Faculty of Aerospace Engineering

Benefits of direct Routing above Europe

Final Report

Gideon Pappie

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Delft University of Technology

Challenge the future

Benefits of direct Routing above Europe

Final Report

Master of Science Thesis

For obtaining the degree of Master of Science in Aerospace Engineering
at Delft University of Technology

Gideon Pappie

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Faculty of Aerospace Engineering · Delft University of Technology

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Control and Simulation

The undersigned hereby certify that they have read and recommend to the Faculty of Aerospace Engineering for acceptance a thesis entitled **"Benefits of direct Routing above Europe"** by **Gideon Pappie** in partial fulfillment of the requirements for the degree of **Master of Science**.

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Acronyms

ADS-B	Automatic Dependent Surveillance-Broadcast
CTR	Tower Control Zone
FIR	Flight Information Region
GCR	Great Circle Route
GNSS	Global Navigation Satellite System
ISA	International Standard Atmosphere
MTOW	Maximum Take-Off Weight
OEW	Operating Empty Weight
SID	Standard Instrument Departure
STAR	Standard Terminal Arrival Route
SUA	Special Use Airspace
TMA	Terminal Maneuvering Area
WOR	Wind Optimal Route

Preface

This thesis concludes seven years of studying at the TU Delft. Performing a research project on my own was challenging and very interesting. It teaches you skills that you won't learn by studying from textbooks and making exams and therefore, I consider it a very useful experience.

I would like to thank my thesis supervisors dr. Joost Ellerbroek and prof. Jacco Hoekstra for their guidance and feedback during this project. It was fun to be a part of the BlueSky team and I wish Joost, Jacco and the other students best of luck with developing this nice ATM simulation tool. Thanks to Xavier Olive for the help with the Special Use Airspace database. Also I want to thank fellow student Anouk Scholtes for her help with understanding BlueSky and the other students of room SIM-008 for their support.

Thanks to my friends for the support and fun during my time as a student. Last but not least, I thank my parents for their support and by making it possible for me to study at the TU Delft. It was a great time!

Gideon Pappie
Delft, June 2018

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Report Outline

This thesis report consists of three parts:

I **Scientific Paper:** Description of the conducted research and relevant results.

II **Appendices:** Additional analysis and detailed results.

III **Preliminary Report:** Literature study and project proposal for this research.

The preliminary report has already been reviewed and graded.

Part I

Scientific Paper

Benefits of Direct Routing above Europe

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***Abstract*—As the amount of air traffic increases every year, the capacity of the current Air Traffic Control (ATC) structure is reaching its limit. Shifting the responsibility of aircraft separation from the ground to aircraft (free flight) eliminates the ATC constraint for aviation growth. Furthermore, free flight allows for direct routing of aircraft. The benefits of direct routing above Europe in terms of efficiency, safety and capacity are studied. ADS-B data of two full days of European air-traffic is collected in order to simulate and compare current flown routes with Great Circle Routes (GCR). Only commercial aviation is taken into account. The impact of having parts of the airspace unavailable for civil use is investigated as well. For European flights above 10,000ft it is found that by optimizing the lateral route only, an average of 1.8% total fuel savings can be realized. Allowing aircraft to resolve conflicts both horizontally and vertically, increases the fuel savings to 3.1%. Direct routing increases the airspace safety as aircraft are more spread out over the airspace. The results suggest that under free flight the total flight efficiency and airspace safety is improved by solely flying lateral direct routes above 10,000ft.**

***Index Terms*—Direct Routing, Free Flight, Air Traffic Control, Aviation, Fuel Benefits, Great Circle Route (GCR)**

I. Introduction

The current air routes can be seen as 'highways in the sky'. Most of these routes originate from the time that aircraft had to fly from radio beacon to beacon in order to navigate. On the road, the motorist is responsible for keeping safe separation between all vehicles. However, in the air it is not the pilot who is responsible, but an Air Traffic Controller (ATCo). The ATCo can command pilots to change their flight track in order to avoid collision with other aircraft. Each ATCo controls a specific part of the airspace, a sector. As the number of air traffic passengers is expected to double over the next 20 years [1], more aircraft will fly within these sectors. Therefore, the workload for the ATCo will increase. There is a maximum number of aircraft a single human controller can handle. When the airspace becomes too crowded, sectors can be split up into smaller parts handled by multiple controllers. However, the more sectors the more coordination between them is needed. Efficiency will be degraded and safety will be at stake. Thus, there is a limit for splitting up a sector [2]. The ATCo workload is a big constraint for increasing airspace capacity. Therefore, the air traffic structure needs to be reorganized in order to deal with the expected growth. Furthermore, as different institutions and organizations agree to limit global greenhouse gas emission due to aviation a more efficient air routing system needs to be established [3].

A novel concept in Air Traffic Management (ATM) is 'free flight'. With free flight, the responsibility of safe separation between aircraft is shifted from the ground to the air. Using the latest navigation, communication and surveillance systems conflict detection and resolution can be performed on board the aircraft. Without the need for ATCo's, the capacity constraint due to the ATCo workload is eliminated. Another benefit of free flight is the possibility for pilots to fly direct routes. By flying direct routes and making better use of airspace capacity, air travel can become more efficient [4].

Research on implementing free flight in Europe has been focused on safety, rather than on resulting efficiency benefits from direct routing [5] [6]. Previous studies on the efficiency of direct routing have been performed under the assumption of current ATC structures [7]. A study that investigates direct routing on large scale under the concept of free flight with the focus on fuel benefits hasn't been performed yet. Results of such research can support the argument of moving to free flight. Furthermore, as stricter regulations on aviation emissions will be imposed, the benefits of alternative flight routes should be researched and quantified. The purpose of this research is therefore to investigate the benefits in terms of efficiency, safety and capacity of direct routing above Europe under the free flight concept. Nowadays most aircraft have Automatic Dependent Surveillance Broadcast (ADS-B) transmitters installed onboard. The aircraft transmists flight-data to ADS-B receivers on the ground. This flight data is used by ATC for surveillance of aircraft. The ADS-B data is openly available to anyone with a receiver. Global networks of receivers are set up by online platform, making ADS-B widely available. European flight data can be obtained and simulated, in order to measure flight safety and efficiency. Based on real flight data, direct routes can be constructed and simulated. A comparison can be made and the difference in efficiency, safety and stability can be analysed.

In section II a brief history of aircraft routing will be given. The multiple causes of current non-direct routing will be discussed. Furthermore, the concept of free flight will be explained. More details on direct routing will be given in section III. The way the experiment is set up and performed is explained in section IV. The assumptions made for this research are stated. The results are presented in section V and will be discussed in further detail in section VI. The effect of the important assumptions will be analyzed. Finally a conclusion is drawn and recommendations for further research are given.

II. BACKGROUND

When investigating direct routing, it is important to understand how current aircraft routing has emerged. First a brief introduction of aircraft routing is given. Then, the existing constraints that prevent direct routing are discussed. Also, the concept of free flight is explained.

A. History

In the beginning of aviation, pilots were free to choose their preferred route. Navigation was done using maps, compasses and visual cues. As the amount of air traffic increased, the need for air traffic organization emerged in order to assure safety [8]. The first radio communication from the ground with pilots started in the 1930s. Shortly after radio communication, the first radars were installed to detect the aircraft's position. In order to manage complex traffic streams, Air Traffic Control (ATC) started to divide the airspace into sectors and layers. Aircraft were forced to fly along predefined routes. These routes were constructed from radio beacon to beacon, which the pilots used for navigation. Although nowadays, radio beacons are not used by commercial aviation and most physical beacons aren't present anymore, the routes that aircraft fly are still via these waypoints.

B. Current Routing

ATC is responsible for the safe separation of all commercial air traffic. In order to do so, traffic is forced to fly via predetermined routes in the sky. On a strategic level, ATC manages traffic flows such that certain air routes won't become too busy and safety will not be at stake. Tactical controllers ensure that the aircraft remain at a safe distance from each other at all times. Each country is responsible for its own airspace. Furthermore, the airspace is divided into layers that are controlled by different ATC-centers per country. Safety is the highest priority of ATC. This is sometimes at the cost of efficiency. Besides ATC structure and procedures, there are other reasons why aircraft don't fly the most direct route from A to B.

1) Airports: The airspace around airports, the Terminal Maneuvering Area (TMA), is highly complex. It has a high density of incoming and outgoing traffic. To comply with the noise and environmental restrictions around airports, ATC designed fixed routes aircraft have to fly in the TMA. When an aircraft departs, it flies a Standard Instrument Departure (SID), a route that connects the take-off with the en-route phase. Arriving aircraft fly a similar procedure called a Standard Terminal arrival Route (STAR). SIDs and STARs make aircraft fly a detour. Furthermore, runway usage dependent on weather conditions causes additional constraints for direct routing.

2) Special Use Airspace: In certain parts of the airspace, (commercial) flight is prohibited or restricted. These areas are called Special Use Airspace (SUA). Examples of SUA are: military training zones, war zones or airspace above nuclear facilities, big cities and royal- or governmental buildings. SUA causes flights to fly detours and therefore less efficient routes. Current research is looking at Flexible Use Airspace (FUA), where civil aviation and the military share airspaces [9].

3) Costs: For flying through a country's airspace, a fee needs to be paid. This fee depends on aircraft weight, distance flown through airspace and a fixed rate of charge. As the fixed rate can significantly differ per country, it can be cheaper for an airline to avoid certain countries even if this implies flying a detour.

C. Free Flight

Free flight shifts the responsibility of traffic separation from the ground to the air. In this decentralized concept, aircraft are all responsible for Conflict Detection and Resolution (CD&R). As the role of ATC becomes redundent, the capacity constraint for air traffic growth due to ATCo workload is eliminated. Furthermore, aircraft won't have to fly along predetermined ATC routes. As communication, navigation and surveillance can be done via GNSS aircraft can fly their most optimal routes. In the next paragraph CD&R is briefly explained.

1) Conflict Detection & Resolution: Each aircraft can be imagined flying with a disk around it with radius R and height h, called the protected zone. When another other aircraft enters the protected zone it is called an 'intrusion' or 'loss of separation'. A conflict is a predicted intrusion within a specified look-ahead time. An on-board system that detects possible conflicts is the Airborne Separation Assurance System (ASAS). In order to predict a conflict, the future trajectories of the surrounding traffic need to be predicted. For aircraft flying straight routes, it is easy to extrapolate the future position by using its current position, speed and heading. When a conflict is detected, it needs to be resolved in order to avoid an intrusion. There are different resolution algorithms being researched. For this study the Modified Voltage Potential (MVP) method developed by the Netherlands Aerospace Center, NLR, is used as it has proven to have a good performance in terms of safety and efficiency [4]. Using MVP, ASAS computes the new route the aircraft has to fly in order to avoid an intrusion.

2) Moving to Free flight: Implementing free flight will enable direct routing. As aircraft won't have to fly along predetermined routes, the most optimal and efficient route can be flown. This could lead to fuel savings, time savings and therefore cost savings. Only severe weather conditions and restricted airspace (e.g. airspace used for military purposes) can still be an obstacle for flying the most efficient route. For this concept to work, countries have to share their airspace. This can be a problematic condition, as airspace borders can be as strict as the borders on the ground. In Europe where most countries have open borders, sharing one airspace seems feasible. Counties sharing military airspace zones can even improve the total efficiency of the airspace. Furthermore, the cost of airspace use should be the same throughout Europe.

III. DIRECT ROUTING

Free flight enables direct routing. However, several constraints won't be eliminated by free flight. Direct routing in the TMA will be restricted as aircraft still have to comply to noise and emission requirements. Furthermore, weather conditions have an effect on how aircraft are routed in the TMA. As TMA and airports are too complex to take into account within

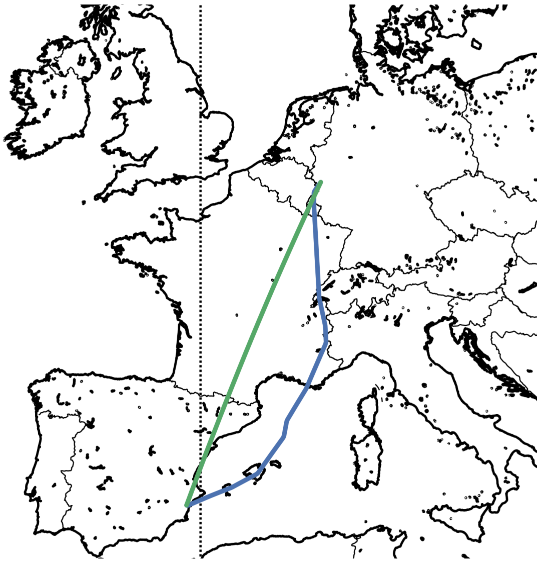

Fig. 1: Actual flight route (blue) and great circle route (green) of a flight from Alicante to Cologne

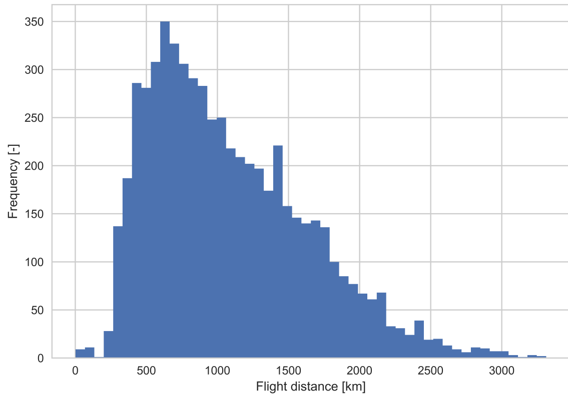

Fig. 2: Great circle distance of European flights in dataset

this research time constraint, only the airspace above 10,000 ft (FL100) will be considered. The limit of FL100 is chosen as this altitude is the point where for arriving aircraft most STARs start and for departing aircraft speed restrictions are no longer in place. The effect of having certain parts of airspace restricted for commercial aviation will be taken into account.

To reduce fuel usage, the most efficient lateral routes are investigated. Evidently, the shorter the distance flown, the less fuel is consumed. To easily compute the shortest route between two points, the earth is assumed to be a perfect sphere with:

- a constant radius of $R = 6371\ km$
- uniform curvature along the surface

The shortest distance between two points on a sphere is called the Great Circle Route (GCR).

$$a = sin^2(\frac{\Delta\phi}{2}) + cos\phi_1 \cdot cos\phi_2 \cdot sin^2(\frac{\Delta\lambda}{2}) \quad (1)$$

$$c = 2 \cdot atan2(\sqrt{a}, \sqrt{(1-a)}) \quad (2)$$

$$d = R \cdot c \quad (3)$$

With ϕ the latitude [rad] and λ the longitude [rad].

In reality the earth has the shape of a flattened sphere (spheroid) with different radii and curvature from the equator to the pole. The error in GCR computation because assuming a spherical earth, varies for GCD and geographical location of the route. This research looks at flights within Europe and relatively short distances. The latitude of the area of interest ranges from $30° < \phi < 60°$. A comparison of the GCR and shortest distance on an ellipse, Great Ellipse Distance (GED) errors are found to be ranging from 0.1% to 0.3% depending on the length and direction of the route [10].

While GCR is the shortest route, it doesn't have to be the most efficient route. Wind can have a great influence on flight performance and duration. Wind Optimal Routes (WOR) take into account the wind direction for constructing the most fuel efficient routes. A well known example of current WOR are the flights across the Atlantic that make use of the jet streams. Jet streams are fast flowing air currents in the atmosphere located above an altitude of 30,000 ft [11]. Commercial aviation use these air streams in order to save time and fuel. Cheng et. al [12] researched the benefits of WOR over GCR and concluded that for short-haul flights the benefits of WOR over GCR are minimal. Only flights longer than 2000 nm (= 3700 km) would benefit more from WOR with relative differences greater than 1 %. As this research focuses on European flights, therefore short distances as can be seen in figure (2), GCR will be considered as the most efficient route. Knowing the start- and end coordinates of actual European flights, lateral direct routes can be constructed. An example of an actual flown route and the corresponding direct route can be seen in figure 1.

IV. Experiment Design

The goal of this study is to find an answer to the following research questions:

1) *What are the benefits of direct routing in terms of efficiency and safety?*
2) *What will be the effect of SUA on direct routing in terms of efficiency, safety and stability?*

To analyze the benefits of flying direct routes above Europe, the currently flown routes need to be modeled and simulated first. Nowadays, flight data obtained from ADS-B receivers is widely available. European flight data will be collected for two different days. From this data, the flown routes will be reconstructed and simulated in order to compute performance metrics as efficiency and safety. Simulation will be done using BlueSky, an open source ATM simulation tool developed at the TU Delft [13]. From the same dataset, direct routing flights will be constructed and simulated. The resulting performance metrics will be compared to those of the actual routes. Furthermore, the effect of having certain SUAs active with direct routing will be researched as well.

The input for BlueSky simulations are traffic scenario files. An schematic overview of the construction process from raw ADS-B data to the different scenario files is shown in figure

3. The steps taken and assumptions made during this process will be explained in this section. First in subsection IV-A an explanation is given how the ADS-B data is obtained and how it is filtered in order to get useful data. In subsection IV-B the construction of the different scenarios from the filtered flight data will be explained. Also, it will be explained why these different scenarios are needed in order to to answer the research questions. After discussing all the steps needed to obtain the input files for BlueSky, it will be discussed what will be measured during the simulations. The dependent measures that are computed in BlueSky for each scenario will be discussed in subsection IV-D.

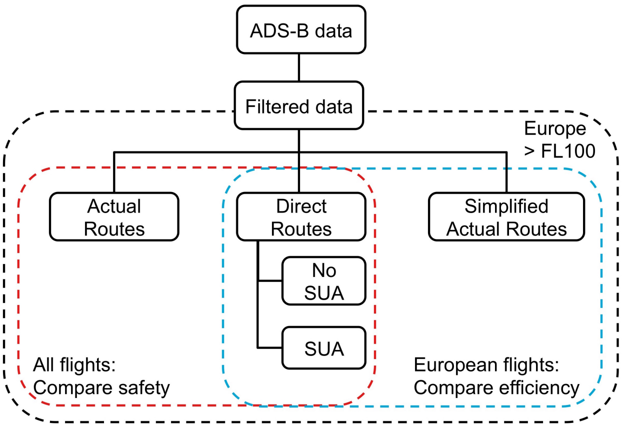

Fig. 3: Schematic overview of ADS-B data processing

A. Flight data

The first step is to obtain actual flight data. Over 80% of the aircraft flying in European airspace are equipped with an ADS-B transmitter. The flightdata of these aircraft is transmitted every second, and is received by receivers on the ground. FlightRadar24 is an online platform that has a network of over 17,000 ADS-B receivers worldwide. From this website the flightdata from flights within the area of research is obtained. For two full days (02/03/18 and 11/03/18) flightdata is collected. Table I gives an overview of the parameters obtained per flight from the ADS-B data. In order to deal fast and efficiently with the large unsorted flight-data set an unsupervised machine learning clustering method, DBSCAN, is used to cluster and sort the data per flight [14]. Flights with insufficient data points available are discarded. For the construction of direct routes further on in the process, it is handy to assign the flight-phase (e.g. climb, cruise or descent) to each data point per flight. Per datapoint, the inputs altitude (h), speed (V) and rate of climb (ROC) will be used to determine the phase. For example, during cruise the aircraft has generally a high speed, it flies at a high altitude and has a ROC close to zero. What is considered to be a high altitude or a high speed is determined with constructed membership functions. These membership functions can be Gaussian, Z-shaped or S-shaped and their outcome are values between 0 and 1. While with Boolean logic a value can only be either 0 or 1, with fuzzy logic a value of a variable can vary between those two numbers. The membership functions used are plotted in figure 4 The following set of rules are used to determine the flight phase per data point:

TABLE I: ADS-B flight data

Parameter	Unit
Altitude (h)	ft
Latitude (lat)	degrees
Longitude (lon)	degrees
Rate of Climb (ROC)	ft/minute
Ground speed (V_{ground})	kts
Heading (hdg)	degrees
Time-stamp (t)	s

$$if\ h_{low} \wedge V_{medium} \wedge ROC_{+}\ then\ Climb \quad (4a)$$
$$if\ h_{high} \wedge V_{high} \wedge ROC_{0}\ then\ Cruise \quad (4b)$$
$$if\ h_{low} \wedge V_{medium} \wedge ROC_{-}\ then\ Descent \quad (4c)$$
$$if\ h_{low} \wedge V_{medium} \wedge ROC_{0}\ then\ Level\ flight \quad (4d)$$
$$(4e)$$

After sorting all of the data, the obtained dataset is analyzed.

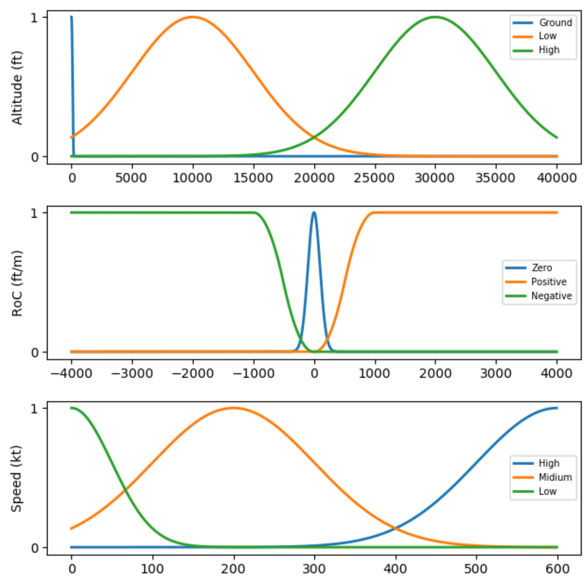

Fig. 4: Membership functions to determine altitude, speed and ROC range [14]

By computing the efficiency loss, η_{loss}, (equation 5) it is measured how close the actual routes are to flying GCRs. The closer the η_{loss} to 0, the more efficient the actual flown route is.

$$\eta_{loss} = (\frac{d_{gcr}}{d_{actual}} - 1) * 100\% \quad (5)$$

Significant outliers are detected and investigated. It is found that the dataset contains also flights of helicopters, aviation academies and other general aviation. As only commercial aviation is taken into account, these flights are filtered out of the dataset by assuming that a flight with $\eta_{loss} > -0.6$ is general aviation. The resulting distribution of η_{loss} per flight is shown in figure 5. In the final dataset that consists of 11500

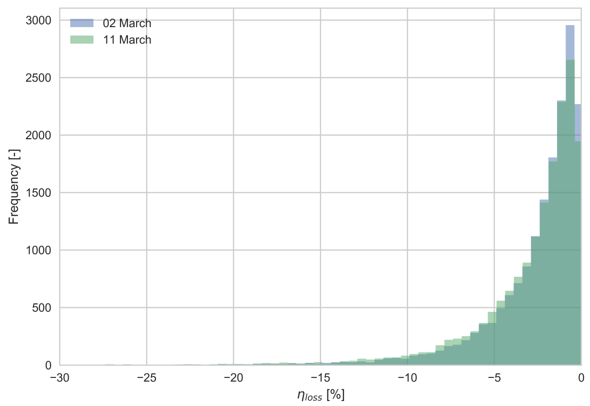

Fig. 5: Distribution of efficiency loss per flight for both datasets

flights (average of the two days), four types of flight are defined:

- 65% European flights. Both origin and destination within the experiment area.
- 17% Arriving flights. Intercontinental flights arriving in the experiment area.
- 16% Departing flights. Intercontinental flights departing from the experiment area.
- 2.5% Passing flights. Intercontinental flights passing over the experiment area.

The experiment area is a square which covers the vast part of Europe and starts at FL100. In figure 6 a top down view of this area is shown. The filtered data of both days will be used to construct all traffic scenarios.

B. *Traffic scenarios*

As can be seen in figure 3, the filtered data is used to construct all traffic scenarios. An aim of this study is to measure the difference in flight efficiency between the actual routes and direct routes. The focus will be on measuring the effect of difference in lateral distance flown. The flight-path of flights flying direct routes will not be optimized. For fuel-burn measurements, in order to make a fair comparison between the actual routes and the direct routes the vertical flight path of the actual routes should be simplified. The simplified actual routes and the direct routes will be compared when measuring efficiency. For each flight the vertical will remain the same in both scenarios. When measuring safety, the (unmodified) actual routes and direct routes will be compared (see figure 3). For the direct routing scenario, the effect of having varying degrees active SUA will be measured and the effect on airspace stability will be investigated. The following scenarios are constructed:

1) Actual routes
2) Simplified actual routes
3) Direct routes
    - No SUA active
    - 10%, 20% or 40% SUA active

In all scenarios the experiment area is the same. Aircraft flying outside the experiment area are deleted and their flight data is logged. Per scenario it will be described how the aircraft routes are constructed.

1) Actual Routes: In BlueSky an aircraft route is defined by waypoints. There are two types of waypoints:

- Lateral waypoints, wp_l. Only have a latitude and longitude constraint.
- Lateral + vertical waypoints $wp_{l,v}$. Besides latitude and longitude, also altitude and speed constraints.

From the ADS-B data for $\Delta t = 10s$; $lat[t]$, $lon[t]$, $V_{ground}[t]$ and $h[t]$ are available. Per time-step these parameters are assigned to a waypoint in order to recreate the trajectory flown by the aircraft. ADS-B data only provides V_{ground}. However, for the simulations and fuel computations in BlueSky the true airspeed, V is needed:

$$V = V_{ground} + V_{wind} \tag{6}$$

As no wind data is available, it is assumed that $V = V_{ground}$. The effect of this assumption is that aircraft fly faster or slower in the simulations than in reality. Airspeed has a big influence on the flight performance and fuel burn. Flying a sub-optimal speed can result in more fuel being consumed. As the same speeds will hold for an aircraft throughout all scenarios, the relative effect of this assumption is expected to be small. Because V is assumed to be equal to V_{ground}, it can happen that the minimum- maximum operating speeds, V_{min} and V_{max} are exceeded. In BlueSky, for each aircraft type it is assured that V_{min} and V_{max} aren't exceeded at all times.

Another important aircraft parameter needed for simulation and efficiency computation is the aircraft mass, m. The aircraft mass is sensitive data for airliners and therefore, it is not transmitted via ADS-B. Mass has a large influence on aircraft performance. Eurocontrol created Base of Aircraft Data (BADA) performances files. These files provide aerodynamic and engine-coefficients for different aircraft models. Furthermore, the BADA-files provide per aircraft type a reference mass, m_{ref}, a minimum mass, m_{min} and a maximum mass, m_{max}. Using the reference mass would result in all flights of the same aircraft type having exactly the same mass. Using the same mass for a large set of aircraft, can result in a higher chance of over- or under estimating the actual mass. In order to get a better resemblance of reality it is assumed that for a set of aircraft of the same type, the mass is normally distributed with $\mu = m_{ref}$ and $\pm 3\sigma = m_{max}, m_{min}$. As all (European) flights start at FL100 in all scenarios, m_{ref} is reduced with 10% in order to account for the fuel burned during the take-off and the first part of the climb. The same initial mass is used per aircraft throughout all scenarios.

2) Simplified Actual Routes: To compare efficiency with direct routes, the actual routes are simplified. For each flight-phase the following simplifications to the altitude and speed profile are made:

- **Climb**
    - Constant ROC
    - Constant speed

- **Cruise**
  - At a single altitude (average of range of altitudes flown during actual cruise phase)
  - At a constant speed (average of actual cruise speeds)
- **Descent**
  - Constant ROC
  - Constant speed

The process of labeling each data-point with the corresponding flight-phase, make it possible to quickly group flight data per flight-phase and simplify each phase. The simplifications to the vertical flight profile may lead to some aircraft not flying their optimal speed and at the optimal altitude at all time. However, this will hold for all scenarios and will still give a fair comparison. The difference between the scenarios will be in the lateral route. To define the vertical flight profile 3 $wp_{l,v}$ are needed;

1) At the beginning of the flight to define the initial height and speed, $wp_{l,v-initial}$
2) At the start of the cruise phase defining the cruise speed and altitude, $wp_{l,v-cruise}$
3) At the end of the flight, defining the final speed and altitude, $wp_{l,v-final}$

wp_l are used to define the horizontal track the aircraft flies. The aircraft flies the shortest distance from waypoint to waypoint.

3) Direct routes: For each flight, direct routes are constructed with the same vertical profile as the simplified actual routes. The aircraft flies the GCR from origin to destination. $wp_{l,v-initial}$ and $wp_{l,v-final}$ are the same as in the simplified actual route scenario. $wp_{l,v-cruise}$ differs only in lateral location. It is placed at the same relative horizontal distance from $wp_{l,v-initial}$ as in the simplified actual routing scenario, such that the same vertical profile is flown.

4) Direct routes with varying degree of SUA: To measure the effect of having a direct routing airspace with allocating some parts of the airspace to special use, this scenario is created. A set of coordinates of SUA in Europe is obtained. As not all SUA's are active at once, multiple scenarios are constructed with a certain degree of active SUA. A SUA is defined in BlueSky as a polygon area ranging over certain altitudes. Aircraft are not allowed to fly into the SUA. For each flight it is checked if the route crosses a SUA. If so, waypoints are placed at the edge of the SUA such that flights are passing them. This results in some flights flying a detour and therefore a decrease in airspace efficiency is expected, compared to the direct routing scenario without SUA. As less airspace is available, the number of conflicts will increase for increasing amount of SUA.

C. Independent Measures

In summary of the previous section, for two different data sets (02 March and 11 March 2018) the following scenarios will be simulated:

- Actual routing
- Direct routing
- Direct routing with SUA (10%, 20%, 40% active)

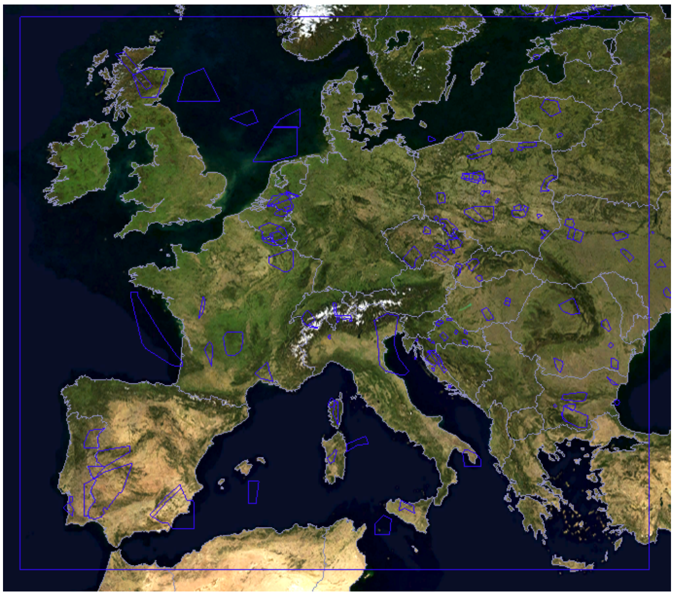

Fig. 6: Experiment area in BlueSky with SUAs

The direct routing scenarios will be simulated with both Conflict Resolution (CR) turned on and off.

D. Dependent Measures

To compare the performance of all scenarios the flight efficiency and airspace safety & stability will be measured. How these performance indicators are assessed will be described in the following paragraphs.

1) Efficiency: Efficiency is a key performance measure of this research. As direct routes are shorter than the conventional routes, a reduction in total fuel burn is expected. All air-traffic is simulated in each scenario, however for efficiency measurements only the European flights will be taken into account. For flights that arrive at or depart from Europe, only a small part of their trajectory is simulated. Therefore, comparing their original route with the simulate direct route for doesn't give a complete picture of the efficiency gain possible for those flights. First the route efficiency loss,η_{loss} (equation 5) as introduced in subsection IV-A is measured for all aircraft. It is important to note that the actual routes used for this computation are always the simplified actual routes simulated in BlueSky, and not the real routes.

For each flight the total fuel burn is computed. This is done using the BADA total energy model shown in equation 7 [15]. For the energy model, there are two input sources used that provide the following parameters:

1) **ADS-B data**:
   - V_{ground}
   - h
   - ROC
   - t
2) **BADA files** (per aircraft type):
   - engine coefficients
   - aerodynamic coefficients

Using these parameters the thrust, T, and fuel flow,f can be computed during each flight phase (equations 7 and 8). with η being the thrust specific fuel consumption and C_T are aircraft specific constants. The total fuel burn, F is finally computed by equation 9.

$$(T - D) \cdot V = m \cdot g \cdot \frac{dh}{dt} + m \cdot V \cdot \frac{dV}{dt} \tag{7}$$

Knowing the thrust at each time, the fuel flow, f can be computed by equation 8

$$f = \eta \cdot T \tag{8}$$

$$F = \int_{t_{start}}^{t_{end}} f \, dt \tag{9}$$

No weather data is available for the fuel burn computations. For example, air density ρ is needed to compute the required thrust. Besides altitude, the air density ρ is dependent on air temperature which can vary per day. For this research the International Standard Atmosphere (ISA) is assumed. As the ISA will be used for each scenario, it will have no effect on the final comparison.

2) Safety: Safety has the highest priority in aviation. Therefore, it is important to evaluate the safety of the airspace for all scenarios. The direct routing scenarios will be compared to the actual routes. Safety will be measured by counting the number of conflicts pairs, n_{conf} and the number of intrusion/loss of separation (los) pairs, n_{los}. Furthermore, the Intrusion Prevention Rate (IPR) is computed by equation 10. The IPR gives insight on the rate that conflicts turn into intrusions.

$$IPR = \frac{n_{conf} - n_{los}}{n_{conf}} \tag{10}$$

For the direct routing scenarios state based conflict detection is used and the MVP resolution method is implemented. All aircraft need to comply to the following safety standards:

- Protected zone around the aircraft with $R = 5\ nm$ and $h = 2000ft$ ($1000ft$ on both sides of the aircraft)
- Look ahead time $t_{look} = 300s$

When the ASAS detects a conflict, aircraft are able to perform a speed change, heading change or both in order to avoid an intrusion. Once a conflict is resolved, the aircraft will return to its original flight path and speed.

There main difficulty with comparing safety between the actual routing scenario and the direct routing scenarios is the difference in conflict resolution strategy. The actual route scenario is composed by ADS-B that corresponds to the actual path flown by the aircraft. An ATCo has intervened in some flight paths in order to avoid aircraft colliding. As for the actual routing scenario the actual flown flight paths are simulated, it is difficult to make a comparison with the artificially generated direct routes where no ATCo comes into play. Aircraft in the direct routing scenario use a distributed resolution strategy while in the actual routing scenario conflicts are already resolved by ATCo. According to Eurocontrol's protocol, the Conflict Detection Tool (CDT) used in ATC centers should show a conflict to the ATCo, 8 to 10 minutes before a possible intrusion [16]. By changing the time horizon for which a conflict is detected, t_{look}, possible resolved conflicts can still be detected. The actual routes will be simulated using with t_{look} = [300s, 450s, 600s] . For the sake of clarity, table II shows an overview of the CD&R settings that will be used for each simulation.

TABLE II: Overview of CD&R setting used for simulated scenarios

	Actual Routes	Direct Routes
t_{look} [s]	300,450,600	300
R [nm]	5	5
h [ft]	2000	2000
Resolution	OFF	MVP

3) Stability: At high traffic densities, resolving conflicts can lead to the generation of new conflicts. This domino effect is used as a measure for airspace stability. The Domino Effect Parameter, DEP, which is used to measure stability works as follows (see figure 7). The set S_1 is defined as the number of conflicts occurring with aircraft flying their desired trajectories without conflict resolution. The set S_2 is defined as the number of conflict occurring when aircraft would fly their desired trajectories with conflict resolution. The subset R_1 represents the stabilizing effect, because these conflict existed when no conflict resolution was done and didn't cause additional conflicts when conflict resolution was performed. The subset R_3 can be seen as the opposite. It consists of conflict that weren't there initially, however due to conflict resolution they occurred. The net domino effect is the difference between these two subset, ($\mid R_3 \mid - \mid R_1 \mid$). This difference is normalized with respect to S_1 in order to compute the DEP. Airspace stability is inversely related with the DEP.

$$DEP = \frac{\mid R_3 \mid - \mid R_1 \mid}{\mid S_1 \mid} = \frac{\mid S_2 \mid}{\mid S_1 \mid} - 1 \tag{11}$$

The DEP can't be measured for the actual routes, however it gives an extra indication of the performance of direct routes with and without SUA.

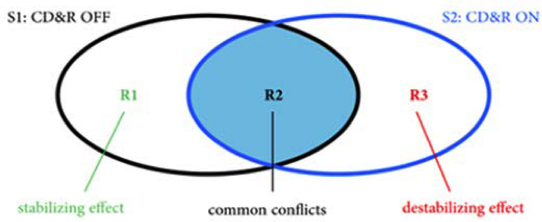

Fig. 7: Venn diagram for Domino Effect Parameter, DEP [17]

V. Results

In this section, for each dependent variable, the results are shown of the performed experiments. For clarity, the following abbreviations are used for the scenarios:

- AR. Actual Routing
- SAR. Simplified Actual Routing scenario
- DR. Direct Routing scenario
- DR-SUA0.1. Direct Routing scenario with 10% of the SUA active

A. *Efficiency*

For efficiency calculations DR was compared to the baseline scenario SAR. To show the additional effect of conflict resolution on efficiency, DR was simulated with CR turned on and CR turned off.

First η_{loss} was computed. In figure 8 a histogram is shown with the computed η_{loss} per single flight for both datasets. Two different distributions can be seen, on where the DR CR-ON scenario is compared to SAR and one where the DR CR-OFF scenario is compared to SAR. For DR CR-OFF, η_{loss} should always be smaller than zero, as the direct route can't be longer than the actual flown route. However, it can be seen in the figure that for some flights the GCR distance flown is longer than the original route. This indicates an error in the simulation. Some of these flights were inspected and the cause of the error was found to be that in some cases the flight in the SAR scenario descended too early and was therefore deleted (in a range of 4-50 km) before the final waypoint was reached. This resulted in a shorter distance flown, compared to the DR flight. By adjustments of BlueSky this error was significantly reduced to an occurrence of 2.4% of the flights. The effect on route efficiency of CR-ON can be seen in the figure. As some aircraft had to fly a slight detour in order to avoid intrusion efficiency is lost. In figure 9 for flights within a range of Great

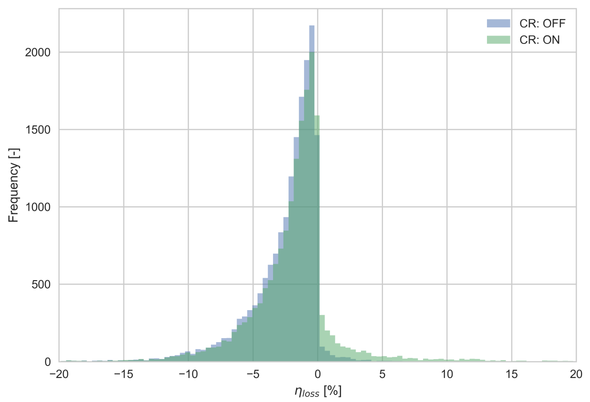

Fig. 8: Distribution of η_{loss} per flight

Circle Distance (GCD) flown a boxplot is shown with the number of flights, n, in that range. The boxplots visualize the distribution of η_{loss} (on the y-axis) for the DR-ON scenario. The horizontal line indicates the median value of η_{loss}. For clarity of the figure, outliers are not plotted. As can be seen the median of the distribution is roughly the same for all distance ranges. For flights with a short range (between 0 and 500 km), the variance of η_{loss} is the largest. The high values of η_{loss} can be due to the fact that CR has a relatively large effect on distance flown for short flights compared to long flights. On the other hand the large negative values of η_{loss}, meaning a high efficiency gain by flying DR, indicate that for the short routes more inefficient actual routes where flown compared to the longer flights. As the set of aircraft flying shorter routes is larger than for longer aircraft, the chances a highly inefficient route was flown is higher. The variance in η_{loss} reduces with increasing GCD flown. To remove the bias that distance flown has in the η_{loss} parameter, for each flight the η_{loss} is divided by kilometers flown. This results in a distribution of efficiency gains per km flown with direct routing. The distribution is shown in figure 10. For visualization, the results are multiplied with 100 resulting in η_{loss} per 100 km flown. The majority of DR flights are within the range of 0.1%-0.5% more efficient than the SAR per 100 km flown. In figure 11 a boxplot is shown of the η_{loss} distribution for all flights per SUA scenario. As can be seen the median η_{loss} reduces slightly for increasing number of active SUA. This was expected, as some aircraft had to fly detours in order to avoid the SUA resulting in lover path efficiencies.

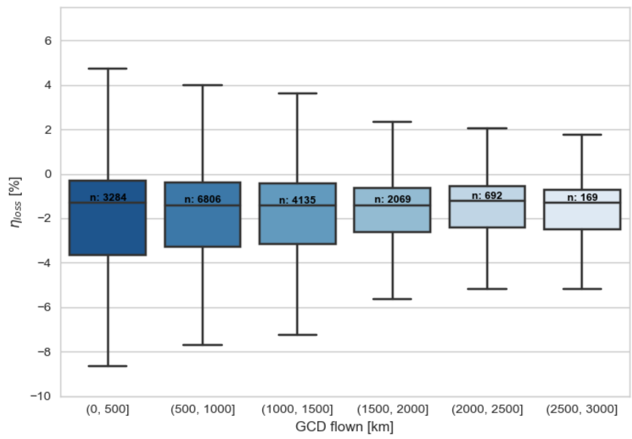

Fig. 9: η_{loss} for different GCD ranges for DR CR-ON

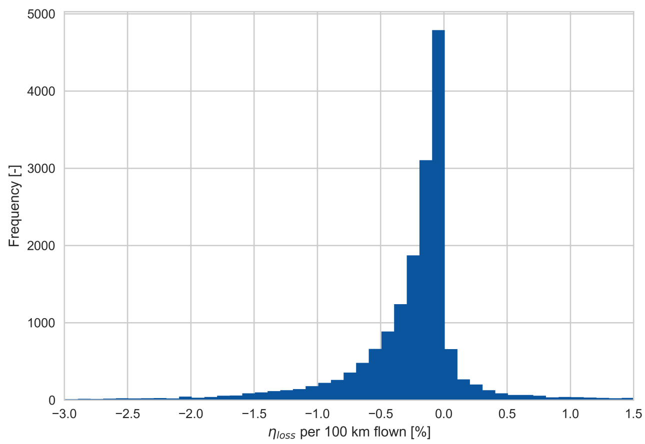

Fig. 10: Distribution of η_{loss} per 100 km GCD flown for DR CR-ON

For each flight in every scenario the total fuel burn was computed. The difference in fuel burn per flight between the

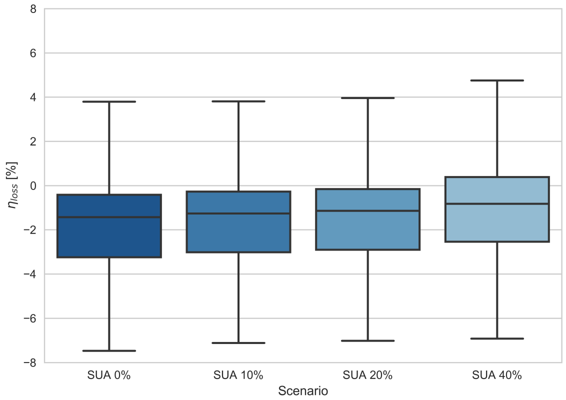

Fig. 11: η_{loss} per flight for different DR-SUA scenarios

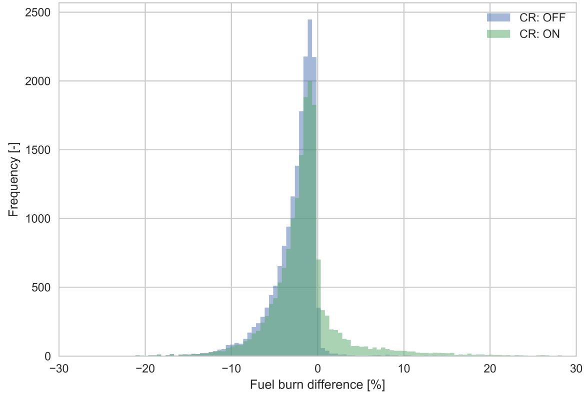

Fig. 12: Fuel burn difference DR with SAR per flight

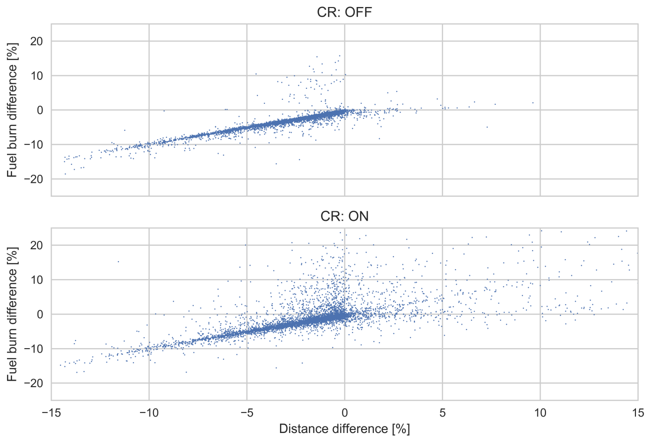

Fig. 13: Distance difference versus Fuel burn difference per flight

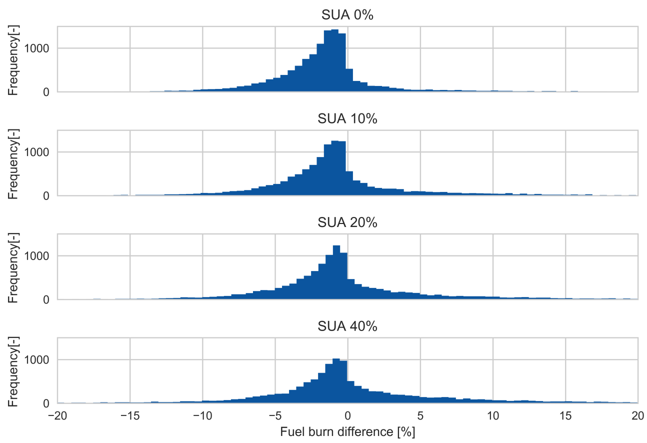

Fig. 14: Distribution of fuel burn difference per flight for DR-SUA

DR and SAR scenarios was computed:

$$\Delta F = \frac{F_{DR} - F_{SAR}}{F_{SAR}} * 100\% \tag{12}$$

This was done both for the DR CR-ON and DR CR-OFF case for all flights in both datasets. The resulting distributions of fuel difference can be seen in figure 12. For most flights, 0-5% fuel savings was realized by flying direct routes. The fuel benefits of DR CR-ON are lower than for DR CR-OFF, as heading- and especially speed resolutions cause an increase in fuel usage. To illustrate this effect, the difference in distance flown between the scenarios against the fuel usage is plotted per flight (figure 13). For DR CR-OFF a clear linear relation can be seen between difference in fuel burn and difference in distance flown. With DR CR-ON this relation exists as well, however many flights are located outside this trend. A higher fuel consumption without flying a larger distance clearly indicates the extra fuel burn due to a speed change resolution. Figure 14 shows the distribution of fuel burn difference for the DR-SUA scenarios. As the number of active SUA increases less fuel savings are realized with respect to SAR, because aircraft had to fly longer distances in order to avoid SUA. Furthermore, less space is available for CR.

In table III the fraction of flights of both dataset is shown per fuel savings range (DR with respect to SAR). For the largest fraction of flights, DR (CR-ON) leads to a fuel saving up to 2%. For 22% of the flights a fuel saving of 2 to 4% was achieved and for even 10% of the flights 4 to 6%. The fraction of flights that achieved over 6% fuel savings was not much different throughout the scenarios even when a high degree of SUA was active. This could be due to an exceptional low route-efficiency for some flights in the SAR scenario. The difference in efficiency and fuel burn for these flights with direct routing was so large, that different number of active SUA didn't have an effect on the difference in fuel burn. In table IV an overview is given of the total fuel burn per scenario and the difference with respect to SAR. The numbers displayed are an average of both data-sets. On average 1.81% fuel can be saved by flying direct routes. The fuel savings decrease for an increasing number of active SUA. Having 40% SUA active leads to more fuel usage than the SAR case.

TABLE III: Fraction of total flights within fuel difference classes (DR with respect to SAR)

Fuel difference[%]	DR CR-OFF	DR CR-ON	DR SUA0.1	DR SUA0.2	DR SUA0.4
>0	0.02	0.16	0.25	0.3	0.36
[0, -2)	0.49	0.41	0.36	0.32	0.35
[-2, -4)	0.26	0.22	0.19	0.16	0.13
[-4, -6)	0.12	0.10	0.08	0.08	0.08
[-6, -8)	0.05	0.04	0.04	0.04	0.04
[-8, -10)	0.02	0.02	0.02	0.02	0.02
<-10	0.02	0.02	0.02	0.02	0.02

TABLE IV: Total fuel burn per scenario (average of both datasets)

	Total fuel burn [tonnes]	Difference w.r.t. SAR [%]
SAR	29508	
DR CR-OFF	28618	- 3.10
DR CR-ON	28980	- 1.81
DR-SUA0.10	29326	- 0.62
DR-SUA0.20	29461	-0.16
DR-SUA0.40	29709	+ 0.68

B. Safety

For safety the non-simplified actual routes, AR, were simulated. The simulations were done using different ASAS t_{look} values. Table V shows the number of conflicts, number of intrusions and IPR per scenario. The numbers displayed are the average of both datasets. For AR, as expected, the number of detected conflicts decreases as t_{look} decreased. It is assumed that the ATCo acts to solve a conflict within this time-frame. The number of intrusions remains unchanged for varying t_{look} indicating unresolved conflicts. Comparing the DR CR-OFF with AR, it is noted that direct routing leads to fewer conflicts and intrusions. This is caused by the spreading of air traffic over the airspace, compared to the current fixed air-routes. This effect can clearly be seen when comparing figures 15 and 16 where each dot indicates a created conflict. The number of conflict pairs in the DR CR-ON scenario is significantly higher compared to DR CR-OFF. This can be due to the domino effect of creating new conflicts while solving one. GCR aircraft were also flying on the same fixed altitude as for the actual routes, which can be seen in figure 17, and only horizontal CR was possible. Therefore, CR could easily lead to creating additional conflicts. However, the number of actual intrusions for DR is way lower. The IPR of 0.99 indicates a good ability of the airspace to avoid intrusions when conflicts arise. The results of DR-SUA are shown in table VI. The number of conflicts increases when less airspace is available for commercial use. The number of intrusions increases slightly. In the SUA scenarios, aircraft flew around the SUA with a certain margin accounted for CR if necessary.

TABLE V: Safety parameters (average of both datasets)

	AR			DR CR-OFF	DR CR-ON
t_{look} [s]	600	450	300	300	300
n_{conf} [-]	118762	77982	43529	10605	65605
n_{los} [-]	7891	7891	7891	4502	456
IPR [-]	0.93	0.90	0.82	0.57	0.99

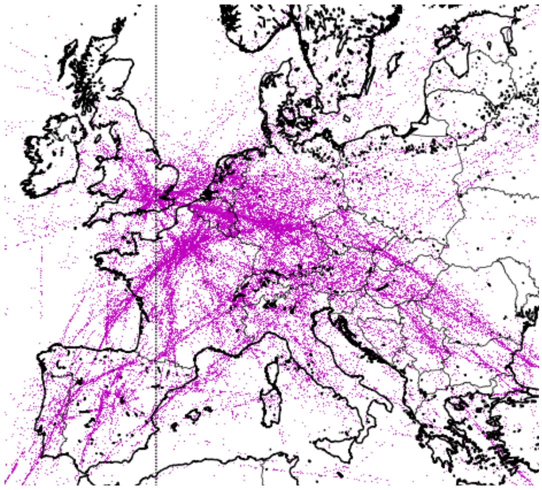

Fig. 15: Location of conflicts for AR

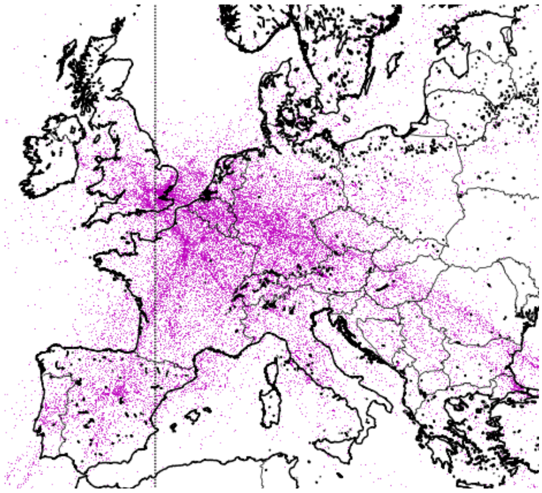

Fig. 16: Location of conflicts for DR CR-OFF

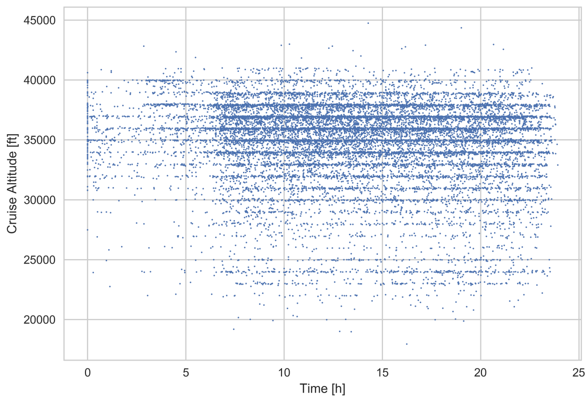

Fig. 17: Cruise altitude of every aircraft in each scenario

C. Stability

As a measure for airspace stability the DEP is computed. An overview is shown in table VII. A high DEP value

TABLE VI: Safety parameters for DR-SUA (average of both datasets)

	DR	DR-SUA0.1	DR-SUA0.2	DR-SUA0.4
n_{conf} [-]	65605	68706	72913	87724
n_{los} [-]	459	452	473	655
IPR [-]	0.99	0.99	0.99	0.99

was measured for DR without any SUA active, especially compared to the DEP values of DR with SUA. The reason for this decrease in DEP is the difference in number of conflicts between the CR-OFF scenarios. As can be seen in table VI for CR turned on, the number of conflicts for DR (no SUA) is n_{conf} = 65605 and for DR-SUA0.1 n_{conf}=68706. This is an increase of 4.7%. However the number of conflicts with CR-OFF between DR and DR-SUA0.1, increases with 112%. This increase can be caused by the change of heading aircraft make in the DR-SUA0.1 scenario in order to avoid the SUA. In the DR scenario aircraft fly straight lines. Changing the flight track can easily lead to new conflicts.

A large DEP indicates a high airspace instability. Because CR is only performed in the horizontal plane and many aircraft fly at the same flight level (figure 17), less space is available to resolve conflicts and therefore CR creates additional conflicts.

TABLE VII: Domino Effect Parameter for DR with varying active SUA

	DR	DR-SUA0.1	DR-SUA0.2	DR-SUA0.4
DEP [-]	2.80	0.89	0.90	1.0

VI. Discussion

As many simplifications and assumptions were made in order to perform this experiment, the effect of them on the results needs to be discussed. During this section two aspects are taken into account:

1) What is the absolute effect of simplifications on the model?
2) What is the relative effect of simplifications on the comparison of scenarios?

First the impact of the assumptions due to the availability of flight data is discussed. Then, the resulting effects of simplifying the flight profiles and using the chosen CR strategy are shown. Finally the limitations of the SUA simulations are discussed.

A. Flight Data

Not all actual daily traffic could be simulated due to a lack of ADS-B data. According to Eurocontrol, March 2017 had an average of 25000 daily flights above Europe [18]. It is assumed that in 2018 at least the same amount of traffic is flying above Europe during this month. However, the average size of the data-set obtained for this experiment consisted of 11500 flights. There are a couple of reasons for having fewer flights available. First of all, not all aircraft are equipped with ADS-B transmitters. For Europe the estimate is that 80% of the commercial aircraft have ADS-B transmitters installed. Furthermore, not all ADS-B data obtained was useful as important flight parameters were missing (e.g. altitudes, speeds). The lacking data was filtered out. General aviation was not taken into account for this research. For performance calculations, BADA files were used which were not available for all aircraft types. For some aircraft types, the BADA files of a comparable aircraft model were used. The experiment area was slightly smaller than the entire continent of Europe, leaving parts of Scandinavia and Turkey out. This all leads to fewer aircraft available for simulations. As the actual amount of traffic is higher, the conflict count is expected to be larger as well. More conflicts result in more resolutions, which have an effect on the flight efficiency. A higher total fuel burn is expected.

B. Effect of weather

For the scope of this research the effect of weather was not taken into account. Weather affects flight performance and fuel consumption. Extreme weather can lead to major disruptions of air traffic, even in the upper airspace. ADS-B data provided only V_{ground}. It was therefore assumed that $V_{ground} = V_{TAS}$ omitting the effect of wind. Also the assumption of an ISA atmosphere was made. To measure the effect of these assumptions on aircraft performance, the Mach number during cruise is being varied. A subset of 500 European flights was simulated to test this effect. Both actual and GCRs were simulated in order to measure the relative effect. In figure 18 it can be seen that at cruise altitude, a higher cruise Mach results in less fuel burn. The difference between actual flights and GCR flights does vary a bit for the different cruise speeds. As the aircraft fly at a faster and more optimum cruise speed, the fuel burn during cruise will get lower and less significant with respect to the fuel burn during the climb and descent phase. Because the other flight-phases are equal for both scenarios, smaller differences in fuel burn are found.

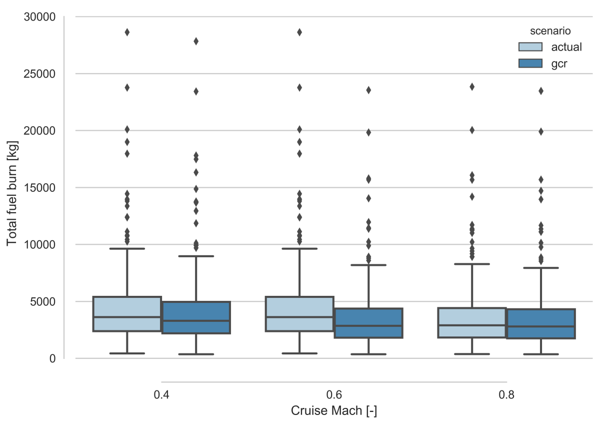

Fig. 18: Effect of varying cruise Mach on total fuel burn

C. Effect of Simplifying the Flight Profile

The flight profile of the actual routes were simplified in order to only compare efficiency for the lateral difference with the GCRs. To measure airspace safety, unsimplified actual routes were simulated in BlueSky. Besides safety, efficiency was measured as well. AR and SAR were compared in order to see the effect off the simplifications made. It was found that the simplifications lead to a decrease of 0.8% in horizontal distance flown. This was caused by the limited number of waypoints that could be placed in BlueSky in order to simulate the simplified route. As the aircraft flies the shortest route between two waypoints, the aircraft in SAR flies a shorter distance than for AR. This is an important note for this research, as horizontal distance is the main control variable. The efficiency benefits of DR can therefore be even higher by 0.8 % than presented in the results. For SAR 9.2% less fuel was consumed than for AR. The difference in total fuel burn can be caused mainly by the difference in climb and descent profile. As the vertical profile for SAR and DR was the same, the this simplification doesn't affect the results

In this study, the DR flights flew at the same constant cruise altitude as the actual flights. However, free flight allows for non-fixed flight altitudes. This can result in a more efficient use of airspace and a reduction in number of conflicts. Furthermore, aircraft flying at their optimum cruise altitude resulting in fuel benefits. Flying continuous climb and descent profile can even lead to additional fuel benefits.

D. *Effect of Conflict Resolution Strategy*

For the implemented MVP resolution strategy, only heading- and speed changes could be made in order to resolve a conflict (CR Horizontal). This choice was made to keep the aircraft on the same flight level during cruise, in order to realize a fair comparison with SAR, for which the cruise level was also kept constant. To see the additional benefits of vertical CR, DR was performed for a case that conflicts could be resolved both horizontally (heading and speed) and vertically (CR H+V). As for all other results, the SAR scenario is taken as baseline to compare with. CR H+V had a small effect on η_{loss} as can be seen in figure 19. Because of the possibility to resolve a conflict vertically, aircraft had to fly less detours in the horizontal plane resulting in a better route efficiency. The effect on fuel usage can be seen in figure 20. Vertical conflict resolution requires less fuel usage than speed or heading changes. In the experiments for this research, it could be even performance beneficial to perform a vertical resolution as aircraft were not always flying on their optimal cruise altitude. Table IX displays a comparison of the fraction of total aircraft per range of fuel savings. CR H+V causes a larger spread of aircraft over the range of fuel savings, which also can be seen in figures 20 and 21. The fuel burn for a vertical conflict resolution also depends on the vertical direction the aircraft had to go in order to avoid an intrusion. For example descending and flying in thicker air for a couple of minutes can result in more fuel burn than if the aircraft could climb into tinner air. In table VIII the effect of both control strategies on safety measures can be seen. As expected, giving the aircraft an extra dimension to resolve conflicts results in fewer conflicts and intrusions. A higher DEP is achieved. CR H+V has a positive effect on airspace stability.

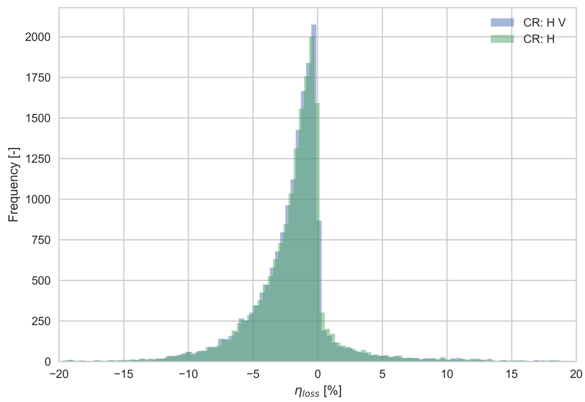

Fig. 19: η_{loss} per flight for different CR strategy

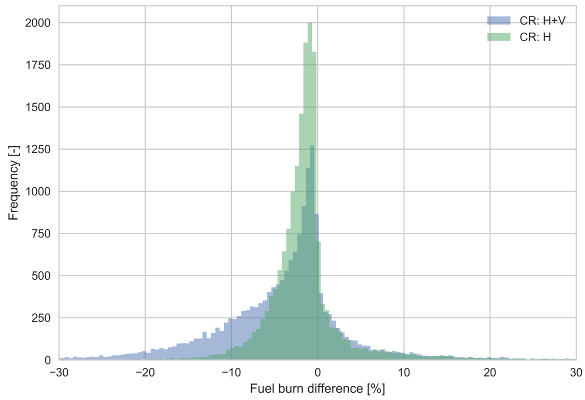

Fig. 20: Fuel burn difference per flight for different CR strategy

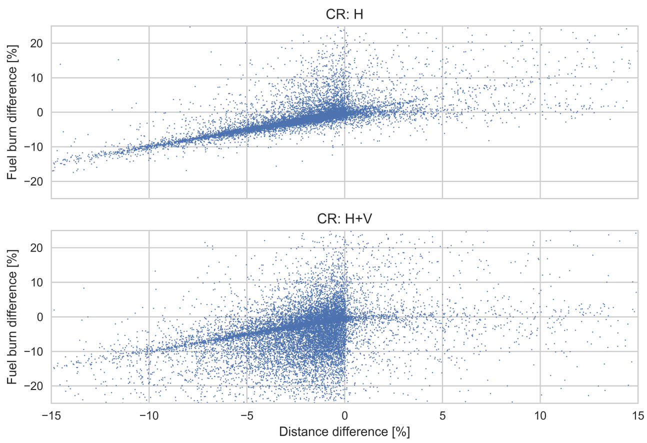

Fig. 21: Distance vs. Fuel burn difference per flight for different CR strategy

E. *SUA*

Several scenarios with a certain degree of active SUA were simulated. The results obtained were as expected, more

TABLE VIII: Performance measures of DR with different CR strategies

	DR CR: H only	DR CR: H+V
Total fuel burn [tonnes]	28980	29523
Fuel savings [%]	-1.81	-4.38
Conflicts [-]	76052	35642
Intrusions [-]	553	340
IPR [-]	0.992	0.990
DEP [-]	2.9	1.0

TABLE IX: Fraction of total flights within fuel difference classes for different CR strategies

Fuel difference[%]	DR CR: H only	DR CR: H+V
>0	0.16	0.18
[0, -2)	0.41	0.24
[-2, -4)	0.22	0.14
[-4, -6)	0.10	0.10
[-6, -8)	0.04	0.08
[-8, -10)	0.02	0.06
<-10	0.02	0.13

SUA active (so less airspace available for the commercial aircraft) leads to more fuel burn, an increase in conflicts and a lower airspace stability. There are several limitations to the simulations performed with SUA. In reality not all SUA is active at once. For aircraft it is possible to get a clearance to fly through the SUA if possible. For this flexible use of SUA was not accounted for in the simulations. In the traffic scenarios aircraft were rerouted if some of their waypoints was placed inside a SUA. The waypoints inside were moved to the edges of the SUA. An additional margin (10 nm) outside the the SUA was taken to make sure aircraft had enough space to perform conflict resolution at the edge of the SUA. In reality, the locations of SUA are known to aircraft at least hours in advance. Therefore more efficient routes can be planned in order avoid the SUA. In the simulation aircraft had to make relative sharp turns in order to avoid SUA. This can be avoided by flying a different track more in advance. This leads to less fuel burn.

VII. Conclusion

This study investigated the benefits of direct routing above Europe in terms of efficiency, safety and stability. The focus was on the effect of difference in lateral distance flown between actual routes and direct routes for two full days of European flight traffic. To do so, the actual flown routes by aircraft had to be simplified in order to make a fair comparison with the constructed great circle routes. For the most conservative case, it was found that on average 1.8% of total fuel burn can be saved by flying direct routes above FL100. For 44% of the total flights between 0% to 2% fuel savings were realized. For 22% of the flights the amount of fuel savings was ranging between 2% and 4% and for even 16% of the flights, fuel savings were found to be larger than 4%. This is a significant amount in terms of yearly cost and emission savings. Comparing safety of direct routes with actual routes was more difficult as for direct routing conflict resolution was done by a decentralized method opposed to ATC resolving the conflicts for the actual routes. Direct routing without CR turned on, lead to fewer conflicts than actual routing. However, turning CR on highly increased the number of conflicts and a high DEP was found. This was caused by the design choices of having CR take place only horizontally, to not influence the vertical flight path of the flights. However, a high IPR of 0.99 was found implying that the vast majority of conflicts never resulted in intrusions. Resolving conflicts both vertically and horizontally significantly reduced the number of conflicts and airspace instability. Furthermore, allowing aircraft to resolve aircraft both vertically and horizontally lead to an increase of average total fuel savings from 1.8% to 3.1%. Additional experiments were performed for direct routing with having a varying degree of active SUA. Having SUA active and therefore decreasing the availability of airspace for commercial use resulted in an increase in total fuel burn as aircraft flew less efficient routes. The number of conflicts increased, but the IPR stayed constant. A slight decrease in airspace stability was found.

The research showed that with free flight by only flying lateral direct routes on average almost 2% of total fuel savings can be obtained. This number is considered to be even conservative. The research only looked at the airspace above FL100, however improving route efficiency in the airspace below can even increase the amount of fuel savings. As free flight allows for optimal routing in the airspace, further research has to be conducted on the benefits of also flying an optimal flight path in the vertical plane. Continuous climb and descent profiles can lead to additional fuel savings. Besides more efficiency benefits, an improvement of safety is expected. As aircraft can fly at their optimal altitude and not on fixed flight levels by ATC, more efficient use of the total airspace capacity can be realized. Further research should take into account the effect of weather. WOR can even lead to additional fuel benefits. Due to limited time-scope, only two days of flight data could be investigated. It is recommended to research the effect of direct routing for multiple day throughout the year, as seasonality has an effect on the number of daily aircraft and traffic flows. An estimate for possible traffic growth under free flight should be made.

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Part II

Appendices

Appendix A

Fuel benefits per aircraft type

In figure A-1 the top 10 most occurring aircraft types in both datasets are shown. The four most occurring aircraft are narrow-body aircraft that can carry around 200 passengers and are used for short range flights. A boxplot of the great circle distance flown per aircraft type is shown in figure A-2. Each aircraft of a certain type was assigned a initial weight from a normal distribution with $\mu = m_{ref}$ and $3 \pm \sigma = m_{min}, m_{max}$ where m_{min}, m_{ref} and m_{max} were obtained from the BADA-files. The weight distributions of the aircraft in the experiments are plotted in figure A-3. The three dashed vertical lines indicate m_{min}, m_{ref} and m_{max}.

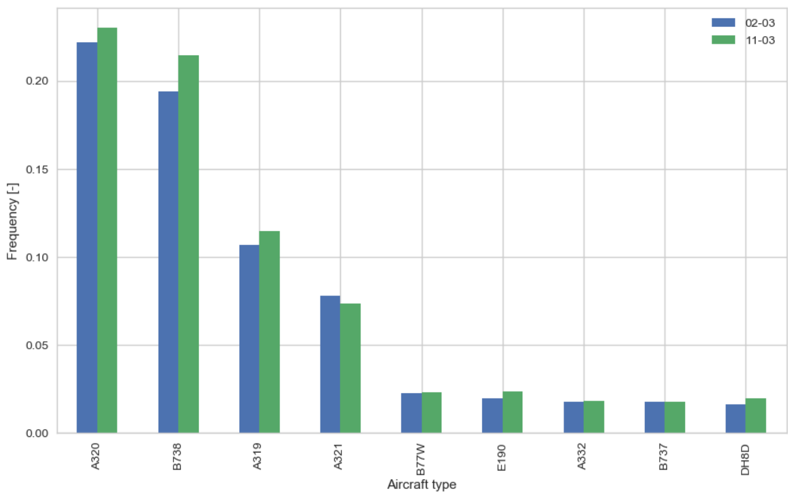

Figure A-1: Most occurring aircraft types

In figure A-4 the distribution of fuel consumption per aircraft in the actual routing scenario is shown per aircraft type. The variance of the distribution per aircraft type corresponds with the variance in great circle distance flown (figure A-2). Figure A-5 displays the distributions

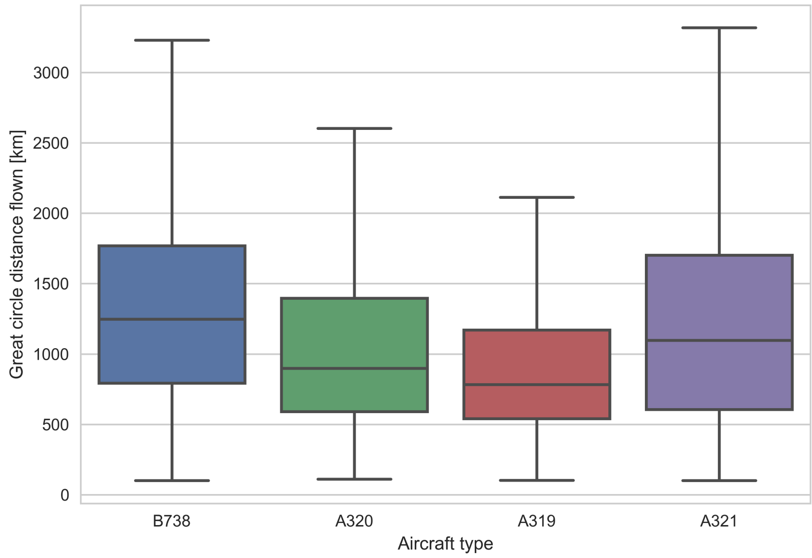

Figure A-2: Great circle distance flown per aircraft type

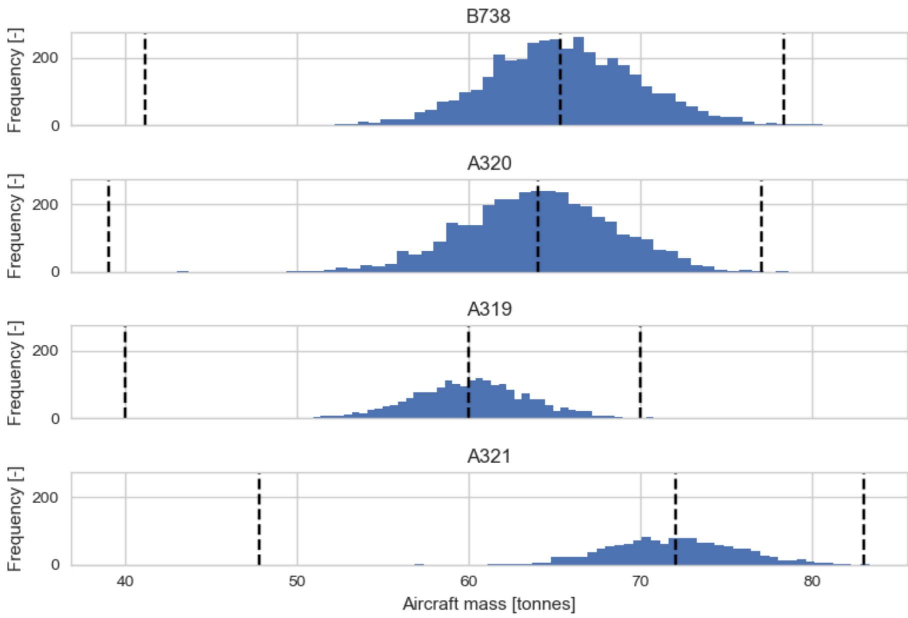

Figure A-3: Aircraft mass distribution per aircraft type

of difference in total fuel burn of direct routing with respect to simplified actual routing per aircraft. The dashed vertical line indicates the median. The distributions and medians are similar for the shown aircraft type. This is logical as the efficiency of the routes is not depended on the aircraft that is flying the route.

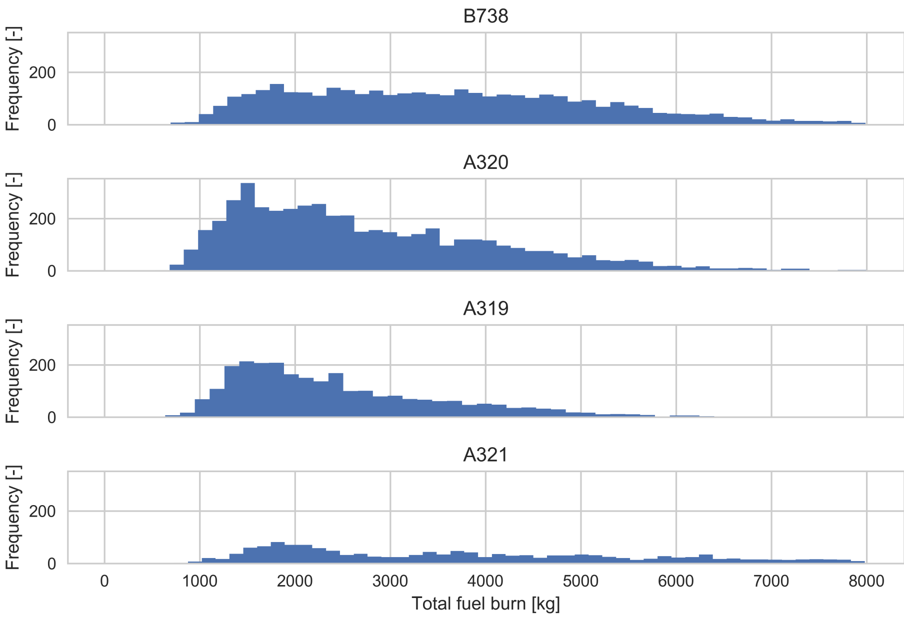

Figure A-4: Total fuel burn distribution per aircraft type for actual routing scenario

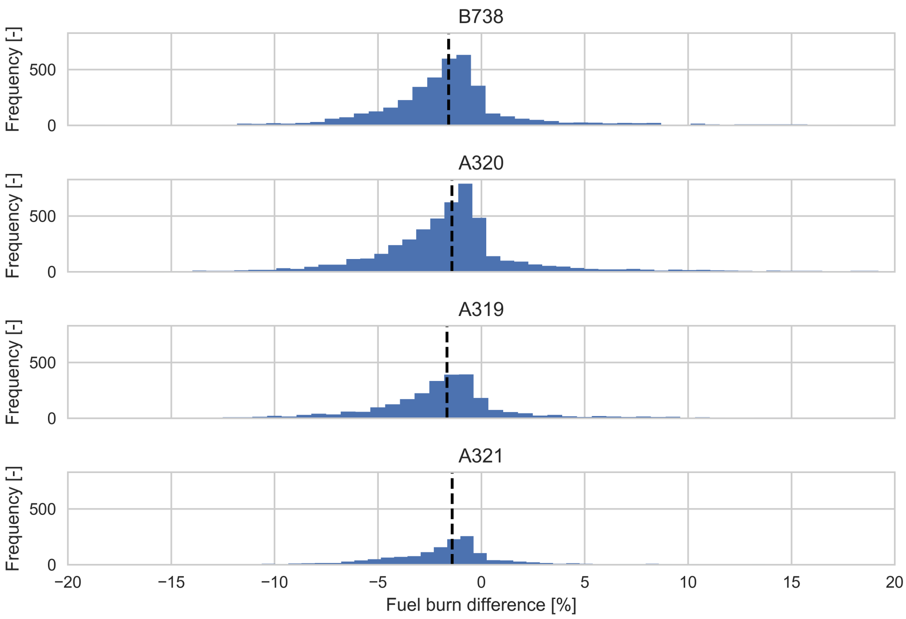

Figure A-5: Difference in fuelburn between direct routing and actual routing per aircraft

Appendix B

Additional Conflict Analysis

This appendix provides additional conflict analysis. In figure B-1 a map is shown with the top 200 locations where the most conflicts occur. The size of the markers are proportional to the number of conflicts. The most conflicts occur in north-west Europe as this area has the highest number of daily traffic volume. Figure B-2 displays the vertical location of conflicts created as a function of time. Most conflicts occur above 30,000 ft at cruise altitude. In figure a distribution of the number of conflicts over time is displayed for both the actual routes as the direct route scenario. The shape of the distribution is the same for both scenarios only the magnitude differs. Peak hours can clearly be seen.

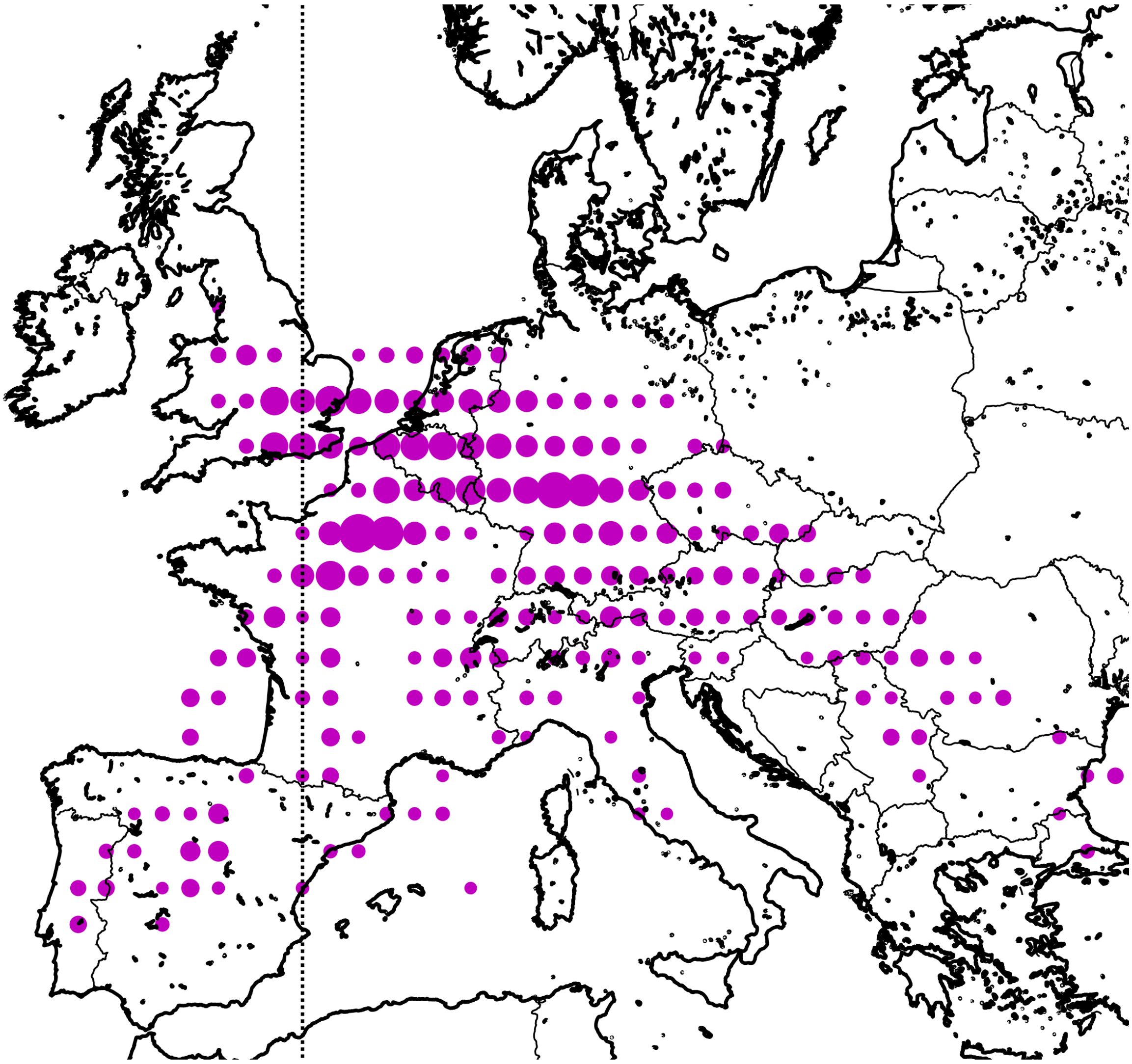

Figure B-1: Top 200 locations where most conflicts occur with actual routing

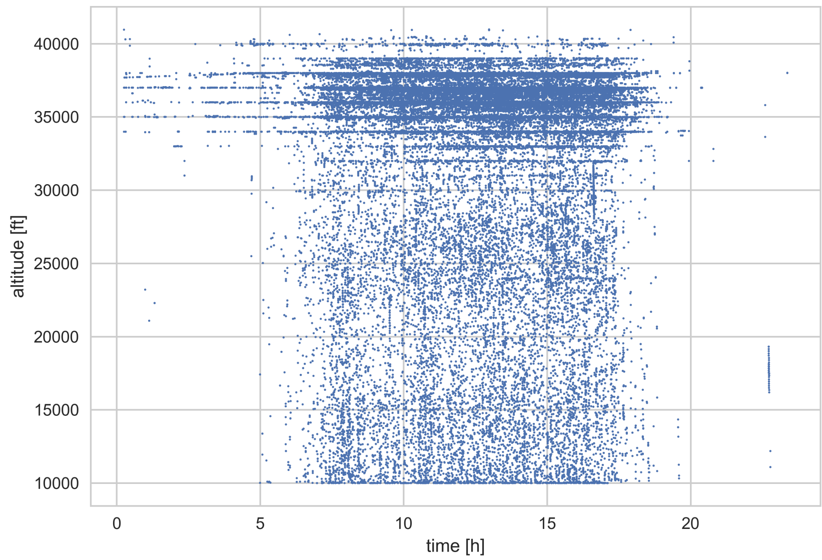

Figure B-2: Altitudes where conflict occur over time

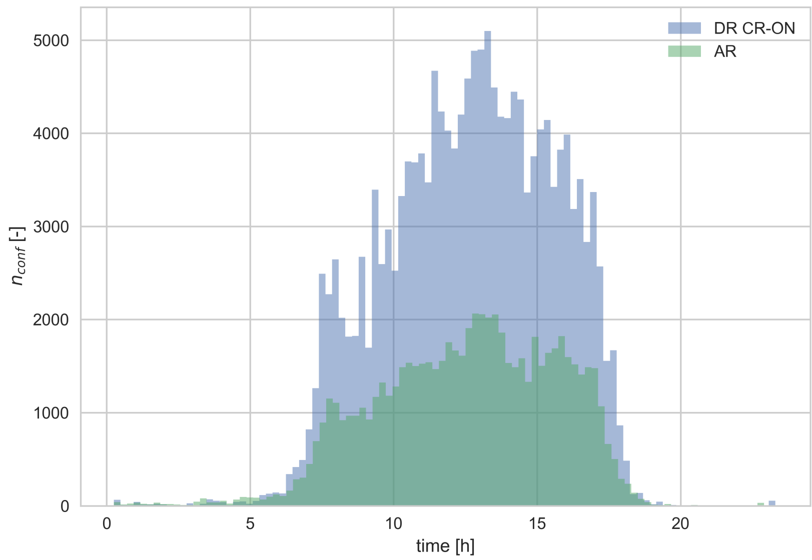

Figure B-3: Conflict occurrences over time for both AR and DR scenarios

Appendix C

Code Structure

This appendix gives a more detailed overview of the modules used to obtain and filter ADS-B data and create the scenario files. In figure C-1 an overview of the process is given. An overview of the in- and output and short description per module is shown in table C-1.

Table C-1: Overview of modules used

	Input	Output	Description
retrieve.py	FlighRadar24-API	unstructured ADS-B data	For a period of 24 hours this script scrapes every 10 seconds flight data from FR24. The data is stored in a database.
flightextract.py	unstructured ADS-B data	filtered and sorted ADS-B data	Using DBSCAN datapoints are clustered per flight. Non -useful data is removed from the dataset
phasedata.py	filtered and sorted ADS-B data	dataframe	With fuzzy logic per datapoint the flight phase is determined and attached. Type of flight is determined (European, arriving, departing, pass). Data is saved in dataframe
weight.py	BADA-files	aircraft mass	Per aircraft-type a random normal distribution is created using the minimum, maximum and reference weights provided by the BADA-files
scenariodata_actual.py	dataframe	scenario file (.scn)	Per flight a route is defined by building a waypoint per timestamp. All parameters are converted to the right units for BlueSky. The create time of a flight corresponds to the real start-time.
scenario_simplified.py	dataframe	scenario file (.scn) waypoint-distance	The initial conditions for the scenario are specified (CR method, experiment area, start time). For all flights the vertical profile of all aircraft is simplified and the route is constructed using waypoints. The distance of the waypoints relative to the start point of the aircraft is computed and saved.
scenario_gcr.py	dataframe waypoint distance	scenario file (.scn)	The initial conditions for the scenario are specified (CR method, experiment area, start time). For each flight a direct route is created. All aircraft have the same starting and ending conditions as in the simplified actual scenario. The waypoint distance list obtained from scenario_simplified.py is used to place the aircraft cruise waypoints at the same relative distance as for the simplified actual routes in order to create the same vertical profile
scenario_sua.py	dataframe waypoint distance SUA coordinates	scenario file (.scn)	The initial conditions for the scenario are specified (CR method, experiment area, start time). From the SUA coordinate database a list of SUA is obtained. A specified fraction is taken of the total number of available SUA. For each flight a direct route is constructed. It is checked if the aircraft passes SUA. If so additional waypoints are placed outside the SUA in order for the aircraft to pass the SUA.

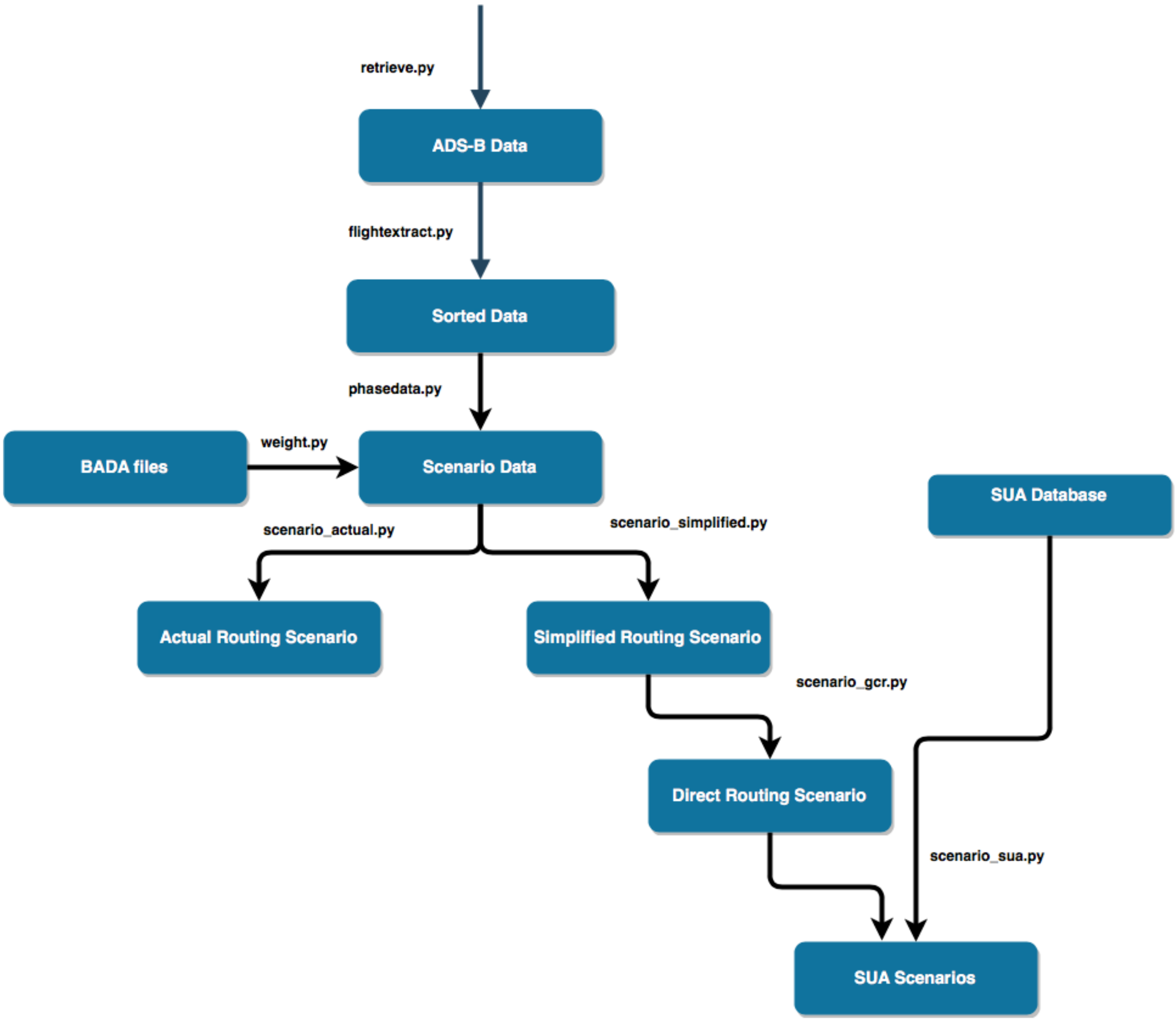

Figure C-1: Flowchart of coding process

Appendix D

Scenario Example

In this appendix an example of a scenario file is given. Two European flights departing at different times are generated flying their simplified actual route.

The first four lines initialize the scenario. In the first line, the experiment-area is defined with the command: **AREA, lat1,lon2,lat2,lon2,top,bottom** The latitude and longitude coordinates are in degrees and the altitudes in feet. The command **FLSTLOG ON** turns on the BlueSky loggers where performance metrics are logged during simulation. The command **ASAS ON** turns on the ASAS and makes sure that conflicts are detected within the specified lookahead time **DTLOOK** of 300 seconds. For the actual routing scenarios, conflict resolution is turned off **RESO OFF**. For the direct routing scenario the conflict resolution method MVP is used and is turned on by the command **RESO MVP**.

On line 9 an aircraft is created with the 'create' command: **start-time** > **CRE ac-id,ac-type,lat [deg],lon [deg],heading [deg],altitude [ft],speed [kts],mass [tonnes]** The route is defined by adding waypoints with the **ADDWPT** command. Per waypoint a latitude and longitude is added and for some waypoints the altitude and speed (in Mach) are defined as well. The last commands of this aircraft on line 20 and 21 make sure that the lateral- and vertical autopilot is turned on (**LNAV ON**,**VNAV ON**).

Listing D.1: scenario-file example

```
1  00:00:00.00>AREA,60,-12,35,30,45000,10100
2  00:00:00.00>FLSTLOG ON
3  00:00:00.00>ASAS ON
4  00:00:00.00>DTLOOK 300
5  00:00:00.00>RESO OFF
6  05:23:20.00>CRE THY4BQ,B738,44.522,26.153,140.0,10000,256,62.5141
7  05:23:20.00>ADDWPT THY4BQ,44.277,26.429,,0.82
8  05:23:20.00>ADDWPT THY4BQ,43.802,26.954,,0.82
9  05:23:20.00>ADDWPT THY4BQ,43.445,27.341,34995,0.82
10 05:23:20.00>ADDWPT THY4BQ,43.405,27.384
11 05:23:20.00>ADDWPT THY4BQ,42.89,27.932
12 05:23:20.00>ADDWPT THY4BQ,42.39,28.451
13 05:23:20.00>ADDWPT THY4BQ,41.891,28.774
```

```
05:23:20.00> ADDWPT THY4BQ,41.452,28.596
05:23:20.00> ADDWPT THY4BQ,41.082,28.586
05:23:20.00> ADDWPT THY4BQ,40.968,28.561,10000,199
05:23:20.00> THY4BQ LNAV on
05:23:20.00> THY4BQ VNAV on
07:33:46.00> CRE AZA345,A319,43.568,7.41,128.0,10000,211,60.6427
07:33:46.00> ADDWPT AZA345,43.41,7.741,,0.82
07:33:46.00> ADDWPT AZA345,43.11,8.374,,0.82
07:33:46.00> ADDWPT AZA345,42.982,8.639,33244,0.82
07:33:46.00> ADDWPT AZA345,42.952,8.703
07:33:46.00> ADDWPT AZA345,42.833,9.469
07:33:46.00> ADDWPT AZA345,42.753,10.315
07:33:46.00> ADDWPT AZA345,42.57,11.057
07:33:46.00> ADDWPT AZA345,42.309,11.626
07:33:46.00> ADDWPT AZA345,42.213,11.96,10000,231
07:33:46.00> AZA345 LNAV on
07:33:46.00> AZA345 VNAV on
```

Part III

Preliminary Report (already graded)

Chapter 1

Introduction

The number of air traffic passengers is expected to double over the next 20 years [3]. The International Air Transport Association (IATA) expects the number of air travelers to be 7.2 billion in 2035 compared to 3.8 billion in 2016. In Europe the same trend is expected [4]. This results in more flights, fuel usage and therefore more greenhouse gas emissions. Currently, 3% of the EU's greenhouse gas emission is due to aviation. Aircraft and engine manufactures are looking at ways to make aircraft cleaner and more efficient. New aircraft designs and propulsion types are being researched and developed. Furthermore, the routes that aircraft fly from origin to destination are not the most efficient. By optimizing these routes an increase in total efficiency may be accomplished. The current air routes can be seen as 'highways in the sky'. Most of these routes originate from the time that aircraft had to fly from radio beacon to beacon in order to navigate. On the road, the motorist is responsible for keeping safe separation between all vehicles. However, in the air it is not the pilot who is responsible for safe separation, but an Air Traffic Controller (ATCo). Within a part of the airspace, a sector, an ATCo has to make sure that all aircraft in that sector keep safe separation from each other. The ATCo can command pilots to change their flight track in order to avoid conflicts with other aircraft. As airspace will become busier and more aircraft will fly within these sectors, the workload for the ATCo will increase. There is a maximum number of aircraft a single human controller can handle. When the airspace becomes to crowded, sectors can be split up into smaller parts handled by multiple controllers. However, the more sectors the more coordination between them is needed. Efficiency will be degraded and safety will be at stake. Thus, there is a limit for splitting up a sector [5]. The ATCo workload is a big constraint for increasing airspace capacity. Therefore, the air traffic structure needs to be reorganized in order to deal with the expected growth. Furthermore, as different institutions and organization agree to limit global greenhouse gas emission a more efficient air routing system needs to be established [6].

With the latest navigation, communication and surveillance systems aircraft don't have to fly via predetermined waypoints in order to navigate. This makes flying the most optimal route from origin to destination possible. Furthermore, systems inside the cockpit make it possible that other aircraft can automatically be detected and that an escape manoeuvre can be flown when a possible collision is predicted. In this way, aircraft can keep safe separation from each other without the need of an ATCo on the ground. The concept of moving the responsibility for conflict resolution from the ground to the air is known as 'free flight'. Without the need of ATCo's, the capacity constraint due to ATCo workload is eliminated. Furthermore, direct routing of aircraft is possible which would increase air travel efficiency. Research has been performed into these benefits on small scale. However, for practical application it would be interesting to know what free flight above Europe will imply. This research will investigate the benefits of direct routing on condition of free flight above Europe. The aim is to find quantitative results that back up the hypotheses: *"Direct Routing will improve air traffic efficiency"*.

In chapter 2 a closer look is taken into what already has been researched regarding the topic of direct routing. The concept of free flight is explained and the latest European research and implementation of a more efficient airspace is discussed. At the end, a motivation for conducting this research will be given. Chapter 3 provides an outline of the project plan.. This project plans contains the research questions, objectives and a clear scope of what is being researched. Necessary assumptions will be stated and the dependent measures used for assessment will be described. Also the tools needed for the research will be described and a planning of the thesis project will be given. In chapter 4 the process of measuring flight efficiency will be discussed in detail and the necessary theoretical content will be provided. Finally, a conclusion (chapter 5) about the research performed so far will be given. The next steps to be taken for this research will be discussed.

Chapter 2

Literature Review

This chapter provide the necessary background for the research into direct routing. A brief overview is given on why current routing is not direct. The ongoing European research into improving current routing is discussed. After, the concept of free flight will be explained in more detail. Finally direct routing itself will be discussed. Previous studies into direct routing will be discussed and the importance of this research will be highlighted.

2-1 Why aircraft don't fly direct routes

Before talking about direct routing, it is vital to know why current air routes are not direct. This section gives a short overview of different reasons and constraints that limit direct routing.

2-1-1 History

In the early days of aviation, pilots navigated using maps, compass and by visual cues on the ground. Flights were preferably conducted by daylight so pilots could easily navigate. When the amount of air traffic started to increase, the need for air traffic organization emerged [7]. The first radio communication from the ground with pilots started in the 1930s. Shortly after radio communication, the first radars were installed to detect the aircraft's position. In order to manage complex traffic situations, Air Traffic Control divided the airspace into sectors and layers. This reduced the freedom of the pilots to choose their route freely and forced aircraft to fly predefined routes. These routes were marked by radio beacons, along which the aircraft navigated next to using on board systems. Although, nowadays radio beacons are not used by commercial aviation and the physical beacons aren't present anymore, the routes that aircraft fly are still via these waypoints.

2-1-2 Air Traffic Control

Air Traffic Control (ATC) is a service provided for the purpose of preventing collisions and expediting and maintaining an orderly flow of air traffic [8]. In order to do so, traffic is forced to fly via predetermined routes in the sky. On a strategic level, ATC manages traffic flows such that certain air routes won't become too busy and safety will not be at stake. Tactical controllers ensure that the aircraft remain at a safe distance from each other at all time. One can distinguish two main control strategies: strategic and tactical. The airspace is divided into different layers, sectors and classes in order to make it controllable. AFlight Information Region (FIR) is the largest division of airspace. Large countries have multiple FIRs while small countries only have a single FIR. Within a FIR there are the following controlled air-spaces:

- Upper Airspace (UTA). Generally controlled by Upper Airspace Control (UAC). In the Netherlands the UAC is controlled by Eurocontrol located in Maastricht. Manages en-route traffic.
- Control Areas (CTA). Generally controlled by Area Control ACC.
- Terminal Control Areas (TMA). Controlled by approach control, controls approaching and departing at airports.
- Control zones (CTR). Controlled by tower control at airports

Using Communication, Navigation and Surveillance (CNS) systems, air traffic controllers know at all time where the aircraft are located and what their speeds are. Commercial aviation is always controlled by ATC. The pilot should always obey what ATCos command, unless an emergency situation occurs. As ATC ensures safety to air traffic it is at cost of flight efficiency as aircraft are in most cases not able to fly the most optimal route from origin to destination.

2-1-3 Airports

The airspace around airports, the Terminal Maneuvering Area, is highly complex. It has a high density of incoming and outgoing traffic. When an aircraft departs, it flies a Standard Instrument Departure (SID) which is a fixed route by ATC, that connects the take-off with the en-route phase. Arriving aircraft fly a similar procedure called a Standard Terminal arrival Route (STAR). The SIDs and STARS are designed by ATC such that aircraft comply to noise, environmental and other airspace constraints set by the airport or government. It also aims to deconflict departing and arriving traffic. The SIDS and STARS cause aircraft to fly detours. Furthermore, runway usage dependent on weather conditions causes additional constraints for direct routing.

2-1-4 Special Use of Airspace

In certain parts of the airspace, (commercial) flight is prohibited or restricted. These areas are called Special Use Airspace (SUA). Examples of SUA are: military training zones, above nuclear facilities, big cities, royal or governmental buildings and war zones. SUA causes flights to fly detours and therefore less efficient routes.

2-1-5 Costs

In order to fly through a country's airspace a fee needs to be paid. The fee to pay is based on the following parameters:

- Rate of charge [price/km]. This rate is different for each country.
- Distance flown through country.
- Aircraft weight.

If country X has a way higher rate of charge compared to neighbouring country Y, it can be interesting for airlines to fly a detour via country Y in order to pay less. Even with the additional flight time and fuel usage accounted flying a detour can be profitable.

2-2 Single European Sky ATM Research

In order to improve the efficiency of the European airspace and to cope with the expected increase in air travel, the European Union founded the Single European Sky ATM Research (SESAR) program [9]. SESAR aims to reduce the cost of Air Traffic Management (ATM) services, doubling air space capacity and realize a total of 10% reduction in fuel burn. Current European airspace is fragmented according to national borders rather than traffic flows. Also, there are over 60 Area Control Centers (ACC), that control the upper airspace in Europe. In order to increase capacity, improve efficiency and reduce fragmentation SESAR proposes Functional Airspace Blocks (FABs) in which several countries share their airspace, controlled by one ATC center. This could lead to more direct routing of aircraft and therefore an increase in efficiency. With flexible use of airspace, military and civil aircraft can share SUA more efficiency. However, due to the strict European and ATM legislation, the implementation of SESAR is progressing slowly. At the time all FABs are implemented, air traffic movements may have been increased such that the new airspace structure becomes inefficient. In this study, a more rigorous ATM concept is used, 'free flight'.

2-3 Free Flight

As a solution to the congesting airspace due to air travel growth, free flight is proposed. By shifting the responsibility for conflict detection and resolution from ATC to the pilot, a more efficient use of the airspace can be realized. Using the newest communication, navigation and surveillance systems, pilots can choose their most optimal route and ATCo workload will not be a limiting factor for airspace capacity growth. In this chapter the concept of free flight will be explained in sufficient detail for this research. First the benefits of the decentralized free flight concept with respect to a centralized separation system will be discussed. The concepts of conflict detection and resolution will be discussed afterwards.

2-3-1 Centralized versus Decentralized Separation Strategies

Free flight is a decentralized system in which each aircraft is responsible for safe separation and resolving conflicts. This is in contrast to a centralized system, like the current ATC system, in which an ATCo is responsible for the separation of multiple aircraft. Before adopting the free flight concept, the benefits of such a decentralized separation strategy with respect to a centralized system will be discussed. As discussed previously, there is a limit for the workload of a ATCo. Using a decentralized system, there is no need of an ATCo that manages multiple aircraft. The airspace capacity limit due to ATCo workload is eliminated. Without the presence of ATC, pilots will not to ask clearance for every change of maneuver they perform or when entering a different air sector. For a centralized system the focus is on ATC maintaining a smooth and orderly flow of traffic. This generally results in system stability at the expense of efficiency and capacity. Using a decentralized strategy, pilots can fly their preferred route which can lead to more optimal paths and a reduction in fuel usage. When aircraft fly their preferred route instead of flying on fixed 'highways in the sky' a more optimal use of airspace capacity can be realized [5].

Krozel et. al. 2001 [10], performed a quantitative study in to the performance of both systems. They looked at the stability and efficiency of both systems under different air traffic densities. To assess stability, the researcher looked at the Domino Effect Parameter (DEP). The DEP is a measure for the additional conflicts created by resolving an initial conflict. In chapter 3 the working of DEP will be explained in more detail. They found that for increasing traffic density, the centralized system indeed remained more stable cause of a suppression of the domino effect. A large domino effect result in a decrease in system efficiency. The conflict resolution method chosen has a large impact on how stable the strategy is. Different conflict resolution strategies could lead to different results. The better the resolution strategy anticipates on the future conflicts that may occur, the more stable the airspace will be at higher traffic densities [11].

2-3-2 Conflict Detection

Before talking about conflict detection, we need to define what a conflict is. Imagine each flying aircraft has a protected zone around it defined by ATC en-route standards. The protected zone is a circular zone of 5 nm radius and a height of 2000ft around the aircraft which defines the minimum separation requirements. The moment another aircraft enters this protected zone, we talk about an 'intrusion' or 'loss of separation'. A conflict is an actual or potential intrusion of a protected zone in a predetermined look ahead time [1]. This look ahead time is usually 5 minutes. An on-board system that detects possible conflicts is the Airborne Separation Assurance System (ASAS). In order to predict a conflict, the trajectories of the surrounding traffic needs to be predicted. The approach to predict traffic is dependent on the look-ahead time. The level of intent information of other aircraft can enhance the prediction. There are different levels of intent:

1. No intent. The current aircraft position is extrapolated using the velocity vector.
2. Mode control panel intent. The autopilot info of other aircraft.
3. The next trajectory change point.

4. Multiple trajectory change points.
5. The complete flight plan as stored in the flight management system of the aircraft.

For a direct routing structure, where all aircraft fly along straight lines, knowing the position and velocity of other aircraft suffice in order to predict its trajectory [1]. Not needing to use intent information of aircraft has a couple benefits. First, the conflict detection system can have low complexity. There is no negotiation required between two aircraft that might be in conflict. For conflict detection, a state based method is used in which the algorithm uses a linear projection of the current state of the surrounding aircraft.

2-3-3 Conflict Resolution

When a conflict is detected, it needs to be resolved. The ASAS has a module that can compute a manoeuvre to avoid intrusion. There are different conflict resolution algorithms that can be implemented. Important requirements for a conflict resolution algorithm is that it can come up fast with an effective resolution. Furthermore, the resolution should be fuel efficient. The algorithm should be able to handle multiple-aircraft conflicts and should provide back up options in order to increase safety. Previous studies have investigated several conflict resolution methods. In terms of route, time and fuel efficiency, the Modified Voltage Potential, MVP, method has a good performance [1]. This resolution method will be explained in more detail and will be used for this study.

2-3-4 Modified Voltage Potential

MVP is a resolution method developed by NASA and the Netherlands Aerospace Center, NLR,. [1] and is based on Eby's algorithm [12]. In figure 2-1 the geometry of the MVP method is shown. When a conflict between the two aircraft is the detected, the future position of both aircraft will be computed in order to determine the moment of minimum distance and the magnitude of minimum distance. The algorithm computes an avoidance vector which is the needed speed or heading change in order to stay out of the intruders protected zone and therefore avoid a loss of separation. The avoidance vector is always the shortest distance out of a conflict. The principle works the same in the vertical plane. The method assumes that the intruder does not changes speed or heading, in order to avoid a conflict. Normally this is not the case. However, by making this assumption the avoidance vector will always point in the opposite direction due to the geometry of the conflict. The conflict can be solved without the two aircraft needing to negotiate. A look-ahead time of 5 minutes is sufficient in order to detect and solve the conflict.

2-3-5 Moving to Free Flight

Implementing free flight will enable direct routing. As aircraft won't have to fly along predetermined routes, the most optimal and efficient route could be flown. This could lead to fuel savings, time savings and therefore cost savings. Only severe weather conditions and restricted airspace (e.g. airspace used for military purposes) can still be an obstacle of flying

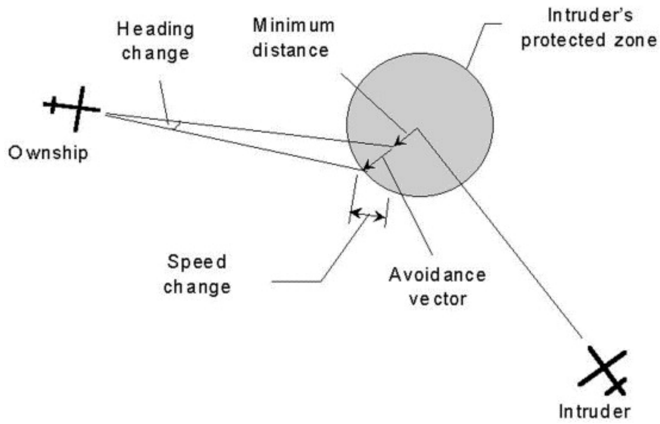

Figure 2-1: Modified Potential Field Conflict Resolution [1]

the most efficient route. For this concept to work, countries have to share their airspace. This can be a problematic condition, as airspace borders can be as strict as the borders on the ground. In the Europe, where most countries have open borders, sharing one airspace seems feasible. Counties sharing military airspace zones can even improve the total efficiency of the airspace. Furthermore, the cost of airspace use should be the same throughout Europe.

2-4 Direct Routing

As free flight eliminates current ATC restriction, more optimal flight paths can be flown.The self-evident question that arises: *What is the most efficient route an airplane can fly?*. While most research performed has been in optimizing the efficiency in for the vertical flight profile, this research is focused on improving efficiency in the horizontal plane.

2-4-1 Efficient Routes

Obviously, the shorter the distance flown, the less fuel is used. The shortest distance between two points on a sphere is called the Great Circle Route (GCR). The earth is not a perfect sphere, but nearly approximates one. Errors in computing the GCR by assuming a spherical earth are not greater than 0.5% for latitude and 0.2% for longitude. Using the Haversine formula, the great circle distance, d, between two coordinates can be computed.

$$a = sin^2(\frac{\Delta\phi}{2}) + cos\phi_1 \cdot cos\phi_2 \cdot sin^2(\frac{\Delta\lambda}{2}) \tag{2-1}$$

$$c = 2 \cdot atan2(\sqrt{a}, \sqrt{(1-a)}) \tag{2-2}$$

$$d = R \cdot c \tag{2-3}$$

Where R is the radius of the earth [km], ϕ the latitude [rad] and λ the longitude [rad].
While GCR are the shortest route, they don't necessary have to be the most fuel efficient and the shortest in time. Wind can have a great influence on flight performance and duration. Wind Optimal Route (WOR) take into account the wind direction for constructing the most

fuel efficient routes. A well known example of current WOR are the flights across the Atlantic that make use of the jet streams. Jet streams are fast flowing air currents in the atmosphere located above an altitude of 30,000 ft [13]. Commercial aviation makes use of these air streams in order to save time and fuel. Cheng et. al [14] researched the benefits of WOR over GCR and concluded that for short-haul flights the benefits of WOR over GCR are minimal. Only flights longer than 2000 nm would benefit more from WOR with relative differences greater than 1 %. Palopo et al. [15] performed a study on flight routing in which current flight routes, WOR and GCR are compared for flights in the American National Airspace System in terms of safety and efficiency. They found that WOR and GCR are more efficient compared to filed flight plan routes. WOR result in a 1.4% improvement and GCR in 0.3%. Furthermore, the number conflicts for GCR and WOR was even less than for filed flight plans. Both WOR and GCR used in this research did not avoid restricted airspace. As the United States already has a single airspace, the results for Europe can differ significantly.

2-4-2 Benefits of direct routing

When aircraft fly their preferred route instead of flying on fixed 'highways in the sky' a more optimal use of airspace capacity can be realized [1]. Magill et al. investigated how direct routing could lead to an increase in airspace capacity [5]. He concluded his research that direct routing could lead to an increase in airspace capacity of roughly 17%. However, these studies all still assume the current ATM structure where air traffic controllers are responsible for safe separation between aircraft. Research on implementing free flight in Europe has been rather focused on aircraft conflicts than on fuel benefits [16] [17]. A study that investigates direct routing on large scale under the concept of free flight with the focus on fuel benefits hasn't been performed yet. Results of such research can back up the argument of free flight. Furthermore, as stricter regulations on aviation emissions will be imposed, the benefits of alternative flight routes should be researched and quantified.

Chapter 3

Experiment Design

To gain a better insight on what is going to be investigated and how this will be done, research questions and objectives are defined. To conduct the thesis within the specified time, the scope of the research will be clearly defined. A project planning will be made in order to perform the research as efficient as possible.

3-1 Research Questions and Objectives

The objective of this research is to compare the current ATM routing structure above Europe with direct routing in order to investigate the benefits by simulating both routing structures using real flight data. The research question which will be answered is: *What are the benefits of direct routing over current routing above Europe in terms of efficiency, capacity and safety?* This leads to the following sub-research questions.

- For commercial flights, how much fuel [tonnes] in total can be saved by direct routing above Europe?
- How efficient is direct when Special Use Airspace is taken into account?
- Is direct routing safe in terms of the current safety standards and will it stay safe with the expected increase in air traffic?

To answer these research questions, the following aims are set for this study:

- Gather European air traffic data for a full day under nominal weather conditions.
- Perform data analysis and filtering on obtained data.
- Identify the Special Use of Airspace (SUA) in Europe.
- Built a model that computes aircraft's fuel burn for different flight-phases.

- Construct Great Circle Routes (GCR), for each of the current routes in the dataset.
- Perform efficiency analysis for both current routing and GCR.
- Investigate the influence of SUA on GCR and how it affects flight efficiency and safety.

In order to achieve the set goals, a project plan is made. In the next sections, the theoretical content of these aims will be described and an experiment set-up will be discussed.

3-2 Scope of Research

As direct routing is a rather broad topic, the scope of the research needs to be clearly defined. Also, the assumptions made need to be stated clearly. The research will be focused on evaluating efficiency. Also, the aspects of air-traffic safety and airspace capacity are being discussed. Furthermore, the dependent measures used to valuate efficiency, safety and capacity will be given.

3-2-1 Efficiency

One of the key drivers to move to a direct air routing system is to improve efficiency and thereby also lower the environmental impact of aviation. Aircraft design and propulsion have a big impact on emissions due to air travel. However, reducing the total distance all aircraft have to fly can make a significant impact on the environment. Reducing fuel usage will lead to lower emissions. Furthermore, a reduction in fuel consumption also lowers the cost of air travel. An aim of the research is to investigate how much fuel can be saved by direct routing. Therefore, the fuel consumption of the current air traffic above Europe needs to be evaluated and compared to GCRs. Minimal fuel burn can be achieved by flying the most fuel efficient route. For this research, only optimization in the horizontal plane will be considered. As discussed in section 2-4, the benefits of WOR compared to GCR are insignificant for short routes. As this research only deals with flights within Europe, and therefore relatively short distances, GCR will be only taken into account. In the vertical plane, the most fuel efficient flight path is more complicated as it depends on many different variables that vary per aircraft type, aircraft weight and weather conditions. Optimization of the vertical flight path is not the focus of this study.

Measure Efficiency

In order to evaluate flight efficiency two different measures will be used:

- Total fuel burn
- Route efficiency

For both the current routes and GCRs the total fuel burn will be computed and compared. Furthermore, the fuel burn of GCRs with a climb-cruise profile will be calculated. Another measure used to evaluate efficiency is the route efficiency, which can be computed by equation 3-1

$$\eta_{route} = \frac{GCR - distance}{actual - distance} \tag{3-1}$$

The route efficiency for direct routing (equation 3-1) is expected to be 1. However, deviations are possible in case an aircraft has to avoid other traffic or SUA. Using route efficiency it can be easily checked which air-routes benefit the most of flying GCRs. The time-savings of flying GCR will be assessed as well.

3-2-2 Capacity

Airspace capacity is a limiting factor for air travel growth. Current air routes forces all the traffic into a restricted volume of airspace, while leaving the remainder unoccupied. It is expected that direct routing will spread out aircraft over the airspace and will therefore increase the total capacity [5]. On the other hand, when aircraft fly along unstructured routes under high traffic densities, resolving conflicts can even lead to an increase in number of conflicts [11]. Airspace capacity is therefore a trade-off between safety and efficiency. There are multiple airspace capacity constraints which will still hold for free flight:

- Airport constraints: noise restrictions, environmental restriction and runway capacity.
- Special Use of Airspace.
- Severe weather conditions.

The way in which is dealt with these constraints for this research will be discussed.

Airport Constraints

Direct routing becomes highly complex around the airports, as there are many constraints as described in section 2-1-3. This study will therefore not focus on route optimization in the TMA and the airports Control Zone (CTR). In previous studies, researchers defined a circular area around airports as a simplified representation of a TMA [16][14]. The radii used for these circular area differed per research. The average boundary of a TMA with as geographical center the airport, is 40nm. For arriving aircraft, the Initial Approach Fix, IAF, is the first waypoint of a STAR. The IAF is located at the boundary of a TMA at a height of 10000 ft. For departing aircraft there is a speed restriction of 250 knots below 10000 ft. As starting and end point of the simulated flights this altitude will be taken. Therefore, take-off, initial climb, final approach and landing will not be taken into account for this study. The effect of direct routing on the arrival rate at the airports should be taken into account. As flying GCR can decrease the travel time, it should be validated if the arrival rate at airports is within reasonable bounds.

Special Use Airspace

By identifying SUA in Europe and performing simulations of direct routing with and without them, the effect on airspace efficiency, safety and capacity can be analyzed. An additional scenario can be created to represent a possible sharing of military aerospace by European countries. Instead of scattered blocks of SUA throughout the airspace, bigger blocks at fewer locations will be created.

Severe weather conditions

Weather conditions have an influence on the airspace capacity available. On days with bad weather conditions parts of the airspace can't be used and aircraft need to fly detours in order to avoid storms. This can lead to an increase in traffic densities in certain areas and therefore destabilize the airspace. Extreme weather conditions cause the most disturbance around airports and for TMA operations [18]. As this research will not focus on these areas, the effect of bad weather on aircraft capacity will not be analyzed. As disturbances in TMA operations might propagate into other parts of airspace, the flight data for this research needs to be gathered on days with nominal weather conditions in Europe.

Measuring Capacity

Capacity is a trade-off between efficiency and safety. Increasing efficiency without decreasing safety would mean that an increase in capacity is possible. The effect of Special Use Airspace (SUA) on efficiency will be tested. Furthermore, the arrival rate at airports will be measured. The difference between the rates of current routing and GCR will be checked. The assessment of safety will be discussed in the next paragraphs.

3-2-3 Safety

The highest priority in aviation is safety. All aircraft need to comply to set separation limits. The research does not cope with the method in which conflicts between aircraft are detected and solved. The MVP resolution method is implemented in the BlueSky simulation tool, cause this method has proven its strength in previous studies [1]. Because of the difference in air traffic control strategies, decentralized for direct routing and centralized for the current routing, it makes a comparison in safety difficult. Furthermore, the ADS-B data of current flights is already deconflicted by an ATCo. To make the comparison between these two scenarios more fair, the time horizon of the look-ahead time, $t_{look-ahead}$ in which a conflict is detected can be scaled. According to Eurocontrol's protocol, the Conflict Detection Tool (CDT) used in ATC centers should show a conflict 8 to 10 minutes before a possible intrusion [19]. Conflicts should be counted using different values of $t_{look-ahead}$ for both actual routes as GCRs. In this way, conflicts already resolved by ATCos can still be detected. The $t_{look-ahead}$ used by the MVP resolution algorithm should remain unchanged. For the MVP the following separation limits are used throughout this research are: a protected zone around aircraft with R = 5nm, vertical separation of 1000 ft and a look ahead time of 5 minutes.

As the efficiency of intercontinental flights won't be assessed, these flights should be taken into account when considering airspace safety and capacity. The GCR of these flight will be computed and used in different scenarios in order to measure safety and capacity.

Measuring Safety & Stability

Conflict count is an useful parameter to consider when assessing safety. Aircraft that encounter a conflict, need to adjust their airspeed, or fly an escape manoeuvre, or both, in order to avoid a loss of separation. These actions will lead to an increase in fuel usage and therefore, a decrease in efficiency. The fewer conflicts occur in total, the more efficient the system will be. A conflict is a predicted loss of separation. When a conflict occurs this doesn't imply that a loss of separation occurs. Furthermore, a loss of separation does not imply a collision. Therefore counting the actual loss of separations and the severity of them can be useful in order to measure how safe the airspace is. The severity of a loss of separation can be computed by equation 3-2 [2].

$$Int_{severity} = max_{t0_{int} - t1_{int}} = [min(\hat{I}_H(t), \hat{I}_V(t))] \tag{3-2}$$

$\hat{I}_H(t), \hat{I}_V(t)$ are the measured horizontal and vertical loss of separation respectively that are normalized with respect to the used minimum separation requirement. $t0_{int} - t1_{int}$ is the time interval in which the loss of separation occurs.

At high traffic densities, resolving conflicts can lead to new conflicts. This domino effect is used as a measure for airspace stability. The Domino Effect Parameter, DEP, which can be used to measure stability works as follows (see figure 3-1). We consider a set of desired trajectories for all aircraft in a system. In our case, direct routes. In most cases, there will be conflicts occurring. The set S_1 is defined as the number of conflicts occurring with aircraft flying their desired trajectories without conflict resolution. The set S_2 is defined as the number of conflict occurring when aircraft would fly their desired trajectories with conflict resolution. The subset R_1 represents the stabilizing effect, because these conflict existed when no conflict resolution was done and didn't cause additional conflicts when conflict resolution was performed. The subset R_3 can be seen as the opposite. It consists of conflict that weren't there initially, however due to conflict resolution they occurred. The net domino effect is the difference between these two subset, ($\mid R_3 \mid - \mid R_1 \mid$). This difference is normalized with respect to S_1 in order to compute the DEP.

$$DEP = \frac{\mid R_3 \mid - \mid R_1 \mid}{\mid S1 \mid} = \frac{\mid S2 \mid}{\mid S1 \mid} - 1 \tag{3-3}$$

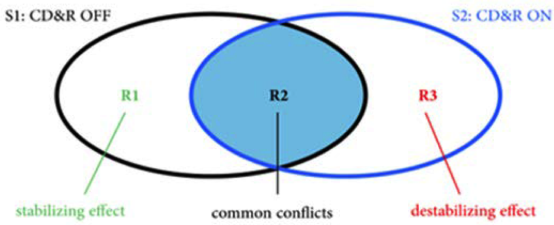

Figure 3-1: Venn diagram for Domino Effect Parameter, DEP [2]

3-3 Tools

For all modelling and computations, Python 3.6 will be used. The advantage of Python is that it is open source and many packages are available that are useful for this research. The Automatic Dependent Surveillance-Broadcast (ADS-B) data used will be obtained from the online platform FlightRadar24. The simulation tool which will be used is Blueksy. BlueSky is an open-source, open-data, air traffic simulation tool developed by students and staff at the Delft University of Technology [20]. The tool is built in Python and is still in development, but has many features which already can be used for this research. Bluesky will be mainly used for measuring the safety metrics for different scenarios. Furthermore, SUA in Europe will be identified and implemented in Bluesky.

3-4 Project Planning

In order to conduct the research within the time of nine full months, a planning is made. The process of the thesis has been divided into four phases. The work to be done for each phase will be briefly discussed. A Gantt chart can be found in appendix A.

3-4-1 Phase 1

The first phase consist of a literature study about the research topic. Next to the literature study some initial programming and modelling is done to get acquainted with the software. The objectives for this phase are:

- Gaining insight into the research topic
- Define the scope
- Select tools for experiment
- Set-up a project plan

3-4-2 Phase 2

During this phase an initial model is built. The data-filtering methods are chosen and an analysis is performed. The objectives are:

- Obtain a sample dataset
- Perform data filtering and analysis
- Built an initial performance model
- Construct GCRs
- Write down research process (phase 1 + 2) and the research plan for the upcoming phases in a preliminary thesis report.

3-4-3 Phase 3

In phase 3, a full dataset (24 hours) is obtained, filtered and analyzed. Improvements on the efficiency model are implemented and all calculations are being done. SUA will be identified and implemented in Bluesky. Safety analysis will be done as well. The objectives are:

- Obtain complete dataset of flightdata

- Improve efficiency model
- Identify SUA
- Run all simulations and log results

3-4-4 Phase 4

All results are obtained and analyzed. Minor improvements to the model can be made. A final paper is written in which the results are presented and discussed. The phase ends with the final defense of the thesis.

- Analysis and discussion of results
- Write research paper
- Present and defend thesis

Chapter 4

Methodology

As the scope of the research is defined and the project plan is set up, the initial model that computes flight efficiency for current routes and GCRs can be build. In this chapter the methodology of the first two research phases is given. First the process of obtaining and filtering the flight data is discussed. An analysis of the data and the process of preparing the data for computation is shown. Then, the construction of the GCR dataset is explained. In the last section the fuel computations are given and necessary assumptions are explained.

4-1 Flight Data

To compute the fuel burn of aviation in Europe, real flight data needs to be obtained. Based on these flight data, the scenario of direct routes will be constructed. Before the flight data can be used for fuel computations, it needs to be analyzed and filtered. The process will be discussed in this section.

4-1-1 Obtaining the flight data

ADS-B is a surveillance technology that provides air traffic controllers and flight crew information about the location and speed of airplanes in a certain area. Using the Global Navigation Satellite System (GNSS) aircraft can precisely determine their position and velocity. With the ADS-B equipment, aircraft can transmit their speed,velocity, flight number, rate of climb and other data to ADS-B receivers on the ground and to other airplanes via a digital datalink. An advantage of ADS-B compared to radar is that it works at low altitudes and on the ground. Therefore, it can be also used to monitor ground traffic at airports. In areas with limited radar coverage, ADS-B can provide a solution [21].

ADS-B ground receivers are relatively cheap and easy to build. Civilians can install receivers at home and can obtain flight data of their area. In 2009 Flightradar24 opened up a network of ADS-B receivers and made it possible for anyone with a receiver to upload their data to the network. Nowadays they have the largest ADS-B network in the world with roughly 17000 connected ADS-B receivers. Many parts of the world are covered and therefore flights can be tracked worldwide. Not all aircraft are equipped with ADS-B transponders. According to the latest figures of Flightradar24 roughly 70% of commercial aviation worldwide have ADS-B transponders. In Europe it is even 80% (compared to 60 % in the US) [1]. In 2020 all commercial aviation in the US and Europe need to be equipped with ADS-B transponders [22].

Using a Python script, live flight data from aircraft flying within a specified area can be scraped from the Flightradar24 website. For a set time, every 10 seconds flight data (see table 4-1) is obtained and stored in a MongoDB database. The script will be run for 24 hours.

Table 4-1: Flight data

Parameter	**Unit**
altitude	ft
latitude	$^\circ$
longitude	$^\circ$
rate of climb	ft/min
speed	kts
heading	$^\circ$
aircraft type	$-$
ICAO address	$-$
flight number	$-$
time-stamp	s

Although during night-time most European airports shut down and only intercontinental flights will be scraped, to make sure most flights will be captured, the script will be run a full cycle. The air traffic volume varies each day. Three sets of data will be recorded on different days. The dataset with the most flights will be used. For the purpose of this preliminary report a smaller data set is used. The flightdata is obtained on the 9th of November 2017 for a 6 hour period (09:00-15:00). During that day, no severe weather conditions occurred in Europe [2].

4-1-2 Data filtering

The flightdata stored in the database is not ordered and structured. At each time stamp (with an interval of approximately 10 seconds), flight data of many aircraft is stored. The aim is to sort the data per single flight and order it on time. Therefore, the ICAO address and timestamp are of major importance when sorting the data. In order to deal fast and efficient with the big data set, unsupervised machine learning is used. Based on Sun et al. [23], a clustering method (DBSCAN) is used in order to cluster the data per aircraft. Furthermore, the data is filtered such that only full flights are taken into account. As this research will not deal with traffic in the Tower Control Zone (CTR) and Terminal Maneuvering Area (TMA)

[1] https://www.flightradar24.com/how-it-works
[2] http://www.eswd.eu/cgi-bin/eswd.cgi

airspace, the start and end points of each flight will be taken at 10,000 ft. Flights of which the aircraft type is unknown are not taken into account as their performance can't be computed.

4-1-3 Data analysis

The dataset of 9 November contained 3225 complete flights. Of all flights the actual flown distance and the great circle distance was computed. In figure 4-1 the relative frequency of GCR trip lengths are shown. It is notable that most European flights have a relatively short trip length (250-750 km). As the benefits of WOR over GCR are only significant on distances greater than 2000 nm which is 3700 km (section 2-4-1), looking at the data GCR is valid to use as most efficient route. Because of the tracking period is 6 hours and only fully flown trajectories are taken into account, the chance that short flights are captured compared to longer flights is higher. Figure 4-2 shows the top 10 of aircraft models occurring in the data-set. As expected the narrow-body medium weight aircraft are the most used aircraft types for flights within Europe. The relative frequencies of route efficiency, η, (equation 3-1) is shown

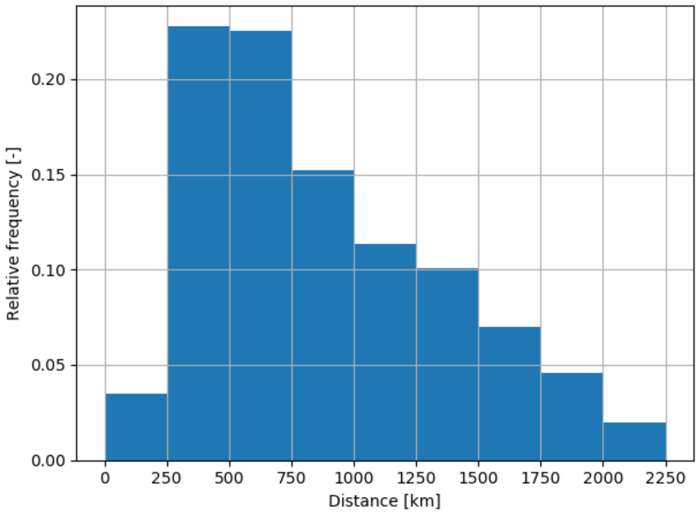

Figure 4-1: Relative frequencies of trip lengths

in figure 4-3. Some surprisingly low route efficiency can be seen. After further investigation of those low efficiency routes, the cause of the extremely low efficiency was discovered. Some general aviation flights, flight academy and even helicopter missions were recorded in the data set. Because those flights start and end at the same point, there GCR is almost zero, while distance flown is way higher. This results in low efficiency and these flights were filtered out of the data set. In figure 4-4 the route efficiency of the filtered data-set is shown. Approximately half of the flights have an efficiency over 0.95. There is still room for improvement. What should be noted is that this figure shows the efficiency of flight trajectories above 10,000 ft. In figure 4-5 the efficiency of the partial trajectories are compared with the efficiency of the full trajectory from origin to destination. A clear difference can be seen between the efficiency distribution. The full trajectories are in general less efficient. Most inefficiencies in flight routes occur in the CTR and TMA airspace, which is obvious due to the Standard

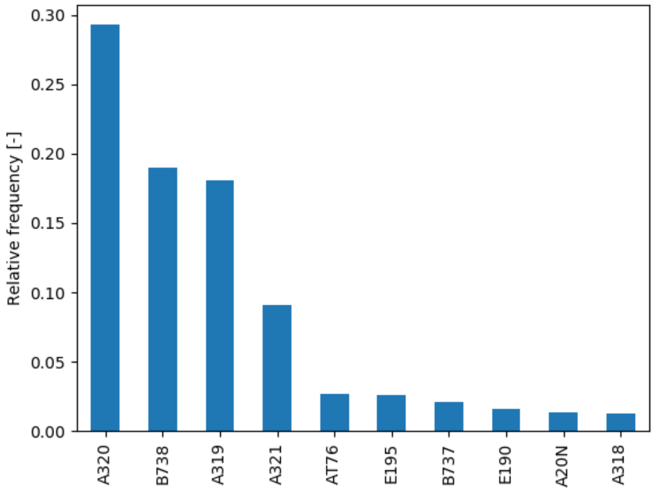

Figure 4-2: Relative frequencies of aircraft models in dataset

Instrument Departure (SID) and Standard Terminal Arrival Route (STAR) ATC routes that aircraft need to fly. For most of the cases a detour has a larger effect on the total route efficiency for a flight on a short distance than for a long distance flight. This can be seen in figure 4-6 where the route efficiency is plotted against the the great circle distance of the flight.

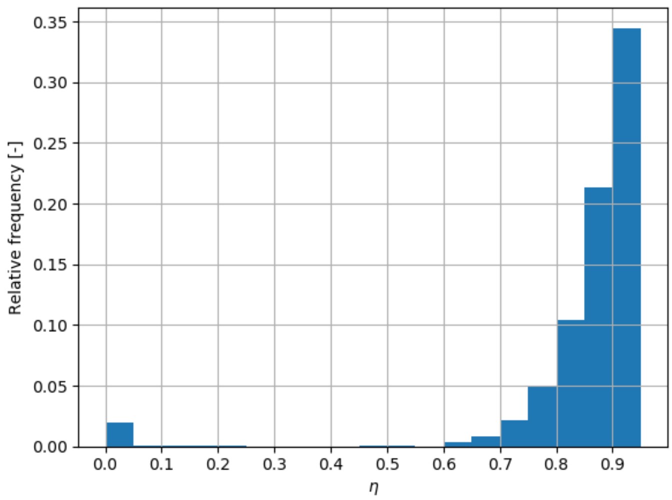

Figure 4-3: Relative frequencies of route efficiency dataset

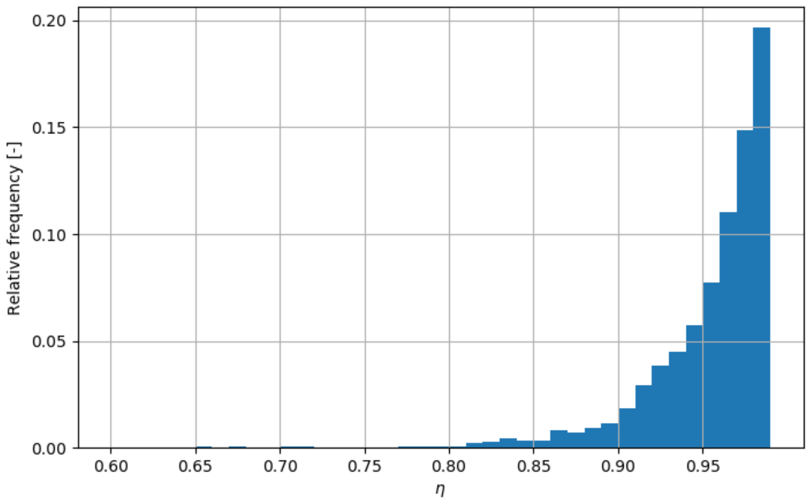

Figure 4-4: Relative frequencies of route efficiency reduced dataset

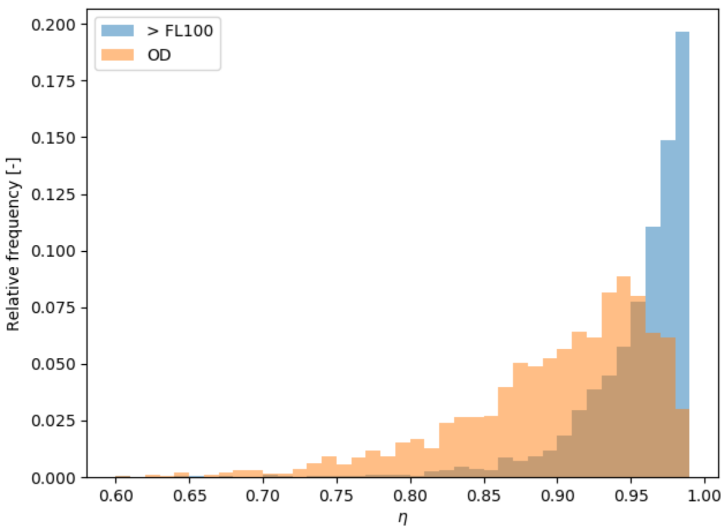

Figure 4-5: Relative frequencies of route efficiency of full vs. partial flight trajectories

4-1-4 Flight phases

For fuel calculations, it is important to know in which flight phase (climb, cruise or descent) the aircraft is in. Looking at the altitude profile of a flight, it is easy for a human to determine the flight phases. For a computer to determine efficiently and fast the flight phases of a flight, fuzzy logic is applied. The computations done are based on Sun et al. [23] and using the python script written by Junzi Sun. To determine the flight phase of a data point three inputs will be used: altitude, speed and rate of climb (ROC). The values of these inputs can

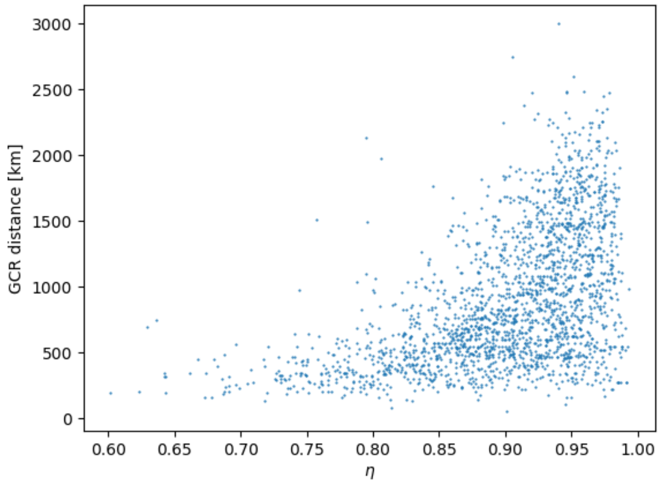

Figure 4-6: Route efficiency vs. GCR distance

give an indication of the flight phase corresponding to the data point. For example, during cruise the aircraft has in general a high ground speed, V_{high}, a high altitude, h_{high} and zero ROC, ROC_0. What is considered to be a high altitude or a high speed is determined with constructed membership functions. These membership functions can be Gaussian, Z-shaped or S-shaped and their outcome are values between 0 and 1. While with Boolean logic a value can only be either 0 or 1, with fuzzy logic a value of a variable can vary between those two numbers. The membership functions used are plotted in figure 4-7. For this dataset, the ground-phase is not present as all flights are above 10,000ft. The following set of rules is used to determine the flight phases:

$$if\ H_{low} \wedge V_{medium} \wedge ROC_{+}\ then\ Climb \tag{4-1a}$$
$$if\ H_{high} \wedge V_{high} \wedge ROC_{0}\ then\ Cruise \tag{4-1b}$$
$$if\ H_{lo} \wedge V_{medium} \wedge ROC_{-}\ then\ Descent \tag{4-1c}$$
$$if\ H_{low} \wedge V_{medium} \wedge ROC_{0}\ then\ Level\ flight \tag{4-1d}$$
$$\tag{4-1e}$$

For each flight in the dataset, the flight phases of the trajectory is determined. In order to improve the speed of the algorithm, the altitude, speed and ROC data is interpolated using a cubic spline. The resulting data points are used as input for the phase detection algorithm. A result of one flight can be seen in figure 4-8. A cubic spline is plotted for all three parameters and the actual data points as well. Green indicates the climb phase, yellow the cruise phase and blue the descent phase. The points in red are not detected due to a software error, but only occur at the end of the flight-data so they will automatically be considered as descent.

4-2 Constructing GCR routes

For each flight in the obtained data-set, a GCR needs to be constructed. The great circle distance can be easily computed using formulae 2-1 and a GCR can be constructed. In figure

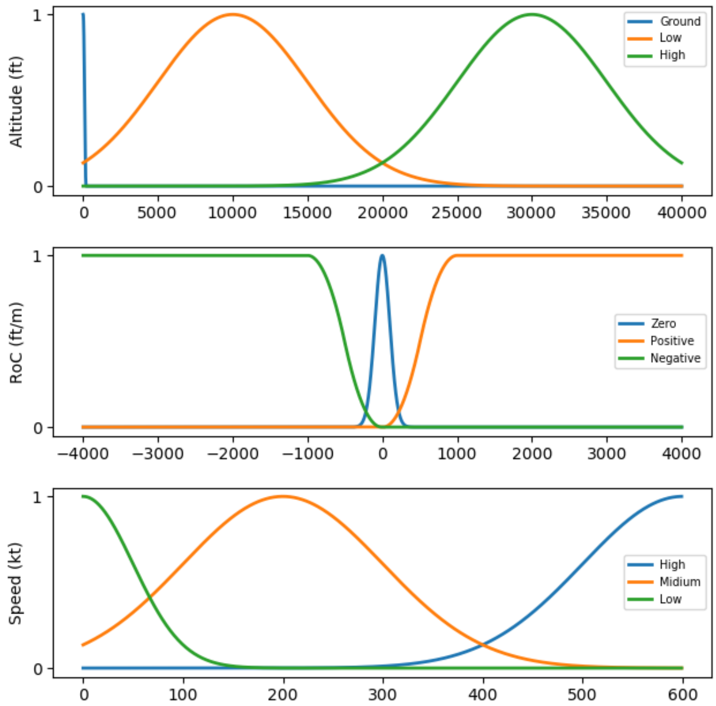

Figure 4-7: Membership functions to determine altitude, speed and ROC range

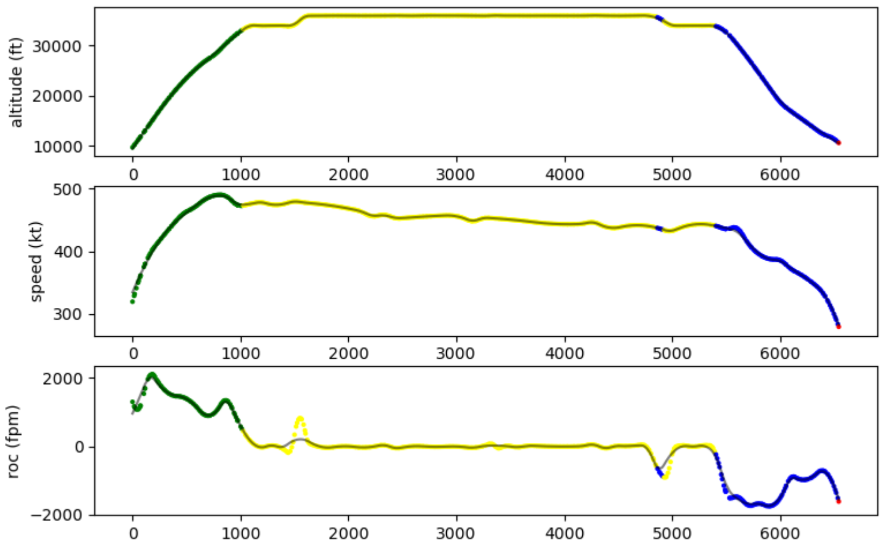

Figure 4-8: Flight phases determination for single flight

4-9 the horizontal trajectory of a flight and its GCR is shown. The colours indicate the climb, cruise and descent phase as described in the previous section. The vertical profile must remain

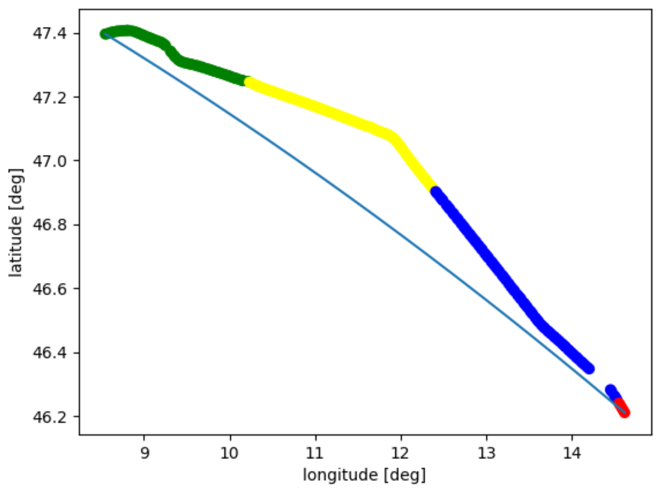

Figure 4-9: Horizontal flight trajectory and GCR of a flight from Ljubljana to Tirana

the same for the GCR in order to see the influence of only horizontal distance flown. For an equal comparison the actual flight trajectories need to be modified. The modified flight trajectories will be compared to the GCRs. For the following datasets the fuel burn will be computed:

1. Real flight route
2. Simplified flight route in Bluesky
3. Great circle route of the simplified flight data (2) in Bluesky

Dataset 1 and 2 will be compared, in order to see how great the error is caused by the simplifications of the model. Dataset 2 and 3 will be compared for assessment of efficiency and safety.

4-2-1 Constructing the simplified route in Bluesky

The actual flight route can be reconstructed by constructing a list of waypoints. The less waypoints, the more efficient the simulation will run. There are two types of waypoints that will be used to reconstruct the flight route:

- **Lateral waypoints**. Only latitude and longitude of waypoint are specified.
- **Lateral/vertical waypoints**. Besides the lateral position also the altitude and speed the aircraft should have at that waypoint will be specified.

Tho construct the simplified actual route, three lateral/vertical waypoints will be used. Besides the aircraft position, the following parameters will be specified:

- Start waypoint. $h = 10000\ ft$ and $V = V_{climb}\ [m/s]$. Furthermore, the initial heading is provided

- Cruise waypoint. $h = h_cruise$ and $V = V_{cruise}$. For the cruise speed and altitude, the mean values of the real cruise data will be used.

- Final waypoint. $h = 10000\ ft$ and $V = V_{descent}$

Besides these three waypoints, n lateral waypoints will be used to specify the aircrafts horizontal path. The aircraft will fly the route along the waypoints. Bluesky works with the logic in which aircraft will climb as soon as possible or descent as late as possible to reach the next waypoint. In figures 4-11 and 4-10, an example of both lateral and vertical flight path of the simplified routes in Bluesky are shown.

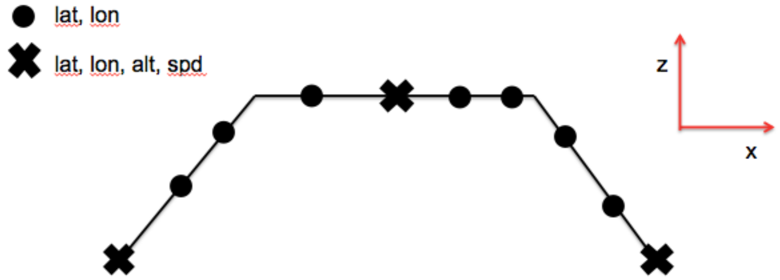

Figure 4-10: Vertical flight path for simplified route in Bluesky

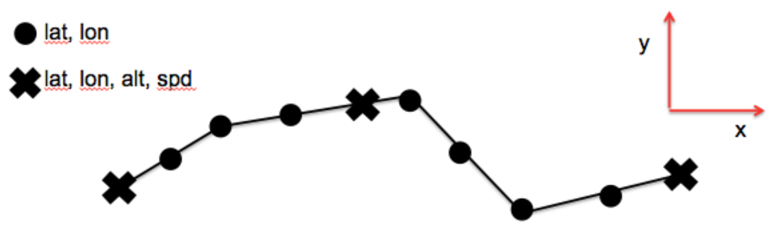

Figure 4-11: Horizontal flight path for simplified route in Bluesky

4-2-2 Constructing the great circle route in Bluesky

The GCR is constructed in the same fashion as the routes in the previous section. All vertical parameters (speeds, altitudes) are kept the same as the simplified routes. For the GCR, no solely lateral waypoints will be specified. The aircraft will automatically fly the shortest route. The cruise waypoint will be placed halfway on the GCR. Figures 4-13 and 4-12 show a schematic view of the routes.

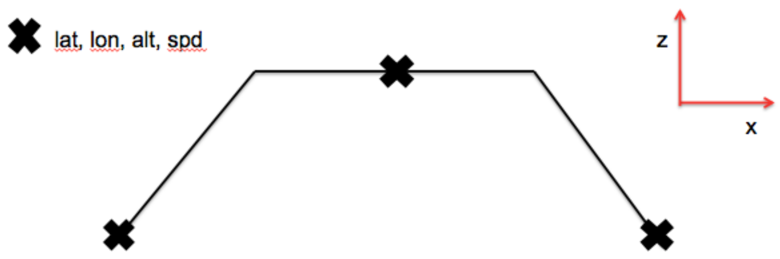

Figure 4-12: Vertical flight path for GCR in Bluesky

Figure 4-13: Horizontal flight path for GCR in Bluesky

4-3 Flight Performance

For all aircraft in the obtained dataset, the fuel usage need to be calculated. Using BADA's performance model [24], BADA aircraft files and the ADS-B data the fuel burn for every flight will be computed. The total fuel burn of the current flight data will be compared with the GCR dataset. In this section the process and method for calculating fuel burn will be described. The necessary assumptions that are made will be stated.

4-3-1 Input data

The main sources of input data are the obtained ADS-B data and the BADA aircraft performance files. These BADA files provide for each aircraft type the aerodynamic characteristics at different flight phases, engine characteristics, available thrust and aircraft operational weights. Not for every aircraft type in the dataset there are BADA performance files available. In these cases, the BADA files of a similar aircraft type will be taken. If there are no comparable aircraft types, the flights will be omitted.

Atmospheric data

Weather has an impact on flight performance. Air temperature and wind have an effect on the performance and engine operations. A tail wind during the flight can reduce the amount of fuel used and a head wind can increase the fuel usage. The ADS-B data provide only the ground speed, V_{ground} of the aircraft. However, for calculation of the thrust, T, the true airspeed, V_{TAS} is required which is $V_{TAS} = V_{ground} + V_{wind}$. As this research deals with a large set of flights in all directions, V_{wind} will assume to be zero. For example, a flight that experience head wind on one way, will most likely experience a tail wind on the way back. Fuel benefits and losses due to the wind will cancel out. Therefore, it is assumed that $V = V_{ground} = V_{TAS}$. For all computation the International Standard Atmosphere (ISA) is assumed. Using the aircraft altitude provided by the ADS-B data, the corresponding ISA density at that height can be computed. Actual performance will differ due to actual weather conditions being non-ISA. However, for both GCR and current routing this assumption is made. This will allow for a fair comparison.

Aircraft weight

Aircraft weight is sensitive information for airlines. It is not provided by the ADS-B data. In the BADA-files, for each aircraft type three different weights are provided: the Operating Empty Weight (OEW) a reference weight the Maximum Take-Off Weight (MTOW) and maximum payload weight ($W_{payload}$). Where:

$$MTOW = OEW + W_{fuel} + W_{payload} \tag{4-2}$$

The reference weight could be used to compute the fuel usage for both current route and GCR. All aircraft of the same type will be assigned exactly the same weight. The final result would be two total fuel weights for the datasets of current routes and GCR. These two numbers would provide no insight in statistical variation of fuel usage. Another approach is to assume the aircraft initial weight to be normally distributed $\mu = W_{ref}$ and $\pm 3\sigma = 1.2\,OEW, MTOW$. A 20% margin is taken on the OEW as no commercial airline will take of with only the OEW. For $n = 100$ samples (depending on the computing time, this number can be increased), the fuel burn distribution is computed of each flight. As fuel burn is independent of all other flights. The sum of the distributions can be taken to end up with the total fuel burn distribution for current routes and for GCR. As GCR routes are shorter, they require less initial fuel. Therefore, fuel optimal fuel reduction is expected to occur at a lower starting weight compared to the same flight flying the current route. As fuel burn will be computed for all aircraft from FL100, the starting weights need to be reduced as fuel is already burned during take-off and the first part of the climb.

4-3-2 Calculating Thrust

In order to compute the fuel burn, first the thrust needs to be calculated. With BADA's total energy model (equation 4-3) this can be done. A description of the thrust coefficients used can be found in table 4-2.

$$(T - D) \cdot V = m \cdot g \cdot \frac{dh}{dt} + m \cdot V \cdot \frac{dV}{dt} \tag{4-3}$$

First, each flight is decomposed into the different flight phases. For each flight phase, the thrust will be computed. For all phases quasi-rectilinear and symmetric flight is assumed. The flight path angle is assumed to be very small. Therefore:

$$L = W \tag{4-4}$$

Before computation, some parameters need to be converted to SI-units.

Thrust during climb

Equation 4-3 can be rewritten as follows:

$$T_{climb} = \frac{m \cdot g}{V} \cdot \frac{dh}{dt} + m \cdot \frac{dV}{dt} + D \tag{4-5}$$

Where:

$$D = \frac{1}{2}\rho V^2 S C_D \tag{4-6}$$

$$C_D = C_{D_{0-cr}} + C_{D_{2-cr}} \cdot C_L^2 \tag{4-7}$$

$$C_L = \frac{2mg}{\rho V^2 S} \tag{4-8}$$

Knowing the aircraft's altitude, the air-density ρ can be computed using the ISA model. $\frac{dH}{dt}$ is the ROC and the acceleration $\frac{dV}{dt}$ can be computed by differentiating the airspeed at each point in time: $\frac{dV}{dt} = \frac{V_{i+1}-V_i}{t_{i+1}-t_i}$ Due to weather conditions it can happen that the calculated thrust exceeds the maximum thrust, $T_{max-climb}$. In that case the maximum thrust is used which is calculated by equation 4-9

$$T_{max-climb} = C_{TC,1} \cdot (1 - \frac{h}{C_{TC,2}} + C_{TC,3} \cdot h^2) \tag{4-9}$$

$C_{TC,1}$, $C_{TC,2}$ and $C_{TC,3}$ are engine thrust coefficients.

Thrust during cruise

During cruise the thrust required is assumed to be equal to drag. Small variations in vertical and horizontal may occur but are assumed to be zero. Therefore, T_{cruise} can be computed by equation 4-10.

$$T_{cruise} = D = \frac{1}{2}\rho V^2 S C_D \tag{4-10}$$

C_D is computed by equation 4-7. As for the climb phase, there is a maximum amount of thrust which may not be exceeded.

$$T_{cruise-max} = C_{T_{cr}} \cdot T_{max-climb} \tag{4-11}$$

Thrust during descent

The thrust used during descent $T_{descent}$ is taken as a ration of $T_{max-climb}$

$$T_{des} = C_{T_{des}} \cdot T_{max-climb} \tag{4-12}$$

4-3-3 Computing Fuel Usage

Per flight phase, the fuel flow, f [kg/min] and total fuel usage, F, [kg] is computed. For climb, the nominal fuel flow is computed using equation 4-13. A description of the fuel coefficients used can be found in table 4-2.

$$f_{nom} = \eta \cdot T \tag{4-13}$$

With the thrust specific fuel consumption, η, $[kg/min \cdot kN]$

$$\eta = C_{f1} \cdot (1 + \frac{V}{C_{f2}}) \tag{4-14}$$

For cruise, the nominal fuel flow is multiplied with a cruise fuel flow factor, C_{fcr}.

$$f_{cr} = f_{nom} \cdot C_{fcr} \tag{4-15}$$

The fuel flow cannot be lower than the minimum fuel flow. The minimum fuel flow will be taken as minimum value in case of $f < f_{min}$

$$f_{min} = C_{f3} \cdot (1 - \frac{h}{C_{f4}}) \tag{4-16}$$

The total fuel burn, F, is computed by equation 4-17.

$$F = \int_{t_{start}}^{t_{end}} f dt \tag{4-17}$$

4-3-4 Python script

In Bluesky, the fuel used for each simulated aircraft is calculated. In order to measure the difference in fuel usage between the actual routes and the simplified actual routes, another script is written. In this script, the fuel usage will be computed using the actual ADS-B data and the BADA performance files. For each aircraft the algorithm works as follows:

1. Determine model type and load the corresponding BADA coefficients from the files.
   (a) At each time step for the climb phase, fuel used is computed and subtracted from the aircraft weight.
   (b) Final climb weight is passed on to function $cruise\_fuel()$ which computes the fuel used each timestamp. The fuel burn is subtracted from the aircraft weight.
   (c) Final cruise weight is passed on to the function $descent\_fuel()$. Again the fuel burn and final aircraft weight, W_f is computed.
   (d) Compute total fuel burn by $F_{total} = W_f - W_i$.

4-4 Verification and Validation

To assure validity of the final results, the model needs to be verified and validated. Parts of the code are extensively tested to assure reasonable results are achieved. As with BADA and ADS-B data, different units are used, it is crucial to check if all units are converted into the same system. The impact of the $V_{ground} = V_{TAS}$ assumption can be checked by computing the influence of wind on aircraft flying in opposite directions. In this way, the benefits on fuel flow of having a tail wind and the disadvantage of experiencing a head wind can be checked. The influence of assuming ISA condition can be assessed by computing the fuel consumption of several flights at different temperatures.

Table 4-2: Thrust and fuel coefficients used in BADA performance model

Symbol	Unit	Description
$C_{T_{c1}}$	N	1st max climb thrust
$C_{T_{c2}}$	ft	2nd max climb thrust
$C_{T_{c3}}$	$1/ft^2$	3rd max climb thrust
$C_{T_{cr}}$	$-$	Maximum cruise thrust
C_{f1}	$kg/min \cdot kN$	1st thrust specific fuel consumption
C_{f2}	kts	2nd thrust specific fuel consumption
C_{f3}	kg/min	1st descent fuel flow
C_{f4}	$ft	2nd descent fuel flow
C_{fr}	$-$	Cruise fuel flow correction

Chapter 5

Conclusion

After a literature study on the research topic, a project plan is made. The scope and research goals are defined. Obtaining, filtering and analyzing of flight data has been done. An initial model is built to compute the efficiency of current air routes and the shortest routes, GCR. For a fair comparison, the actual flight path is modified and GCRs are constructed using the modified flight data. Computing the total fuel burn is done with the BADA model. As the exact aircraft-weight is unknown, for different samples of a weight distribution, the total fuel burn can be computed. For the next steps of the research, the model needs to be improved and flightdata of a full day need to be obtained. The effect of simplifications made to the model, e.g. $V_{ground} = V_{true}$ and ISA assumption, need to be validated. Furthermore, SUA needs to be identified and implemented in Bluesky. For all scenarios safety analysis needs to be performed and the effect of SUA on efficiency needs to be computed. In this way, conclusions can be drawn regarding the airspace capacity.

Due to the time constraints of this research project, the result of fuel savings due to direct routing will be rather conservative. For further research on this topic, it is recommended to investigate the benefits of direct routing in TMAs, optimize the complete flight path using concepts as continuous climb, cruise-climb profile, continuous descent, and take into account the effect of wind.

Appendix A

Gantt Chart

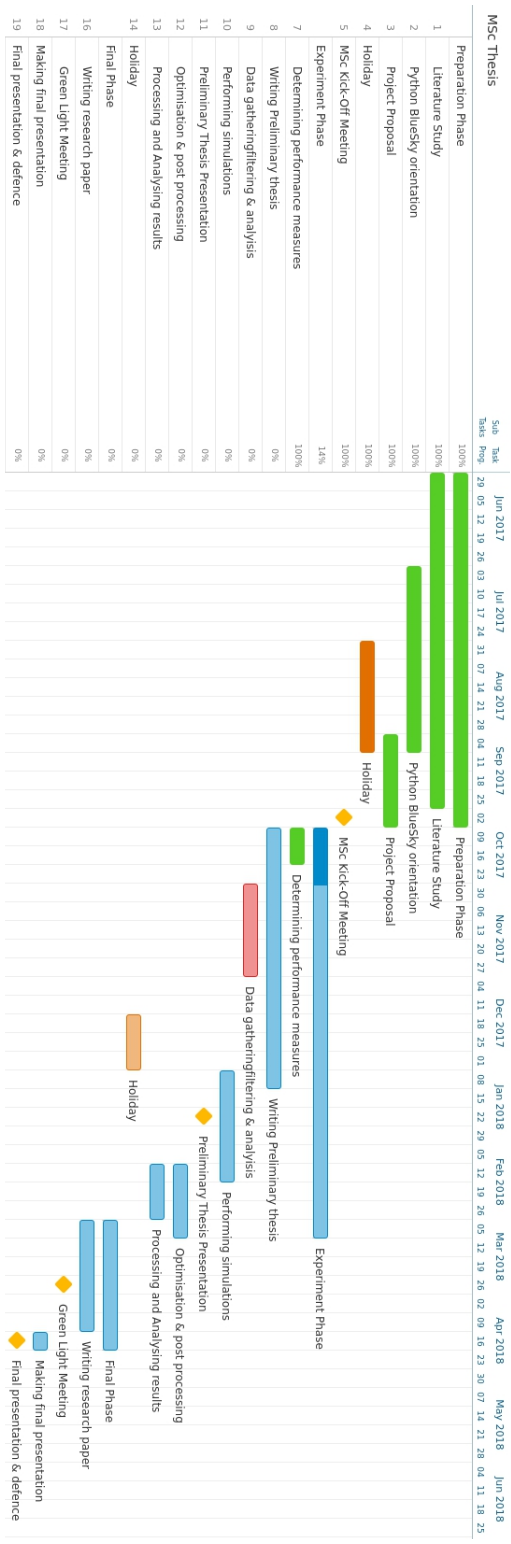

Figure A-1: Gantt-chart of thesis

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