel calculations. BADA4 is already released and is able to simulate the performance of an aircraft more reliable. BlueSky, currently, doesn't have BADA4 capabilities. Carrying out this approach on an air traffic simulator with improved fuel calculations such as BADA4, will enhance the accuracy of the output. Moreover, for the current simulations, only the cruise phase has been simulated. By incorporating the climb and descent of a flight in a simulation, the authenticity will improve. Furthermore, an improvement can be made on the interaction between aircraft. For these simulations, the interaction between aircraft had been disabled. By integrating interaction of aircraft in a simulation, the effects of delay can be studied better.

10. Conclusion

Schedules based on TWs are developed in various ways to improve the punctuality of aircraft. Thus, the need to compare and evaluate these different schedules arises. In this report, a method is developed and proposed to evaluate various TW-schedules.
Every schedule is carried out in BlueSky, an open-source air traffic simulator. For these simulations, multiple plug-ins are created. An A-FMS has been developed to simulate the behaviour of aircraft who adhere to such schedules. A previously developed weather ensemble plug-in is used to take the variance of the wind into account.
During the simulation, the punctuality is monitored at waypoints and at the final destination. The simulator also makes use of a BADA3 plug-in to estimate the fuel consumption. Then, with the use of the monitored data, the schedules are compared with respect to wind, speed changes, punctuality

and fuel consumption. The comparison is done on the level of a trajectory and over the entire set of trajectories.
Thus, the analysis of these schedules supports an objective decision making process on TW-schedules.

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Part B:
Literature Review
Preliminary Research
Graded under AE4020

Delft University of Technology

AE5050 - Literature Study

Evaluation of Time-window Trajectories with respect to Fuel Consumption and Arrival Time

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Table of Contents

1 Introduction

Flight planning is a crucial process in today's air traffic systems and has become a prerequisite for every flight operating within Europe. This task is carried out by EUROCONTROL which works towards a Single European Sky. This goal will help overcome the challenges facing European aviation in the future regarding safety, capacity and performance[1][2]. The purpose of this report is to provide insight into flight planning and on the method of evaluating flight plans based on the time-windows concept.

This chapter will cover the current flight planning process in Chapter 1.1. The consideration of wind and fuel calculations are covered in Chapter 1.2. Chapter 1.3 provides an oversight on the report and the research questions.

1.1 Flight Planning in Europe

To ensure an efficient flight plan management within Europe, the flight plan processing and distribution has been centralised. The Network Manager Operations Centre (NMOC) is entrusted with carrying out this task. The NMOC is supported by the Initial Flight Plan Processing System (IFPS) which collects the initial flight plans and distributes them to ANSPs. The centre is located in Brussels and Paris to ensure an around-the-clock service even in the case of a disaster[1][3].

The NMOC is tasked with processing and distributing of up to 90,000 flight planning messages a day covering over 500 European airports and airfields. The IFPS is also used to analyse the detailed instructions of the flight plans against the airspace structure. Incompatibilities can rise up at this part of the process and have to be solved. In about 2% of the cases, manual interventions are needed to resolve these inconsistencies. The NMOC suggests alternatives to the initially filed flight plans as well. If the flight plan has been accepted, then the flight plan is distributed to every ATC-centre overflown by that flight in Europe[3].

1.2 The Flight Efficiency Initiative

The European Commission has concluded that routes are on average 40 kilometres longer than their optimal flight route. This leads to unnecessary fuel consumption and emissions. EUROCONTROL has therefore been incited to introduce the Flight Efficiency Initiative (FEI) in 2013. The goal of the FEI is to offer aircraft operators the most efficient routes on the day of operations. This process can be performed up to two hours before the flight and is accomplished by inspecting the flight plans and checking for a faster or more cost-effective one. To generate these improved flight plans, a catalogue is maintained of routes flown in the past and airline operators provide certain cost criteria. These cost criteria include among others; flying time costs, fuel costs and costs of delays. This initiative has already shown environmental, operational and financial benefits due to the early collaboration between aircraft operators and the NMOC[4].

The FEI consists of two phases where in the first phase flight plans are compared and in the second phase re-routing proposals are sent to airline operators.
During the first phase, the DDR interface is used as a support tool. This tool allows the airline operators and service providers to compare their flight plans with the accepted flight plan by the IFPS. Furthermore, the differences in the distances between the flight plans are shown. This allows the tool to assess individual flight plans and it's able to incorporate network performance developments. The latter is particularly useful as the European airspace network benefits considerably through the Flexible Use of Airspace (FUA) concept which allows military airspace to be used by civil aviation. These routes through military airspace are called conditional routes (CDR) and are made available before and on the day of operations. The CDRs can provide better flight plans or shorter routes than the initially filed flight plan. Hence, operators who are aware of such options can make better use of all their available flight planning possibilities.
The second phase includes a network impact assessment with a screening of the complete IFPS valid flight plan database to find improvements. If these flight plans are operationally acceptable, then they'll be proposed to the airline operators. If a flight plan is filed again, then it's estimated using the provided cost criteria from the airlines, the latest ATFCM situation and the current weather data which also includes wind. This network impact assessment is performed six times a day[4].

Over the past years, the FEI has resulted in a significant reduction in fuel consumption. The potential savings can lead up to 20-25,000 nautical miles a day. From all the proposals, up to 15% are accepted by airlines. This has lead to a saving of 32,644 minutes and 375,000 kilometres in 2014[4]. The FEI continues to tackle inefficiencies in the European airspace and strives to further optimise the flight plans.

1.3 Layout of Literature Study

The goal of this Literature Study is to give insight into the different phases of flight planning and on the method of evaluating flight plans constituted using the time-windows concept. To properly understand these subjects, the report has been divided into five chapters.

Chapter 1 deals with an introduction to the current flight planning process along with the Flight Efficiency Initiative. Chapter 2 handles the various stages in flight planning and different modelling techniques in the industry. Also, the time-windows concept and ensemble weather forecasting are dealt with into more detail. Chapter 3 copes with the evaluation of the flight plans. It considers the simulation of the flight plans in an air traffic simulator and calculation of fuel consumption. Chapter 4 provides an oversight on the most important papers discussed in the literature study. Chapter 5 presents the research questions. A Gantt-chart of this project is added to Appendix A as well. This offers a general idea on the subjects that have to be covered and their dependencies.

2 Flight Planning

This section covers various parts of flight planning in a step-by-step approach. Chapter 2.1 deals with the various stages and types of flight planning processes. Subsequently, Chapter 2.2 handles the different types of modelling techniques used in the airline industry. And Chapter 2.3 explains the time-windows concept in detail.

2.1 Flight Planning Process

The flight planning process is an extensive and long process that can be subdivided into short term and long term planning. Another way of classifying the process is into types of decisions. These types would be strategic, tactical and operational decisions. A schematic overview is given in Figure 2.1 (B. F. Santos, personal communication, Nov 1, 2016).

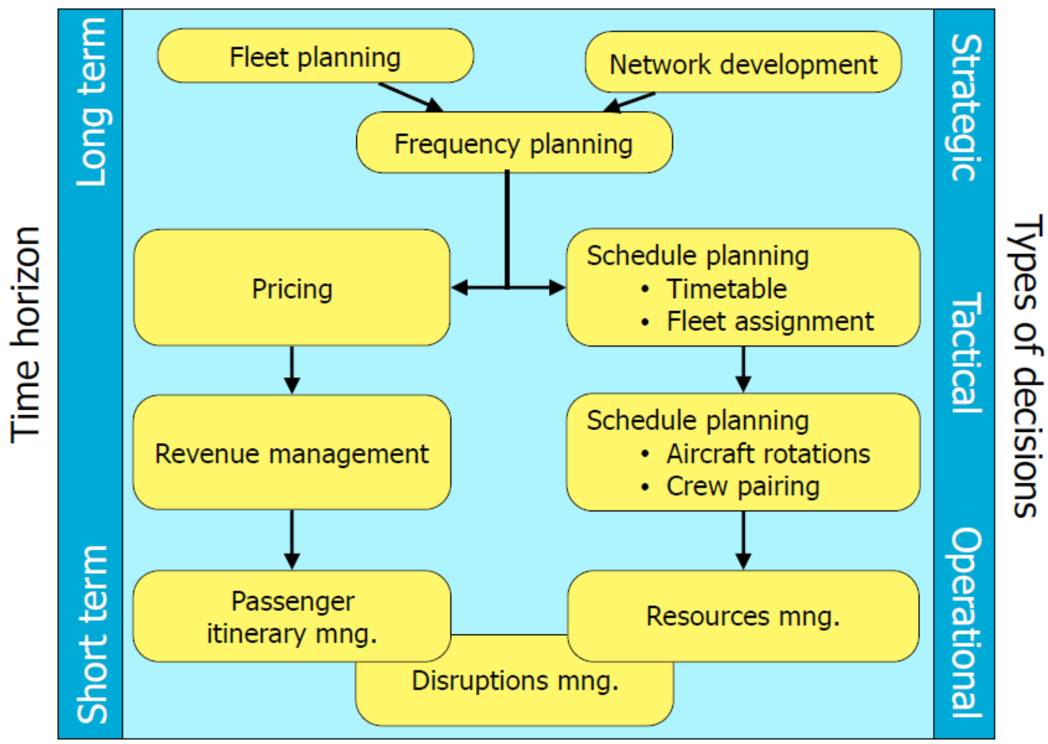

Figure 2.1: Planning framework for a regular airline as presented during lectures

For this study, the strategic and tactical planning are of concern and are dealt with in chapter 2.1.1 and 2.1.2. The differences between network and single flight planning are dealt with in chapter 2.1.3.

2.1.1 Strategic Planning

Strategic flight planning entails the long term planning for an airliner. This involves decisions such as hub location, flight routes decision and frequency planning. Uncertainty in this phase brings a lot of unpredictability along with it. This makes decisions which rely on deterministic models troublesome as they fail to capture this uncertainty.

From EUROCONTROL's perspective, the strategic planning phase carries on up to a week before the flight is carried out. Air Traffic Flow and Capacity Management (ATFCM) is a focal point in running operations of the air traffic management network. The goal is to optimise air traffic flows while adhering to Air Traffic Control (ATC) capacities and maintaining a high level of safety and efficiency. To help the ATFCM in accomplishing its goal, the Network Manager Operations Centre (NMOC) has been created as a support. The NMOC oversees the airspace capacity and the traffic load continually. It also relays information regarding capacity usage and prediction to Air Nagivation Service Providers (ANSPs). A routing scheme is also prepared by the NMOC to avoid demand-capacity imbalances introduced by for example planned events or military exercises[5].

2.1.2 Tactical Planning

The tactical phase starts from six days before the day of operations up till the day of operations itself. During this period, the NMOC helps set up the initial network plan and informs ATC-centres and aircraft operators about the day of operations. Any ATFCM measures which will be enforced in European airspace will be published in the agreed plan[5].
At the day of operations, the NMOC observes and updates the daily plan according to the situation. There is a continuous effort as well to optimise the capacity to real time traffic demand. An example of such a method would be to offer alternative solutions to minimise delays[5].
As mentioned in Chapter 1.2, EUROCONTROL introduced the FEI in 2013. This initiative makes it possible to adjust the flight plan up to two hours before the flight[4].

2.1.3 Network and Single Flight Planning

The flight planning phase can be approached in either a network setting or from a single flight planning perspective. There are several differences between these two methods. Various other papers show the capabilities of these approaches.
It can be seen that single flight planning allows trajectory optimisation to be taken into account[6]. This allows an approach with the help of control theory. An analysis on the time-windows concept has been published using reachability on a game-theory framework as well[7].
However, there is considerable research done on network planning. For example, a network model is used to describe and compute the time-windows concept[8]. The paper also performs a sensitivity and feasibility analysis on the model. There is also an analysis done on the impact of a time-windows system with respect to the current system[9]. The paper focuses on the (potential) benefits, drawbacks and limitations of such a system on the airlines, airports and ANSPs. A Network Flow Model of the National Airspace System has been developed which is able to incorporate

various flow problems[10]. The model is used to analyse the network-wide costs of these disruptions and attempts to solve them optimally.

2.2 Modelling Techniques

Linear programming is a strong and useful tool to solve large scale or computational intensive problems. Problems solved using this technique are for example the Generalised Tactical Flow Management Problem, the Ground Holding Problem and the Network Flow Model. Most linear programming models can be classified into two categories; deterministic models and stochastic models. Chapter 2.2.1 describes an example of the former type of models and Chapter 2.2.2 converts the aforementioned example to the latter type. In Chapter 2.2.3, ensemble weather forecasts are introduced. Chapter 2.2.4 provides a comparison between the deterministic and stochastic modelling types.

2.2.1 Deterministic Modelling of the Ground Holding Problem

Several examples of deterministic models of air traffic flow management problems are provided[11]. One of these examples is the Ground Holding Problem (GHP)[12]. For this model the following definitions have been adhered to;

N_k^i is the number of aircraft of class k scheduled to arrive at the destination airport during period i (k=1,...,K; i=1,...,T);

M_{qi} denotes the airport capacity in period i under scenario q (q=1,...,Q; i=1,...,T);

X_{qkij} represents the number of aircraft of class k originally scheduled to arrive at the destination airport during period i, and rescheduled to arrive during period j under capacity scenario q, due to a ground delay of j-i time periods (q=1,...,Q; k=1,...,T; i $\leq$ j $\leq$ T+1);

W_{qi} are auxiliary variables representing the number of aircraft unable to land at the destination airport during period i under capacity scenario q, i.e., the number of aircraft incurring airborne delay during period i (q=1,...,Q; i=1,...,T);

If it can be assumed that a certain capacity scenario q will be realised, then this will result into the consideration of only one scenario. This assumption makes it possible for the model to be treated as a deterministic one. This results in the model shown in Figure 2.2[11][12].

The Objective Function (OF) of the model is set on a minimisation of the total delay costs. The first set of constraints forces all scheduled flights landing in period i to land in period i or later. The second set of constraints ensures the flow to be consistent at the airport[11][12].

Model 2a

$$\text{Minimize} \quad Cost(q) = \sum_{k=1}^{K} \sum_{i=1}^{T} \sum_{j=i+1}^{T+1} C_g^k (j-i)\, X_{qkij} + c_a \sum_{i=1}^{T} W_{qi}$$

subject to:

$$\sum_{j=i}^{T+1} X_{qkij} = N_{ki} \qquad k=1,\ldots,K; \quad i=1, \ldots, T$$

$$W_{qi} \geq \sum_{k=1}^{K} \sum_{h=1}^{i} X_{qkhi} + W_{qi-1} - M_{qi} \qquad i=1, 2, \ldots, T+1$$

$$X_{qkij}, W_{qi} \geq 0 \text{ and integer.}$$

Figure 2.2: Deterministic model of the GHP[11][12]

2.2.2 Stochastic Modelling of the Ground Holding Problem

An assumption on the certainty on the realisation of a specific scenario can not always be made. This leads to the incorporation of a set of scenario's with each scenario q having the *Prob(q)* to fulfilment. The OF has to take every possible scenario into account and weigh it against their probability. This leads to the set-up of a stochastic model. To create such a model, the deterministic model has to be solved first. Figure 2.3 shows the stochastic model for the GHP example of the previous section[11][12].

The OF of the model minimises the total cost by weighing the cost of a scenario q with its probability *Prob(q)*. The set of constraints for every scenario q is the same set of constraints as for the deterministic model. There is an additional set of constraints introduced in this model which are the coupling constraints. These constraints originate from the fact that the decisions end up branching in a tree-like fashion. These branches in the tree are represented and upheld by the coupling constraints. An overview of a part of the tree is shown in Figure 2.4[11][12].

Model 2b:

Minimize $\sum_{q=1}^{Q}$ Cost(q) Prob(q)

subject to:

set of constraints for q=1

.

.

.

.

set of constraints for q=N

Coupling constraints: $X_{1kij} = ... = X_{Qkij}$ " k;i;j

Figure 2.3: Stochastic model of the GHP[11][12]

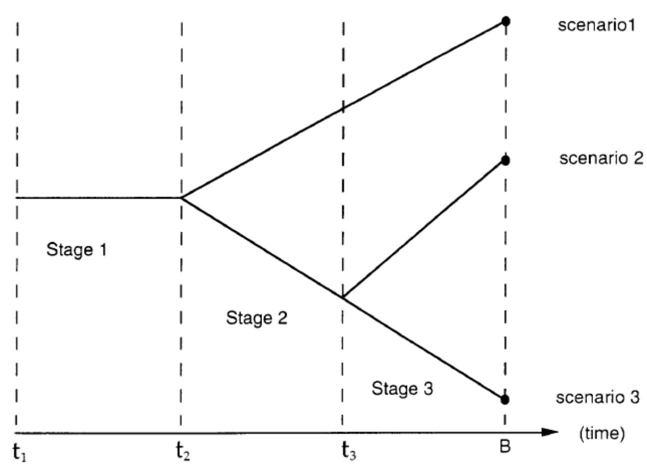

Figure 2.4: Branching of the scenario's in a stochastic model[11][12]

2.2.3 Ensemble Weather Forecasts

Weather and especially wind impact the daily operations of air traffic significantly. Hence, to model air traffic accurately, it is required to take these effects into account. This can be done using deterministic forecasts. However, ensemble weather forecasts are preferred as this method allows to take the wind and its uncertainty into account[13].

An ensemble weather forecast is a set of forecasts that try to include all the future weather possibilities. The forecasts are obtained by small variations in the initial conditions and perturbing the weather models slightly. The uncertainty is represented by these variations and produce a range of probable weather conditions. The ECMWF uses this method to produce fifty perturbed forecasts and one control forecast. The perturbed forecasts are used to create the ensemble[13].

The difference between this method and single deterministic forecasts is that deterministic forecasts don't provide this uncertainty. Due to this uncertainty, the range of possible weather outcomes is provided at different forecast times. This range of possibilities gives an indication on the likelihood of the different scenarios. This means that a small range in the ensemble forecast indicates a higher consistency and thus the forecast is more likely[13].

A probabilistic analysis is provided of aircraft fuel consumption using ensemble weather forecasting[14]. Two types of ensemble weather forecasting are considered for this analysis; ensemble trajectory prediction and probabilistic trajectory prediction.

In ensemble trajectory prediction, a member of the weather forecast ensemble is used to create a deterministic trajectory predictor(TP). The set of trajectory predictors are used to create an ensemble of trajectories[14].
In probabilistic trajectory prediction, probability distributions are evolved along the aircraft trajectory using a probabilistic trajectory predictor(pTP). The pTP is then used to create probability distributions of trajectory parameters[14].
A schematic overview of these methods are presented in Figure 2.5 and Figure 2.6.

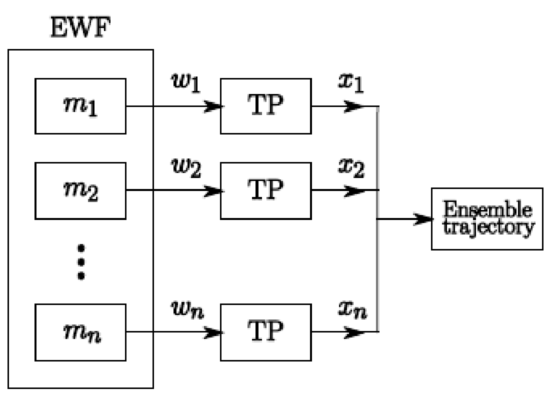

Figure 2.5: Ensemble trajectory prediction with m - member, w - weather, x - trajectory[14]

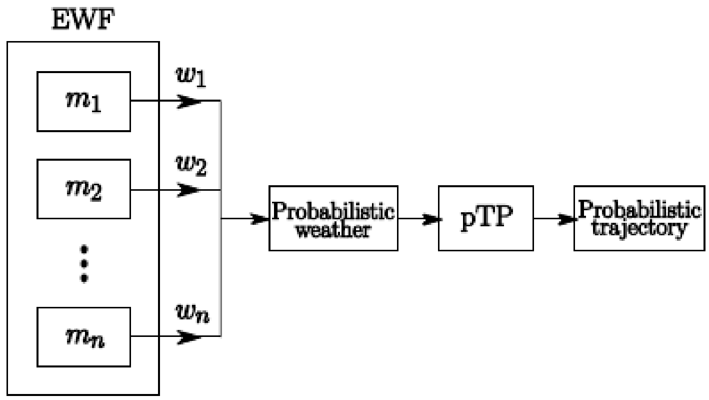

Figure 2.6: Probabilistic trajectory prediction with m - member, w - weather[14]

2.2.4 Deterministic vs Stochastic

The main difference between these two types of models, is the incorporation of and approach to uncertainty in the problem. The output of deterministic models is fully determined by the parameter values and the initial conditions. This doesn't hold true for stochastic processes, as they will lead to an ensemble of different outputs. This is due to the fact that they generally take the variation of the output into account.
A deterministic model would be preferable in areas with a considerable amount of stability. This includes for example an area with predictable weather forecasts or airport capacities[11].
Another benefit would be that ATC systems don't deal with probabilities. Thus, deterministic models could approach daily operations closer rather than stochastic ones[11].
A stochastic model has a clear advantage on modelling natural processes better. As most processes in nature aren't deterministic but rather stochastic. This does bring a downside as well since stochastic models bring forth an additional layer of complexity.

2.3 Time-Windows Concept

This section covers the time-windows concept. An overview of the costs involved with delays are presented in Chapter 2.3.1. Chapter 2.3.2 provides a description of the concept and Chapter 2.3.3 describes the modelling approach for these kind of concepts. Chapter 2.3.4 presents a comparison of the pros and cons of this approach.

2.3.1 Costs of Delay

Whenever an aircraft is delayed, there is a possibility for the delay to propagate over the network. This can lead to undesired effects like an amplification of the initial delay. Extensive research has been done on the costs of delays[15]. Not only were trends found in the costs, but a quantification was made as well. For example, Figure 2.7 shows a good linear fit between delay costs and the number of aircraft seats. In this case, short and long delays were specified as 15 and 65 minutes respectively.

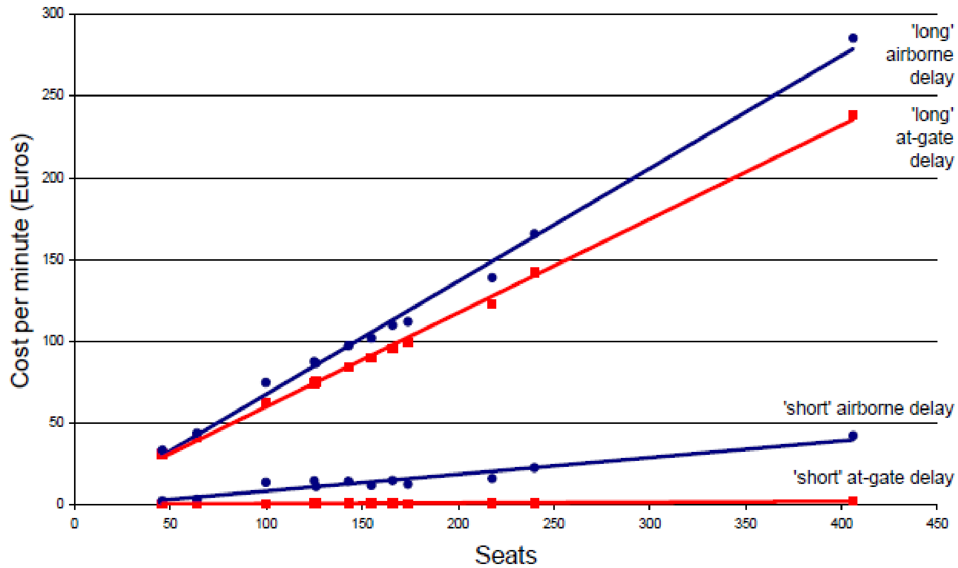

Figure 2.7: The average cost of delay per minute[15]

Some of the conclusions from the report are that the per-minute tactical costs of delay vary according to the length of delay, number of seats and the phase of flight.
Longer delays show an increase in per-minute costs. Also, the costs increase with larger aircraft and with higher load factors. And airborne delays are shown to be costlier than at-gate delays. These costs vary rather wide in range as well and can reach as low as less than one Euro per minute (short at-gate delay) and as high as 289 Euros per minute (long airborne delay)[15].

2.3.2 Description of the Time-Windows Concept

The Time-Windows (TWs) concept, formally called the Contract of Objectives (CoOs) concept, is an ATM concept based on a concept of CATS which was initiated by EUROCONTROL. The CoO acts as an operational link between all air navigation actors (airlines, airports and ANSPs) and represents a commitment between and for all the actors involved. These commitments are based on well-defined, shared and agreed objectives. These objectives are set at delivering a particular aircraft within temporal and spatial intervals, so called TWs. These TWs are defined for transfer of responsibility areas such as between two Area Control Centres (ACCs). The sizes of the TWs are influenced by factors such as runway capacity, congestion, aircraft performance and others[16][17].

If TWs can't be reached, then a renegotiation is initiated. This renegotiation is a standard process which is started whenever a CoO can't be fulfilled. This process uses a Collaborative Decision-Making (CDM) process and is supported by System-Wide Information System (SWIM). This leads to a new CoO which has to be accepted by all the actors involved and takes their constraints into account[16][17].

The effects of these CoOs are researched further in an Analytic Hierarchy Process (AHP)[9].

These contracts are defined in 4D windows (latitude, longitude, flight-level and time). It's purpose was set to increase punctuality among ATM actors. These windows take constraints such as runway capacities and congestion into account and any divergence from these windows triggers a re-negotiation.

The flights can be divided down into critical and non-critical flights as well[8]. Critical flights are defined as flights with little to no slack time. These flights end up having a large downstream effect on the performance of the ATC system if faced with even small delays. It is therefore important to keep these flights on schedule.

2.3.3 Modelling of the Time-Windows Concept

In literature, there are several ways to incorporate the TW-concept into a model. This can be done by for example a reachability framework[7] or a linear programming model[9]. A preference has been given to the approach discussed in the linear programming model.

The model is used to calculate the width of the time-window for each flight. These time-windows are defined for every flight which operate in a part of the airspace. The model works by determining the optimal closing time of the time-windows. There are two assumptions made for the model. The first one is that "a time-window is composed of a discrete and limited number of contiguous time periods of fixed width". And the second assumption is that "each phase of a flight is executed in exactly one time period"[9](p.104).

The decision variables in this model are binary values. There is a binary value defined for each flight in an airspace element for a time period. These binaries correspond to whether a time-window for a flight in an airspace sector is available or not at a specific time period. A sequence of these values indicate the length of the time-window for a flight[9].

The OF can be defined in a rather straightforward way, namely a maximisation of the total width of the time-windows. However, such an approach by itself would be insufficient as no distinction can be made between time-windows of an equal or uneven distribution. Time-windows with unit-widths of 1 and time-windows with alternating unit-widths of 2 and 0, will be indistinguishable to the OF. To solve this issue, coefficients can be introduced into the OF. These coefficients allow the incorporation of a weight-factor to the distribution of time-windows[9].

The constraints of a TW-model can be divided into several categories. The first set of constraints describes the properties of the model such as the departure and airspace capacity limits and makes sure to uphold them. The second set of constraints upholds the consistency of the time-windows with for example the speed of the aircraft. The third set ensures the time-connectivity between the binary values such that binary values are chosen which lie ahead in time. The first set describes the utilisation of the airspace capacity[9].

2.3.4 Advantages and Disadvantages of the Time-Windows Concept

The main objective of the CoO approach is to provide improved punctuality of aircraft at the destination. Other benefits include improved system efficiency and predictability of the system. This is achieved by enhanced collaboration between actors of Air Traffic Services (ATS). Also, TWs provide some leeway in case of disruption and conflict management. This approach ensures a certain level of resilience in such cases. In other words, the uncertainty involved in flight planning isn't removed, but kept under control. This can be achieved by managing disruptions via the size of the TWs and limiting the side effects of any disruption. If deviations from the planning occurs, regardless of the reason, a renegotiation is triggered. This negotiation takes place on a system-wide level and takes all actors' constraints into account. It's therefore possible to optimise on a system-wide level, instead of an individual case by the "first come, first served" approach[17].

To evaluate the concept, an experiment has been set-up. The workload was then measured using two subjective methods; the Instantaneous Self Assessment of Workload (ISA) and the NASA-Task Load Index (NASA-TLX). This experiment used a similar traffic management situation, but with three differing conditions. The first one was carried out without TWs and the other two with TWs from which one involved a renegotiation and the other didn't. The experiment was also repeated on two different traffic loads (2008 vs 2020)[17].

The results show that the workload of the Air Traffic Control Operators (ATCOs) wasn't impacted by TW management or renegotiation. The ATCOs described the renegotiation as quite easy, but the duration of the renegotiation or a change in a renegotiated flight level could impact their workload[17].
On the contrary, the workload of the pilots was significantly impacted by TW and renegotiations. Debriefings of the pilots show that the impacted workload can vary from the pilots' point of view and their means of communication. Using RT communications with TWs increases the workload considerably. This makes the use of a data-link as a means of communications essential to maintain an acceptable level of workload. Further evaluations are also required during high workload situations such as emergency situations and descent in complex environments. The questionnaires and debriefings show that the workload was fair during the experiment, but the workload did show an increase when the number of renegotiations was raised[17].

Both the controllers and pilots concurred that TWs are easy to use and expressed this feeling during the debriefings. They showed quick familiarisation with the concept and supported this statement. Furthermore, renegotiations didn't complicate the daily tasks of controllers further. However, they did confirm a need of receiving renegotiations of TWs by data link to avoid increasing RT communications.
Contrarily, the pilots judged the equipment and tools to be inadequate to support the renegotiation process. Improvements on the Command Display Unit (CDU), speed management and electronic messages have been suggested[17].

The ATCOs and pilots didn't notice a particular increase in communications between them when TWs was introduced. This resulted from the fact that both parties worked with the same TW data. Though, the controllers were unable to reach a consensus on the effects of renegotiations. The effects depended on the size and nature of changes in the TWs. The pilots did suggest improvements in the communications by for example the use of electronic messaging. Nonetheless, both parties did express the need for additional phraseology[17].

A safety assessment was made as well by assessing the number of Short-Term Conflict Alerts (STCAs), questionnaires, debriefings and an analysis of aircraft separation performance. There was no indication of any party involved in every control condition to have been negatively impacted on their level of safety[17].

Likewise, an analysis has been made on the traffic efficiency. This has been assessed through the flight duration, the number of TWs fulfilled and the duration of the renegotiation. The flights flown under different conditions are compared to a reference flight which was performed in a simulator. From the results, no impact could be assessed from the traffic load. The flight duration was shorter with TWs and the aircraft flew closer to the flight plan.
The percentage of failed TWs is considered low with the median value at 0% and a maximum of under 10%. The fulfilment rate seems to be sensitive to the sector shape, airspace structure and traffic conditions.
The duration of the processes of renegotation average out to 158 seconds. This was deemed acceptable by the actors and operators, but it was stated that a lower duration would result in a lower impact[17].

An assessment on the capacity was made as well. Two levels of capacities were run during the experiments. The 2008 capacity and the 2020 forecasted capacity and both were properly and safely managed[17].

3 Air Traffic Simulation

Modelling of air traffic is an important tool for optimising the current ATM-processes. There are multiple air traffic simulators available such as BlueSky, NEST and CASSIOPEIA. Chapter 3.1 describes the choice for BlueSky and its advantages. And Chapter 3.2 explains BADA and its usage.

3.1 BlueSky

BlueSky is an open-source air traffic simulator developed by Delft University of Technology. The program is developed to serve as a tool to visualise, analyse or simulate air traffic without any restrictions, licenses or limitations. To run a simulation in BlueSky, only basic knowledge is required on some of the commands[18].

A strong advantage of using BlueSky is that the source code is freely available. This makes it possible to adapt the tool to the user's desires and needs. However, knowledge of Python is necessary for the development of additional plugins as the source code is written in Python 3[19].

An implementation of BlueSky for research purposes has been shown before[20]. In this report, an arrival management research model of Amsterdam Schiphol Airport had been developed. The model was based on the arrival management system used by Schiphol and omitted or simplified certain advanced features. Henceforth, an experiment on the effect of pop-up flights was set up and simulated in BlueSky successfully.

3.2 BADA

The Base of Aircraft Data, abbreviated to BADA, is an Aircraft Performance Model (APM) developed and maintained by EUROCONTROL. It is designed for simulation and prediction of aircraft trajectories intended for ATM research and operations[21].

BADA itself consists of the model specifications and the data sets. The model is based on an energy model to calculate aircraft parameters. The data sets contain aircraft-specific coefficients which are needed to make the calculations. To obtain these data sets, EUROCONTROL works and cooperates with aircraft manufacturers and airlines[21].

There are two families of BADA APM; BADA Family 3 and BADA Family 4. The former has become the standard for the industry and the models cover at least 95% of the air traffic operations in European Civil Aviation Conference (ECAC) members' airspace. The latter is a newer model intended to meet functional and precision requirements of new ATM systems and R&D. However, the coverage is reduced to 70% of current aircraft types operating in ECAC airspace[21].

BADA is used by users such as aircraft manufacturers and air navigation service providers. Examples for using BADA include fast- and real-time modelling and simulation of air traffic and calculating the trajectory prediction component of ground-based operational ATM systems[21].

BlueSky has an existing plugin available, which allows the use of BADA in air traffic modelling[19].

4 Table of Papers

An oversight of the most important papers are presented in Table 4.1 and Table 4.2. The tables provide a schematic oversight of the attributes of the papers. The first three columns hold the numbering and references of the papers, the title and a short description respectively. Columns four till nine describe the subjects discussed in the papers. The fourth columns indicates whether the paper touches upon the tactical planning *(T)*, strategic planning *(S)* or both *(S/T)*. Column five indicates whether a deterministic *(D)* or probabilistic *(P)* trajectory approach is used. The sixth columns touches upon the type of linear programming model in the paper if it's present. A deterministic model is indicated with *(D)* and a stochastic one with *(S)*. The seventh columns shows if the weather *(W)* is considered in the paper. EWF is a method of incorporating the weather into models. Hence, if this method is mentioned, this will be indicated with *(W+)*. An important distinction has to be made between planning methods in network planning *(N)* and single flight planning *(F)*. This distinction is indicated in the eight column. The final column shows whether the time-windows *(X)* concept is considered in the paper. It is possible for a paper to discuss multiple approaches and methods and this can lead to the inclusion of multiple types of planning and modelling.

As can be seen from the table, most of the papers cover the strategic planning aspect of the flight planning process. This is due to the use of models which are discussed in the papers. These models are used to solve network problems which are part of the strategic planning process as can be seen in Figure 2.1. Papers 8 and 9 provide a good overview and comparison between these two types of decisions.
Some papers touch on the trajectories of the aircraft. These trajectories are primarily approached in a deterministic manner. Paper 5 approaches these trajectories in both ways.
Another important aspect in the papers is the type of linear programming model if one is used at all. There are two papers focused on each type of the linear programming model and one which focuses on both. Paper 4 provides a clear implementation of the time-windows concept with the use of a deterministic linear programming model. Paper 8 provides several examples of both types and compares them. This comparison covers among others the set-up of the problem, the definitions of the models and an analysis of the results and computations.
There are five papers which take the weather into account. This is shown in the seventh column from which can be seen that paper 5 focuses on EWF. This paper focuses on a deterministic approach and a probabilistic one. The two methods are discussed and compared.
The eighth column presents an indication on the solution method of the model. It provides a distinction between a network approach or a single flight approach. It can be seen that the vast majority of the papers follow a network-wide approach to the problems. The single flight approach is used for three papers, of which two are focused on the impact of weather on the trajectories. The third paper uses a method from game theory to propose a method to solve a model based on the target windows concept.
The last column indicates whether the time-windows is examined in the paper. Paper 4 creates a linear programming model and examines its performance. Paper 9 looks at the impact, benefits and limitations of the concept. Paper 10 provides a different solution method for the concept.

Table 4.1: Table of Papers I

#	Title	Description	Tactical/ Strategic planning	Det./ Prob. traj.	Det./ Stoch. lin. prog. model	Weather or EWF (W+)	Network or Single Flight (F) planning	TW
1-[22]	Stochastic air freight hub location and flight routes planning	to introduce a stochastic programming model to address the air freight hub location and flight routes planning under seasonal demand variations	S		S		N	
2-[20]	Analysis on the Impact of Pop-Up Flight Occurrence when Extending the Arrival Management Horizon	the extent of the negative effects of pop-up flights on the (extended) arrival manager	S		S		N	
3-[23]	A Concept for Multi-Criteria Environmental Assessment of Aircraft Trajectories	A multi-dimensional environmental assessment framework is proposed to optimize impact on climate, local air quality and noise simultaneously	S			W	N	
4-[8]	Critical Flights Detected with Time Windows	Analysis of the time-windows concept	S	D	D		N	X
5-[14]	Analysis of aircraft trajectory uncertainty using Ensemble Weather Forecasts	Analysis between ensemble trajectory prediction and probabilistic trajectory prediction	S	D / P		W+	F	
6-[10]	Network Model to Address Capacity/Demand Imbalances in the National Airspace System	A new Network Flow Model is presented and the solutions and impacts are analysed	S	D	D	W	N	

Table 4.2: Table of Papers II

#	Title	Description	Tactical/ Strategic planning	Det./ Prob. traj.	Det./ Stoch. lin. prog. model	Weather or EWF (W+)	Network or Single Flight (F) planning	TW
7-[6]	Minimum-Cost Cruise at Constant Altitude of Commercial Aircraft Including Wind Effects	Analysis of trajectory optimisation		D		W	F	
8-[11]	A Critical Survey of Optimization Models for Tactical and Strategic Aspects of Air Traffic Flow Management	A critical review of the principal existing optimization models, mainly Generalized Tactical Flow Management Problem and the Ground Holding Problem	T / S		D / S		N	
9-[9]	An AHP analysis of air traffic management with target windows	Analysis of the potential benefits and limitations of the time-windows concept for airlines, airports and ANSPs	T / S				N	X
10-[7]	Air Traffic Management with Target Windows: An approach using Reachability	An application of reachability (game theory) on Target Windows (time-windows)	S	D			F	X
11-[15]	Evaluating the true cost to airlines of one minute of airborne or ground delay	The results of a study that has evaluated the true cost to airlines of one minute of airborne or ground delay	T			W	N	

5 Research Questions

This Literature Study is focused on two main research questions and several subquestions:

1. How to evaluate the impact on fuel consumption and arrival time on flights that are scheduled using the time-window concept while also considering the flight time variation due to wind and departure time?
   (a) How to calculate the fuel consumption?
   (b) How to compare arrival times?
   (c) How to incorporate the variation in wind?
   (d) How to incorporate the variation in departure time?
   (e) How to compare different types of time-windows?
2. How to further improve the time-windows based flight schedules to optimise for fuel consumption and arrival time?
   (a) How to improve the punctuality?
   (b) How to optimise the fuel consumption?

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Appendix A: Gantt Chart