Effects of Flexible Use of Airspace Availability and Plannability on Fuel Efficiency

Master Thesis Report

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Effects of Flexible Use of Airspace Availability and Plannability on Fuel Efficiency

Master Thesis Report

by

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Preface

Firstly, I would like to thank my TU Delft supervisors Jacco Hoekstra and Joost Ellerbroek for their guidance, insights and experience. I want to thank Joost in particular for challenging me to think outside of the box and teaching me to have a more analytical outlook on the problem. From the Knowledge Development Centre, I would like to thank Ferdinand Dijkstra for his continued support, contagious enthusiasm and long and passionate conversations, which I hope we continue to have in the future.

Secondly, I have been lucky enough to do this thesis in collaboration with the KDC in LVNL, which not only has given me a more operational perspective on the problem but also enabled me to meet many people who made this year a memorable experience. These are Stefan van der Loos, whose help and knowledge in the development of the project has been crucial, and I will never forget his effort and kindness; Jonah Bekkers for his knowledge as ATCO; René Francken for providing me with the military reservation data; Evert Westerveld for his interest in my research and the weight he places on the topic of FUA; and to Yoram Obbens, Marcel van Delden and Marcel Sijbrandij for their help in kicking off the project. As for the students, I want to thank Edzer, Max, Jan, Rebekka, Bob, Daan, Stijn Brunia, Stijn van Selling, Mitchell, Wesley, Mithun, Ajay, Bart and the rest, for making every day more enjoyable and helping me with my Dutch.

On a more personal level, this marks the end of my university education, which has developed myself on an academic and, more importantly, on a personal level. I thank my parents and friends from home for having my back from the other side of this adventure; and the many friends I have made in Delft, without whom I could not have gone this far. Thanks to TU Delft I have come across the most passionate, thoughtful, kind and fun people I have ever met and I continue look up to: Max, Marek, Andrés, Alexis, Vlad, Quim, Sebas, Adrián, Diego, Luismi, Carlos, Dmitrij, Timon and many, many others. Finally, I would like to thank my girlfriend Margara for her support, the years together and, of course, for designing the cover of this thesis.

E. Rodríguez
Amsterdam, August 2022

Thesis Structure

This final thesis report consists of three main parts:

1. **Scientific paper:** summarises the research and contains the final findings and conclusions of the project.
2. **Thesis appendices:** additional information and results supporting the scientific paper.
3. **Preliminary thesis report:** covers more extensively the background, motivation and initial choices of the methodology.

A considerable effort has been made to continue updating the preliminary report after the midterm presentation, but some discrepancies still remain between that and the scientific paper, especially in the methodology used to answer research question 1. Wherever a discrepancy is found, the scientific paper and appendices are to be considered the final version.

Revision History

Version	Date	Changes
0	**Thursday 17$^{\text{th}}$ February, 2022**	**First draft of the preliminary thesis report**
0.1	**Wednesday 9$^{\text{th}}$ March, 2022**	**Second draft of the preliminary thesis report** Section 2.1.1: examples added, CDR 1 and 3 better explained. Section 2.1.2: clarified last sentence of FUA availability. Section 2.2.2: clarified subsection and added Figure 2.1. Chapter 4: clarified RQ-1 and RQ-2 sub-goals. Section 4.4: updated Gantt chart with BlueSky steps. Section 5.3: clarified that the GCR is to only substitute the cruise phase segment. Section 5.4.5: implemented Step 5 for Experiment 2. Section 5.4.10: rewritten second assumption. Chapter 6: methodology explained in greater detail. Chapter 6: reorganised plots. Section 7.3: added fuel consumption considerations. Deleted in Version 0.2 and placed in Section 5.6. Chapter 7: added BlueSky as future work.
0.2	**Sunday 27$^{\text{th}}$ March, 2022**	**Final preliminary thesis report** Cover: added logo of Knowledge Development Centre. Section 2.2.2: changed colors of the reservations in the figures for consistency with other chapters. Chapter 4: eliminated previous RQ-1.2 and rewritten chapter accordingly. Section 4.4: updated Gantt chart. Section 5.3: added flowchart of Experiment 1 (Figure 5.4). Section 5.3: added pseudo-code in Algorithm 1 and extended explanation. Section 5.3 and Section 5.4.10: assumptions of no wind and ISA. Section 5.4: added flowchart of Experiment 2 (Figure 5.11). Section 5.4.4: added pseudo code in Algorithm 2. Section 5.5.3: added note on computation times. Section 5.5.4: rewritten subsection on results extrapolation. Section 5.6: added section on experiment tools (replacing Section 7.3 from Version 0.1). Section 5.7: added section on verification and validation. Added new chapter on software architecture. Section 6.3: section on the selection of independent variables. Chapter 7: rewritten future work chapter.
0.3	**Thursday 23$^{\text{rd}}$ June, 2022**	**Draft of the thesis report** Nomenclature: updated lists with missing items. Section 5.4.6: corrected Breguet's equation and derivation. Section 5.1: added section about the flight subsets considered. Section 5.3: added speed modes and RQ-1.2 methodology. Section 5.3.5: updated assumptions with RQ-1.2. Section 5.4: changed datum for plannability horizons. Section 5.4.5: updated with usage of historical trajectories.

Version	Date	Changes
		Section 5.4.10: deleted the assumption that plannability does not affect transit. Route efficiency still penalised in Experiment 1. Chapter 2: changed CFMU and AFMU to current function names (Network Manager and FC-L/FC-M). Deleted chapter on Software Architecture from the Preliminary Thesis Report (its contents are updated in the Appendices of the Final Report). Added Scientific paper and Appendices.
1.0	**Monday 15th August, 2022**	**Final thesis report** Preface added. Nomenclature updated. Scientific paper: simplified operational jargon. Scientific paper: improved the methodology determining the deviated route in Section VI-D. Scientific paper: changed independent variable values of the cutoff time for the Multiple Horizons concept in Experiment 2. Scientific paper: added average fuel consumption reduction per flight in Experiment 1 results. Scientific paper: use of the former Baseline 2 as the only baseline in Experiment 2 results. Scientific paper: added Discussion (Section XI). Scientific paper: improved Conclusions (Section XII). Appendix A: implemented work results of Experiment 3. Appendix B: added verification of surplus fuel calculation. Appendix E: expanded explanation on the scripts. Added Appendix F.

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
ADS-B	Automatic Dependent Surveillance - Broadcast
AFUA	Advanced Flexible Use of Airspace
AIP	Aeronautical Information Publication
AMC	Airspace Management Cell
ANSP	Air Navigation Service Provider
ATC	Air Traffic Control
ATCO	Air Traffic Control Operator
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
ATS	Air Traffic Service
AU	Airspace User
AUP	Airspace Use Plan
BADA	Base of Aircraft Data
BDT	Business Development Trajectory
BPPR	Booking Procedures and Priority Rules
CAGR	Compound Annual Growth Rate
CAS	Calibrated Airspeed
CBA	Cross Border Area
CDM	Collaborative Decision Making
CDO	Continuous Descent Operation
CDR	Conditional Route
D-0	Day of operations
D-1	Day before operations
DAC	Dynamic Airspace Configuration
DARP	Dutch Airspace Redesign Programme
DMA	Dynamic Mobile Area
ECAC	European Civil Aviation Conference
EHAA	Amsterdam FIR
EHAM	Amsterdam Airport Schiphol
EI	Emission Index
FC-L	FUA Cell LVNL
FC-M	FUA Cell MUAC
FIR	Flight Information Region
FL	Flight Level
FMS	Flight Management System
FRA	Free Route Airspace
FUA	Flexible Use of Airspace
GAT	General Air Traffic
GCR	Great Circle Route
ICAO	International Civil Aviation Organization
ISA	International Standard Atmosphere
LVNL	Luchtverkeersleiding Nederland
MME	Military Mission Effectiveness
MTOW	Maximum Take-Off Weight
MUAC	Maastricht Upper Area Control

Abbreviation	Definition
NM	Network Manager
OAT	Operational Air Traffic
OEW	Operative Empty Weight
RBT	Reference Business Trajectory
RCA	Reduced Coordination Airspace
RNLAF	Royal Netherlands Air force
SBT	Shared Business Trajectory
SUA	Special Use Airspace
SWIM	System Wide Information Management
TBO	Trajectory Based Operations
TMA	Terminal Manoeuvring Area
TPR	Aircraft range at MTOW
TRA	Temporary Reserved Airspace
TSA	Temporary Segregated Area
TSFC	Thrust-Specific Fuel Consumption
UUP	Updated Use Plan
VPA	Variable Profile Area

Symbols

Symbol	Definition	Unit
C_D	Drag coefficient	[-]
C_L	Lift coefficient	[-]
c_j	Specific fuel consumption of a jet engine	[kg/Ns]
D	Drag	[N]
d	Distance flown	[m]
f	Fuel flow	[kg/s]
g_0	Gravitational force	[m/s^2]
Hp	Geopotential pressure altitude	[ft]
h	Geodetic altitude	[m]
L	Lift	[N]
m	Aircraft mass	[kg]
R	Mission range	[m]
S	Wing reference area	[m^2]
T	Thrust	[N]
t	Time	[s]
V_{TAS}	True airspeed	[m/s]
W	Work/Weight	[J/N]
W_{MTOW}	Maximum Take-Off Weight (MTOW)	[kg]
W_o	Operative Empty Weight (OEW)	[kg]
W_{pl}	Payload weight	[kg]
η	Thrust-Specific Fuel Consumption (TSFC)	[kg/min $\cdot$ N]
ρ	Density	[kg/m^3]

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Part I

Scientific Paper

Effects of Flexible Use of Airspace Availability and Plannability on Fuel Efficiency

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***Abstract*—The expected growth of civil air traffic and the inclusion of advanced systems in the Royal Netherlands Air Force result in more demanding airspace requirements across all users, making this a scarce resource. To optimise its usage, military airspaces in Amsterdam Flight Information Region are used as Flexible Use of Airspace (FUA), which no longer considers airspace as entirely 'civil' or 'military', but as a continuum to be allocated temporarily according to user requirements. Given its importance for civil-military cooperation, FUA is at the core of the Dutch Airspace Redesign Programme, considering both a reorganisation of FUA structures and the plannability policies they are reserved with. In order to inform these decisions, this study analyses the effect of FUA availability and plannability on the fuel efficiency of civil commercial traffic. Historical traffic data from the Eurocontrol R&D data archive is sampled for the month of March 2019 and used in three experiments. On the one hand, Experiment 1 investigates FUA availability by considering flights losing route efficiency due to FUA sectors and comparing them with Great Circle Route alternatives and similar flights historically transiting them. On the other hand, Experiment 2 considers flights making use of FUA sectors during times when these have been delegated to civil use to assess the effects of carrying a surplus fuel due to an insufficient airspace plannability. By proposing new plannability policies, the hypothetical reduction in fuel consumption as a result of not taking the surplus fuel is assessed. Lastly, Experiment 3 combines the benefits found in Experiment 1 with the plannability policies of Experiment 2 to determine the fuel benefits resulting from a tactical rerouting enabled by the new plannability concepts. A total of 1,548 simulations have been performed in the open source air traffic simulator BlueSky to compute the fuel efficiency metrics. The results suggest that making both the Alpha and Delta sectors completely available would result in a yearly reduction in fuel consumption of 70,198 and 100,022 tonnes, respectively; 8,908 and 13,301 of which would be saved solely by adopting a new plannability policy (corresponding to 28,060 and 41,898 tonnes of CO_2). Finally, not carrying a surplus fuel due to this concept would contribute to an extra 270 and 394 tonnes of fuel consumption being reduced in 2019 (851 and 1,241 tonnes of CO_2).**

***Index Terms*—Flexible Use of Airspace (FUA), Direct Routing, Great Circle Route (GCR), Plannability, Fuel Efficiency, Airspace**

I. Introduction

The International Civil Aviation Organization estimates an average Compound Annual Growth Rate in Revenue Passenger-Kilometres of 2.7% between 2018 and 2050 in Europe, accounting for the post-pandemic recovery of the aviation industry [1]. This growth of commercial air transport goes hand in hand with more demanding requirements for airspace capacity, route efficiency and airport accessibility. At the same time, the Royal Netherlands Air Force (RNLAF) utilises the airspace for training purposes and other missions which call for their own requirements for an effective operation. In order to use the airspace efficiently, this is shared under the concept of Flexible Use of Airspace (FUA), which aims to allocate airspace resources in a temporary manner based on user requirements. Despite this objective, the current Air Traffic Management infrastructure lacks the enablers for on-demand and real-time airspace allocation, for which FUA is currently limited to specific volumes of airspace being reserved with some plannability.

Despite its current limitations, FUA enables users to utilise the airspace for their objectives. This however results in specific preferences in the operation of each user, yielding contradictory requirements on FUA usage. On the one hand, both users benefit from having as much airspace usable for as long as possible. On the other hand, civil users benefit from plannability in operations while the RNLAF benefits from flexibility. Given its central role within civil-military coordination, FUA has become a cornerstone of the Dutch Airspace Redesign Programme. This aims to make a more efficient use of the airspace and reduce noise impact and emissions by enabling a closer collaboration between civil and military aviation. The steps considered to realise these objectives are, amongst others, a redesign of the airspace structures and a new procedure of airspace reservation to mitigate the effects of FUA availability and plannability, respectively.

In order to inform such new policies, it is first needed to understand the effects of FUA availability and plannability on civil traffic. To limit the scope of this study, the performance area chosen is that of fuel efficiency, which best encapsulates the environmental and economic interests of the civil user and is hypothesised to yield considerable benefits with relatively lenient plannability requirements on the RNLAF. The study therefore consists of three experiments considering the effects of availability and plannability, and the assessment of a series of proposed plannability policies.

This paper is structured as follows. First, Section II offers the background of the study and identifies the motivation and research gap of the project, which are detailed in Section III. This leads to the experiment design, describing the general components in Section IV and the specific methodologies in sections V, VI and VII for each experiment. Next, Section

VIII shows the results of the experiments, which are extrapolated to a yearly estimation in Section IX. Furthermore, the assumptions on the fuel flow calculation implied by the limitations of the database used are validated in Section X. Finally, a discussion on the results and final conclusions and recommendations are given in sections XI and XII.

II. Background

The following serves as a brief background of the research project. First, the FUA concept and its role within civil-military cooperation are described, in order to understand how the same tool is used under inherently contradicting goals. Next, Advanced FUA is discussed to gain an understanding on what a future FUA concept is to be, as well as outlining its necessary enablers. Finally, the Dutch Airspace Redesign Programme and its challenges for FUA are described.

A. Flexible Use of Airspace

The Flexible Use of Airspace (FUA) concept considers airspace a continuum to be shared by several users whereby any segregation can only be temporary and based on real-time use, allocated with the aim to meet user requirements to the greatest possible extent [2].

In essence, FUA is aimed at improving civil-military cooperation by making the same airspace available for different purposes and objectives. Nonetheless, while civil aviation is aimed at supporting the (economic) interests of business and customer stakeholders, military aviation is to train efficiently and develop defence capabilities. Despite their interests can be summarised as striving for efficiency in their operations, their requirements on FUA are very different. Firstly, each user benefits from having as much airspace as possible, as it improves route efficiency and capacity for civil and training possibilities for military aviation. Secondly, while the civil user benefits from a high plannability to optimise trajectories and distribute the flow in advance, the military user benefits from a good flexibility to maintain the training possibilities due to their dependence on equipment, weather conditions and support resources on land and sea [3]. This leads to the same concept being used under inherently conflicting interests.

The academic literature surrounding FUA focuses on decision support tools and Collaborative Decision Making infrastructure improving the allocation of the airspace to different parties. For instance, Krozel [4] investigates a mechanism streamlining airline user preferences into amended flight plans. A tool for the similar purpose of making the airspace more dynamic is proposed by Torres [5], where contingency plans are created to update the flight plan such that these can be used in case a FUA becomes inactive. These indicate, together with Mihetec [6], that the benefits attainable for civil aviation once a FUA becomes inactive are twofold. First, if the FUA availability is known en-route, the aircraft may still benefit from a more direct routing thus saving some fuel. However, the flight still loaded the fuel needed to fly the expected deviation around the airspace. If the sector availability is known before the last flight plan is issued, no surplus fuel is loaded, the weight of which would lead to an increase in thrust and thus fuel burnt.

B. Advanced Flexible Use of Airspace

The main inefficiencies in the current FUA system are inherent to the present Air Traffic Management infrastructure. Advanced Flexible Use of Airspace (AFUA) consists of making optimal use of FUA, enabled by tools making relevant and transparent information available to all stakeholders in real-time [7]. These enablers are explained in the following.

First, System Wide Information Management is used as an intranet for Air Traffic Management providing all the information relevant to airspace users in a timely and reliable manner, thus enhancing their collaboration. Secondly, the Trajectory Based Operations concept consists of characterising each flight as a series of four-dimensional coordinates: latitude, longitude, altitude and time. In such an environment, a precise knowledge of every flight trajectory is known to all parties. Although this is best exploited with a high plannability allowing strategic de-confliction of the trajectories, this common situational awareness also means that changes occurring at any moment of the flight planning and execution process can be accommodated and the airspace can still be optimally used by all parties. Further, advanced and extensive Collaborative Decision Making may enhance FUA by performing airspace allocation with a better adherence to the objectives of specific airspace users. This centralised communication infrastructure can also provide a common situational awareness of the planned trajectories of all airspace users, therefore enabling a continuous and iterative planning over the different airspace management phases known as the rolling process [7]. Lastly, and resulting from the previous enablers, Dynamic Airspace Configurations are to enable AFUA to optimise the airspace allocation by using a wide variety of airspace configurations, both for civil users to improve the balance between demand and capacity and reduce workload, and for the RNLAF to have an airspace more flexible, extensive and tailored to its needs.

C. Dutch Airspace Redesign Programme

Given its importance to civil-military cooperation and to the effectiveness in the operations of both users, FUA has a major role within the Dutch Airspace Redesign Programme (DARP), which addresses the revision of the airspace sectorisation, routes and procedures.

Airspace user requirements such as the need to maintain the network quality of the Netherlands and accommodate a growing demand, while ensuring the successful training and effectiveness of the RNLAF with more demanding systems such as the F-35, make airspace a scarce resource. These user requirements add to the concerns on aviation noise and emissions which further constrain the design of routes. The number and significance of these desired changes has led to a complete airspace revision carried out by the DARP, with a time span expected to go from 2023 onwards [3].

With these objectives in mind, the airspace structure is to be reorganised with the aim to optimise the northern region for military use and the southern one for civil use and reducing the impact of air traffic on the environment. For this, it is being considered to remove the southern region either partially or entirely. In order to steer these considerations, it is desired to have an understanding of the effects of FUA availability on civil traffic. Further, another task of the DARP is to propose new Booking Procedures and Priority Rules, i.e. new rules of reservation and priority, such that the airspace can be better planned. For this, new concepts of plannability and its benefits for civil traffic should be investigated.

III. Research Gap and Motivation

The presented background has identified the motivation for the research project and the gap to cover. In the following, the project is separated into two main parts: FUA availability and plannability, each with its corresponding research question.

A. FUA Availability

FUA availability can be defined as having the airspace accessible for a specific user. The main benefits of FUA availability to civil traffic are the increase in route efficiency, thus reducing fuel burnt and emissions; and capacity, as the extra airspace allows for more aircraft to be handled while maintaining safety and Air Traffic Control Operator (ATCO) workload. For the Royal Netherlands Air Force (RNLAF), a significant FUA availability in terms of volume and time of airspace reservation is required for the successful completion of the training curriculum and other missions.

Given that the Dutch Airspace Redesign Programme is considering the (partial) removal of the southern FUA sector, it is desired to understand its effect on civil traffic, and how this compares to the northern sector. While an aspect such as capacity could also be examined, the research has been limited to fuel efficiency, as this better represents the economic and environmental interests of the civil users. Thus, this leads to the research question of *"How much fuel consumption is saved by making FUA completely available for civil use?"*.

B. FUA Plannability

This section describes the problem of FUA plannability by presenting the current practices of FUA reservation and its effects on civil traffic.

1) Current Practices of FUA Plannability and Usage: The current Booking Procedures and Priority Rules establish that the RNLAF has priority over the civil user, and there is no requirement for a plannability in which they must compromise and give up unused airspace. This results in three main stages of FUA plannability. First, the standard times of reservation are outlined six months in advance (D-180). It is common for the RNLAF to reserve all areas they can for as long as possible. These standard schedules remain the norm throughout the following months and are published in the Aeronautical Information Publication (AIP). Secondly, on the day before operations (D-1), the availability of the conditional routes is published in the Airspace Use Plan and Updated Use Plans (AUP and UUPs). They are often detailed to be closed for a smaller period of time than that established in the AIP, meaning that part of the FUA reservation is given up guaranteeing transit to the civil user. Lastly, during the day of operations (D-0) the AUP reservation is further detailed into smaller intervals (D-0 reservations) as the day progresses and the RNLAF decides not to use the airspace during specific periods of time. This results in transit enabled through the FUA tactically, yet without a previous guarantee of transit. These three reservation steps are exemplified in Figure 1.

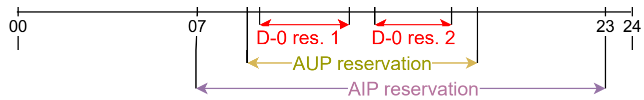

Fig. 1. Example of AIP, AUP and D-0 reservation intervals

For simplicity, the periods of reservation are classified into three categories in the following experiments. First, the intervals outside of the AIP reservation, i.e. those intervals when the airspace had never been reserved, are hereby referred to as "available". The D-0 reservations, i.e. those periods not only preliminary reserved by the RNLAF, but which also remained blocked during the day of operations, are referred to in the following as "unavailable". The remaining periods of time, i.e. those preliminary reserved but eventually delegated to be used by Air Traffic Services (called ATS delegations), are referred to as "delegated", regardless of whether they fall within or outside of the AUP reservation. Thus, the simplified periods of time are shown in Figure 2.

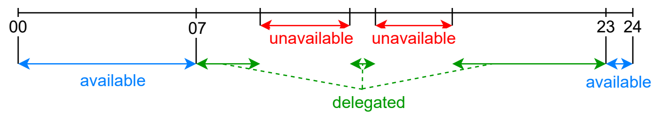

Fig. 2. Simplified labelling of periods

2) Effects of FUA Plannability on Civil Traffic: FUA plannability affects many different aspects of the operation. First, if the availability of a sector is known earlier in advance, additional flights can be scheduled and thus capacity is increased. If transit cannot be guaranteed, however, part of the demand is preemptively not met in order to avoid risking delays. In other words, an earlier certainty in the airspace available and thus in the flow would lead to a better demand predictability and consequently better informed Air Traffic Flow and Capacity Management measures. Furthermore, the earlier the sector capacity is determined, the earlier Air Navigation Service Providers can schedule their ATCO allocation and optimise their productivity.

Finally, and even if the flight ends up traversing the FUA, the lack of guarantee results in the last flight plan assuming a deviation around it. To fly the extra distance, additional fuel is loaded which is eventually not needed (referred to as surplus fuel in the following). This increases the total weight and thus the thrust required and fuel burnt. In the following and as for FUA availability, only fuel efficiency is studied. Not only does it best encapsulate the environmental and economic interests of civil stakeholders, but it is hypothesised that a change in plannability policy to improve fuel efficiency would be less demanding of the RNLAF than striving for a policy benefiting the other aspects discussed above, making it the most realistic and valuable compromise between users. Thus, the research question is *”How much fuel consumption is saved by making FUA available for civil use with a higher plannability?”*.

IV. Experiment Design

Given the different nature of the research questions, the methodology is separated into three experiments in sections V, VI and VII. The following describes their common aspects, namely the flights and FUA sectors considered, the fuel efficiency metrics, the data sources and their sampling.

A. Flights Considered

The subsets of flights used differ per research question and thus experiment. For FUA availability, where it is desired to know the effects of making the FUA sectors completely available, the flights considered must be those which historically did not make use of FUA, but would have benefited from it, during the days with reservations of the sampled time. Within these (hereby called flights with lost route efficiency), a distinction can be made between those which would have benefited from the transit during a period when the FUA is available (outside the AIP reservation), unavailable (during a D-0 reservation) or delegated (during an ATS delegation). The implications of this interval matter: if a flight loses route efficiency during a period when the FUA is available, this loss is not because of the FUA, as it had never been reserved during that time. If the transit would have been during a period when the FUA is unavailable (a period of actual FUA usage), this efficiency loss is deemed to be due to FUA availability. Finally, if the transit would have occurred during a period when the FUA is delegated, the loss is also penalised as a route efficiency, yet the cause can be deemed due to FUA plannability instead.

On the other hand, Experiment 2 is set to answer the effects of carrying a surplus fuel for the flights which eventually made use of the FUA sectors. The period of transit once again has implications: if they transited during a time when the FUA sector is available, they were never planning on a route around it. If they transited during a period when the FUA sector is unavailable, this is assumed to be equitable and not penalised, as D-0 reservations are to be used by the RNLAF. Else, i.e. if the transit took place during a delegated period, when the guarantee of transit could have been given with a higher plannability, this is penalised with a surplus fuel.

Finally, and although not directly taken from the research questions, the findings of Experiment 1 lead to the conclusion that the effects of FUA plannability on route efficiency are not negligible, for which it is deemed appropriate to investigate the benefits in route efficiency that the policies proposed in Experiment 2 would bring. In this manner, while Experiment 1 describes the effects of route efficiency loss due to the FUA, Experiment 3 investigates how much of these effects would already be recovered solely by implementing a new plannability policy. The breakdown of the subsets can be seen in Figure 3.

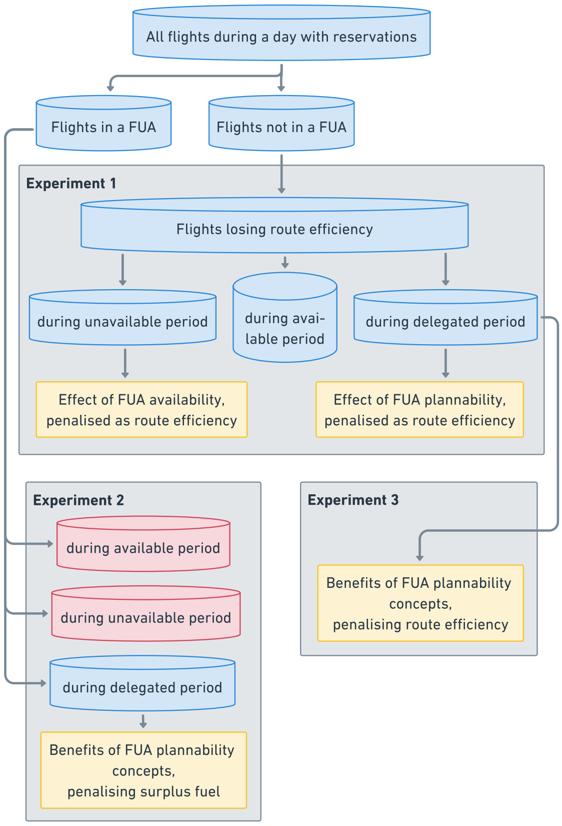

Fig. 3. Subsets of flights considered per experiment

B. Airspace Sectors Considered

Every military airspace in Amsterdam FIR is considered to be Flexible Use of Airspace. These are shown in Figure 4. Here, Restricted Areas appear in red, Danger Areas in blue, Temporary Reserved Airspaces in yellow, Temporary Segregated Areas in white and Cross Border Areas in green, as published in the Aeronautical Information Publication [8]. The Alpha and Delta sectors, covering the regions highlighted in red in the North and South, respectively, are the higher level of grouping. Not only does segregating the Alpha or Delta sectors block all smaller airspaces within them, but once any of these smaller sectors are reserved, the entire Alpha or Delta sector is also blocked. As a consequence, the airspace reservation and segregation is done on the basis of these two regions. Given that all other military airspaces are lower altitude ones, irrelevant to civil commercial traffic, it becomes clear that the Alpha and Delta sectors ought to be the airspaces considered for the analysis.

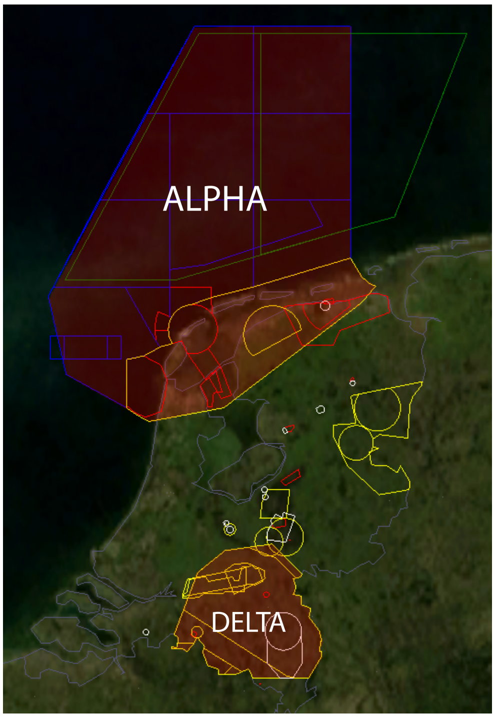

Fig. 4. FUA sectors in Amsterdam Flight Information Region

C. Dependent Variables

Whilst the independent variables vary per experiment and concept, the dependent variables are in all cases fuel efficiency metrics: fuel consumption, work and CO_2 emissions. To have a more tangible sense of the metrics analysed and to verify the BlueSky implementation, the following formulae are manually checked in Appendix B using an example scenario.

1) Fuel consumption: although it provides a direct indication of the actual fuel consumed, this metric relies on more BADA coefficients than work, making the results more sensitive to their approximations. The relations below are given by the BADA User Manual [9] and are valid for jet engines. In essence, fuel consumption is integrated from fuel flow f over time (Equation 1). Fuel flow is calculated as shown in Equation 2, with the Thrust-Specific Fuel Consumption (TSFC or η) and Thrust force T.

$$F_{burnt_i} = \int_{t_0}^{t_i} f dt \quad (1) \qquad f = \eta \cdot T \quad (2)$$

Firstly, TSFC is given as a linear function of the airspeed in Equation 3. Here, V_{TAS} is the true airspeed in knots and C_{f1} and C_{f2} are the TSFC coefficients 1 and 2, respectively. Equations 2 and 3 can be used together in all flight phases except idle descent and cruise [9]. For idle descent, a minimum fuel flow is directly calculated based on the geopotential pressure altitude H_p as shown in Equation 4. For cruise, equations 3 and 5 are used. $\mathrm{C_{f3}}$, $\mathrm{C_{f4}}$ and $\mathrm{C_{fcr}}$ are all coefficients given by the aircraft performance database BADA per aircraft type.

$$\eta = C_{f1}\left(1 + \frac{V_{TAS}}{C_{f2}}\right) \tag{3}$$

$$f_{\min} = \mathrm{C_{f3}}\left(1 - \frac{\mathrm{H_p}}{\mathrm{C_{f4}}}\right) \quad (4) \qquad f_{\mathrm{cr}} = \eta \cdot \mathrm{T} \cdot \mathrm{C_{fcr}} \quad (5)$$

Secondly, Thrust is taken from the total energy equation in Equation 6. Here, m is the aircraft mass, $g_0 = 9.80665\ m/s^2$ as the gravitational acceleration, h the geodetic altitude and D the aerodynamic drag. The latter is given by Equation 7, with ρ and S the air density and wing reference area, and C_D the drag coefficient. This is then given by Equation 9, composed of coefficients C_{D_0} and C_{D_2} for a given flight condition e.g. cruise, approach or landing, and the lift coefficient C_L. This is in turn given in Equation 8 assuming a flight path angle of zero and once again using the aircraft mass.

$$T = \frac{mg_0}{V_{TAS}}\frac{\mathrm{d}h}{\mathrm{dt}} + m\frac{\mathrm{d}V_{TAS}}{\mathrm{dt}} + D \tag{6}$$

$$D = C_D\frac{1}{2}\rho V_{TAS}^2 S \quad (7) \qquad C_L = \frac{mg_0}{\frac{1}{2}\rho V_{TAS}^2 S} \quad (8)$$

$$C_D = C_{D_{0,X}} + C_{D_{2,X}} C_L^2 \tag{9}$$

2) Work: despite still relying on the BADA coefficients needed to calculate T, the work calculation relies on less coefficients than fuel consumption, making it a less sensitive metric as well as being more robust to new engine types. As given in Equation 10, work W is defined as the thrust T applied to move the aircraft over a distance flown d.

$$W = T \cdot d \tag{10}$$

3) CO_2 emissions: having calculated the fuel consumption, the corresponding emissions of CO_2 can be attained with the emission index of kerosene (3150 g/kg). Hence, it can be approximated for every kilogram of fuel burnt to generate 3.15 kilograms of CO_2 [10].

D. Data Selection and Sampling

In order to gain a concrete understanding on the effects of specific FUA structures in Amsterdam FIR, historical traffic data is to be used. The following discusses the rationale behind the data selection for historical civil traffic and military reservations of FUA at D-0, as well as the sampling.

1) Traffic data: historical traffic data was considered from different sources: ADS-B, radar tracks and the Eurocontrol R&D data archive [11]. First, while ADS-B provides worldwide data for about 80% of European flights [12], is openly available and has no limit for sampling, the long scraping times make this an unfeasible option for the size of the time and region desired to be sampled. Contrarily, radar tracks from LVNL are readily available, yet they do not cover trajectories outside of Amsterdam FIR, which is a requirement to compute the fuel consumption of full trajectories. Lastly, the Eurocontrol R&D data archive is readily available and contains the full trajectories for all flights traversing Europe, making this the best option for the purposes of this research. The shortcomings of this database are the low frequency of the flight points (one track update each five to seven minutes) and the limited sampling time of four months (March, June, September and December) for the years 2015-2019, for which an extrapolation method is needed to attain yearly benefits.

2) D-0 reservation data: the results of Experiment 2 directly depend on the number of flights flying through the delegated periods of time, and consequently on the historical unavailable periods or D-0 reservations. For this reason, it is critical for the sampling of historical traffic and D-0 reservations to match. For this, the historical records of military ATC supervisors have been retrieved, going as far back as 2019.

3) Data sampling: although it would be more informative to process several months, a single month needs to be chosen given the long process times of the experiments. Knowing the availability of the historical traffic and reservation data, it is decided to sample the month of March 2019. 2019 is the busiest and thus preferred year before the pandemic, and March has a traffic density level in Amsterdam FIR closer to the yearly average than the other three months available, according to the Schiphol traffic figures [13] and the Eurocontrol Aviation Intelligence report [14]. Furthermore, the military reservations offer a representative set of reservation frequency and times throughout March as well. Using this month, there are a total of 18 days with D-0 reservations after disregarding the weekends (when military airspaces are not reserved), two days when data is missing from the historical records and one with cancelled reservations due to bad weather. These are shown in Table I.

TABLE I
DATES SAMPLED AND D-0 RESERVATIONS PER FUA SECTOR

Date	Alpha sector	Delta sector
05-03-2019	08:00-14:30	08:00-14:43
06-03-2019	08:30-14:26	08:00-14:26
07-03-2019	08:00-10:15 & 12:00-14:28	08:00-15:10
08-03-2019	08:05-14:05	08:05-14:25
11-03-2019	08:00-11:20	08:00-15:04
12-03-2019	08:00-10:30 & 12:00-14:30	08:00-15:35
13-03-2019	08:00-14:21	08:00-15:10
14-03-2019	08:15-11:25 & 12:45-15:00	09:00-15:00
15-03-2019	08:45-12:35	08:00-15:07
18-03-2019	09:00-14:15	09:00-14:30
19-03-2019	08:30-11:15	12:15-14:55
20-03-2019	08:45-14:56	08:45-15:05
21-03-2019	08:45-11:05 & 12:30-15:08	08:45-15:08
22-03-2019	09:00-14:47	07:20-14:47
25-03-2019	09:00-14:10	08:30-14:30
26-03-2019	09:00-15:28	09:00-14:46
27-03-2019	08:30-15:05	08:30-15:05
28-03-2019	08:30-12:52 & 13:30-14:57	09:00-12:52

E. Experiment Tools

Each of the main experiments has the same two overarching parts consisting of the same tools, all using Python 3. First, a data processing step is done to filter the flights of interest and create trajectories. This uses the libraries pandas for database filtering, shapely to find the points in a polygon of coordinates and pyproj for the cartographic projections and distance computations. This results in a series of scenario files to be used by the open source air traffic simulator BlueSky [15].

BlueSky is then used to compute the metrics by propagating the trajectories from the initial conditions given, as previously done by Inaad [16], Klapwijk [17] and Adriaens [18]. Given the large number of scenario files used (one per day, FUA, concept and independent variable), the batch simulation functionality of BlueSky is essential, enabled by a multi-CPU core computer. For this, the 36-logical processor computers at the Innovation LABs of LVNL are used, enabling 36 simulations to run in parallel.

F. General Assumptions

All experiments are done under the following assumptions.

- Trajectories fly directly from point to point registered.
  Due to the low frequency of position entries of the Eurocontrol database, it may occur that historical points are outside the FUA, yet the line connecting them does cross the FUA. This assumption allows to establish if a flight transited the FUA. In most cases this crossing is clear, while for the rest this assumption may indicate the FUA was used while this was not the case. This is deemed acceptable for two reasons. First, when this occurs (around corners of the sector) the deviation of these flights is minimal, and thus the corresponding benefits are small as well. Secondly, given that the study aims to understand the impact of FUA and the benefits of its use, labeling more flights to have used the FUA than in reality only makes the findings more conservative.
- No wind.
  This enables ground speed to be set equal to airspeed. Ground speed can be calculated from the trajectory data using the coordinates and timestamps of each entry. By assuming ground speed to be equal to airspeed, this can be converted into the calibrated airspeed used by BlueSky. The effects of this assumption are a slightly inaccurate portrayal of the historical scenario in the simulated flights. Nonetheless, slight variations in wind are not to make a considerable difference in the results when accumulating all errors given the size of the sampled data.

- Each aircraft is assigned the BADA reference mass.
  Due to the sensitivity of this information, aircraft mass is unavailable from all data sources considered. Although BlueSky deducts the weight of fuel burnt at each timestep, each aircraft is initialised with the reference mass of its type from BADA by default. The error created by this approximation in the fuel flow calculation is assessed in the validation of Section X.
- International Standard Atmosphere (ISA) is assumed along with the ideal gas law.
  This assumes a linear relation of temperature with altitude for each of the layers in which this model divides the atmosphere, enabling to calculate density, temperature and pressure and with it the calibrated airspeed.

V. Experiment 1: FUA Availability

The first experiment is to answer the question *"How much fuel consumption is saved by making FUA completely available for civil use?"*. As shown in Figure 3, this experiment considers the flights which did not make use of the FUA sectors historically, yet they would have hypothetically benefited from transiting them. In other words, the comparison is made between historical trajectories deviated around the FUA and alternative ones transiting it. The latter need to be found, and for that two methods are proposed. The first (the GCR method) consists of creating direct routing alternatives, while the second (the Pairing method) searches for similar, historical flights that transited the FUA. Both methods and the assumptions of the experiment are discussed in the following.

A. GCR Method: Creating Direct Routes

The first method consists of substituting (part of) the historical trajectory with a Great Circle Route (GCR) segment making use of the FUA sector. To understand the effects of the distance from the FUA where the direct segment is enabled, three options are considered: in a square around EHAA (i.e. Amsterdam FIR, as 2 to 8 degrees longitude and 50.5 to 55 degrees latitude), in a larger square covering a region of Europe (-5 to 15 degrees longitude and 45 to 60 degrees latitude), and finally without any range limitation.

In this manner, the square selected covers a number of points of the trajectory. From the points within the square, the last one is taken as the merging point, and from the first one a GCR is created between this and the merging point. If the waypoints of the GCR created traverse the FUA sector, this is taken as the concept trajectory, as the first point found to enable a GCR yields the most optimal direct. Else, the next point is considered. Once the direct segment has been found, all points before the bifurcation and after the merging points are disregarded, as computing the metrics would yield the same for these segments. This logic is shown in Algorithm 1 and an example result is shown in Figure 5.

1) Original and Optimised speed settings: given that a deviation around a FUA and a shortcut are compared, the benefits may be examined considering two speed settings, hereby referred to as Original and Optimised. To better investigate the effects of route efficiency on the fuel metrics, airspeed is kept constant per concept in Experiment 1. For the historical trajectory, the speed chosen is the average of the ground speed of the historical entries, calculated from the timestamps and coordinates. Assuming no wind, this is taken as the airspeed. This same average airspeed is used for the Original speed setting. For the Optimised however, the airspeed is chosen to minimise the fuel consumption.

Algorithm 1 Experiment 1, GCR method

```
for each square:
  for each flight:
    Get flight points within the square above FL95.
    if the flight has points within the square:
      Merging point = last point within the square.
      for each point within the square, in historical order:
        Create GCR segment from this to merging point.
        if the GCR traverses a FUA sector:
          Route efficiency was lost due to the FUA.
        else:
          Continue to the next historical point.
    else:
      Continue to the next flight.
```

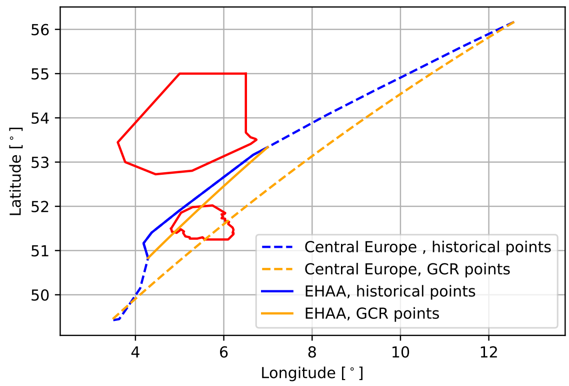

Fig. 5. Historical and GCR trajectory segments for a flight RKSI-LFPG (Incheon-Paris), limiting the GCR to EHAA and Central Europe

As taken from [19] and shown in the dimensional analysis of Equation 11, V_{TAS}/f can be interpreted as the specific range, i.e. distance that can be flown with 1 kg of fuel. Its inverse (Equation 12), would thus be the amount of fuel burnt per meter of distance, i.e. what must be minimised to optimise the fuel consumption over a constant distance.

$$\frac{V_{TAS}}{f} = \frac{[m/s]}{[kg/s]} = [\frac{m}{kg}] \tag{11}$$

$$\frac{f}{V_{TAS}} = \frac{[kg/s]}{[m/s]} = [\frac{kg}{m}] \tag{12}$$

With these, an f/V_{TAS} curve is created for each flight, using as inputs the altitude to calculate air density and thus C_L, and the aircraft type with its corresponding coefficients from BADA. The airspeed yielding the minimum of the curve is thus used for the Optimised speed setting. It was first hypothesised that this would be a smaller airspeed in the vast majority of cases, given the presence of V_{TAS}^2 in the Drag force formula and TSFC (Equation 5) also increasing with airspeed. However, a larger V_{TAS} decreases C_L and in consequence C_D and D. This usually results in a marginal difference between the fuel flows at each instant of the simulation, for which the total consumption greatly depends on the total time flown. For this reason, and intuitively shown with $\frac{f}{V_{TAS}}$ favouring a larger airspeed, this results in the optimal airspeed to be larger than the historical one, with a slightly increased consumption at each instant but compensating by flying for less time.

B. Pairing Method: Using Historical Data

The Pairing method yields more realistic routes transiting the FUA by using historical data. Each flight is here paired with a similar flight, defining similar flights as those sharing the same departure-destination or vice-versa. To have a larger pool of similar flights to select for this step, the flights traversing the Alpha and Delta sectors have been found not only for the sampled dates of March 2019, but also for the full month of June 2019. In this manner, the chances of not finding a similar flight when transit through the FUA sector occurs for this departure-destination pair are minimised. The original and similar trajectories are then trimmed to consider only the part of the trajectory deviated due to the FUA sector.

For this, the bifurcation and merging points between the similar flights around the FUA sector need to be found. It was first attempted to search for the closest coordinate by computing the distance of each point from a trajectory with every point of the other, yielding for each the distance to its closest points. Then, the points with the smallest distances in each side of the FUA would be the bifurcation and merging points. Nonetheless, this technique proved to be too computationally expensive for the number of flights considered, and a simpler approach has been used. First, the trajectory is cut in two parts before and after approximating the FUA. Then, each entry of each part is paired with the entry of the similar trajectory with the closest value in longitude. Although this is done only in one dimension, it offers a good candidate to the closest point of the similar trajectory for each entry, as most trajectories traverse the FUA in a horizontal rather than vertical direction. Next, the first points before and after the FUA with a distance to its closest point of the similar trajectory smaller than e.g. 10 km are chosen as the bifurcation and merging points, respectively. If none is found, this minimum distance is increased. Finally, it is checked for this similar trajectory to have a smaller range than the original one going through the FUA. An example is shown in Figure 6 for a VIDP-EGLL flight (Delhi-London), where the section of the trajectory considered is found between the bifurcation and merging points.

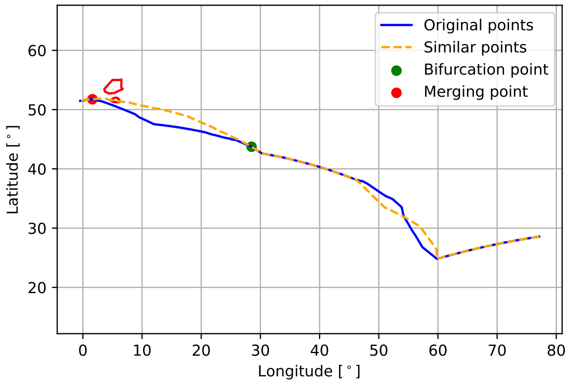

Fig. 6. Example of similar trajectories found by the Pairing method of Experiment 1 for a flight VIDP-EGLL (Delhi-London)

C. Method Comparison

Having described the two methods used to find the flights affected by FUA availability, the following discusses the main differences between these. The following is supported by the examples shown in Appendix F. The first and most important aspect to consider are the limitations of each method to capture flights. To respect climb and descent procedures, it is desired for the experiment to analyse only the trajectory segments above FL95 (the floor of the FUA sectors considered). To this end, the GCR method creates shortcuts in the points only above FL95. Nonetheless, such an approach would not work for the Pairing method, as the bifurcation and merging points often lie below FL95. In this manner, the latter finds the flights regardless of the phase, and then the scenario files are created only with the points above FL95. This creates an inherent advantage in capturing and thus analysing more flights than the GCR method: even if the trajectories simulated are in all cases entirely above FL95, the Pairing method considers more flights by enabling it to find them in all phases. Still, the GCR method has the advantage that the GCRs are considered for all flights (above FL95), thus finding shortcuts in flights where the Pairing method could not find a similar flight.

Moreover, the GCRs created completely disregard the flight procedures or any Special Use Airspace from other countries, for which the GCR method (and specifically the concept that does not limit the GCR to a square around the FUA) may give an unrealistic view of the effects of FUA availability by creating a direct route through regions of airspace where the FUA from Amsterdam FIR were not the cause of the route inefficiency. The Pairing method on the other hand provides a more realistic comparison by finding the actual bifurcation and merging points from other historical trajectories.

Lastly, for the concepts of the GCR method where the GCR is limited to a square, the GCR acts as an amendment of an inherently suboptimal trajectory, while the results of the Pairing method show that the bifurcation and merging may occur at larger distances away from the FUA, and they are seen to make a better use of it. This aspect has an even greater effect when considering that similar flights transiting the FUA are often found for flights significantly deviated away from the sector, for which the amendments created by the GCR method could not have traversed it.

D. Independent Variables

The independent variables mentioned are summarised below per method.

- **GCR method**
  - Square around the FUA sector enabling the GCR: in Amsterdam FIR (2 to 8 degrees longitude and 50.5 to 55 latitude), in a region of Europe (-5 to 15 degrees longitude and 45 to 60 latitude), and without limit.
  - Speed setting: Original or Optimised.
- **Pairing method**
  - No independent variables

E. Assumptions

Experiment 1 introduces the additional assumptions below, similar to the direct routing study by Pappie [20] which simplifies the trajectories to better investigate the effects of routing. These do not apply to Experiment 2, where all trajectory phases and changes in altitude and speed are considered.

- The trajectories are only compared above FL95.
  Both for methods, only the horizontal profile of the flight above FL95 is optimised. This is done to respect the current climb and descent procedures. The manner in which this is applied differs per method. For the GCR method, the points are only considered above FL95 directly at the start of the analysis. Doing the same for the Pairing method would make it difficult in many cases to find the bifurcation and merging points of similar flights. For this reason, the Pairing method uses only the points above FL95 when writing the BlueSky scenarios, making sure the comparison is suitable by having previously compared their distances considering these points only.
- Speed and altitude are constant for the entire trajectory.
  Given that it is desired to see the effects of routing only, other variables ought to be kept constant. In this manner, the cruise speed and altitude are averaged and applied to the entire trajectory considered.

VI. Experiment 2: FUA Plannability

The second experiment is to answer the question *"How much fuel consumption is saved by making FUA available for civil use with a higher plannability?"*. As shown in Figure 3, this experiment considers the flights transiting the FUA during the periods of time this is delegated, and penalises those which hypothetically loaded a surplus fuel due to late planning. The following discusses the baseline and concepts used to represent current and hypothetical plannability policies, the finding of flights carrying a surplus fuel and its calculation. Finally, the independent variables and assumptions are summarised.

A. Baseline

As explained in Section III, the current practice of FUA reservation consists of three stages: the Aeronautical Information Publication (AIP), the Airspace Use Plan (AUP) and the final reservations made during the day of operations (D-0). While the AIP and AUP reservations guarantee the transit outside of them, the D-0 reservations do not. This subsection discusses the translation of the first two reservations into a baseline, while the following subsection proposes a series of plannability policies or concepts substituting the current system to guarantee the transit in the delegated periods.

The baseline describes the current situation by implementing the two reservation systems which guarantee the transit in the FUA outside of the periods of time reserved: the AIP and the AUP. First, no records of the AIP are available for the sampled month, for which this is assumed to reserve every day from 07:00 to 23:00 hours, as this is the usual reservation interval seen in the AIP [8] throughout the development of the research project for the winter period (to which the month of March belongs). Secondly, the AUP is implemented by assuming a margin of an hour and a half before the start of the first D-0 reservation and after the end of the last one, and assuming an announcement time at 14:30 hours the day before operations (D-1). These assumptions are seen as representative when examining the available AUP records [21]. The baseline thus represents the effects of the current reservation practice the following concepts proposed should improve upon.

B. Concepts

Each of the following concepts is a proposed plannability policy containing specific independent variables driving its performance. Each of them offers an alternative to the current system independent of the AUP (except for the AUP Updating concept), yet contrary to the current operation they all eventually guarantee transit through the delegated periods of time.

1) Single Horizon Concept: guarantees transit for all delegated periods of the day at the same time, regardless of the number of D-0 reservations, and with some plannability relative to the start of the first delegated period (shown in Figure 7). This policy is advantageous for the civil user, as transit is guaranteed through the afternoon delegated periods with a significant buffer of time, even with a low plannability. As a result, military flexibility is limited, as all reservations of the day must be fixed in the early morning of the day of operations at the latest. The independent variable of the Single Horizon concept is therefore the plannability horizon.

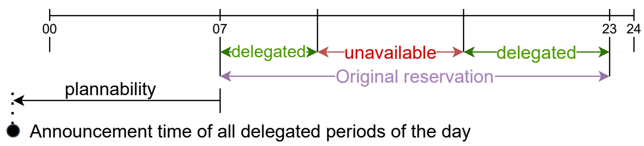

Fig. 7. Single Horizon concept policy

2) Multiple Horizons Concept: offers a better alternative to the Royal Netherlands Air Force (RNLAF) than the Single Horizon concept by fixing the D-0 reservations (unavailable periods) separately, thus allowing to compromise on the afternoon schedule later than on the morning one. As shown in Figure 8, each D-0 reservation is fixed at a different announcement time. However, given that D-0 reservations are allowed to be planned one after the other, each D-0 reservation made can only guarantee the transit through the delegated periods preceding it. In order to give an eventual guarantee of transit through the afternoon delegated periods, a cutoff time is implemented. Up until the cutoff time, D-0 reservations can be made. At the cutoff time, no more reservations are made and transit is guaranteed through all remaining periods. The independent variables of the Multiple Horizons concept are the plannability horizon (using the same value for all D-0 reservations) and the cutoff time, in absolute time during D-0.

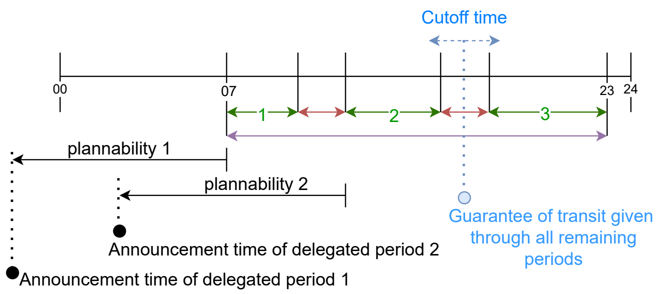

Fig. 8. Multiple Horizons concept policy

3) Reservation Shrinking Concept: proposes a strategy expanding the idea of the AUP. While the AUP shrinks the reservation interval once with some plannability, the Reservation Shrinking concept proposes a more gradual reservation in discrete steps which, as oppose to the current Updated Use Plans, guarantees the transit through each newly delegated period. The rationale behind the Reservation Shrinking concept is that the RNLAF becomes more confident about their desired usage of the FUA the smaller the plannability, reducing the length of the reservation as seen in Figure 9. The independent variables driving the performance of this policy are to capture the rate at which airspace is delegated and the absolute time at which the delegation process starts. For simplicity, the delegation rate is described as the amount of time given up with a constant update frequency, e.g. 30 or 60 minutes every hour. Lastly, the start of the delegation is described in hours relative to the start of the first delegated period.

4) AUP Updating Concept: after attaining preliminary results from the previous concepts, the most promising characteristics of each have been combined to create a fourth concept. It has been observed that the AUP provides significant benefits already, for which adopting this current practice into a new concept would not only ensure a good baseline for its driving parameters to improve upon, but also make this concept more implementable into the current reservation process. Further, it has been understood that in order for most Schiphol inbound

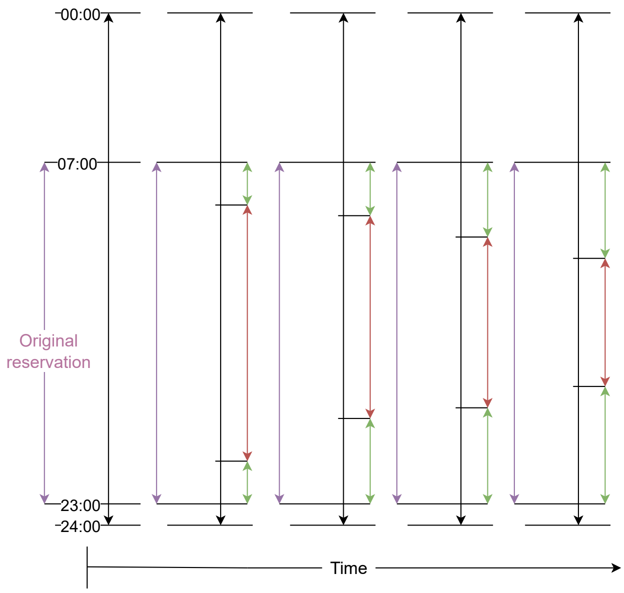

Fig. 9. Reservation Shrinking concept policy

flights to benefit from the morning delegated periods within the AUP, transit ought to be guaranteed from the evening of D-1. Guaranteeing transit at this point for the delegated periods in the afternoon is seen to be unnecessary, for which these, together with any in-between delegated periods, may be compromised on during the morning of D-0. This policy, shown in Figure 10, would provide comparable benefits in fuel consumption to the most promising concepts while ensuring a better flexibility for the military user. Moreover, this concept accounts for the human factor by not having any updates in the early morning when no reservations would be made. The independent variables of the AUP Updating concept are thus the absolute time for each of the two updates.

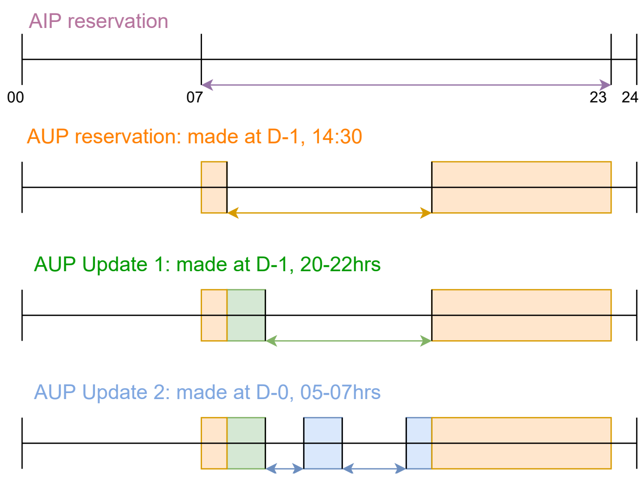

Fig. 10. AUP Updating concept policy

C. Identifying the flights carrying a surplus fuel

The delegated periods and, in consequence, the flights historically traversing the FUA within them, are the same regardless of the concept and depend only on the D-0 reservations (unavailable periods) of the given day. The concept does however determine whether each individual flight carries the surplus fuel or not. In essence, each concept dissects all delegated periods of the day and assigns an announcement time to each period.

For each flight within the given delegated period, it is checked whether the announcement time guaranteeing the transit occurs before or after the last flight plan is issued. From interviews with KLM representatives, this is established to occur at H-3, i.e. 3 hours before the time at the gate. For the analysis, the time at the gate is assumed to be 45 minutes (an approximation of the turnaround time) before the filed Off-Block Time, with the latter available in the Eurocontrol database. This logic is summarised in Algorithm 2.

Algorithm 2 Check if each flight carries a surplus fuel

for each delegated period:
  Based on the concept, get the announcement time (t_a).
  for each flight within the delegated period:
    Calculate the time the last flight plan is issued (t_{fp}).
    if $t_a < t_{fp}$:
      Flight does not load a surplus fuel.
    else:
      Flight loads a surplus fuel.

D. Determining the Deviated Range and Surplus Fuel

Having found the flights loading a surplus fuel, its weight must be calculated. This depends on the extra distance flown due to deviating around the FUA sector. Conveniently, this has already been determined by the Pairing method of Experiment 1. There, each flight not transiting the FUA was paired with one making use of it, and the hypothetical reduction in range was registered. This range is now used by the flights of Experiment 2 (which transited the FUA) as the hypothetical extra range a deviation around the sector would suppose.

In this manner, for each flight transiting a FUA during a delegated period, another flight having the same departure-destination airports or vice-versa was searched from those resulting from the Pairing method specifically for the same sector. This was successful in 96% and 97% of flights for the Alpha and Delta sectors, respectively. For each remaining flight, a deviated distance needs to be assumed. It was first hypothesised for the extra range to be proportional to the total distance flown, for which their relationship has been examined for all flights found by the Pairing method (11,372 and 22,898 for the Alpha and Delta sectors, respectively), as shown in Figure 11. Here it is seen that the deviated distance does not vary significantly with the distance flown, for which it is deemed acceptable to apply the average additional distance to all remaining flights for which a pair could not be found (which once again amounts to roughly 3.5% of flights). This average deviated distance is 100.65 and 74.15 km for the Alpha and Delta sectors, respectively. The distribution in deviated distances is shown in the box plot of Figure 12 for both sectors without outliers, with the median shown as the horizontal orange line and the mean as the green triangle.

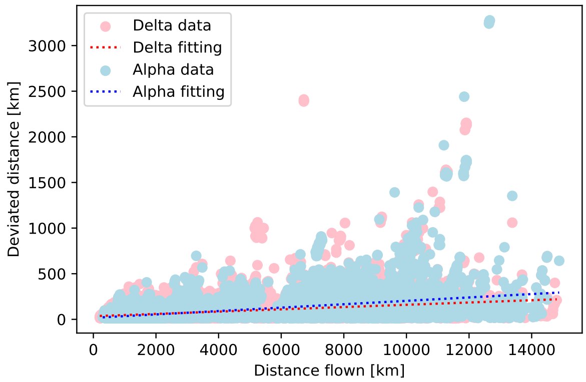

Fig. 11. Deviated distance from the FUA per total distance flown

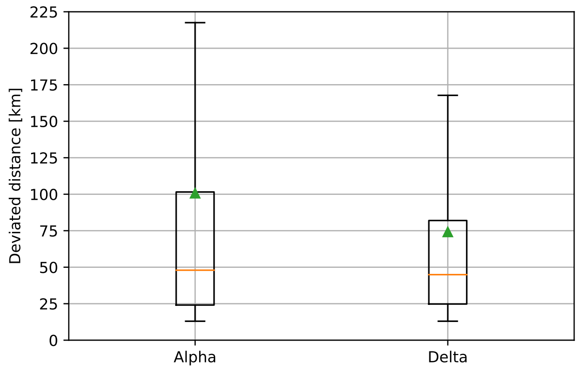

Fig. 12. Distribution of deviated distances

Once the deviated range has been determined, the corresponding surplus fuel can be calculated. For brevity, the full derivation is here omitted but can be found in Section 5.4.6 of the Preliminary Thesis Report. In summary, Breguet's equation (shown in Equation 13) is derived into Equation 14 to yield an extra fuel weight required based on an additional range, as proposed by Wink [22]. In Equation 13, V is the aircraft's speed, C_L, C_D and c_j the Lift, Drag coefficients and specific fuel consumption of the jet engine $[kg/Ns]$, and W_{Start} and W_{End} the weights of the aircraft at the start and end of the phase, respectively. In Equation 14, $W_{f_{after\ cruise}}$, W_o and W_{pl} are the fuel weight needed after cruise, Operative Empty Weight and payload weight; R_1 and R_2 are the ranges needed to transit the FUA and to deviate around it, and C is a parameter created to be independent from C_D and C_D, as these depend on the mass and thus fuel taken. By taking a standard case the weights of which are given by aircraft specifications (and defining TPR as the range at MTOW), the parameters needed can be taken as a constant C holding for any condition of the same aircraft type, as shown in Equation 15.

$$R = \frac{V}{g_0 c_j} \frac{C_L}{C_D} \ln\left(\frac{W_{Start}}{W_{End}}\right) \tag{13}$$

$$\Delta W_{f_{cr}} = \left(W_{f_{after\ cruise}} + W_o + W_{pl}\right)\left(e^{\frac{R_2}{C}} - e^{\frac{R_1}{C}}\right) \tag{14}$$

$$C = \frac{V}{g_0 c_j} \frac{C_L}{C_D} = \frac{R}{\ln\left(\frac{W_0 + W_p + W_{\text{fuel}}}{W_0 + W_p}\right)} = \frac{TPR}{\ln\left(\frac{W_{MTOW}}{W_0 + W_p}\right)} \tag{15}$$

E. Independent Variables

The independent variables mentioned above appear summarised in the following per concept, together with the values used to attain the results.

- **Concept 1: Single Horizon**
  - Plannability horizon: as 0, 2, 4, 6, 8, 10, 12, 14 or 16 hours before the start of the first delegated period.
- **Concept 2: Multiple Horizons**
  - Plannability horizon per D-0 reservation (unavailable period): as 0, 8 or 16 hours before each D-0 reservation.
  - Cutoff time: as 08:00, 10:00 or 12:00 hours at D-0.
- **Concept 3: Reservation Shrinking**
  - Start of the delegation process: as 8 or 16 hours before the start of the first delegated period.
  - Delegation rate: as 30 or 60 minutes of delegated time per update (fixing one update per hour).
- **Concept 4: AUP Updating**
  - AUP update 1: as 20, 21 or 22 hours at D-1 (the day before operations).
  - AUP update 2: as 05, 06 or 07 hours at D-0 (the day of operations).

F. Assumptions

Apart from the general assumptions mentioned in Section IV, Experiment 2 also relies on the assumptions implied during the selection of flights considered in Figure 3. Firstly, it is assumed for flights traversing the FUA during a D-0 reservation not to be penalised as this is considered equitable use of the FUA by the RNLAF. However, it can be argued that if civil traffic has made use of the FUA during that interval, it should have also been delegated and thus guaranteed with some plannability, leading to more benefits. Secondly, Experiment 2 considers the benefits of plannability concepts only penalising surplus fuel, with Experiment 3 considering the route efficiency penalisation.

VII. Experiment 3: Bridging the Gap

Upon starting the research project, it was hypothesised that FUA plannability has no effect on whether a flight enters a FUA sector or not. This was argued based on conversations with Air Traffic Control Operators, who would explain that once a FUA becomes available, all flights deviated in the vicinity are given a direct through the sector. This statement is indeed true, and it can be observed from historical traffic and reservation data using BlueSky. Nonetheless, when examining the resulting trajectories from the Pairing method of Experiment 1, one can see that the bifurcation between two similar flights (one transiting the FUA and another not) often occurs much before Amsterdam FIR is reached. This means that the decision time at which a flight decides to deviate around a FUA takes place much before it reaches its vicinity. Hence, the possibility of having the tactical route benefit is lost much before reaching the FUA, which means that plannability also affects route efficiency, putting a greater emphasis in the need for a better policy of airspace reservation.

This notion is further supported by the fact that, as it will be seen in Section VIII, a significant percentage of flights found to lose route efficiency would have traversed the FUA during a delegated period, i.e. had they traversed the FUA, it would have been during a period when it was actually possible to do so. This percentage is much higher than those losing route efficiency during the periods of time which had always been available, suggesting that the effect of plannability on the trajectory is indeed not negligible, and a significant part of the effects of FUA availability on route efficiency are in fact due to FUA plannability. This creates the gap for an additional experiment linking the two previous ones to investigate the benefit that a new plannability concept would bring by enabling a tactical direct through the FUA sectors. Therefore, the following explains the methodology and assumptions of Experiment 3.

A. Methodology

This newly found gap between Experiments 1 and 2 is investigated by combining the tools developed in both experiments. First, the subset of flights considered is that found by the Pairing method of Experiment 1. These are the flights which historically lost route efficiency and a historical, similar flight is found to make use of the FUA. From these, only those found to hypothetically traverse the FUA during a delegated period are used in the following, i.e. when the airspace was preliminary reserved but eventually delegated. To approximate the hypothetical time of transit of a flight in an airspace where it never transited, the time of the point with the coordinates closest to the FUA is taken.

For every flight of this subset, it is desired to know whether a plannability concept from those proposed in Experiment 2 would allow the flight to have a tactical route benefit. For this, a similar methodology is used as to that determining whether a flight carried a surplus fuel, defining here the decision time as the time when the trajectory would have bifurcated, based on the similar trajectory found. This is better understood by examining Figure 6. The Pairing method of Experiment 1 found the bifurcation and merging points between these two similar trajectories, and analysed the segments between them to yield the benefits of the shortcut. What Experiment 3 does is to take the time when the original flight flew over the bifurcation point and, if this time is later than the hypothetical announcement time of the delegated period, the benefits of the alternative trajectory are assumed to be attained. This logic is summarised in Algorithm 3.

Algorithm 3 Check if each flight attains a tactical route benefit

```
for each delegated period within the assumed AUP:
    Based on the concept, get the announcement time (t_a).
    for each flight losing route efficiency during the
    delegated period:
        Get the time of bifurcation (t_bif).
        if t_a < t_bif :
            Similar (shortcut) route is assumed (route benefit).
        else:
            Original (deviated) route is kept (no route benefit).
```

Nonetheless, an important caveat needs to be discussed. The so-called delegated periods contain not only periods delegated during D-0 but also those delegated by the Airspace Use Plan (AUP). As aforementioned, the AUP records are not available for the sampled time, for which an AUP margin has been assumed in Experiment 2. Despite being a good approximation considering the available AUP records, it needs to be considered that, as oppose to the AIP schedules, the AUP ones vary considerably, for which the assumptions on the AUP schedule are not robust. In Experiment 3, the plannability enables flights to take a tactical route benefit. It is observed that many of the flights losing route efficiency in a time outside of the assumed AUP would have had a sufficient guarantee of transit (because of the assumed AUP) to take the tactical route benefit, yet they still historically deviated around the FUA. This clearly conflicts with the assumption that, if the period's announcement time occurs before the bifurcation time, the flight always benefits from the direct. Nonetheless, the lack of robustness of the AUP reservations assumed make this altogether inconclusive. For this reason, it is decided to disregard the subset of flights losing route efficiency during the delegated periods and outside of the AUP reservation, and consider only those in delegated periods within the AUP reservation. Despite still relying on the assumptions of the AUP reservation, these flights are closer to the unavailable periods, for which their transit on the FUA sector is more likely to depend on the sector's plannability. This, together with the fact that this is a smaller subset of flights, allows to more confidently speculate that most of the flights further considered would change their trajectory with a better plannability concept. This coarseness of the assumptions on the AUP reservation is still prevalent in the baseline created in Experiment 2, yet there all plannability concepts are hypothetical and result in the possible addition of a surplus fuel relative to an already arbitrary aircraft mass (BADA's reference mass), making the conclusions less sensitive to this assumption.

For all flights that the plannability concept enabled for the similar, shorter route to be assumed, the benefits in fuel efficiency metrics are directly taken from those found in Experiment 1, thus avoiding the need to do any new simulations.

B. Assumptions

This experiment uses the assumptions of Experiment 1 and introduces the following two:

- If the bifurcation time of a flight occurs after the announcement time of the delegated period during which it historically lost route efficiency, the flight is always assumed to have the tactical route benefit.
  This assumption is not robust, as other aspects may influence the FUA transit such as sector capacity, flow management, etc. Not only that, but the fact that (a minority) of flights lose route efficiency during periods of time the FUA had always been available means that availability is not the only aspect FUA transit depends on, for which the results of Experiment 3 ought to be taken cautiously.
  The most notable conflict of this assumption is the fact that the flights losing route efficiency outside of the assumed AUP reservation still avoided the FUA historically, which should not make sense given that the AUP was in reality implemented. Nonetheless, the coarseness of the AUP assumption makes this inconclusive. Given this frail assumption, it is decided to consider only the flights making use of the FUA within the assumed AUP, which is a much smaller subset than those outside of it. The flights further considered thus lost route efficiency in the delegated periods closer to the D-0 reservations, in which plannability has more of an effect, making the results of the experiment a more conservative approximation of the effects of plannability on route efficiency.
- The bifurcation time is approximated based on only another similar trajectory.
  For simplicity, brevity and a lack of multiple alternative trajectories deemed suitable for many flights, the bifurcation point of each original trajectory is attained based on only one similar trajectory. This yields a bifurcation point which may vary when comparing other similar trajectories. This is deemed acceptable due to the fact that the difference between bifurcation points would be in the order of minutes, while the proposed plannability concepts and therefore announcement times are chosen in a resolution of hours.

VIII. Results

The following presents the fuel consumption results of all three experiments in sections VIII-A to VIII-C, with the work results being given in Appendix A.

A. Experiment 1 Results

The results of Experiment 1 are shown in Figures 13 and 14 for the GCR and Pairing methods, per FUA. While Figure 13 presents the average fuel consumption reduction per flight along with the number of flights considered n, Figure 14 shows the total fuel consumption reduction. The results of each specific method are discussed in the following.

1) GCR Method: on the one hand, the GCR method takes historical trajectories not going through the FUA sector and substitutes (part of) the trajectory with a GCR segment, as explained in Section V-A. While this allows to consider the points above FL95 of every single flight to see whether it would benefit from a direct route through the FUA, this concept disregards flight procedures and routes, which may result in unrealistic benefits. The results of the GCR method are shown as the vertical bars in Figures 13 and 14, per FUA and speed setting. As expected, these show how a larger square in which the GCR segments are enabled yields greater benefits. The third option (without a limiting square) thus shows a significant jump in the fuel consumption reduction as this consists of the benefits of enabling a fully direct routing alternative above FL95 to all flights once their GCR traverses a FUA sector. Furthermore, it is seen that the Optimised speed setting further enables an average reduction from 30 to 100 kg per flight, totalling a maximum of 890 tonnes of benefit in the concept without a limiting square for the Delta sector. Furthermore, the larger deviation around Alpha leads to greater benefits per flight in this sector, yet the higher number of flights found for Delta eventually results in the total fuel reduction being similar between sectors.

2) Pairing Method: on the other hand, the Pairing method finds similar trajectories to compare the effects of FUA availability in a more realistic manner, as described in Section V-B. Further, each pair of similar trajectories is simulated at the average airspeed of the original (i.e. only the Original speed setting is considered). These aim to provide the most realistic results of FUA availability, accounting for the current procedures and route system. For this reason, the results of the Pairing method are those considered in the breakdown of Section VIII-A4, as well as in Experiment 3 and the extrapolation of Section IX. The results of the Pairing method are shown as the horizontal lines in Figures 13 and 14, per FUA. As for the GCR method, the Alpha sector brings greater benefits per flight yet the Delta sector yields a higher total fuel reduction due to the greater number of flights found. Upon examining the average benefits per flight, it is seen that the results of the Pairing method are below those of the GCR method without a range limitation, suggesting that the Pairing method bifurcates the flights in a considerable range outside of Amsterdam FIR. It must be noted that, as explained in Section V-C, the GCR segments created are often an amendment to a suboptimal trajectory, while finding a historical trajectory making use of the FUA may actually bring greater benefits. Furthermore, the concept of the GCR method without a limiting square does not mean that all flights captured there have a GCR for the entire trajectory, but only once a GCR segment created is found in the FUA. Still, the outcome of the Pairing method thus suggests that the bifurcation and merging points between historical flights making and not making use of the FUA are found at a large range away from the sectors. This in turn implies that the decision time when a flight must decide whether to transit a FUA or not often occurs before reaching Amsterdam FIR, and therefore FUA plannability has an effect on route efficiency. Finally, Figure 14 establishes that the total fuel consumption reduction is approximately 5,086 and 7,206 tonnes for the Alpha and Delta sectors for the sampled month.

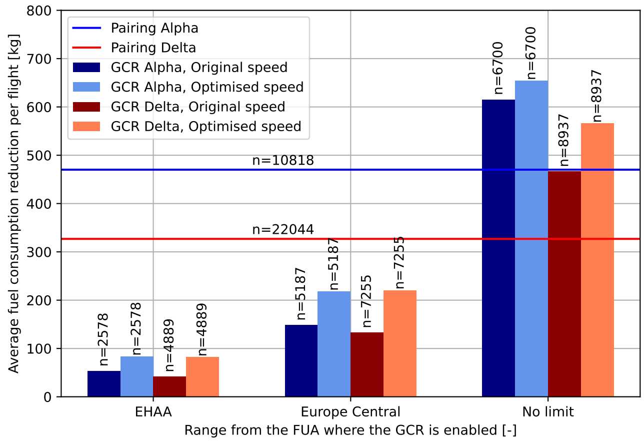

Fig. 13. Experiment 1 results: average fuel consumption reduction per fight

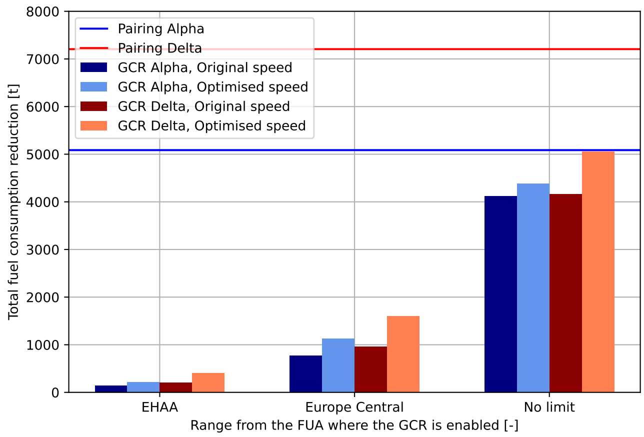

Fig. 14. Experiment 1 results: total fuel consumption reduction

3) Comparison: having described the results of each method used in Experiment 1, these can now be compared. The first point to discuss is the total fuel consumption reduction of Figure 14. First, for both FUA sectors the total benefits are greater in the Pairing method as this considers more flights (see Figure 13). This may not be intuitive, as creating GCR segments should consider more flights and thus bring more benefits than searching for other historical trajectories.

However, there are several reasons for this. First, only points above FL95 are considered to create GCR segments, whilst the similar flights were found considering all flight phases. Secondly, the GCR segments created are often amendments to an inherently suboptimal trajectory, while flights historically making use of the FUA may have a very different trajectory and thus take a greater advantage of the sector, further increasing the total benefits.

Lastly, the Pairing method finds considerably more flights benefiting from the Delta sector than from Alpha, while the GCR method does not. This suggests that the GCR method fails to find flights for Delta. In other words, the much higher traffic density around the Delta sector is visible in the results of the Pairing method but not in those of the GCR method. Upon examining the flights found to lose route efficiency due to the Delta sector by the Pairing method but not by the GCR one, two main issues are identified. First, the GCR method relies on connecting historical points and selects a flight only if the GCR crosses the FUA. Given the reduced number of points of the database and the fact that the Delta sector is an inherently small airspace, the GCR segments created do not traverse the FUA in many cases. In other words, a smaller airspace makes it harder to find more optimal trajectories through it from a given set of points. Secondly, for EHAM flights and in particular for inbounds, altitudes below FL95 are reached while still deviating around the FUA, meaning that the merging point does not lie ahead of the FUA sector and thus the GCR segment does not cross it. This is better illustrated in Figure 15, where it is shown how considering only the horizontal profile of a trajectory to create a GCR segment does not fully encircle the Delta sector in some cases, for which a GCR cannot be found, while a similar flight did traverse the FUA and is thus considered in the Pairing method.

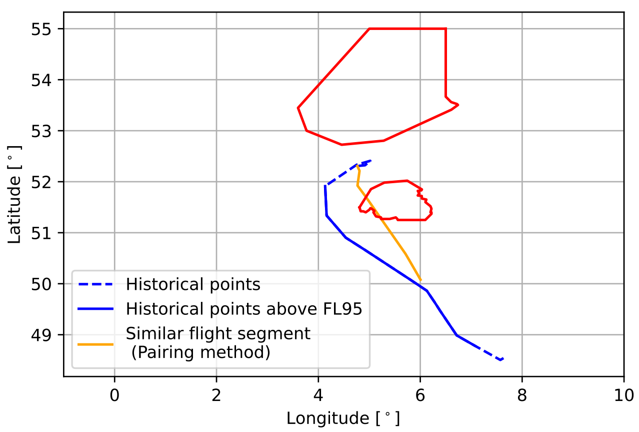

Fig. 15. Historical points and the segment of the resulting similar flight found by the Pairing method, for a flight LFST-EHAM (Strasbourg-Amsterdam)

4) Breakdown of flights: the flights considered by the Pairing method vary in their relation to Schiphol (inbounds, outbounds or none) and the period of time they would have hypothetically benefited from the FUA. These are during an available period (never reserved), delegated period (preemptively reserved, but eventually delegated for civil use) or unavailable period (preemptively reserved and kept as a reservation made during the day of operations); see Figure 2. The number of flights, fuel and work reductions, are classified in Tables II to VI, for the sampled month of March 2019.

TABLE II
TOTAL FLIGHTS, FUEL AND WORK REDUCTION PER FUA

	Flights [-]	Fuel reduction [t]	Work red. [TJ]
Alpha	10 818	5085.813	91.423
Delta	22 044	7205.687	122.725

TABLE III
BREAKDOWN OF FLIGHTS WITH RESPECT TO SCHIPHOL - ALPHA SECTOR

	Flights [-]	Fuel reduction [t]	Work red. [TJ]
Inbounds	1324	724.891	12.490
Outbounds	858	171.839	2.775
None	8636	4189.084	76.158

TABLE IV
BREAKDOWN OF FLIGHTS WITH RESPECT TO SCHIPHOL - DELTA SECTOR

	Flights [-]	Fuel reduction [t]	Work red. [TJ]
Inbounds	2831	696.724	9.803
Outbounds	1879	450.713	7.141
None	17 334	6058.250	105.780

TABLE V
BREAKDOWN OF FLIGHTS BASED ON PERIOD OF HYPOTHETICAL TRANSIT - ALPHA SECTOR

	Flights [-]	Fuel reduction [t]	Work red. [TJ]
Unavailable	4642	2403.038	43.211
Delegated	4902	1736.341	30.383
Available	1274	946.434	17.829

TABLE VI
BREAKDOWN OF FLIGHTS BASED ON PERIOD OF HYPOTHETICAL TRANSIT - DELTA SECTOR

	Flights [-]	Fuel reduction [t]	Work red. [TJ]
Unavailable	9730	3551.716	61.154
Delegated	9944	2545.717	41.593
Available	2370	1108.254	19.977

B. Experiment 2 Results

The following presents the results for the concepts proposed in Section VI-B, using the baseline for the Alpha and Delta sectors as the datum of all relative benefits of each corresponding airspace. This baseline describes current operations by implementing both the Aeronautical Information Publication (AIP) and the Airspace Use Plan (AUP) reservations, as explained in Section VI-A. These results assume for the AIP reservation to span every day from 07:00 to 23:00 hours, for the AUP reservation to start and end with 1.5 hours of margin before the start of the first D-0 reservation and the end of the last one, and for it to be announced at 14:30 hours during the day before operations (D-1). A concept proposed is better than the current operation only if its fuel consumption reduction is positive. Further, the sampled time used for all these results is the month of March 2019; which contains a representative scheduling of D-0 reservations over 18 days of the month, as shown in Table I.

1) Single Horizon Concept: the result of the Single Horizon concept, with policy shown in Figure 7, appears in Figure 16 for both FUA sectors during the month of March 2019. This plannability strategy consists of delegating all periods of time the FUA is to be given up at the same time, with a plannability relative to the start of the first delegated period. This creates a significant buffer of time between the announcement of the delegation and the delegated periods of the afternoon, even at low plannability horizons. This makes this first concept to be considerably advantageous to the civil users.

The results of the Single Horizon concept yield better results than the baseline with a plannability as low as 0 and 2 hours relative to the start of the first delegated period (i.e. guaranteeing the transit at 07:00 and 05:00 hours, D-0) for the Delta and Alpha sectors, respectively. As expected, the larger the plannability horizon the greater the fuel consumption reduction, reaching up to 37 and 45 tonnes for the Alpha and Delta sectors for the sampled month, using a plannability of 16 hours (i.e. an announcement time of 15:00 hours, D-1).

As predicted, this is the most beneficial concept for the civil user, as all D-0 reservations are compromised at the same time in the morning of D-0 at the latest. This creates a great buffer between the announcement time and the delegated periods of the afternoon, at the expense of limiting military flexibility. Furthermore, note how the Delta sector performs worse than the Alpha sector at low plannability horizons but not at higher ones. The reason for this is found in Table I: while the Alpha sector has multiple days in March with two D-0 reservations, the Delta one has none. Multiple D-0 reservations in one day create in-between delegated periods, which are not guaranteed in the current AUP system while the concepts proposed take advantage of them. In this manner, while a plannability of 0 hours (i.e. guarantee given at 07:00, D-0) is of no use for the first delegated period (approximately 07:00-08:00), it may however help in guaranteeing transit through any in-between delegations, for which poor planning horizons benefit the Alpha sector more than the Delta one.

2) Multiple Horizons Concept: the result of the Multiple Horizons concept, with policy shown in Figure 8, is given in Figure 17 for the Alpha and Delta sectors for the sampled month. This strategy is a more flexible version of the previous concept, where now every delegated period may be announced (i.e. transit through it may be guaranteed) independently from one another. When allowing for this flexibility, a problem arises: if different D-0 reservations are made at different

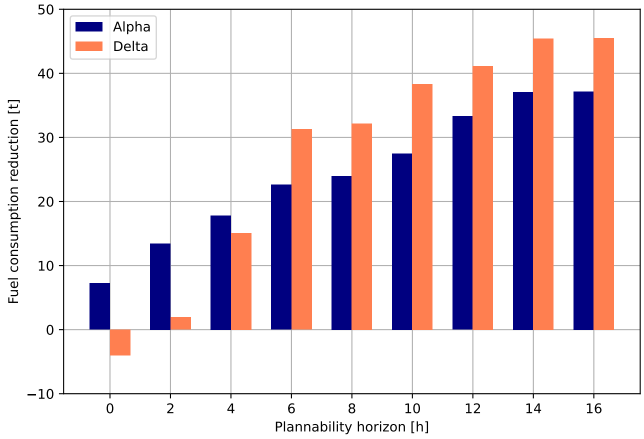

Fig. 16. Fuel consumption reduction of the Single Horizon concept per planning horizon

times, each reservation cannot guarantee the transit after it, but only before. In order to give an eventual guarantee of transit, a cutoff time is introduced. Before the cutoff time, new D-0 reservations may be made. At the cutoff time, all periods not reserved are delegated. This would enable the RNLAF to make D-0 reservations flexibly with each one made guaranteeing the transit before it, until the cutoff time. The two independent variables are thus the plannability horizon (used as in the previous concept, but here applied separately to each delegation) and the cutoff time, in absolute time during the day of operations. In summary, the later the cutoff time, the later a guarantee of transit is given through the delegated periods of the afternoon, resulting in less benefits. Similarly, the greater the plannability horizon for each D-0 reservation, the more flights have the guarantee of transit through the preceding delegated period, resulting in more benefits.

In this manner, the x-axis of Figure 17 describes the cutoff time in the three discrete values chosen (08:00, 10:00 and 12:00 hours at D-0). For each value of the cutoff time, three different values are shown per FUA, corresponding to the three plannability horizons (0, 8 and 16 hours relative to the start of the delegated period preceding the corresponding D-0 reservation). The results show that the Multiple Horizons concept yields a poorer performance than the rest of the concepts, and better than the current operation in only a handful of variable combinations. It is only at a cutoff time of 10:00 hours or earlier and a high plannability horizon that the Multiple Horizons concept proves a better alternative than the current system, yet such an early cutoff time defeats the purpose of the concept, which is to give the delegated periods one by one throughout the day. The results therefore span from a fuel reduction of 24 tonnes to an increase of 31 per FUA and month.

The Multiple Horizons concept thus fails to provide a better alternative than the current system in favour of maintaining the flexibility of the RNLAF. The reason behind the poor performance of the concept is that even if the delegated periods preceding each D-0 reservation are guaranteed with a large horizon (e.g. 16 hours in advance), this accounts for the first or in-between delegated periods of the day. As seen in Table I, these are one to three hours of FUA usage, while the afternoon interval amounts to around eight hours of usage which are left to be guaranteed by the cutoff time. The earliest value of this is 08:00, which becomes useful for any flight taking off only after 11:45 with the parameters explained in Section VI-C. While this proves to generally improve the results of the baseline, the following cutoff times considerably decrease the performance; guaranteeing transit through the afternoon delegated periods to flights taking off only after 13:45 and 15:45. All in all, the results of the Multiple Horizons concept show that delegating the periods one by one throughout the date requires of early cutoff times which defeat the purpose of the concept. This suggests that if a good level of military flexibility is to be maintained, it becomes more beneficial for the civil user to delegate the unused reservations in a conservative manner yet with high plannability (i.e. with a rough estimate such as the AUP) than rendering the exact periods on a one-by-one basis throughout D-0. As a final note, it is seen here as well how the Alpha sector shows greater benefits than the Delta one, as at overall low plannabilities the former can still take advantage of its in-between delegated periods.

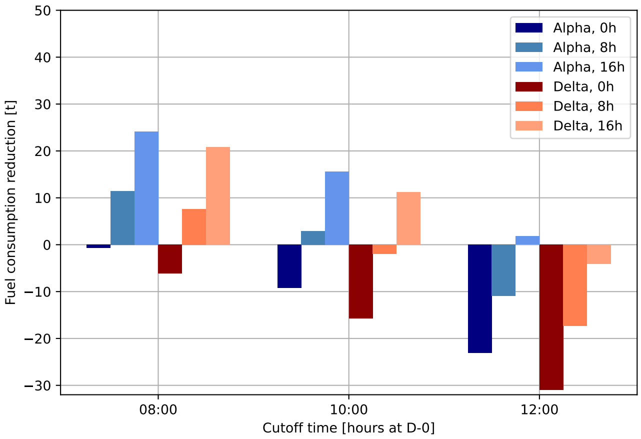

Fig. 17. Fuel consumption reduction of the Multiple Horizons concept per cutoff time and planning horizon

3) Reservation Shrinking Concept: the results of the Reservation Shrinking concept, with policy shown in Figure 9, appear in Figure 18 for both FUA sectors. This concept is based on the idea that the RNLAF becomes more confident about their desired usage of the FUA the smaller the plannability, for which the reservation may be reduced in a gradual approach with time, as a sort of binding and more continuous Updated Use Plan. The performance of this concept is driven by the rate of the delegation (i.e. the amount of time the FUA is delegated per update) and the time when the delegation process starts. The former is implemented at a fixed update, e.g. delegating 30 or 60 minutes of FUA usage at each hour. The latter is described in hours relative to the start of the first delegated period. The earlier the delegation process starts and the greater the period of time delegated per hour, the greater the benefits.

Thus, the x-axis of Figure 18 describes the start of the delegation process i.e. when the airspace starts to be delegated for civil use, taking two discrete values as 8 and 16 hours relative to the start of the first delegated period. For each of these, two results are given per FUA. These represent the two rates of delegation considered: 30 and 60 minutes per hour. The best combination of the variables considered reaches 30 and 45 tonnes of fuel consumption reduction for the Alpha and Delta sectors. The result of the Delta sector matches that of the Single Horizon concept, while the result of the Alpha sector does not reach the 37 tonnes in fuel reduction formerly attained. This is because, in the Reservation Shrinking concept, the in-between delegated periods are only delegated at a plannability of zero, for which the concept at hand does not successfully take advantage of them. Furthermore, it can also be seen that for this concept, and for any other where the proposed plannability is considerably better than the current operation, the Delta sector yields greater benefits than Alpha, as hypothesised due to the higher traffic density in the South. It is only at low plannabilities that the in-between delegated periods of the Alpha sector make the difference, yielding for this greater benefits.

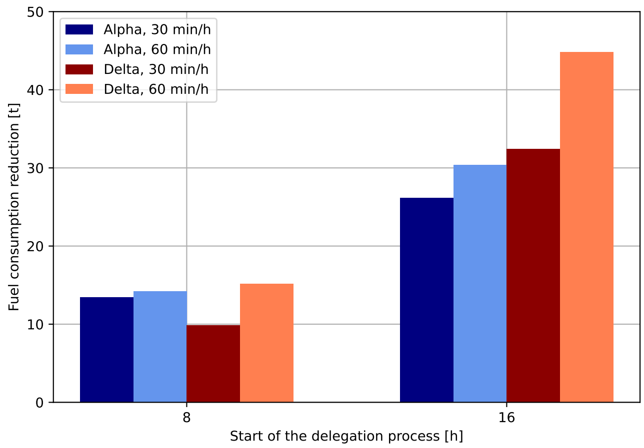

Fig. 18. Fuel consumption reduction of the Reservation Shrinking concept per relative start of the delegation and minutes delegated per hour

All in all, it is seen that this concept provides a comparable alternative to the Single Horizon concept if the delegation start and rate result in a high enough plannability overall, with the former being the driving parameter. Nonetheless, this concept gives up the morning and afternoon concepts at the same time, which once again implies a limitation in military flexibility. Upon analysing the results, delegating both morning and afternoon at the same time is seen not to be necessary, as an unnecessarily large buffer of time between the announcement time and the afternoon delegations is created. This notion has developed into the AUP Updating concept, a simplified and more pragmatic version of the Reservation Shrinking concept.

4) AUP Updating Concept: from the concepts above, the following conclusions have been gathered. First, having an early guarantee of transit through the delegated period of the afternoon is critical for the performance of the results. It is however not necessary for these to be compromised as early as D-1, but instead they could be given at D-0 to maintain military flexibility. Further, enabling a guarantee of transit through any in-between delegated periods is seen to improve the performance, albeit only for the Alpha sector which contains these in the sampled month. Lastly, the AUP is seen to be a very effective planning strategy with the parameters assumed for this analysis. These considerations, made here on the basis of the fuel consumption results but anticipated in Section VI-B, are implemented in the fourth concept: AUP Updating. This is a simplified and more pragmatic approach of the idea behind the Reservation Shrinking concept, as it is attempted for this to be as adaptable as possible to current procedures and human factors by building upon the AUP and by not having updates in the early morning, respectively. This concept consists of three steps. First, the AUP is implemented with the same parameters as for the baseline: announced at 14:30, D-1 and having a margin of 1.5 hours before the first and after the last D-0 reservations. Then, two updates are made. First, Update 1 compromises on the morning delegation, and is announced in the evening of D-1. Next, Update 2 details the afternoon and any in-between delegated periods and is made in the morning of D-0.

In this manner, the results of the AUP Updating concept, with policy shown in Figure 10, are shown in Figure 19. Here, the x-axis represents the time of the AUP Update 1, with discrete values of 20:00, 21:00 and 22:00 hours at D-1. For each of these there are three values per FUA, each corresponding to a value of the AUP Update 2 time: 05:00, 06:00 and 07:00 hours at D-0. The earlier each of these updates, the greater the benefits. The most advantageous combination thus reaches a total of 28 and 35 tonnes in fuel consumption reduction, i.e. approximately 10 tonnes less than the Single Horizon concept with a plannability of 16 hours. This loss in reduction is considered acceptable considering the arguably better flexibility given to the RNLAF by allowing to compromise on the in-between and afternoon delegated periods in the morning of D-0, as well as providing a more acceptable and implementable concept on the operations and human aspects.

C. Experiment 3 Results

Finally, Experiment 3 considers the flights found by the Pairing method of Experiment 1 to lose route efficiency during a delegated period within the assumed AUP reservation and, using the policy of the AUP Updating concept, all flights flying over the bifurcation point at a time later than the hypothetical announcement of the FUA are assumed to have taken the direct trajectory and the corresponding benefits are attained.

The results of Experiment 3 are shown in Figure 20, showing the same behaviour as the penalisation of surplus fuel in Figure 19 yet with significantly greater benefits in fuel

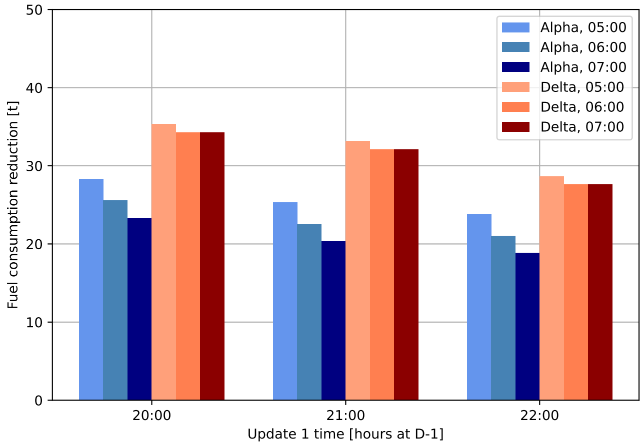

Fig. 19. Fuel consumption reduction of the AUP Updating concept per combination of AUP update times

reduction. It is observed that the benefits are approximately 650 and 930 tonnes for the Alpha and Delta sectors, i.e. about 13% of the total effects quantified by the Pairing method of Experiment 1 (shown in Table II). This is because, as it can be seen in Tables V and VI, the number of flights losing efficiency during a delegated period is almost half of the total, and once again given the frail assumptions of Experiment 3, to make the results more conservative only the flights losing route efficiency within the AUP are considered, which amount to around a third of that half. This suggests that for the month of March 2019, at least a 13% of flights could have recovered the route efficiency loss resulting from the FUA reservation simply by adopting a new plannability policy.

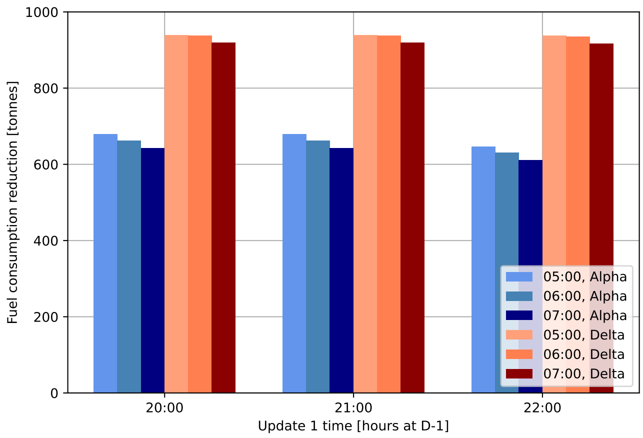

Fig. 20. Fuel consumption reduction due to tactical route efficiency benefits enabled by the AUP Updating concept

IX. Extrapolation of the Results

As explained in Section IV-D, only the month of March 2019 has been sampled for the analysis to limit process times. In order to attain yearly estimations of the benefits proposed, the results obtained are to be extrapolated.

In order to make the method more informed, the extrapolation is done on the basis of the flights considered rather than the benefits themselves. This number of flights is extrapolated to the rest of 2019 by means of the historical D-0 reservations of the entire year. Despite the method is largely the same across the three experiments, the different subsets of flights used lead to the following subsections.

A. *Extrapolating the Results of Experiment 1*

For Experiment 1, the results considered are those of the Pairing method, arguably the better approximation of the effects of FUA when penalising route efficiency. These are the flights which lost route efficiency, i.e. those historically not transiting the FUA, yet hypothetically benefiting from it when compared with other similar, historical flights.

Since it is the number of flights what is being extrapolated, the sensitivity of the amount of time reserved per day on the flights affected must be investigated. This is shown in Figure 21, where the x-axis shows all sampled days, the left y-axis the number of flights affected (bar plot), and the right y-axis the time of the D-0 reservation in minutes (dashed line plot).

Several conclusions can be taken from this plot. First, the Delta sector is generally reserved for longer periods of time than Alpha. As seen in Table I, this is partly due to the fact that in-between delegated periods are created for Alpha and not Delta. When examining the end times of the schedule, it is also seen that the training exercises usually end 15 to 40 minutes later in Delta than in Alpha. This is because the military aircraft depart from the southern base (Volkel) and exercise in the northern sector (Alpha), for which that time is used for the longer return to the base and any final exercises there. The second and most valuable conclusion is that, despite the oscillations in the amount of time reserved per day (varying in a range of 200 minutes), the number of flights affected remains somewhat constant for each FUA, resulting in a reasonably robust base to extrapolate the results from.

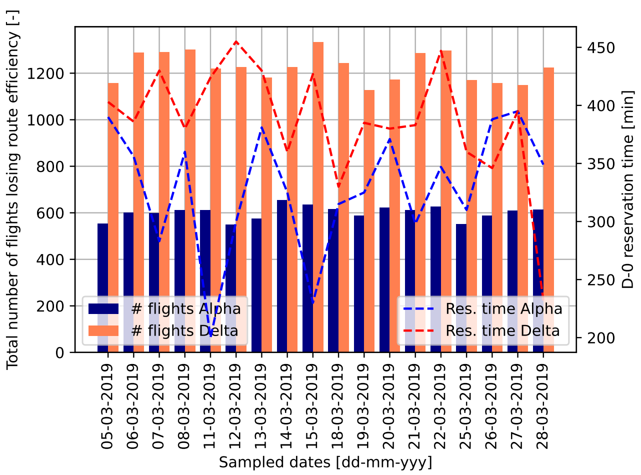

Fig. 21. Total number of flights found by the Pairing method of Experiment 1 (left y-axis) and time reserved (right y-axis) per day of the sampled month

With Figure 21 showing how the total number of flights losing route efficiency remains reasonably constant despite variations in the reservation time, one may argue where the effect of the amount of time reserved permeates. This is shown in Figure 22, where the total number of flights is dissected by the period they would have hypothetically made use of the FUA. The periods are either unavailable (i.e. D-0 reservations; preemptive reservations kept during the day of operations), available (i.e. outside of the AIP reservation; periods which had never been reserved) and delegated (i.e. ATS delegations; periods preemptively reserved yet eventually made available to civil use). This figure is better understood together with Tables V and VI. On the one hand, the number of flights found in an available period is lower and independent of the D-0 reservation time. On the other hand, the flights losing route efficiency in a delegated or unavailable period balance themselves: the longer the D-0 reservation, the more flights lose route efficiency in them and not in a delegated period. As previously mentioned, flights losing efficiency during a delegated period are deemed to be because of FUA plannability.

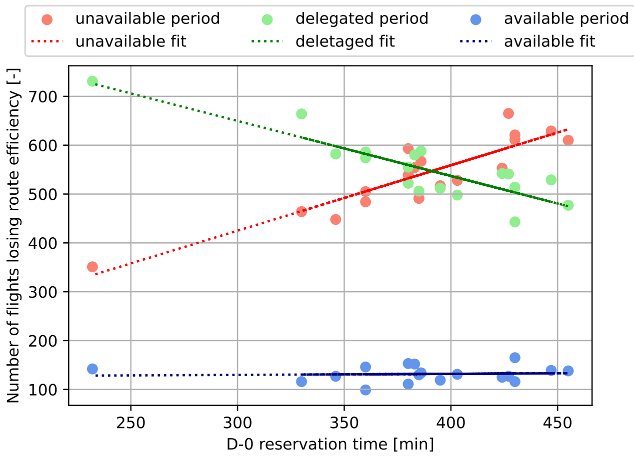

Fig. 22. Number of flights losing route efficiency in the Delta sector from the Pairing method of Experiment 1, per time reserved and period of hypothetical FUA transit

The number of flights for every day of 2019 with D-0 reservations is thus extrapolated using the trends of Figure 22 corresponding to each period and FUA, on the basis of the amount of time historically reserved per day. Furthermore, in order to account for the monthly variations in traffic density throughout the year, the extrapolated number of flights per FUA and period are adjusted using the Aviation Intelligence analytics of Eurocontrol for 2019 [14]. With this, an average number of flights per month transiting the Netherlands is found, enabling to see the fluctuation of traffic relative to March. This results in multiplying the number of flights extrapolated with a factor capturing the traffic density variation with respect to the sampled month.

Finally, the number of flights found are multiplied with the average fuel reduction benefits per flight. The latter is obtained by normalising the total fuel reduction on the basis of the number of flights found, thus yielding an approximation of the fuel reduction that the Pairing method of Experiment 1 creates per flight considered and airspace. This results in a total fuel reduction of 70,198 and 100,022 tonnes for the Alpha and Delta sectors for the year 2019, had each been completely available for civil use. The breakdown per period of hypothetical FUA transit is given in Tables VII and VIII.

TABLE VII
YEARLY EFFECTS OF ROUTE EFFICIENCY LOSS, PER PERIOD OF HYPOTHETICAL FUA TRANSIT - ALPHA SECTOR

	Flights [-]	Fuel reduction [t]
Total	149 317	70 197.662
Unavailable period	67 266	31 623.432
Delegated period	64 799	30 463.633
Available period	17 252	8110.597

TABLE VIII
YEARLY EFFECTS OF ROUTE EFFICIENCY LOSS, PER PERIOD OF HYPOTHETICAL FUA TRANSIT - DELTA SECTOR

	Flights [-]	Fuel reduction [t]
Total	305 993	100 022.218
Unavailable period	131 247	42 901.687
Delegated period	141 826	46 359.724
Available period	32 920	10 760.806

B. Extrapolating the Results of Experiment 2

For Experiment 2, the same procedure is followed with the corresponding subset of flights. These are the those making use of the airspace during a delegated period, which are shown in Figure 23 together with the minutes reserved per day.

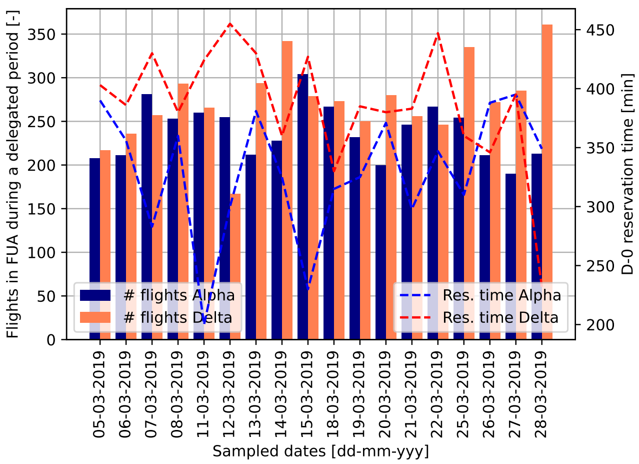

Fig. 23. Total number of flights considered by Experiment 2 (left y-axis) and time reserved (right y-axis) per date

It follows that, as oppose to what is shown in Figure 21 for Experiment 1, the difference between the number of flights considered does not differ greatly between the Alpha and Delta sectors for Experiment 2. This is due to the fact that here it is actual usage of the FUA what is being considered rather hypothetical benefits, as well as looking only at a small window of time (the delegated periods). In conclusion, while the actual usage of the FUA during a delegated period may be similar, many more flights are found to lose route efficiency for the Delta sector than for Alpha. This also permeates to the results of Section VIII, where the benefits of the Delta sector with respect to Alpha are much greater proportionally for Experiment 1 than for Experiment 2.

Similarly, the number of flights considered is correlated with the amount of time reserved per day, as shown in Figure 24 for both airspace sectors. The more time the FUA is reserved, the less flights transit the FUA during a delegated period. This can also be seen in Figure 23, e.g. comparing the 12th and 28th of March for the Delta sector.

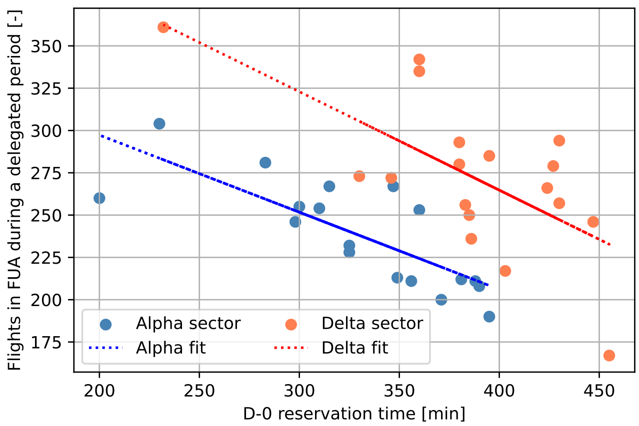

Fig. 24. Number of flights transiting each FUA during a delegated period, per time reserved and FUA sector

Using the linear regression of Figure 24 and accounting for the monthly fluctuations in traffic as done for Experiment 1, the number of flights are extrapolated for every date with reservations of 2019 outside of the sampled month and multiplied by the average fuel consumption reduction per flight. Given the similarity in the results amongst all concepts, only the AUP Updating concept is considered in the extrapolation; using the combination of Update 1 at 22:00 and Update 2 at 06:00 hours, which as seen in Figure 19 resulted in a reduction of 21 and 28 tonnes for the Alpha and Delta sectors, respectively. This results in a total yearly benefits of 269.91 and 394.06 tonnes for the Alpha and Delta sectors for Experiment 2.

C. Extrapolating the Results of Experiment 3

Finally, the results of Experiment 3 are extrapolated in a homologous manner as for the two main experiments. The subsets of flights considered are those losing route efficiency in delegated periods within the assumed AUP reservation and benefiting from a tactical route benefit, and the same variables from the AUP Updating concept as the previous extrapolation are used. For March, the results showed 650 and 930 tonnes of fuel consumption reduction for the Alpha and Delta sectors.

When extrapolating this to a yearly estimation using the same method as before, this leads to a fuel consumption reduction of 8,908.2 and 13,300.8 tonnes for the Alpha and Delta sectors, which is once again about a 13% of the fuel consumption extrapolated for Experiment 1 (see tables VII and VIII). As aforementioned, the results of Experiment 3 should be taken cautiously given the coarse assumption of the AUP reservation intervals, which has led to considering solely a smaller subset of flights, closer to the D-0 reservations and thus more liable to depend on plannability. The full effects of FUA plannability penalising route efficiency are hard to quantify, yet using the reduced subset of flights it can be confidently stated that at least a 13% the effects of FUA on route efficiency could be recovered simply by using a better plannability policy.

X. Fuel Flow Validation

The main aspect of the project to be validated is the use of the fuel consumption model. This uses the formulae outlined in Section IV-C and the coefficients from BADA 3.12 to compute the aircraft performance. These coefficients have been validated by Eurocontrol and other independent studies, e.g. Nakamura [23]. The model is already present in BlueSky, implemented and validated within the simulator by Metz [24].

Although the model has not been modified, assumptions have been introduced for this project deteriorating the results. First, the unavailability of aircraft mass creates an inherent error in the fuel flow calculation. Next, the lack of airspeed in the Eurocontrol R&D data archive results in the assumption of no wind and the usage of ground speed instead. Finally, the low frequency of entries of the database result in a more homogeneous fuel flow failing to capture local variations.

To investigate the impact of these assumptions, Aircraft Condition Monitoring System (ACMS) data provided by KLM is used. This contains detailed and continuous information of a flight's trajectory including actual weight, true airspeed and fuel flow. To simulate the performance of the experiment's methodology, this data is processed to be comparable to that of the Eurocontrol R&D data archive by greatly reducing the frequency of points. With this simplified database, three methods are considered to check the impact of the different assumptions. First, method V1 uses BADA's reference mass and the ground speed calculated from the coordinates and time, thus making V1 the closest representation to the performance of the model under the assumptions of the experiments. Next, method V2 differs from V1 simply by using the true airspeed, available from ACMS data. Finally, V3 builds upon V2 by simulating the flight with the real aircraft weight taken again from ACMS data. The three methods together with the validation data are shown in Figure 25 for the Airbus A330.

Several conclusions can be taken from Figure 25. First, it shows that using the true airspeed (V2) instead of the ground speed (V1) improves the results, and correcting for the real mass (V3) reduces the error further. Despite the underestimation shown for the Airbus A330, it is seen that even with the simplification of the data points, the estimated BADA coefficients still manage to provide a good approximation of the true fuel flow.

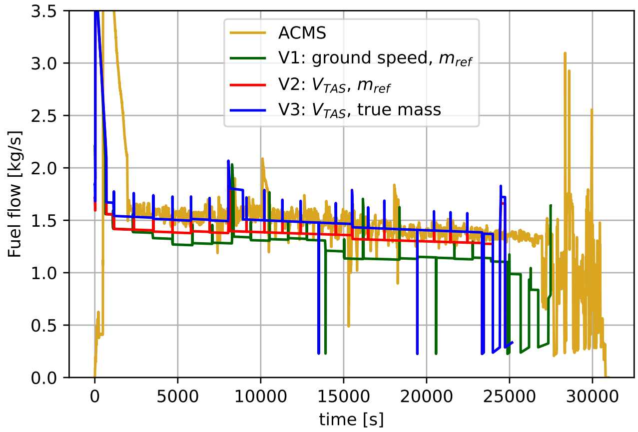

Fig. 25. Fuel flow validation for Airbus A-330

When examining the other example flights shown in Appendix C, these indicate that V2 generally improves the results only slightly from V1, meaning that the assumption of no wind is largely valid. Contrarily, V3 generally proves to be a much closer approximation to the true data, suggesting that the main source of the error is initialising the simulated flights with the reference mass from BADA instead of a greater value closer to the maximum take-off weight.

Moreover, the low frequency of updates usually yields only one or two data entries during climb and descent, creating two main problems. First, it results in the initial peak in fuel flow to be much shorter in the simulation than in the validation data. Secondly, due to the apparent short climb, the simulated flight reaches the cruise phase sooner than in reality, thus reaching the destination also earlier (which is aggravated by the fact that a lower frequency of waypoints results in small shortcuts throughout the trajectory). Both of these problems result in the simulation underestimating the total fuel consumed. Nonetheless, it is not the absolute consumption but the difference between simulated concepts that the experiments consider, for which the analysis is still valid. Finally, it can also be observed that the simulated fuel flow contains many data points with isolated spikes and drops. These correspond to the instants when the flights reach a waypoint constraining them to a higher or lower speed than the current one. All in all, the inherent limitations of the database used are seen to deteriorate the results to some extent, mainly due to using BADA's m_{ref} and the limited frequency of updates. This error with true data cancels out when comparing only simulated concepts created by BlueSky, as is done in the experiments. In this manner, it is argued that the approximated fuel flow is sufficiently acceptable to be used as the basis of the comparisons.

XI. Discussion

This study has investigated the benefits on fuel consumption and work of making FUA completely available for civil use as well as planning the airspace to be delegated with a higher plannability. With this aim, a total of 396 and 1,152 simulations have been performed for Experiments 1 and 2, respectively. The following serves as a discussion on the results attained and how they relate to one another.

Overall, it is seen that the fuel consumption reduction is much greater when strategies are taken to avoid a route efficiency penalty when compared with a surplus fuel one. As shown, the flights considered to be penalised with route efficiency would benefit from 5,085 and 7,206 tonnes of fuel consumption reduction in March 2019, had the Alpha and Delta sectors been completely available. This can then be compared with the 28 and 35 tonnes of fuel consumption reduction when the flights penalised with a surplus fuel do not load it due to the plannability policy of the AUP Updating concept. In other words, the effects of penalising route efficiency are two orders of magnitude higher than those of penalising a surplus fuel. Nonetheless, the effects of plannability do not end with a surplus fuel penalisation but have also been linked to the route efficiency loss of Experiment 1. Despite the frail assumptions of this last experiment, this suggests that implementing the AUP Updating concept would lead to a reduction of at least 650 and 930 tonnes for the Alpha and Delta sectors, suggesting that a better plannability concept would recover a visible part of the total effects of FUA on route efficiency.

A. Experiment 1

For Experiment 1, the flights considered are those deemed to have lost route efficiency, i.e. they historically did not transit the FUA, yet they would have benefited from it. For these, two different methods have been used to compare the historical flights with alternative trajectories making use of the FUA. First, the GCR method artificially creates Great Circle Route segments within the historical trajectories. One of the objectives of the first research question is to compare how the fuel benefits would change when enabling the GCR at different ranges from the FUA: within Amsterdam FIR, within a larger part of Europe, or without limit (although this option is not a fully direct routing scenario, as the GCR segments are only accepted if they traverse the FUA). As expected, the greater the range at which the GCR is created, the greater the benefits, going for example for the Alpha sector in March 2019 from 137 tonnes of fuel consumption reduction in Amsterdam FIR, to 769 tonnes in a region of Central and Northern Europe to finally 4,122 tonnes without a range limit. This proves once again that route efficiency is key to reduce fuel consumption, with the independent variable of the speed setting having less of an effect.

To provide a more grounded comparison and thus see the effects of the current route system and procedures, the Pairing method has been used. This compares the historical flights losing route efficiency only for flights with the same departure-destination airports or vice-versa which did make use of the FUA. This leads to a fuel consumption reduction of 5,086 and 7,206 tonnes for the Alpha and Delta sectors, proving the higher impact in route efficiency of the latter airspace. This difference between sectors was not prevalent in the GCR method due to its inability to account for many Schiphol flights, given it only considers the horizontal profile (see Figure 15). It is however clear with the Pairing method that the Delta sector holds a greater potential in fuel consumption reduction due to the higher traffic density around it. Furthermore, the Pairing method has also shown that the bifurcation and merging points of similar flights take place far from Amsterdam FIR. Not only does this lead to more efficient trajectories when transiting the FUA, but it also suggests that the decision point at which it is decided what route to take depending on whether the FUA is available or not occurs much before reaching Amsterdam FIR. This poses an even greater weight to the problem of plannability, as flights lose route efficiency during delegated periods of time due to the bifurcation occurring far away from the FUA.

B. Experiment 2

For Experiment 2, the flights considered are those transiting the FUA during a delegated period, i.e. those for which the plannability of the FUA affected whether they carry a surplus fuel or not (the sole penalisation of this experiment). Three plannability concepts have been first created: the Single Horizon, the Multiple Horizons and the Reservation Shrinking concepts. The Single Horizon concept delegates all periods of FUA reservation not desired by the Royal Netherlands Air Force (RNLAF) at the same time, which limits military flexibility but proves very advantageous to the civil user, yielding the best results across all concepts. This is largely due to the fact that the longest delegated period, namely the afternoon one, is here given with a large buffer of time even at poor plannability horizons. The Multiple Horizons concept proposes a more flexible alternative to the RNLAF by enabling each D-0 reservation to be made separately, thus having multiple horizons of plannability. The caveat here is that if D-0 reservations can be made one after another, no reservation can guarantee the transit after it, but only before. In order to guarantee an eventual transit through the later delegated periods, a cutoff time is used. This becomes the driving parameter, and the results have shown for this concept to be better than the current operation only at early cutoff times which defeat the purpose of the concept, which is to give the RNLAF flexibility by reserving on a one-by-one basis during D-0. This suggests that a coarse reservation shrinking such as that made by the Airspace Use Plan (AUP) the day before operations (D-1) can be more beneficial for civil users than delegating the precise scheduling gradually with a shorter plannability. Using the notion of the AUP, the proposed Reservation Shrinking concept acts as a continuous and binding AUP, using as parameters the rate of delegation (i.e. the minutes delegated per hour) and the start of the delegation (i.e. when the process starts). This is shown to have comparable results to the first concept, yet the assumptions made on the operation make this a difficult strategy to integrate to the current process. More importantly, it is seen that a good balance between civil plannability and military flexibility would be the delegation of the afternoon periods after the morning ones, but both at a sufficiently high horizon.

Having gathered preliminary conclusions on the concepts, the most promising strategies are combined into the AUP Updating concept. This is considered to be a more balanced and pragmatic strategy benefiting both civil and military users by providing comparable benefits to the best performing concepts while enabling a stepped approach of making reservations, as well as being more integrable to the current operation. This concept builds upon the baseline by implementing it directly, and updates it twice afterwards. Firstly, the morning delegated period is given up during the evening of the day before operations. Secondly, the afternoon and any in-between delegated periods can be compromised during the morning of the day of operations. This results in a reduction of 28 and 35 tonnes of fuel consumption for the Alpha and Delta sectors.

C. Experiment 3

Finally, Experiment 3 combines the notions of the two main experiments upon the realisation that almost half of the flights losing route efficiency by the Pairing method do so during a delegated period, suggesting that FUA plannability permeates to some degree as a route efficiency penalisation. Given the frail assumption of the AUP schedule, seen in the available records to oscillate considerably, conclusions cannot be drawn confidently when considering the entire subset of flights in all delegated periods. Instead, only the flights within the AUP reservation are considered, which yields not only a smaller subset but also one the flights in which are closer to the D-0 reservations and thus more likely to depend on the plannability of the sector. In this manner, by using the AUP Updating concept as plannability policy, and assuming that every flight flying over the bifurcation point after the announcement time of the airspace would benefit tactically from a more optimal route, the benefits of this plannability policy when penalising route efficiency are analysed. This results in 650 and 930 tonnes of fuel consumption reduction for the Alpha and Delta sectors. All in all, nearly all of the flights losing route efficiency in the delegated periods considered, which amounts to 13% of the total, attain a tactical route benefit with the proposed plannability concept, thus recovering a significant part of the effects of Experiment 1.

XII. Conclusions

This research project set out to investigate the effects of Flexible Use of Airspace (FUA) availability and plannability on fuel efficiency, with the aim to inform some of the decisions to be made by the Dutch Airspace Redesign Programme. This considers a reorganisation of FUA structures and the plannability policies they are reserved with. For this, three experiments have been carried out by sampling historical traffic data from the Eurocontrol R&D data archive for March 2019 and performing a total of 1,548 simulations in the open source air traffic simulator BlueSky.

The first experiment considered the flights losing route efficiency due to a FUA, and calculated the fuel consumption, work and CO_2 benefits of alternative routes making use of the sectors using two methods. The results of the Pairing method, which compares each flight with one with similar departure and destination airports, have been extrapolated to a yearly estimation to yield a fuel consumption reduction of 70,198 and 100,022 tonnes for the Alpha and Delta sectors (corresponding to 221,124 and 315,069 tonnes of CO_2 emissions). This proves the greater potential of the Delta sector over the Alpha one in mitigating the effects of FUA on civil traffic, given the higher traffic density around the South. Parallelly, four plannability concepts have been proposed in Experiment 2 to investigate the effect of FUA plannability by penalising the loading of a surplus fuel. These concepts create hypothetical scenarios where the delegated periods of the FUA are given at a greater plannability, thus allowing for flights to have the guarantee of transit through the FUA and avoid taking a surplus fuel. This resulted in a yearly fuel consumption reduction of 270 and 394 tonnes for the Alpha and Delta sectors (corresponding to 851 and 1,241 tonnes of CO_2 emissions). Comparing the results of the different concepts proposed suggests that delegating a conservatively large interval with a high plannability (such as the current Airspace Use Plan reservation) is more beneficial to the civil user than delegating the exact intervals with a lower plannability. Another objective posed for Experiment 2 was to obtain an insight on the largest planning horizon affecting fuel efficiency. As shown in Section 6.2.1 of the Preliminary Thesis Report, this is around 16 hours, which translates to 15:00 hours at D-1, and is seen in the results of the Single Horizon concept to yield the greatest possible benefits.

Comparing the results of the two first experiments, it can be concluded that the key to mitigate the effect of FUA on the fuel efficiency of civil traffic is to avoid the penalisation in routing, with the surplus fuel loaded having an effect two orders of magnitude lower. This route efficiency penalisation does however not only come from FUA availability, as formerly hypothesised. Instead, the results of Experiment 1 show that the trajectory of a flight not only varies significantly depending on whether or not it transits the FUA, but the bifurcation point between the possible trajectories occurs much before reaching Amsterdam FIR. This, together with the fact that almost half of the flights losing route efficiency do so during a delegated period of time, suggests that FUA plannability has a considerable effect on route efficiency. In other words, the current poor plannability of FUA does not allow for a tactical transit through the sector in many cases, as the decision to deviate around it occurs much before this becomes available. Quantifying this dependency becomes complex given the effect of other factors in FUA transit and the coarse assumption of an AUP reservation. Nonetheless, taking a smaller subset of flights closer to the D-0 reservations and thus more liable to depend on the plannability of the delegated periods, it can be confidently established that the AUP Updating concept would result in a fuel consumption reduction of at least 8,908 and 13,301 tonnes for the Alpha and Delta sectors during 2019 when penalising route efficiency (corresponding to 28,060 and 41,898 tonnes of CO_2 emissions), approximately a 13% of the total effects of Experiment 1.

Furthermore, the methodology carried out makes use of a low-frequency database which greatly simplifies the flight trajectory in favour of considering a large sample size. The limitations and simplifications of this database have been investigated, using as validation data the fuel flow of the Airbus A330 from Aircraft Condition Monitoring System data provided by KLM. Three validation concepts have been considered to test the effect of the assumptions on wind and mass, as the real value of true airspeed and actual weight are not available in the experiments. It is seen that, while the wind has a small effect in correcting the fuel flow estimation, the main source of error between the true and simulated fuel flow is the usage of the reference mass given by BADA instead of the true aircraft weight. Despite this error, it is seen that the approximation is acceptable when considering the assumptions made, especially when analysing differences between different simulated concepts. Still, a recommendation for future work is to initialise the simulated flights with a weight closer to the maximum take-off weight rather than the reference mass of BADA, especially when considering the climb phase.

As a closing remark, the research at hand provided an overview of the effects of Flexible Use of Airspace availability and plannability on the fuel efficiency of civil commercial traffic, penalising both routing and surplus fuel, to understand the impact of each sector and thus inform future changes in the FUA structures in Amsterdam FIR. As recommendations for future work, research on Flexible Use of Airspace may go from the development of new policies to make a better use of the current system, to investigating the integration of Advanced FUA concepts. For example, it has been briefly mentioned the hypothesised effect of a lack of FUA plannability on the uncertainty in traffic demand on a sector downstream, which if resolved may result in a better demand predictability and consequently better informed Air Traffic Flow and Capacity Management measures in the current operation. A good understanding of the effect of FUA availability and plannability on all performance measures will become even more useful as airspace sectors progress into Advanced FUA. This is to enable an integration of Airspace Management and Air Traffic Flow and Capacity Management concepts to assist with demand and capacity imbalances. In this manner, aspects of FUA airspace volume and time of reservation, as well as the plannability of the sectors, could be used as a tool to further strengthen civil-military coordination and cooperation and thus better serve the needs of both airspace users.

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Part II

Appendices

Appendix A: Work Results

Experiment 1

Shown in the same manner as the fuel consumption plots of the scientific paper, Figure 1 presents the benefits in work of the concepts proposed for Experiment 1. Taking the Pairing method as reference, it can be seen that the effect of FUA in Amsterdam FIR in the month of March 2019 when penalising route efficiency results in approximately 91 and 123 TJ of work for the Alpha and Delta sectors, respectively.

Furthermore, one can see how the Optimised speed setting, which is chosen to minimise fuel consumption, yields a smaller work reduction as the number of flights considered grows, which may seem counterintuitive. This is because work ($W = T \cdot d$) is independent of the time taken to fly a given distance, for which when considering the difference between the two speed settings (which fly the same distance), work differs based only on T. As explained in the analysis, the Optimised speed setting usually uses a greater airspeed than the historical one in order to save fuel by reaching the destination sooner despite a marginal increase in fuel flow throughout the trajectory. This increase in fuel flow is due to the increased Thrust force resulting from the greater airspeed. In this manner, the Optimised speed setting minimises the total fuel consumed yet increases Thrust and thus work, leading to less work benefits.

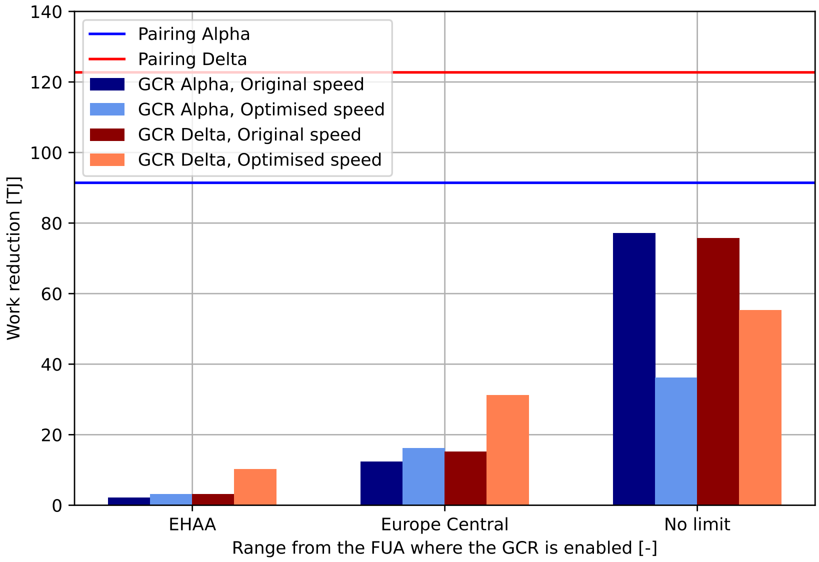


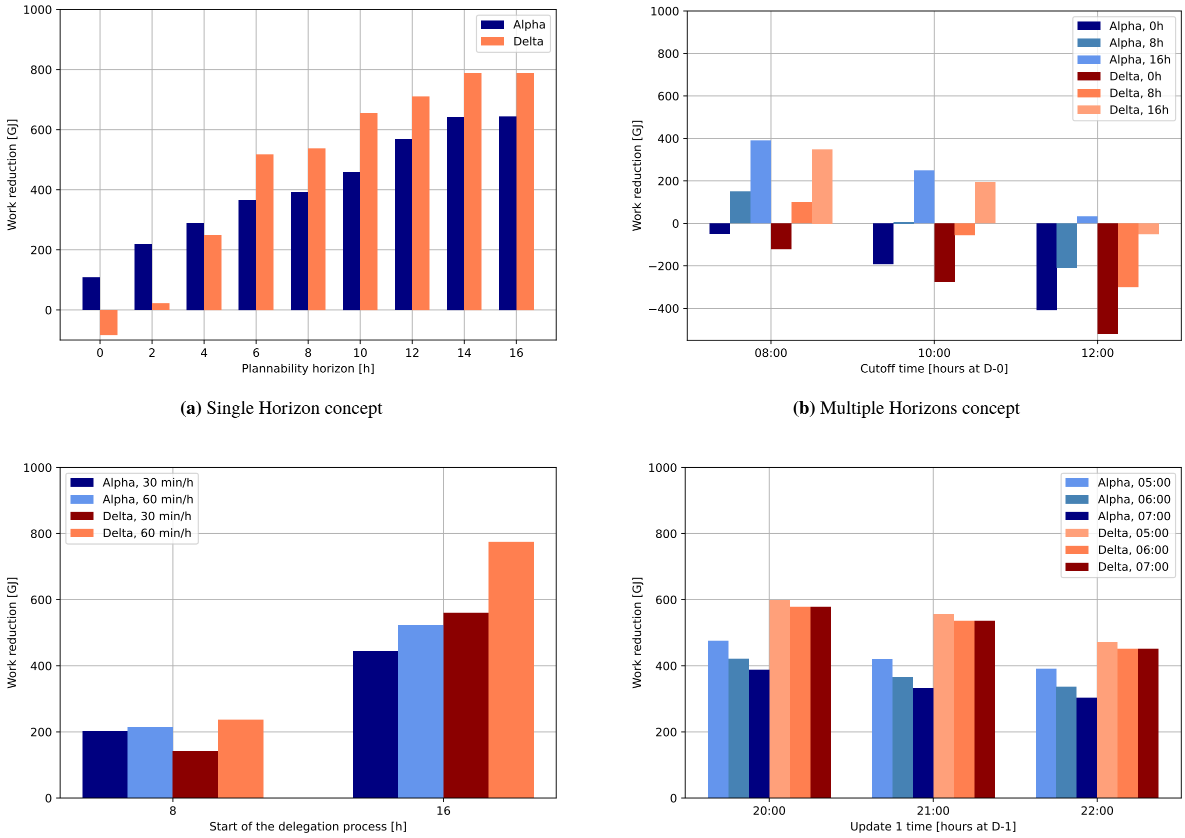
Figure 1: Experiment 1 work results for the GCR and Pairing methods

Experiment 2

Similarly, the work results for Experiment 2 are shown in Figure 2. In the same fashion as in the scientific paper, the Baseline is taken as the reference for all other results. The results of work correlate with those of fuel consumed in every aspect: the more flights that do not take the surplus fuel, the greater the benefits in work, with the Single Horizon and the Reservation Shrinking concepts presenting the best results. Analogous to fuel consumption, the results of work are two to three orders of magnitude smaller when penalising the surplus fuel when compared with penalising the route efficiency.

Experiment 3

Finally, the results of Experiment 3 for March 2019 have also been gathered and are presented in Figure 3. These are calculated under the same assumptions and using the same subsets as discussed in the scientific paper.



(a) Single Horizon concept

(b) Multiple Horizons concept

(c) Reservation Shrinking concept

(d) AUP Updating concept

Figure 2: Experiment 2 work results for all concepts

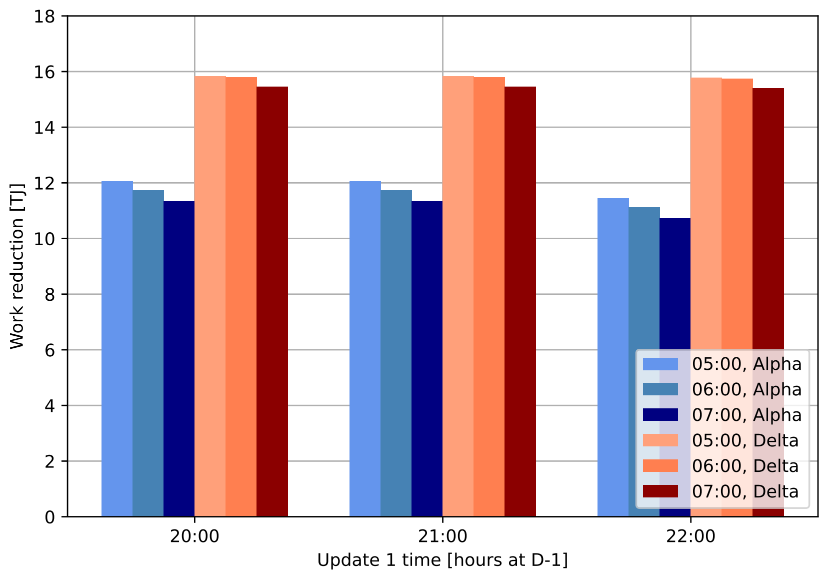


Figure 3: Work reduction due to tactical route efficiency benefits enabled by the AUP Updating concept (Experiment 3)

Appendix B: Verification of Fuel Efficiency Metrics and Surplus Fuel Calculation

Verification of Fuel Efficiency Metrics

In order to have a more tangible sense of the metrics analysed and to verify the BlueSky calculations, a simple example is here constructed and compared with a calculation done by hand.

Example Description and Simulation

The following creates an example scenario describing two flights: one deviated around Alpha (DEV) and one traversing it directly (GCR). First, the scenario file is described in Listing 1. The resulting trajectories in BlueSky are shown in Figure 4. Note that the logged variable traf.perf.E has been implemented in BlueSky as the work done for each step.

```
00:00:00>POLY ALPHA, [lat_Alpha_1 lon_Alpha_1, lat_Alpha_2 lon_Alpha_2, ...]
00:00:00>COLOR ALPHA RED
00:00:00>POLY DELTA, [lat_Delta_1 lon_Delta_1, lat_Delta_2 lon_Delta_2, ...]
00:00:00>COLOR DELTA RED
00:00:00>TRAIL ON
00:00:00>CRELOG FUEL 1
00:00:00>FUEL ADD traf.id, traf.perf.fuelflow, traf.perf.E
00:00:00>FUEL ON
00:00:00>CRE DEV A320 52 3 68.59 34000 286
00:00:00>DEV ADDWPT 53.35 7.3
00:00:00>DEV ADDWPT 55.9 7.5
00:00:00>DEV ATDIST 55.9 7.5 1 DEL DEV
00:00:00>DEV LNAV ON
00:00:00>DEV VNAV ON
00:00:00>CRE GCR A320 52 3 68.59 34000 286
00:00:00>GCR ADDWPT 55.9 7.5
00:00:00>GCR ATDIST 55.9 7.5 1 DEL GCR
00:00:00>GCR LNAV ON
00:00:00>GCR VNAV ON
03:00:00>FUEL OFF
```

Listing 1: BlueSky scenario of a simple verification example

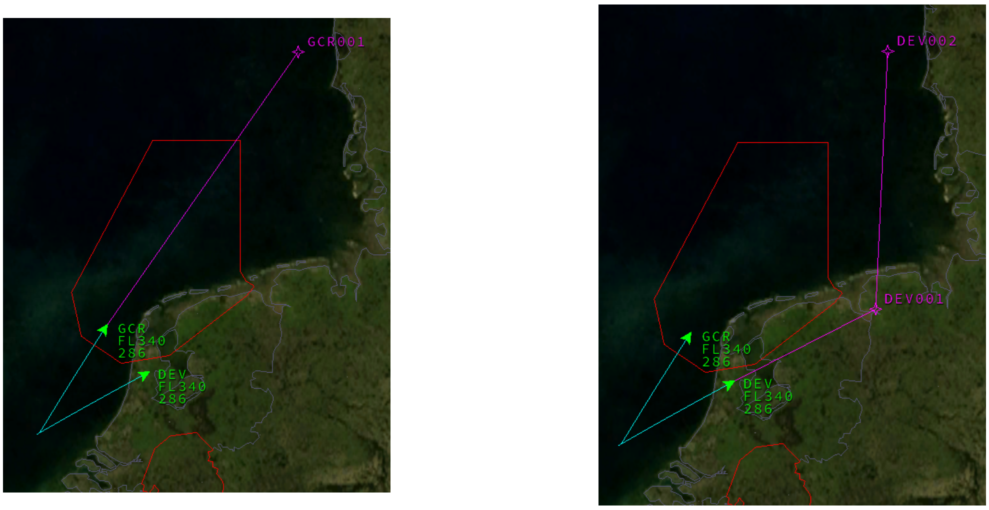


Figure 4: Direct and deviated example trajectories

Finally, the results of the simulated example are given in Table 4. While the average fuel flow shows, as expected, a negligible difference as the speed and altitude is the same for both trajectories, the fuel consumed and work show a visible difference: approximately 60 kg of fuel consumed and 4,000 MJ of energy.

	Average fuel flow [kg/s]	Total fuel consumed [kg]	Total work [MJ]
Direct	0.69178	1479.11	25,532.24
Deviated	0.69181	1719.77	29,686.62

Table 4: Results of the example scenario

Manual Verification

Having the results of the simulation, now the problem is replicated manually in Listing 2 to verify the results and get a tangible sense of the effect of each variable.

```
g0 = 9.80665        # [m/s^2]
m  = 64,000         # [kg] m_ref of A320 as given by BADA
S  = 122.6          # [m^2]

CAS   = 286         # [kts]
V_TAS = 244.34      # [m/s] with CAS of 286 kts

h     = 34,000      # [ft]
rho   = 0.39433996 # [kg/m^3] at FL340


# This yields a CL of:
CL = m * g0 / 0.5 / rho / V_TAS^2 / S = (64,000 * 9.80665 )/ ( 0.5 * 0.39433996 *
    244.34^2 * 122.6 )= 0.43489 # [-]

# Get the drag coefficients:
CD0_cruise, CD2_cruise = 0.026659, 0.038726 # [-] of A320 as given by BADA

# Dag coefficient and Drag force:
CD = CD0_cruise + CD2_cruise*CL^2 = 0.026659 + 0.038726*0.43489^2 = 0.033983 # [-]

D = CD*0.5*rho*V_TAS^2*S =  0.033983*0.5*0.39433996*244.34^2*122.6 = 49,044  # [N]

# During cruise: dh/dt = 0, dV_TAS/dt = 0. Thus energy equation becomes:
T = D     = 49,044 # [N]

# Before calculating the fuel flow, the Thrust Specific Fuel consumption is needed:
Cf1       = 0.75882
Cf2       = 2938.5
V_TAS_kts = 244.34*1.944 = 475                                    # V_TAS in knots
eta       = Cf1*(1+V_TAS/Cf2) = 0.75882*(1+ 475/2938.5) = 0.88148 #[kg/(min*kN)]
eta       = 0.00088143                                            #[kg/(min*N)]

# Finally, calculate fuel flow:
Cf_cr     = 0.96358                                               #[-]
ff        = eta*Cf_Cr*T = (0.00088143*0.96358*49,044)/60 = 0.694  #[kg/s]
```

Listing 2: Simple verification example

The fuel flow calculated matches the average calculated by BlueSky, yielding only a slightly larger value. This is due to the fact that the full m_{ref} was taken, while BlueSky continuously deducts the weight of fuel burnt. Assuming this setting for the entire trajectory, the aim is now to see how the different trajectories affect the final results.

For the fuel consumed, the time needs to be found during which the fuel flow calculated is burnt. This depends on the given trajectory and airspeed. For the direct trajectory, going from 52 and 3 to 55.9 and 7.5 degrees, the total distance flown is 524,845 m. For the deviated trajectory, going from 52 and 3 to 53.35 and 7.3 degrees, and then to 55.9 and 7.5 degrees, the distance flown is 611,435 m. To fly such distances at 244 m/s, it takes 2,151 and 2,506 seconds, respectively. This is then multiplied with the fuel flow calculated to yield 1,493 and 1,739 kilograms of fuel consumed, once again presenting very similar results to those of Table 4, barring the overestimation due to taking m_{ref} for the entire trajectory.

For the total work, the calculation is slightly different. Total work is defined as the total Thrust force needed to move the aircraft for a distance d, i.e. $W = T \cdot d$. The simplest way to calculate this using BlueSky is to multiply the Thrust force exerted each timestep with the increment in distance, the latter computed with the true airspeed and timestep itself. This is shown in Equation 1: at each timestep ran by BlueSky, the thrust calculation (T_i) is multiplied by the increment in distance Δd. In this manner, the only step left to be done as post-processing is to sum all work entries of the log file.

$$W = T \cdot d = \sum T_i \Delta d \tag{1}$$

To do this manually, one simply needs to multiply the Thrust found (49,044 N), assumed now constant, by the distance to be flown. This results in 25,740 and 29,987 MJ, once again showing a slight overestimation of the results of Table 4.

Verification of the Surplus Fuel Calculation

Similarly, the following verifies the calculation of the surplus fuel in Experiment 2. In this case, no external or simulation model is involved, yet the code implementation of the formulae can still be checked manually for a better grasp of the variables and orders of magnitude. In this manner, the code is here verified with a manual calculation.

The example taken is one of the first flights found to use the FUA during the sampled dates: a Boeing 737-800 (B738) from Málaga (LEMG) to Oslo (ENGM) with its trajectory shown in Figure 5. By means of retrieving the results of the Pairing method, it is calculated that for a flight LEMH-ENGM, deviating around the Alpha sector results in an average increase in distance flown of 75.831 km. This, together with the actual distance flown of the flight at hand and the data from BADA, is all of the information needed to calculate the surplus fuel. Listing 3 thus follows the formulas outlined in the scientific paper, the full derivation of which can be found in Section 5.4.6 of the Preliminary Thesis Report.

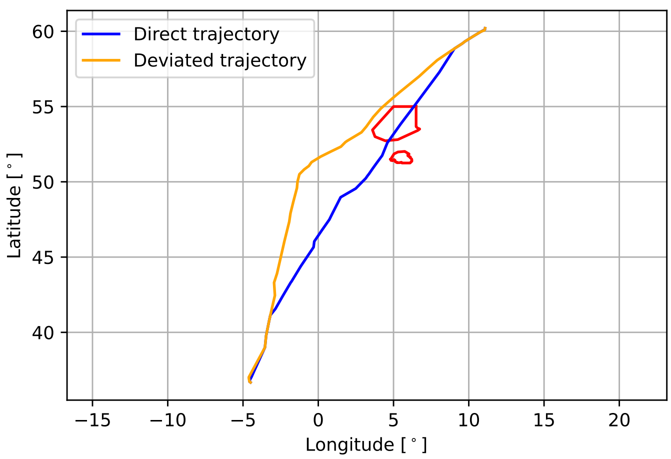


Figure 5: Two flights LEMG-ENGM, one traversing the Alpha sector (considered in Experiment 2) and another deviating from it, found in the Pairing method

```
# Corresponding data from the BADA database, of aircraft type = 'B738'
TPR  = 3,704  #[km], range at MTOW
MTOW = 78,300 #[kg], Maximum Take-Off Weight
OEW  = 41,150 #[kg], Operational Empty Weight
Wpl  = 20,300 #[Kg], Payload Weight

# Calculate C of a specific condition (MTOW)
C    = TPR/ln(MTOW/OEW+Wpl) = 3,704/ln(78,300/41,150+20,300) = 15,285.33518 #[km]

# Distances
R1   = 2,874.304 #[km], actual distance flown by the flight at hand (through the FUA)
```

```
dR   = 75.831    #[km], average extra range of the corresponding ADEP-ADES without FUA
     transit, as found by the Pairing method
R2   = abs_R + extra_R = 2,950.135 #[km] total deviated distance

# Calculate surplus fuel during cruise

W_f_after_cruise = 300 #[kg] Assumption of 300 kg needed to descend

W_surplus_fuel   = (e^(R2/C) - e^(R1/C))*(OEW + Wpl + W_f_after_cruise)
                 = (e^(2,950.135/15,285.33518) - (e^(2,874.304/15,285.33518))*
                 *(41,150+20,300+300)
                 = 370.64 #[kg]
```

Listing 3: Surplus fuel calculation

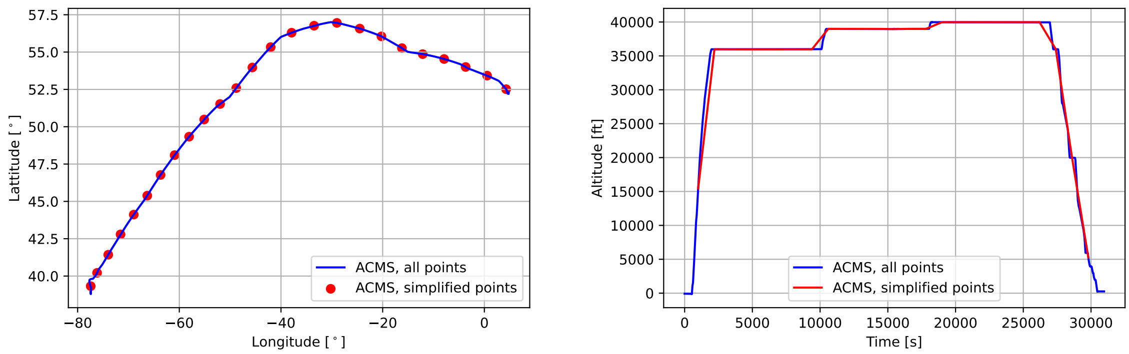
Using this methodology for all flights considered, it is observed that deviating around a FUA sector requires a surplus fuel weight generally in the range from 50 to 500 kg.

Appendix C: Extended Validation

This appendix provides a more extensive explanation of the method used to validate the fuel consumption model in the scientific paper.

Methodology

As explained, the validation data used is that of the Aircraft Condition Monitoring System (ACMS) from a series of KLM flights. It contains continuous and detailed information on all relevant parameters needed for the analysis, including those which are not available in the database used such as true airspeed and actual gross weight per timestep. The aim is to use this data in a manner comparable to that of the Eurocontrol R&D data archive. For that, the data points are significantly reduced in order to have a frequency of entries similar to the data used for the experiments. This can be seen in Figure 6, which shows all ACMS points and the reduced number of them which is used in the following.



(a) Coordinate points

(b) Altitude points

Figure 6: Complete and simplified trajectory points, for the flight KL0651 Washington D.C. (KIAD) - Amsterdam (EHAM) on 25-09-2021

The goal of the validation is therefore to prove that, even with greatly simplified trajectory data, the number of points is sufficient to describe not only the historical trajectory of the flight but also to yield a result in fuel flow similar to the one given by ACMS data and shown in Figure 7.

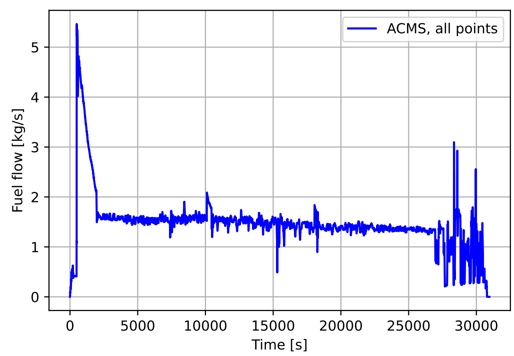


Figure 7: Historical fuel flow as given by ACMS data, for flight KL0651 Washington D.C. (KIAD) - Amsterdam (EHAM) on 25-09-2021

Once the trajectory points have been simplified such that they are comparable to the database used for the experiments, the two other main limitations of the Eurocontrol R&D data archive need to be recreated on the ACMS data. First, the true airspeed should not be available, for which the ground speed is calculated for the ACMS data in the same manner as for the experiments, i.e. from the coordinates and time stamps. Secondly, the true mass at each instant is also not available for the Eurocontrol database, for which the reference mass of the corresponding aircraft type from BADA may be taken. In this manner, three different validation concepts are input into BlueSky to analyse the effects of these limitations. First, concept V1 incorporates the two assumptions, i.e. taking ground speed as the airspeed and using BADA's m_{ref}. Secondly, V2 is to examine the effect of the assumption of no wind by using the true airspeed from ACMS data instead of the ground speed. Finally, V3 builds on top of V2 by also using the actual gross weight. This last step is done using the surplus.py plugin used for Experiment 2, meaning that the weight correction is only applied when the flight is first created rather than continuously, with BlueSky deducting the weight of burnt fuel from that point. In this manner, the weight to be added to the V3 flight is simply the difference between the actual weight of the first entry from the ACMS data and m_{ref}. Once the information needed for the three validation concepts is found, this is translated to BlueSky scenario files as explained in Appendix D. This results in log files where the fuel flow calculated is recorded per simulated timestep, yielding the fuel flows per concept as explained in the following.

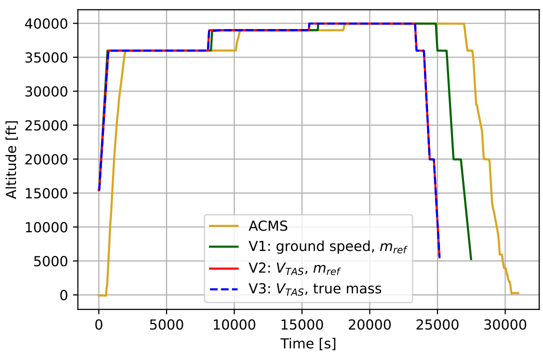
Results

For the example outlined above, the results are shown in Figure 8. This is the same example used in the scientific paper. Additional examples are provided in the set of figures of 9, 10, 11 and 12; all corresponding to flights of Airbus A330.

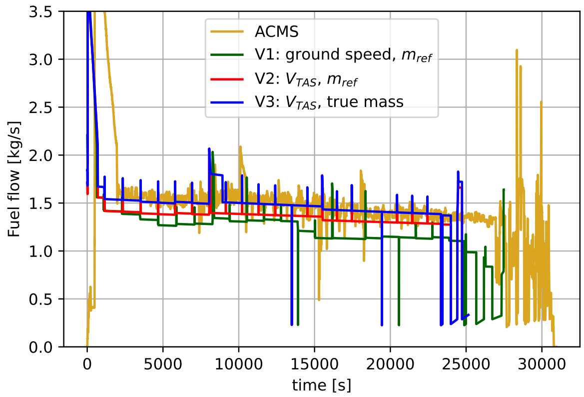
Generally speaking, the simulated trajectories tend to end sooner than the historical flight. This is due to the fact that the reduced number of waypoints given to BlueSky create small shortcuts in the trajectory with respect to the historical path taken. Not only that, but this also results in a smaller number of climb and descent points, thus constraining the flight to cruise settings for a longer period of time than in reality. It is also shown that the V3 flight (carrying the real gross weight) usually arrives later to the destination than the other simulated flights, as the greater weight results in a longer flight time. In summary, based on these examples one can observe the correlation between the speed setting and weight chosen, the resulting time spent on each phase and the corresponding fuel flow calculated. All of these result in the total fuel consumption simulated to be lower than in reality, as the historical flight flies for a longer period of time. Nonetheless, as explained in the scientific paper, given that what is being compared are different simulated concepts, rather than aiming to realistically depict the true fuel consumption of each flight, the underestimation in total fuel consumption is acceptable.

Furthermore, another characteristic of the recorded fuel flow are the peaks and drops occurring at isolated instants. These correspond to promptly changing the airspeed to reach a new requested altitude (peaks when gaining altitude, drops when losing it), and one can see the correlation between these abrupt changes and tangible trajectory changes when comparing the fuel flow and altitude plots.

Lastly, when comparing the validation concepts themselves, it is seen that in all cases V1, that which is representative of the methodology used, results in an underestimated fuel flow. This is seen to be largely due to the incorrect mass assigned to the flight by BADA (m_{ref}). Although the usage of the correct true airspeed usually brings an improvement in the results, it is V3 which makes the fuel flow calculation the closest to the validation data. This suggests that, when examining the full trajectory of a flight; correcting the initial weight to have a closer value to the MTOW would significantly improve the results, as the error is carried over through the entire trajectory.

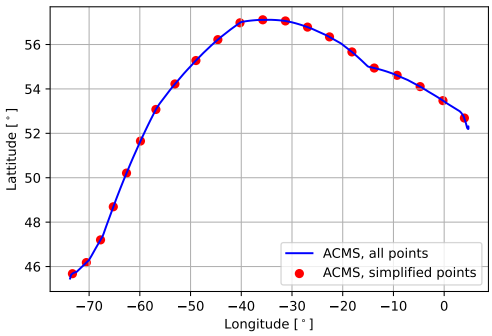


(a) Recorded altitudes

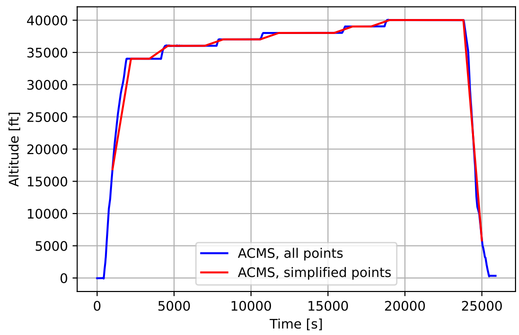


(b) Recorded fuel flow

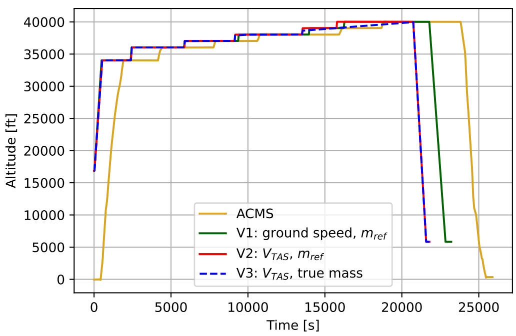
Figure 8: Altitude and fuel flow data as simulated by BlueSky, for the flight KL0651 Washington D.C. (KIAD) - Amsterdam (EHAM) on 25-09-2021



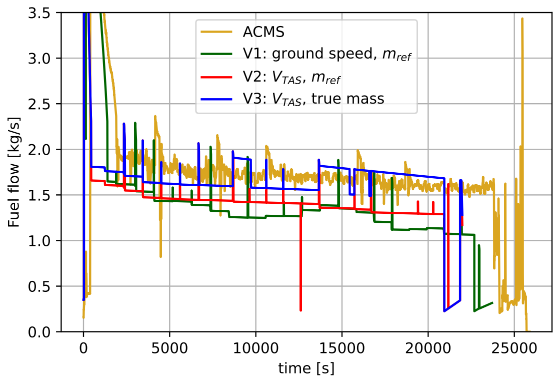
(a) Complete and simplified coordinate points



(b) Complete and simplified altitude points

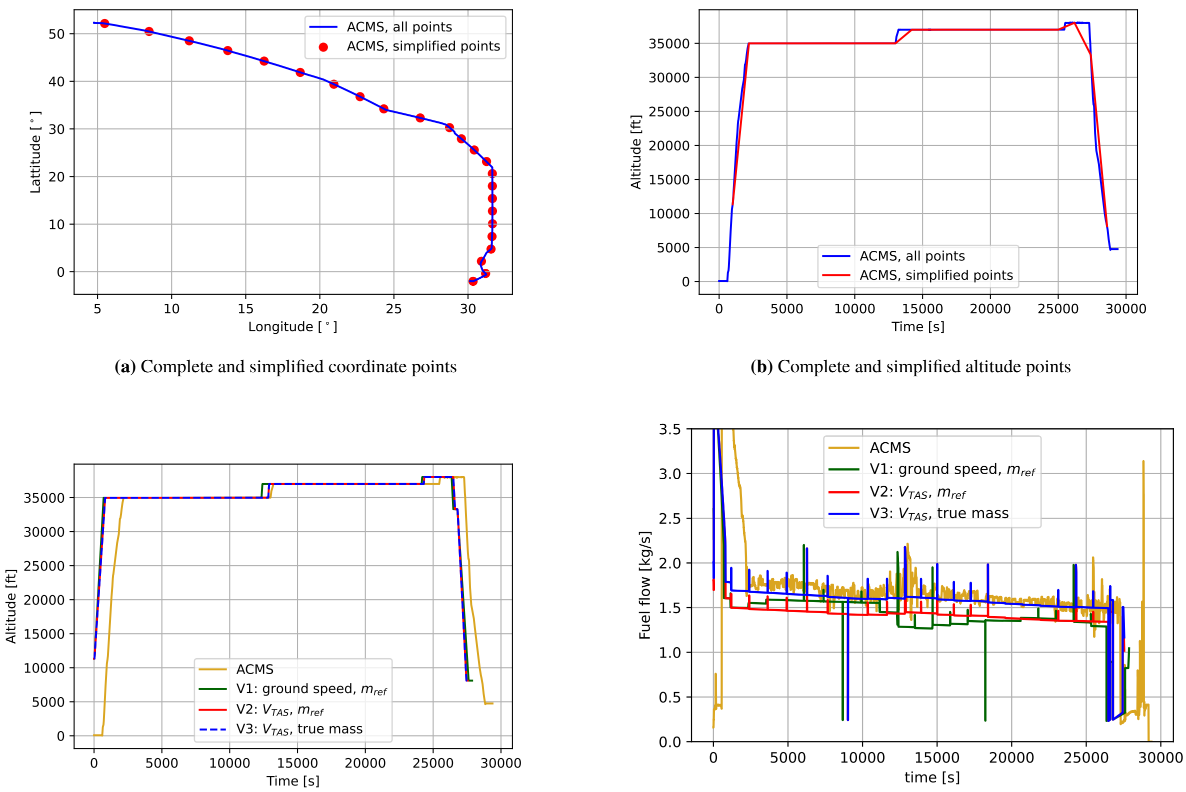


(c) Recorded altitudes



(d) Recorded fuel flow

Figure 9: Simplified points and simulation results for the flight KL0671 Amsterdam (EHAM) - Montréal (CYUL) on 08-09-2021



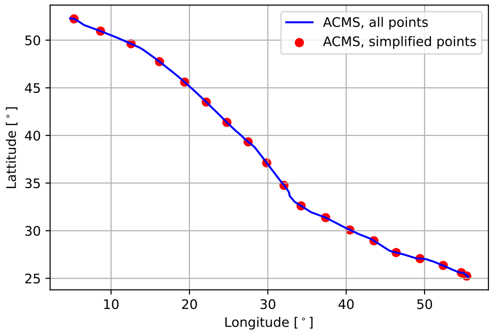
(a) Complete and simplified coordinate points

(b) Complete and simplified altitude points

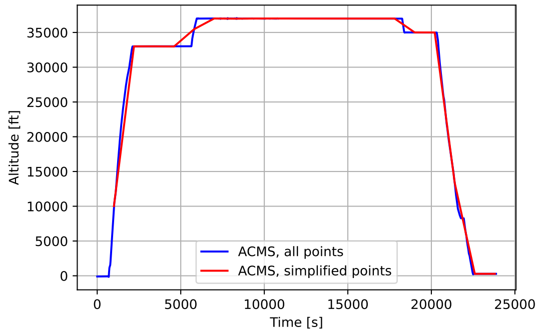
(c) Recorded altitudes

(d) Recorded fuel flow

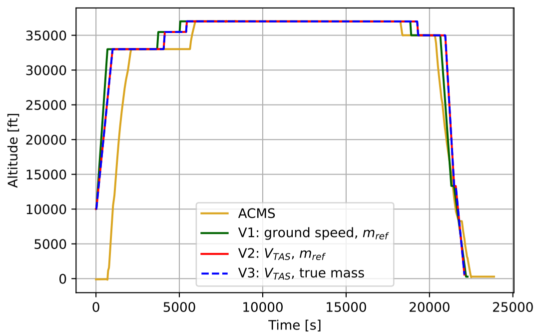
Figure 10: Simplified points and simulation results for the flight KL0535 Amsterdam (EHAM) - Kigali (HRYR) on 15-09-2021



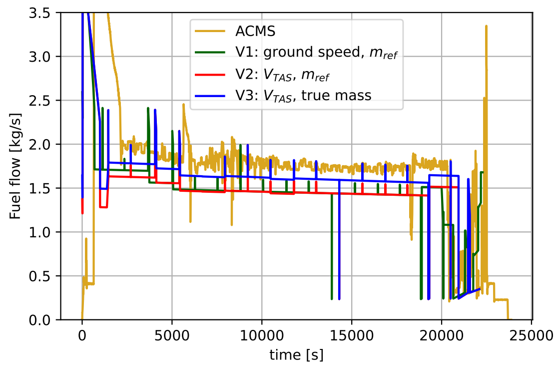
(a) Complete and simplified coordinate points



(b) Complete and simplified altitude points

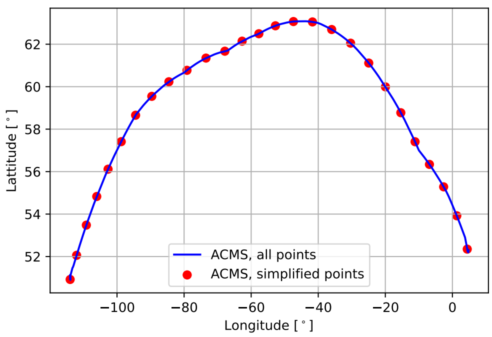


(c) Recorded altitudes

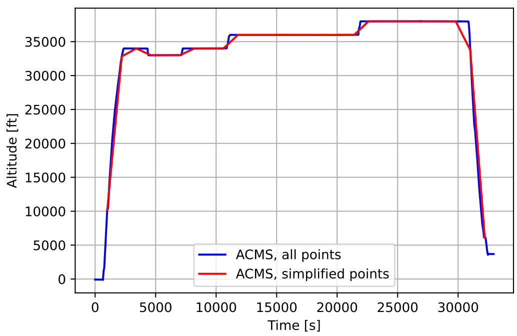


(d) Recorded fuel flow

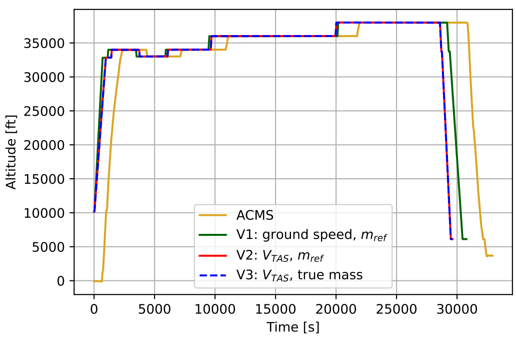
Figure 11: Simplified points and simulation results for the flight KL0427 Dubai (OMDB) - Amsterdam (EHAM) on 18/09/2021



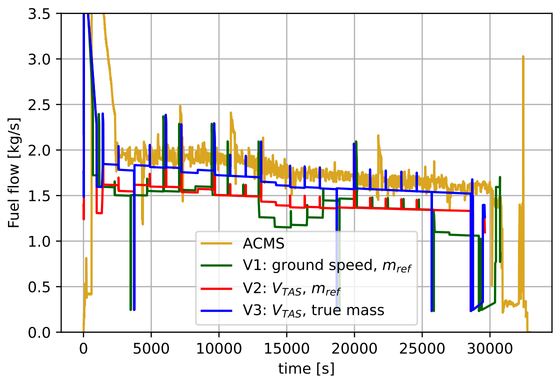
(a) Complete and simplified coordinate points



(b) Complete and simplified altitude points



(c) Recorded altitudes



(d) Recorded fuel flow

Figure 12: Simplified points and simulation results for the flight KL0679 Amsterdam (EHAM) - Calgary (CYYC) on 25-09-2021

Appendix D: Simulation

The following details the method in which the simulation aspects of the project have been carried out. It includes the rationale behind the simulation as well as the inputs, processing and outputs of the open source air traffic simulator BlueSky [1].

Rationale

As explained in the Preliminary Thesis Report, the low frequency in the trajectory data points makes the fuel computation directly from the pandas DataFrame extremely coarse, for which a simulation environment is needed to propagate the state of the aircraft and compute the fuel flow at a sensible timestep. For this reason, BlueSky is used. In order to implement it with the rest of the project, specific files and a plugin are needed. These are discussed in the following.

Inputs

The main input given to BlueSky are scenario (scn) files, which are used to easily repeat and change an initial condition and, for the purposes of this research, to input at once a specific set of flights with initial conditions and the trajectories to follow. The scenario file contains the commands given to each individual flight ordered by time.

The entire trajectory of each flight is described by the commands `CRE`, `ADDWPT` and `ATDIST`. First, `CRE` is used to define the initial condition of the flight, and specifies its coordinates, altitude, heading and calibrated speed. This command is executed at the time of the first entry of the flight or, in the case of long-haul flights starting the trajectory the day before the one considered, it is created at 00:00 for simplicity. Secondly, each waypoint of the trajectory to follow, whether it is historical or hypothetical, is input as an `ADDWPT` command. This specifies the target coordinates, altitude and airspeed of the flight at hand. All waypoint commands are input after the `CRE`, each one a second after another to ensure the correct sorting between all entries. Lastly, it is desired for the flight to be deleted once the last waypoint is reached. If the `DEL` command was to be used, however, inaccuracies in the trajectory or simply the different flight paths used by the hypothetical trajectories of Experiment 1 make the time to execute this command uncertain. To circumvent this problem, the `ATDIST` command is used to delete the flight when it reaches the last waypoint. Finally, in order for the flight to follow the commands, lateral and vertical navigation are switched on, essentially hooking the autopilot up to the FMS with the commands `LNAV ON` and `VNAV ON`.

Once the trajectories of all flights considered have been described and all commands have been sorted by time, a few extra commands are needed. First and foremost, the log recording the information needed is created with `CRELOG FUEL 1`, which creates a log called 'FUEL' with a timestep of 1 second, i.e. recording the data of all flights each second. Then, the data needed (flight id, fuel flow and work) is added to the log with `FUEL ADD traf.id, traf.perf.fuelflow, traf.perf.E`, with the latter implemented in perfbada.py for the purposes of this project. Then, the log is switched on and off at the start and end of the scenario file with `FUEL ON` and `FUEL OFF`, respectively. Additionally, the FUA can be displayed using the command `POLY`. One last custom command `PLAN` is needed for Experiment 2. It specifies the FUA, plannability concept and combination of independent variables, such that the plugin surplus.py retrieves the corresponding csv file containing the value of the surplus weights to be added to the flights of the scenario at hand. These are all summarised in the example scenario file below (Listing 4).

```
00:00:00>PLAN cs1,06
00:00:00>POLY ALPHA, [lat_Alpha_1 lon_Alpha_1, lat_Alpha_2 lon_Alpha_2, ...]
00:00:00>POLY DELTA, [lat_Delta_1 lon_Delta_1, lat_Delta_2 lon_Delta_2, ...]
00:00:00>CRELOG FUEL 1
00:00:00>FUEL ADD traf.id, traf.perf.fuelflow, traf.perf.E
00:00:00>FUEL ON
11:52:48>CRE KL1 A333 53.79 -2.28 281.86 38406.1932 246.818
11:52:48>CRE KL2 B747 53.79 -2.28 250 38406.1932 268.861
11:52:49>ADDWPT KL1 54.19 -4.72
11:52:49>ADDWPT KL2 52.32 -5.12
```

```
11:52:50>ADDWPT KL1 54.46 -7.19
11:52:50>ADDWPT KL2 50.16 -6.18
11:52:51>ADDWPT KL1 54.69 -9.67
11:52:51>ADDWPT KL2 47.11 -10.34
11:53:22>KL1 ATDIST 54.69 -9.67 5 DEL KL1
11:53:22>KL2 ATDIST 47.11 -10.34 5 DEL KL2
11:53:23>KL1 LNAV ON
11:53:23>KL2 LNAV ON
11:53:24>KL1 VNAV ON
11:53:24>KL2 VNAV ON
23:59:00>FUEL OFF
23:59:59>HOLD
```

Listing 4: Scenario file example

Having discussed the scenario files, two more inputs can be discussed. These are the csv and BADA files. First, as many csv files as concepts and independent variable combinations of Experiment 2 are created and added to the plugins\surplus_fuels folder of BlueSky. While different trajectories are considered for Experiment 1, the trajectories of the flights are constant through all concepts of Experiment 2. Thus, the only difference of the scenario files for different concepts of Experiment 2 (of the same FUA and date) is the `PLAN` command, used to retrieve the different csv files. Each concept and combination of independent variables has a corresponding csv file containing a list of all flights considered (those traversing the FUA during a delegated period) and the weight of the surplus fuel taken. For simplicity, this is done for all flights, with those not taking the surplus having a surplus fuel weight of 0 kg. Each of these files make the scenario run differently each time, by means of the plugin discussed in Appendix E. Lastly, the files of BADA 3.12 are also used as input for aircraft performance.

Processing

Using the inputs described above, BlueSky simulates the initial conditions given as commands and computes the fuel flow and work for each timestep based on the aircraft performance coefficients from BADA. On the one hand, the fuel flow calculation is already present in perfbada.py. On the other hand, the work calculation has been implemented by multiplying the thrust times the increment in distance at each timestep; the latter calculated with the true airspeed and timestep in seconds.

For Experiment 2, the processing is done using the plugin surplus.py. This is a simple module created to read the corresponding csv file as given by a `PLAN` command and, with each new aircraft created, the unique identifier is searched in the csv file read for the concept at hand. Once found, the corresponding surplus fuel is retrieved and added to the mass variable of the aircraft within the traffic object. This plugin is explained in depth in Appendix E.

Outputs

When creating the scenario file, commands are added to create and turn on a log within BlueSky, which saves the acid, fuel flow and work of each flight in the simulation at each timestep. This log is then retrieved from BlueSky to integrate the fuel flow into fuel consumption in a Jupyter notebook file, as explained in Appendix E.

Appendix E: Software Architecture

This appendix outlines the overall structure of software scripts, files and tools used for the experiments. The blue cylinders represent databases and results, the orange squares the steps of the methodology and the red blocks external tools outside of the script. The following is divided on a section per experiment, in order of execution.

Script transit.ipynb

The first script to execute is transit.ipynb and its main parts are shown in Figure 13. This selects the subsets of flights to further consider based on their date and whether they transited a FUA sector or not. The inputs of this script are the Flights and Flight_Points_Actual csv files from the Eurocontrol R&D data archive for March 2019, containing all European flights of the month and their trajectories. The aim is thus to find all flights operating during the days of the month with D-0 reservations, and to classify them on making or not making use of the FUA.

The first step therefore consists of selecting all flights operating during a day with D-0 reservations, the latter being taken from the historical records of reservations of the RNLAF. It is thus needed to assign a date of operation for all European flights of the month. For all flights departing and taking off on the same day (flights_samedate), this is clear, and thus all of these operating on a date with D-0 reservations are further considered. For all flights departing and taking off on different dates (flights_diffdate), an extra step must be taken to assign one of the two dates. For this, first it is checked whether the trajectory of the flight has points within a large square around the FUA, with dimensions 47 to 58 degrees latitude and -2 to 11 degrees longitude. If points are found within the square, the date from those points is taken. If not (meaning that the trajectory is far away from Amsterdam FIR) the date of departure is taken. This is approximated as such because 1) the experiments that follow analyse changes in the flight plan, and thus the earlier the point in time considered, the more useful the flight is for the analysis; 2) the previous argument is especially true for these flights which transited considerably away from the FUA, as the deviation must have occurred considerably much earlier in the flight plan; and 3) this approximation is even more acceptable when considering that the flights that do not have points in the square defined above are very unlikely to be considered in any of the experiments that follow, and thus the number of flights for which this decision matters is very low. Finally, after having assigned a date of operation to the flights in flights_samedate and flights_diffdate, all operating on a date having D-0 reservations are grouped in flights_subset and are further considered.

The second step divides all flights of flights_subset (flights operating on a date with D-0 reservations) into three groups: those transiting the Alpha sector, the Delta sector or neither. First, all flights in Alpha and Delta sectors are searched in two main steps. The first step consists of finding all flights with historical points within the FUA. To do this while keeping reasonable computation times, use is made of a preliminary filtering using rectangles. Using the shapely library to check whether each point is within a complex polygon is time-consuming and works on a point-by-point basis. For this reason, only the flights with points within a rectangle limiting the sector are checked with shapely. To further reduce computation times, rectangles are placed within the sectors, and thus if a flight has points in these it is certain that it has points within the FUA and does not need to be checked with shapely either. The second step to find all flights historically transiting the FUA stems from the low-frequency of points of the Eurocontrol R&D data archive: given that the position updates are registered every five to ten minutes, it may be the case that a flight does not have points within the FUA yet connecting them shows the flight to have transited it. In this manner, all flights with points in a large square around the FUA yet without points found within the FUA are checked by creating additional waypoints in-between the historical points. These waypoints are created as a Great Circle Route segment, i.e. assuming that the flight flew directly from point to point registered. The caveats of this assumption are discussed in the scientific paper. Combining the flights with historical points within a FUA sector and those with intermediate waypoints within the FUA yields all flights historically transiting the Alpha and Delta sectors (flights_inALPHA and flights_inDELTA). All remaining flights of flights_subset are therefore deemed as not to transit any of the FUAs considered (flights_notinFUA). The results of this script are thus DataFrames of flights historically transiting Alpha, Delta or none of the FUAs, during a date with D-0 reservations.

Lastly, this process is repeated at the end of the main script to find all flights transiting the FUA sectors during the full month of June 2019. This is done to have a larger pool of flights to consider in the Pairing method of

Experiment 1 (M2.ipynb). There, a pair transiting the FUA is searched for every flight found not to be in it. This part is abridged as the similar trajectories of the Pairing method are compared regardless of the date. In this manner, this additional part of transit.ipynb yields flights_inALPHA_extra and flights_inDELTA_extra, which contain all flights in the corresponding sectors for the full month of June 2019 and are to be used solely by M2.ipynb.

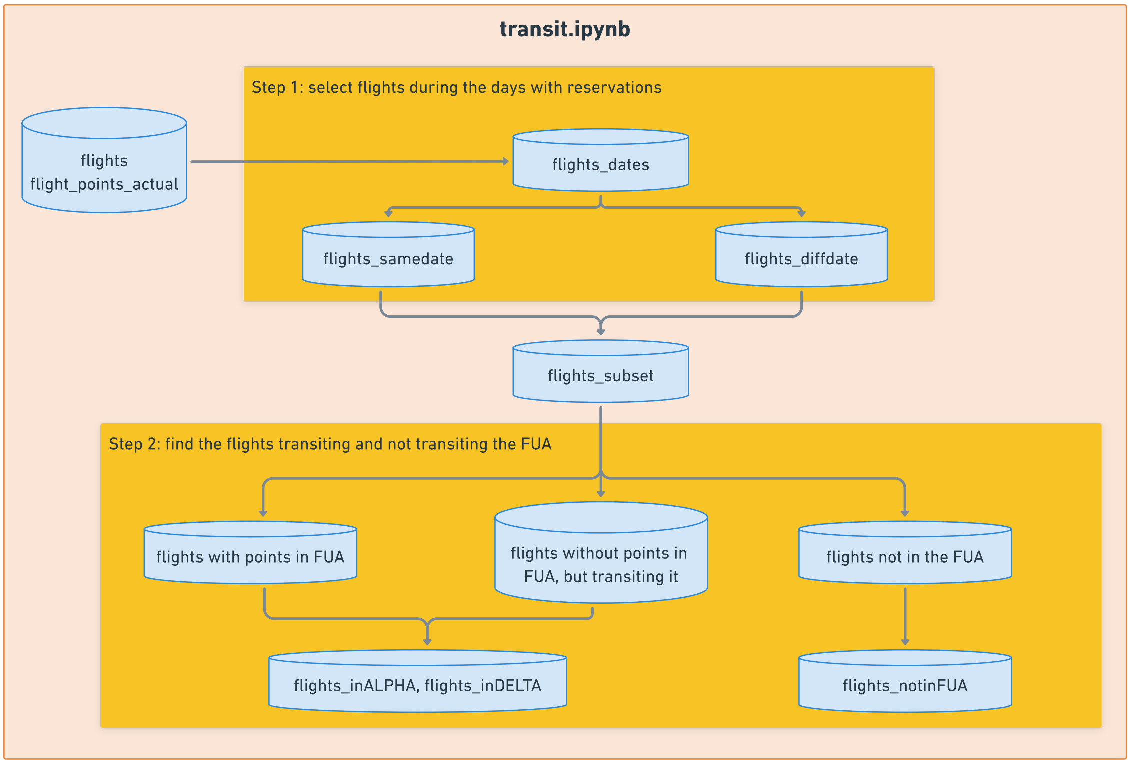


Figure 13: Main components of the transit.ipynb script

Experiment 1

The first experiment consists of the scripts M1.ipynb, M2.ipynb and exp1_results.ipynb, described below.

Script M1.ipynb (GCR method)

The GCR method of Experiment 1, referred to in the code as Method 1 (M1 for brevity) is discussed in the following, with the simplified flow chart detailing its parts shown in Figure 14. The first part of the M1 script consists of finding all flights which would benefit from traversing a FUA sector by means of substituting (part of) their historical trajectory with a Great Circle Route (GCR) segment. For this, the dataframe flights_notinFUA is used as input, which contains all European flights found not to traverse any FUA sector during the days of the sampled time with D-0 reservations, along with the historical trajectories in Flight_Points_Actual. The flights considered thus also contain connections which not only do not transit the FUA, but are also too far away to benefit from it, e.g. a flight Barcelona-Rome. In order to disregard such flights, a first step is to consider only the flights of flights_notinFUA which have points within a rectangle considerably larger than Amsterdam FIR, with dimensions -5 to 15 degrees longitude and 45 to 60 degrees latitude. For each of those considered, the second step is as follows. First, the flight points above FL95 are attained and may be limited to a rectangle around EHAA or a region of Central/Northern Europe based on the independent variable. From the points considered, the last one is taken as the merging point. Next, the points are considered in historical order as the bifurcation point, and a GCR segment is created between the bifurcation and merging points. In other words, a GCR segment is yielded for each point, and the waypoints are checked to be in the FUA. As usual, a preliminary filtering is done on a rectangle limiting the sector: only if the GCR waypoints are found within this rectangle, is the shapely library used to check. For each flight found in a sector, it is saved in the dataframe flights_m1 specifying the FUA and range describing the rectangle used. The common sections between historical and direct trajectories are discarded for efficiency in the simulations, and the resulting (trimmed) trajectories are saved in the dataframes points_m1_his and points_m1_gcr.

Lastly, it must be mentioned that the direct transit is considered on both FUA sectors, which makes the script much more time consuming and, in the cases that a direct segments are found for both Alpha and Delta, the trimmed trajectories are different. For this, the point dataframes are saved by marking the flight identifiers with ‘A’ and ‘D’.

The second part of the script consists of translating the flights and trajectories found in the previous part into scenario files readable by BlueSky. A scenario file is created for all flights corresponding to a FUA (Alpha or Delta sector), date (within those considered from the sampled time), rectangle around the FUA on which the GCR is limited (EHAA, a region of Europe or without limitation) and concept (historical trajectory and GCR trajectory with Original or Optimised speed setting). For simplicity and to better investigate the effects of route efficiency, the speed and altitude are averaged over the points considered, all of them already being above FL95. The calibrated airspeed used by BlueSky is converted from the true airspeed. Since the latter is not available, no wind is assumed and the ground speed is used instead, which is calculated from the coordinates and times of the historical entries. The Optimised speed setting is calculated as explained in the scientific paper and using the BADA coefficients. This results in 324 scn files, as yielded from the combination of the 2 FUA sectors, 18 dates, 3 range options and 3 concepts considered. The information given in the scn files is discussed in Appendix D.

Outside of the script, the scn files are placed in BlueSky, in a folder named sceario/eneko/AV/M1/ (otherwise the batch file batch_m1 does not find them). The batch file can be placed simply in the folder scenario/. Running the batch prompts the simulation resulting in 324 log files as output, to be analysed in exp1_results.ipynb.

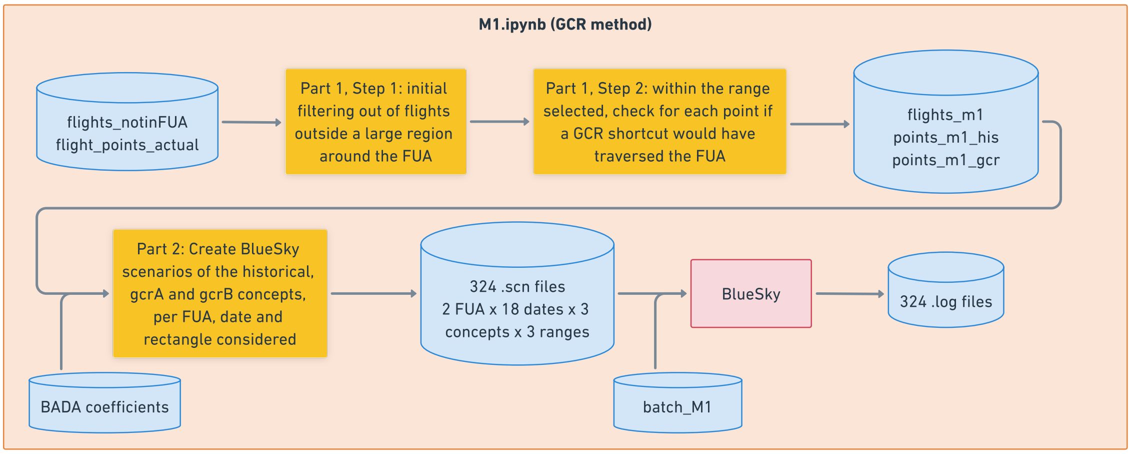


Figure 14: Main parts of the M1.ipynb script, the GCR method of Experiment 1

Script M2.ipynb (Pairing method)

The Pairing method, as explained in the scientific paper, compares the flights found not to traverse the FUA with other historical flights transiting it. Like the GCR method, this script has two main parts: the search and acceptance of the similar flights and conversion of the ones found into scenario files readable by BlueSky. The main components of this script are thus shown in Figure 15.

The first part starts in the same manner as the Pairing method: filtering out the flights without points in a large region around the FUA, so as not to unnecessarily check flights which, although they did not transit the FUA, they could not have benefited from their availability anyway (Step 1). For all flights still to consider (hereby referred to as original flights), each is taken individually and its similar flights are found in Step 2. The similar flights are those sharing the same departure-destination airports, or vice versa. The pool of flights to choose from are all of the processed sampling in transit.ipynb, and to find as many flights as possible not only the sampled dates of March were processed but also the entire month of June 2019. To compare only the part of the trajectory deviated due to the FUA, the bifurcation and merging points between original and similar trajectories are found (Step 3). This is done by first finding, for each entry of the original points, the closest entry of the similar points. In this manner, each entry has assigned the closest, homologous entry, and the distance between each entry paired is calculated. These distances are a measure of the divergence between the trajectories, and can thus show when the two trajectories bifurcate and merge again. For simplicity, the historical points are split into two parts, before and after (approximating) the FUA, and thus the merging and bifurcation points are the first ones, going from the closest point to the FUA, for which the distance to the closest point calculated reaches a minimum specified.

Once the bifurcation and merging points have been found, the distance flown by each of the (trimmed) segments is calculated (Step 4). The fact that the similar flight transits the FUA does not necessarily mean that this trimmed trajectory (going from bifurcation to merging points) is always more optimal. All similar trajectory segments ought to be more optimal than the original ones, and thus the flight and points are saved in flights_m2, points_m2_his and points_m2_sim only if they are accepted in this step. This adds another caveat to this part: even if a similar flight is found, it may occur that the comparison is not necessarily better given the bifurcation and merging points found, for which less flights are considered in the following than those found in Part 1. Furthermore, the points considered eventually must only be those above FL95, for which the flights are accepted (and thus the distance flown is computed) based solely on those points.

Finally, the BlueSky scenarios are created in the same manner as M1.ipynb, simply without considering an Optimised speed setting. In this case, a total of 72 scn files are created: one per FUA, date and concept (original or similar flight). These are used as input for BlueSky to yield the corresponding 72 log files used in exp1_results.ipynb.

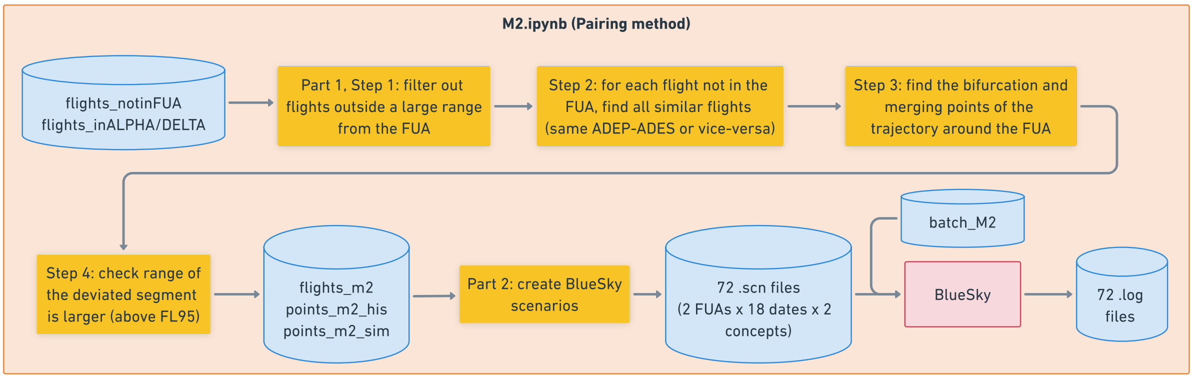


Figure 15: Main parts of the M2.ipynb script, the Pairing method of Experiment 1

Script exp1_results.ipynb

Lastly, exp1_results.ipynb (Figure 16) uses the 324 and 72 log files from the GCR and Pairing methods (M1 and M2 scripts) to yield the results shown in the scientific paper. For this, Step 1 rewrites the log headers for these to be read as a pandas DataFrame. Next, Step 2 calculates the fuel efficiency metrics per concept, whilst filtering out the flights with overshot entries in the fuel flow (Step 2). Finally, Step 3 considers the results of the Pairing method only (deemed the most realistic approximation of the effects of FUA on route efficiency) to classify the number and percentage of flights based on the period of FUA transit (unavailable, delegated and available) and their relation with respect to Schiphol (inbounds, outbounds or none). The results attained are gathered in the scientific paper.

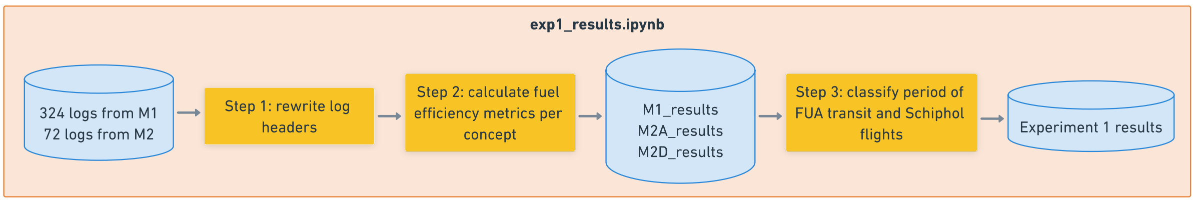


Figure 16: Main parts of the exp1_results.ipynb script, used for Experiment 1

Experiment 2

The second experiment considers the flights transiting the FUA sectors during the periods of time these are delegated to the civil user (i.e. ATS delegations) and finds the benefit in fuel consumption given a hypothetical planning horizon which enabled them to have the guarantee of transit and thus avoid loading a surplus fuel. The main parts of this experiment are done in plan.ipynb, with exp2_results.ipynb quantifying and presenting the results after the BlueSky simulations have been performed with the plugin surplus.py, also presented below.

Script plan.ipynb

The main parts of the plan.ipynb script are outlined in Figure 17. From transit.ipynb, the flights making use of the FUA during the sampled dates of March 2019 have already been found. The first step of plan.ipynb thus consists of finding the entry time in the FUA (simply using the time of the first point found in the sector, or of the nearest one in the absence of the former). Knowing their entry time, the flights transiting the FUA in the delegated periods (i.e. ATS delegations) are found in Step 2, based on the log of D-0 reservations. In Step 2 it is also determined whether each flight would hypothetically carry a surplus fuel or not, based on the proposed plannability concept. The specific methodology of this step is discussed in the scientific paper (Algorithm 2). Once the flights hypothetically loading a surplus fuel have been determined, its weight must be calculated, for which the extra range (additional distance needed to fly around of the FUA) needs to be found. The flights_m2 subset found in the Pairing method is used, as for every flight not making use of the FUA, an alternative one through the sector was there found, and the extra distance recorded. The range that in Experiment 1 was deemed as that which would have been saved by traversing the FUA, is here considered the hypothetical extra range around it. In this manner, Step 3 uses the departure-destination airports for every flight in Experiment 2 to assign an extra range. This is then used in Step 4 to calculate the surplus fuel, which depends on the aircraft data as taken from BADA. The flights taking the surplus fuel depend on the value of the independent variable and concept, for which the surplus fuels and the corresponding flight identifier are saved in a csv file per each concept, regardless of the date, resulting in a total of 64 files. These csv files are saved in the folder plugins \surplus_fuels of the BlueSky project, for the plugin surplus.py to find them. Parallelly, the commands for each scenario file are created for each sampled date, regardless of the concept. Based on the concept, however, the PLAN command is written and thus a scenario saved per concept, independent variable combiantion and date. The simulations of each concept are thus ran in BlueSky by the corresponding batch file, and the resulting logs are saved in \output.

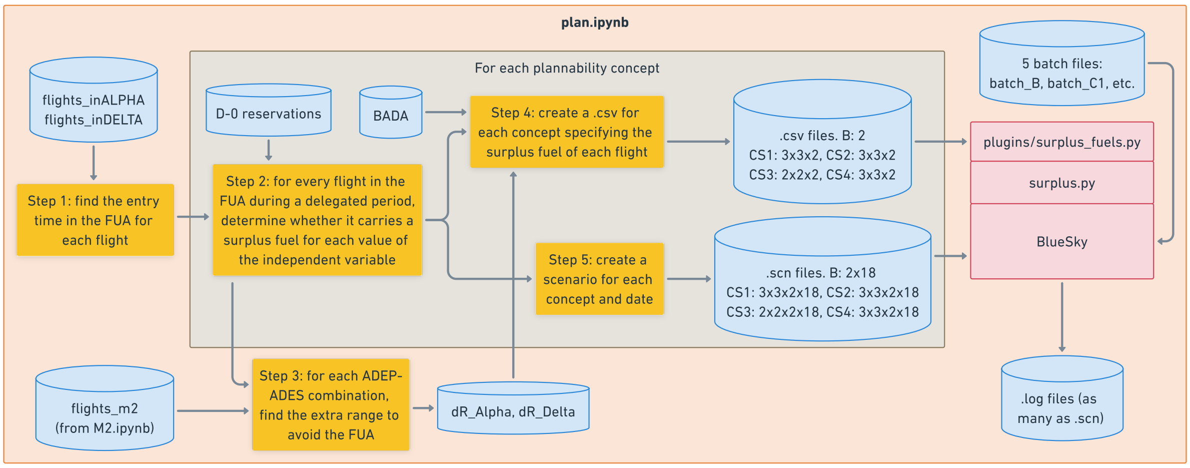


Figure 17: Main parts of the plan.ipynb script, used for Experiment 2

BlueSky Plugin surplus.py

Given the large number of concepts and thus scenario files, the simulations are ran in batches, for which a straightforward manner to open the csv file corresponding to each concept is required. For this, the BlueSky plugin surplus.py has been created to assign to each aircraft its corresponding surplus fuel.

The (simplified) code of the plugin is shown in Listing 5, and consists of the following main steps. First, the plugin is initialised and a new stack function called "PLAN" is created. This essentially enables the scn created by plan.ipynb to call the csv file matching the concept at hand based on the FUA sector and the independent variables. Next, it defines the function named "choose_plannability_csv()" to retrieve the specific csv file based on the variables given after the command PLAN. The csv is read once per scenario and saved as a pandas DataFrame. Finally, the periodically timed function create() is executed every time a new aircraft is created. It retrieves the flight identifier and with it the corresponding surplus fuel is found from the DataFrame of surplus fuel weights.

Using the current mass from BlueSky (BADA's reference mass), the two are summed and thus the total new aircraft mass (original + surplus fuel) is saved once again as traf.perf.mass.

```
# import libraries

current_path = os.getcwd() # relative path
val          = False       # get masses to perform validation (outside Experiment 2)

# Initialisation function of the plugin.
def init_plugin():

    surplus = Surplus()  # Instantiate the entity ''surplus''

    # Configuration parameters
    config = {
        'plugin_name':'surplus', # needs to be added to settings.cfg
        'plugin_type':'sim'      # Specifies this is a simulation plugin
        }
    # create the command PLAN. This is called from the scns to load a specific .csv
    stackfunctions = {
        'PLAN': [
            'PLAN FUA,CX,var1,[var2]',
            '[string,string,float,float]',
            surplus.choose_plannability_csv,
            'Choose the concept of plannability' ]
    }
    return config, stackfunctions

# Entity Surplus
class Surplus(core.Entity):

    def __init__(self):
        super().__init__()

    def choose_plannability_csv(self, *args):

        global surplus_fuel_table

        # Perform validation: get the csv with masses needed to correct wrt ACMS data
        if val == True:
            surplus_fuel_table = pd.read_csv(current_path+"\\plugins\\surplus_fuels\\
    val_mass.csv")
        else:
            # the plan command must be input as PLAN FUA,CX,var1[,var2] without spaces
            info = args[0].split(',')

            FUA, concept     = info[0], info[1] # Get data to determine the concept.

            # Read table containing all surplus fuel weights per ac. No surplus -> = 0
            if 'C' in concept: # For the Concepts
                var1         = info[2]
                if concept  != 'C1': # For concepts 2, 3 & 4 -> get 2nd variable
                    var2     = info[3]
                    filename = '\\surplus_fuels_'+FUA+'_'+concept+'_'+var1+'_'+var2+
                               '.csv'
                else:                # concept 1
                    filename = '\\surplus_fuels_'+FUA+'_'+concept+'_'+var1+'.csv'
            elif concept == 'B':     # For the baseline
                filename = '\\surplus_fuels_' + fua + '_' + concept + '.csv'
            else:
                sys.exit('A wrong plannability command has been input')

            # Having found the filename, read the corresponding table of surplus fuel
            surplus_fuel_table = pd.read_csv(current_path + "\\plugins\\surplus_fuels"
                                     + filename)

    def create(self, n=1):
        ''' This function gets called automatically when new aircraft are created. '''

        # This only works for flights created one-by-one
        acid = traf.id[-n:][0]                # Get identifier and find it in the table
```

```
        current_mass = traf.perf.mass[-n:][0] # Get the current mass

        # Get the entry of the saved DataFrame
        row = surplus_fuel_table[surplus_fuel_table['ECTRL ID'] == acid]

        # find the surplus fuel in the surplus_fuel_table DataFrame
        if len(row) == 0:
            sys.exit('Flight not found in surplus_fuels_table')
            # This should not occur, so used only as flag
        elif len(row) == 1:
            surplus_weight         = row['Surplus Weight'].item()
            traf.perf.mass[-n:][0] = current_mass + surplus_weight
        else:
            sys.exit('Flight found in surplus_fuels_table multiple times')
            # This should not occur, so used only as flag

        #print(acid, current_mass, traf.perf.mass[-n:][0]) # Verification
```

Listing 5: BlueSky plugin surplus.py (simplified)

Script exp2_results.py

Analogously as for Experiment 1, the log files created by BlueSky are retrieved and the results are plotted in exp2_results.ipynb. As before, the log files are modified, and after filtering out the outliers of flights overshooting the fuel flow, the fuel efficiency metrics are calculated for each concept.

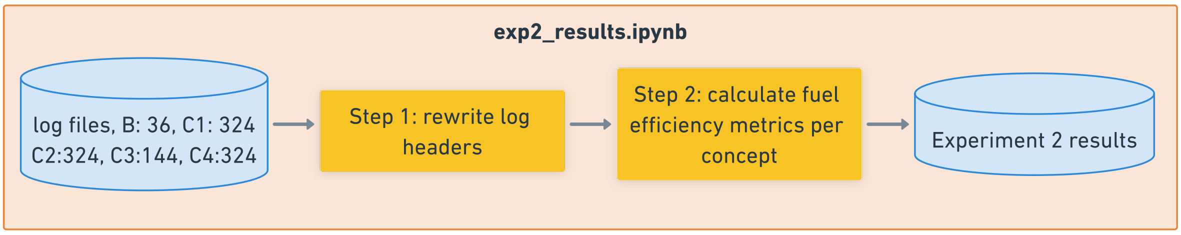


Figure 18: Main parts of the exp2_results.ipynb script, used for Experiment 2

Experiment 3 (exp3.ipynb)

The third experiment requires no further BlueSky simulations as it largely depends on results found in the previous two experiments, for which all its code and results are self-contained in exp3.ipynb, outlined in Figure 19. This first loads the results of exp1_results.ipynb (M2A_results and M2D_results), which relate each flight found by M2.ipynb to its corresponding fuel consumption and work reduction had they transited the FUA. As explained in the scientific paper, only the flights of these subsets losing route efficiency during a delegated period within the AUP are further considered. The only plannability concept proposed here is the AUP Updating concept (Concept 4), and for each combination of their independent variables each delegated period is given a hypothetical announcement time. For each flight, the decision time at which it could have flown through the FUA is assumed to be the time it flies over the bifurcation point (found as its first entry in points_m2_his). If the announcement time takes place before the bifurcation time, it is assumed that the flight attains the tactical route efficiency benefit. Once all flights are checked, the corresponding benefits (found in the simulations of the Pairing method of Experiment 1) are grouped and the results are plotted.

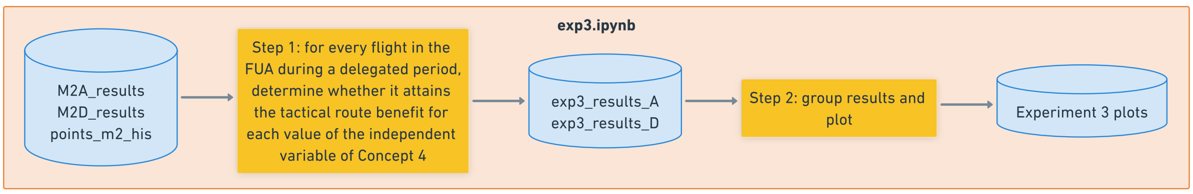


Figure 19: Main parts of the exp3.ipynb script, used for Experiment 3

Results Extrapolation (extrapolation.ipynb)

After attaining the results for all experiments, the extrapolation is done to yield the yearly benefits. As explained in the scientific paper, the process is analogous for all three experiments, differing mainly in the subset of flights used. For this reason, the common steps are shown in Figure 20. Overall, in order to make the results more informed it is the number of flights which are extrapolated instead of the fuel consumption reduction, on the basis of the D-0 reservations of the months not sampled. To verify this procedure is consistent, the first step consists of verifying and establishing a relation between the flights considered and the amount of time reserved during D-0, as shown in the scientific paper. Once this relation has been established, Step 2 extrapolates the number of flights based on the D-0 reservation time of the months of 2019 not sampled. The traffic density varies per month, for which a factor is applied to modulate the extrapolated flights based on the relative traffic density of each month with respect to March (Step 3). Having now the flights, the corresponding fuel consumption reduction is left to be found. For this, an average fuel consumption reduction per flight is calculated from the month sampled (Step 4), and this is applied to every other flight of the non-sampled months (Step 5), yielding the total benefits.

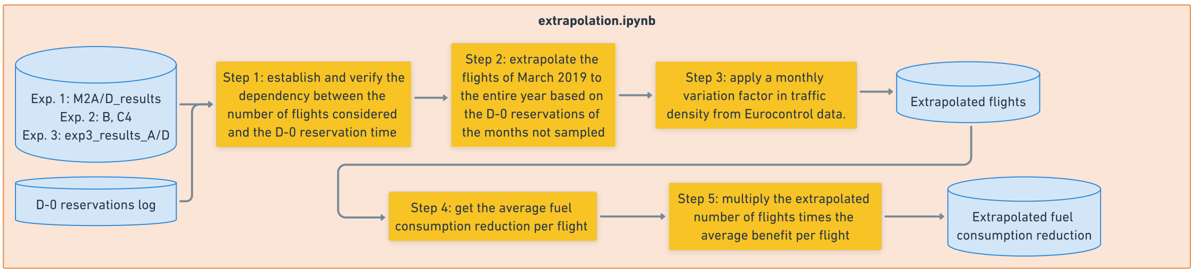


Figure 20: Main components of the script extrapolating the experimental results (extrapolation.ipynb)

Validation of Fuel Flow Calculation Assumptions (validation.ipynb)

Finally, the validation of the assumptions under which the fuel flow calculation is done is carried out in validation.ipynb (Figure 21). Here, ACMS data is taken and the trajectories are simplified as explained in Appendix C. Then, the ground speed approximated for each entry is calculated to be used for validation concept V1 and all concepts (V1, V2 and V3) are input into BlueSky creating one scenario file. In parallel, the gross weight given by ACMS data is compared with the reference mass of BADA to yield the extra mass, and this is saved as the val_mass.csv file used in the same manner as for Experiment 2, yet using solely three flights (V1, V2 and V3). BlueSky thus runs the scenario and yields a log file used to calculate the validation results.

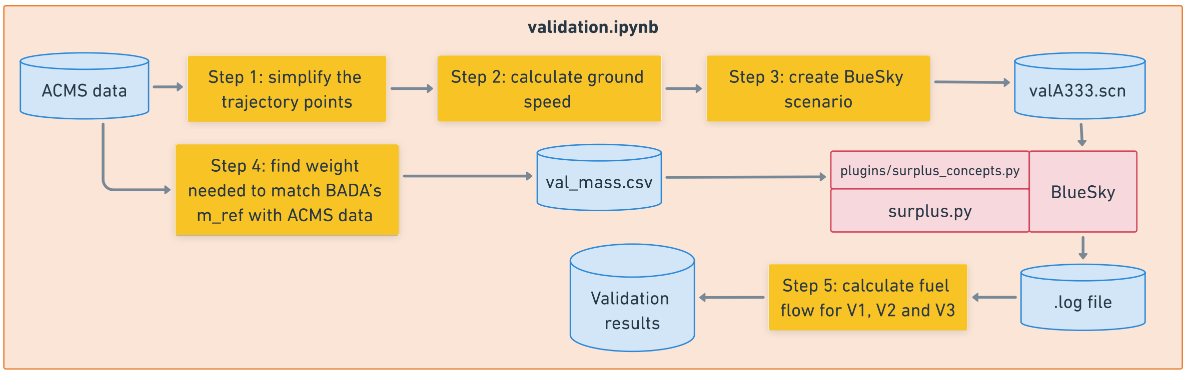


Figure 21: Main components of the script validating the fuel flow calculation under the experiment assumptions (validation.ipynb)

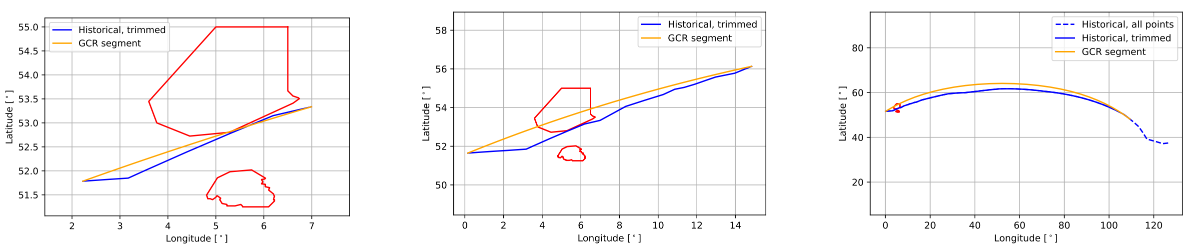
Appendix F: Examples and Comparison of Experiment 1 Methods

This Appendix provides the reader with more examples of the trajectories created in Experiment 1 to assess the influence of FUA on route efficiency. In this manner, examples of the GCR and Pairing methods are considered separately, and then these are compared by showing flights identified by both methods.

GCR Method

As explained in the scientific paper, the GCR method considers all flights found not to transit a FUA but with points in a considerable range around Amsterdam FIR, in order to find the flights losing route efficiency if a Great Circle Route (GCR) segment is created. To test the effect of enabling this GCR segment at different distances from the FUA, the points are considered at two different squares. First, one around Amsterdam FIR (as 2 to 8 degrees longitude and 50.5 to 55 degrees latitude). Secondly, one in a greater region of Europe (as -5 to 15 degrees longitude and 45 to 60 degrees latitude). And lastly, the points are considered without any range limitation. A flight may have a GCR in several of these squares, with a greater range leading to more possible GCR segments and thus more flights benefiting from a direct. The effect of this range can be seen in Figure 22, clearly showing how the earlier the GCR segment is enabled, the greater the route and thus fuel benefits.

More examples of flights found by the GCR method are shown in Figure 23 and Figure 24 for the Alpha and Delta sectors, respectively. These allow to explain some aspects mentioned in the scientific report. First, Figure 23b clearly shows how the flight is only further considered if the GCR segment traverses the FUA, and not necessarily for the entire trajectory. As formerly explained, this leads to the fact that the direct segments found by the GCR method are artificial amendments to an inherently suboptimal trajectory. This can be seen in Figure 23d, Figure 24c and Figure 24e, as these distinctly portray how the GCR method created proposes a very limited shortcut instead of making a truly good use of the FUA sector.



(a) Square around Amsterdam FIR **(b)** Square around a part of Europe **(c)** No range limitation

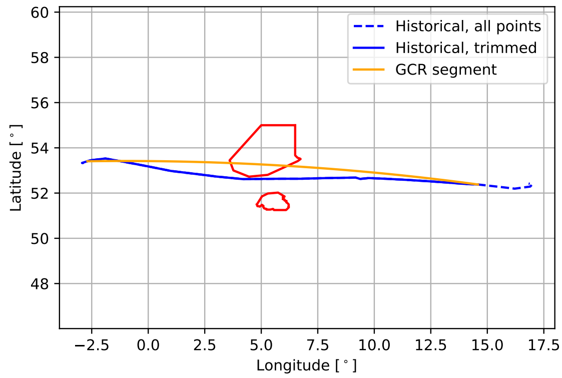
Figure 22: Historical trajectory and GCR segments of a flight RKSI-EGLL (Incheon-London) at different ranges from the FUA

Pairing Method

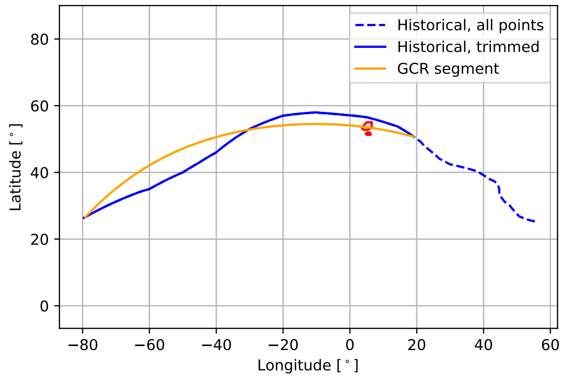
Several examples of flights found by the Pairing method to benefit from traversing a FUA are shown in Figure 25 and Figure 26 for the Alpha and Delta sectors, respectively. Before examining all figures, it is important to consider Figure 25a, as this verifies a caveat of the method used. This method, in order to be time efficient, paired the entries of the original and similar flights solely on the basis of the longitude, and only after accounted for the distance between the entries to accept the similar flight as a good alternative. This led to the question whether the method would perform as well for flights travelling vertically, which is verified in the flights from Bergen to Amsterdam as shown in Figure 25a. For the rest, it can be observed how, despite the similar pair may only result in a small shortcut sometimes (see Figure 25d), in the majority of cases the similar flights make a good use of the FUA transited, with a trajectory often vastly different than the original flight.

Comparison

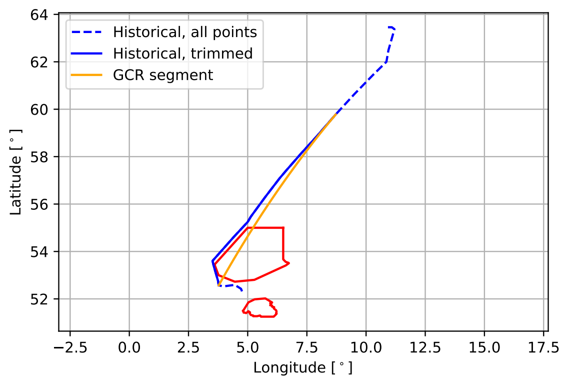
When considering the flights found by both methods, the difference between these can be clearly seen. Figure 27 shows the trajectory segments considered by each method, for the Alpha and Delta sectors on the left and right, respectively. Note that the GCR segments shown are all created without a limiting square. First, it is surprising to see how the GCR segment appears to be quite close to historical flights transiting the FUA in some cases, as shown in Figure 27a and Figure 27b. Nonetheless, in most cases the GCR without any limit proves, as expected, to overestimate the effects of the FUA sectors in Amsterdam FIR on the routing of the flights which could benefit from them, as seen in Figure 27c and Figure 27d. Lastly, Figure 27e and Figure 27f show once again how the GCR segments are created with the first direct traversing the FUA, which often results in limited shortcuts to amend a suboptimal trajectory instead of making a truly good use of the available sector.



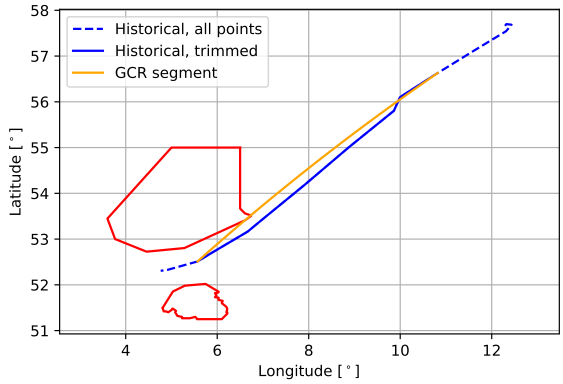
(a) EGGP-EPPO (Liverpool-Poznań); Europe square



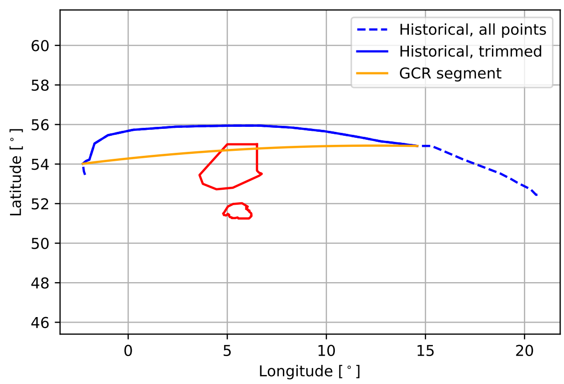
(b) OMDB-KFLL (Dubai-Fort Lauderdale (USA); no range limitation



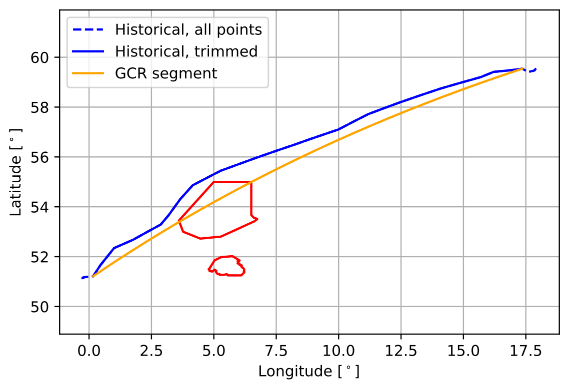
(c) ENVA-EHAM (Trondheim-Amsterdam); Europe square



(d) ESGG-EHAM (Göteborg-Amsterdam); no range limitation

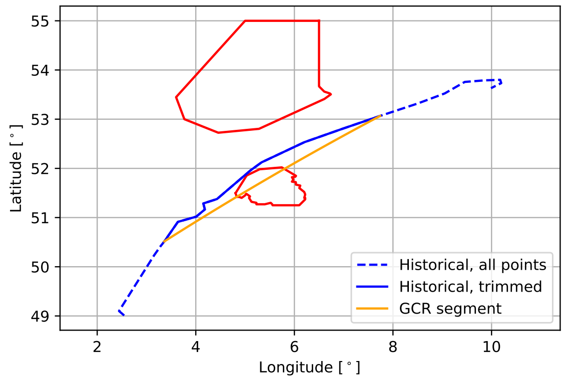


(e) EPMO-EGCC (Warsaw-Manchester); Europe square

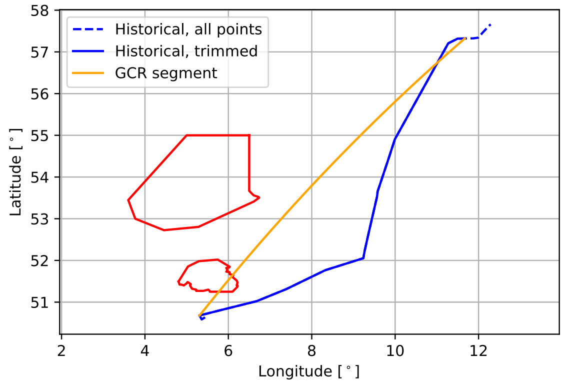


(f) EGKK-ESSA (Gatwick-Stockholm); no range limitation

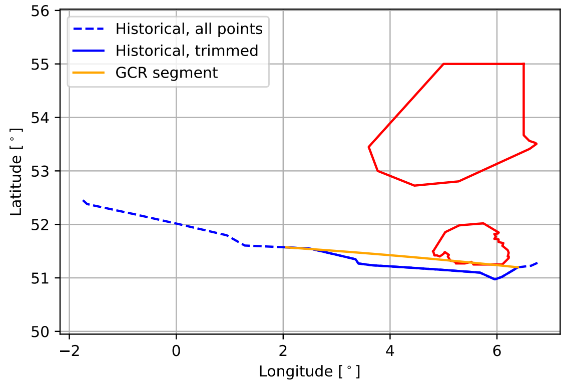
Figure 23: Examples of flights found by the GCR method to traverse the Alpha sector



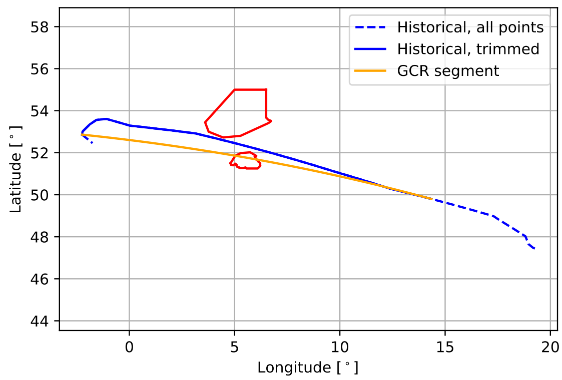
(a) LFPG-EDDH (Paris-Hamburg); Amsterdam FIR square



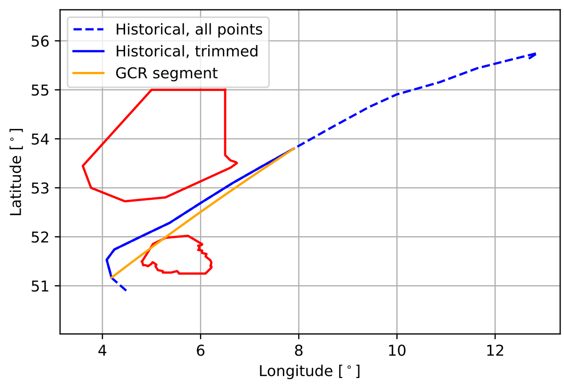
(b) EBLG-ESGG (Liege-Göteborg); Europe square



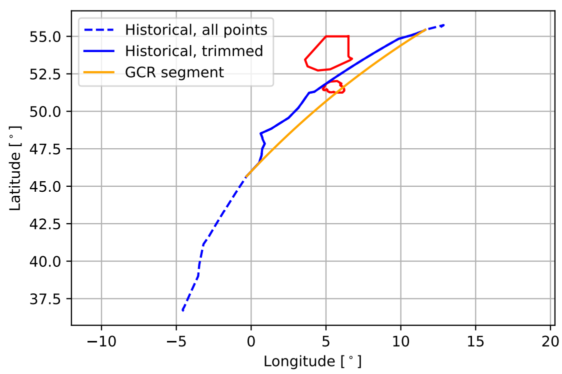
(c) EDDL-EGBB (Düsseldorf-Birmingham); Amsterdam FIR square



(d) LHBP-EGBB (Budapest-Birmingham); Europe square

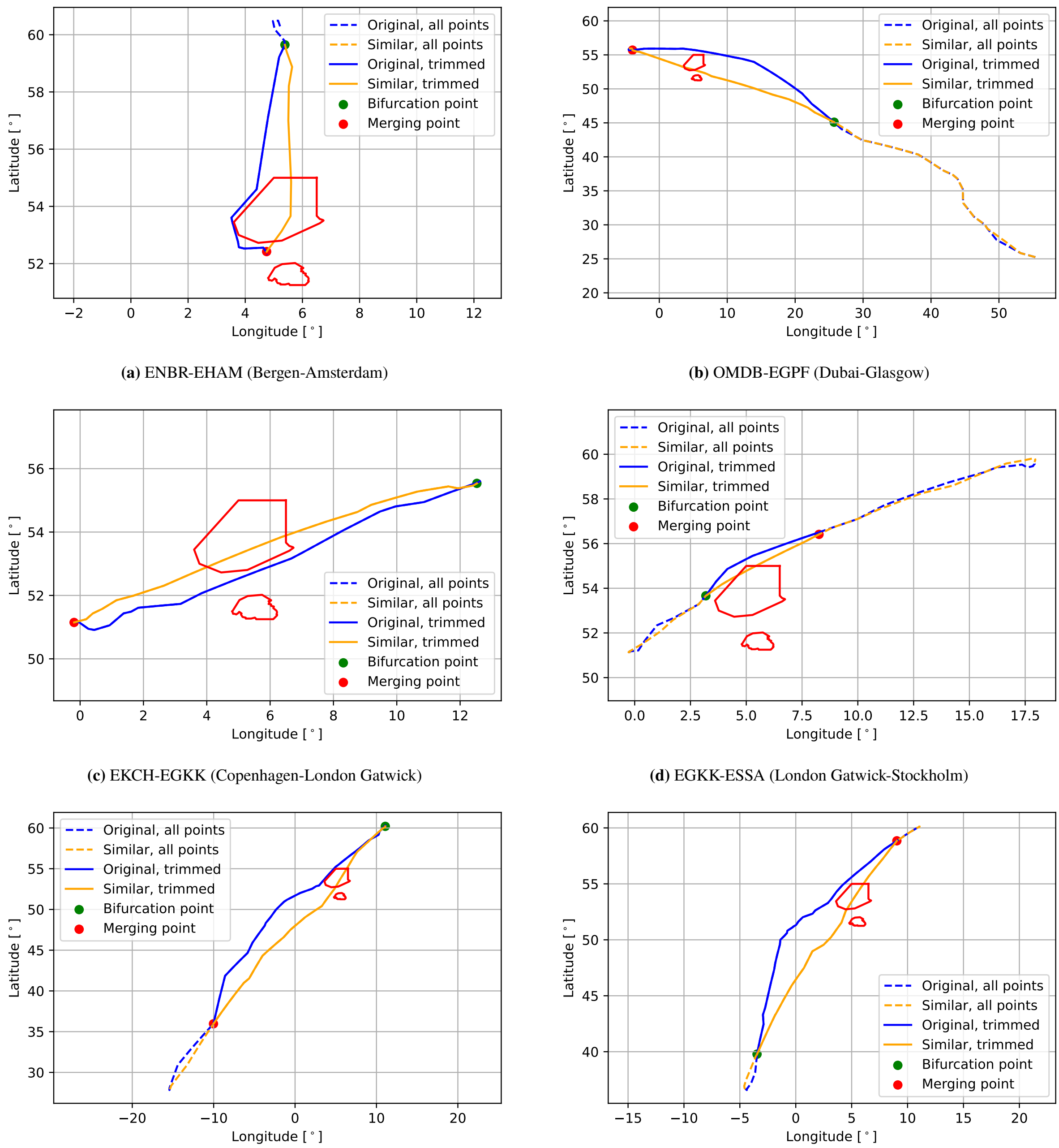


(e) EBBR-EKCH (Brussels-Copenhagen); Amsterdam FIR square



(f) LEMG-EKCH (Málaga-Copenhagen); Europe square

Figure 24: Examples of flights found by the GCR method to traverse the Delta sector



(a) ENBR-EHAM (Bergen-Amsterdam)

(b) OMDB-EGPF (Dubai-Glasgow)

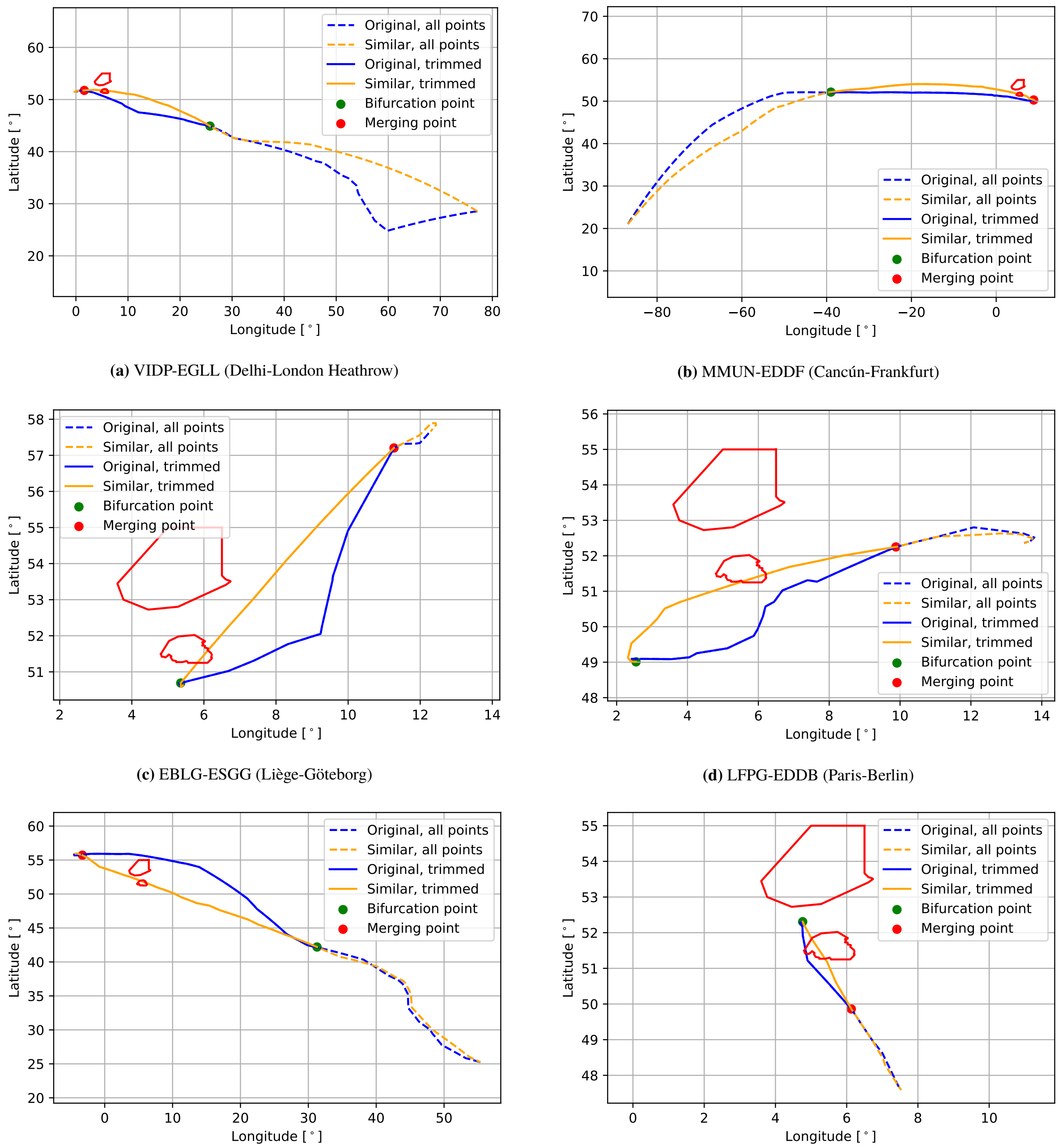
(c) EKCH-EGKK (Copenhagen-London Gatwick)

(d) EGKK-ESSA (London Gatwick-Stockholm)

(e) ENGM-GCLP (Oslo-Las Palmas)

(f) LEMG-ENGM (Málaga-Oslo)

Figure 25: Examples of flights found by the Pairing method to traverse the Alpha sector



(a) VIDP-EGLL (Delhi-London Heathrow)

(b) MMUN-EDDF (Cancún-Frankfurt)

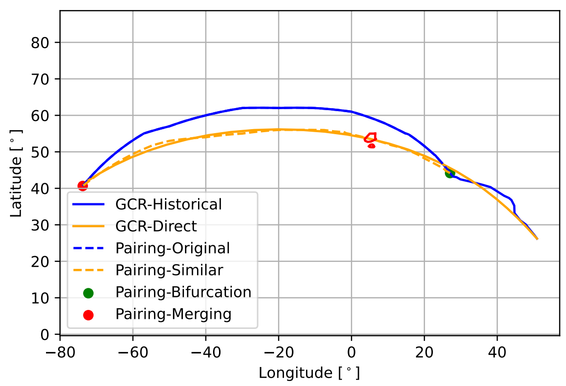
(c) EBLG-ESGG (Liège-Göteborg)

(d) LFPG-EDDB (Paris-Berlin)

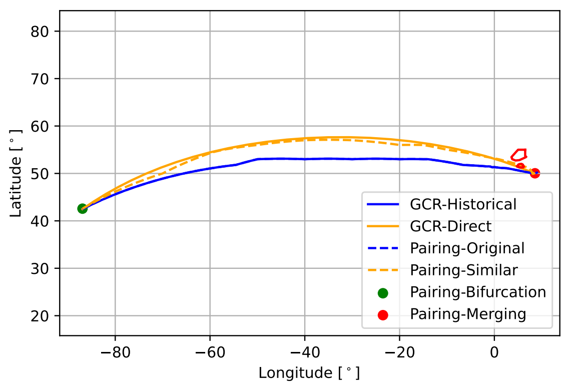
(e) OMDB-EGPF (Dubai-Glasgow)

(f) EHAM-LFSB (Amsterdam-EuroAirport Basel Mulhouse Freiburg)

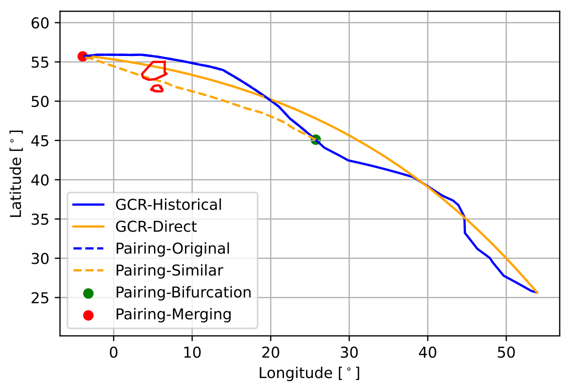
Figure 26: Examples of flights found by the Pairing method to traverse the Delta sector



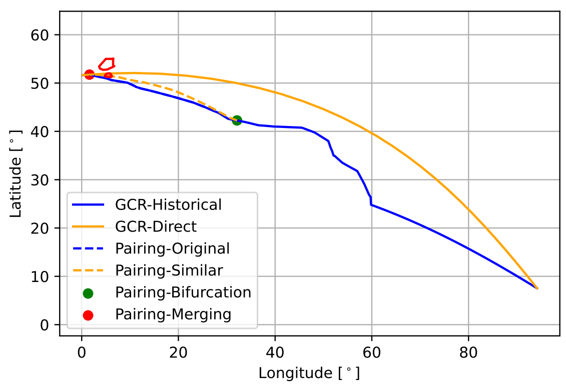
(a) OTHH-KJFK (Doha - New York)



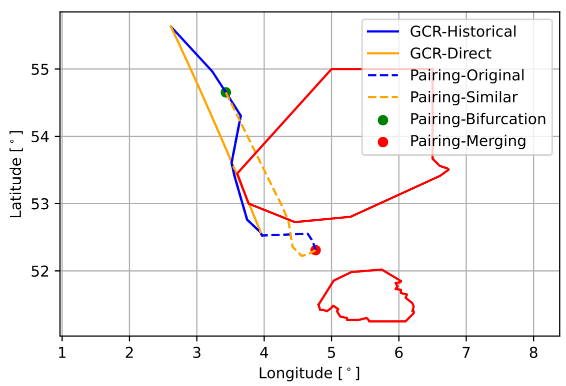
(b) KORD-EDDF (Chicago-Frankfurt)



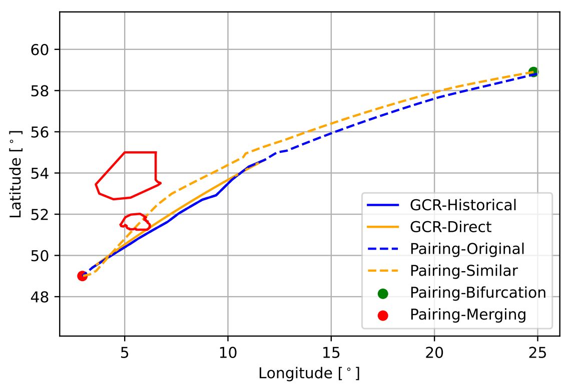
(c) OMDB-EGPF (Dubai-Glasgow)



(d) WSSS-EGLL (Singapore - London Heathrow)



(e) CYVR-EHAM (Vancouver-Amsterdam)



(f) ZSPD-LFPG (Shanghai-Paris)

Figure 27: Examples of flights found by both methods, showing the corresponding trajectory segment pairs considered, for the Alpha sector (left) and the Delta sector (right)

Part III

Preliminary Report (already graded)

1 Introduction

The International Civil Aviation Organization estimates an average Compound Annual Growth Rate (CAGR) in Revenue Passenger-Kilometres in Europe of 2.7% between 2018 and 2050, accounting for the post-pandemic recovery of the aviation industry [2]. This growth of commercial air transport goes hand in hand with more demanding requirements for airspace capacity, route efficiency and airport accessibility. At the same time, the Royal Netherlands Air force (RNLAF) utilises the airspace for training purposes and other missions which call for their own requirements for an effective operation. In order to use the airspace efficiently, this is shared under the concept of Flexible Use of Airspace (FUA). FUA aims to allocate airspace resources in a temporary manner based on user requirements. Despite this objective, the current Air Traffic Management infrastructure lacks the enablers for on-demand and real-time airspace allocation, for which FUA today is limited to specific volumes of airspace being reserved with some plannability. Given its importance to civil-military cooperation and to the effectiveness in the operations of both users, FUA has a major role within the Dutch Airspace Redesign Programme (DARP), which addresses the revision of the airspace routes, sectorisation and procedures. The aspects of FUA the DARP aims to redesign are both in terms of airspace design and plannability. On the one hand, different possible FUA structures are being considered, with the southern one possibly being removed. On the other hand, the rules for making reservations are also being examined, and it is desired to find a new standard of plannability that improves civil efficiency without hindering considerably the flexibility desired by the military user.

In order to support the deliberation of such new policies, this research project is to analyse the effects of both FUA availability (whether a FUA is accessible or not to the civil user) and plannability (the time in advance the guarantee of transit through an airspace originally reserved by the military is given to the civil user) on the fuel efficiency of civil traffic. For this, two experiments are to be carried out tackling each of these main points, and the process from rationale to preliminary results is here presented. This report therefore provides the reader with an introduction to the research, from the general background in literature and operations to identifying the loss of efficiency and proposing alternative concepts with respect to the current system.

This Preliminary Thesis Report is structured as follows. Firstly, the background given in Chapter 2 provides a literature review on FUA and explains the operational problem in depth. Secondly, Chapter 3 motivates the research project by summarising the sources of lost efficiency found and focusing the aim of the research to undertake. Thirdly, Chapter 4 contains the project planning, from the research questions to solve to tangible goals to achieve, as well as laying these out in a feasible and timely plan. Next, Chapter 5 discusses the methodology of the experiments. Finally, preliminary results are presented in Chapter 6 and the future work to carry out is outlined in Chapter 7.

2
Background

This chapter provides the reader with an introduction to the literature and operational background of Flexible Use of Airspace (FUA), with the purpose of identifying a research gap and thus determining what analyses ought to be undertaken. First, Section 2.1 introduces the general concept of FUA, describing it as a key enabler for civil-military cooperation and surveying the related scientific literature. Secondly, Section 2.2 describes in detail how the FUA plannability process works by showing a historical example. Thirdly, future developments of FUA are outlined in Section 2.3 together with their key enablers. Finally, Section 2.4 addresses the Dutch Airspace Redesign Programme and the role of FUA within it as the cornerstone of modern civil-military cooperation.

2.1. Flexible Use of Airspace

The Flexible Use of Airspace (FUA) concept considers airspace a continuum to be shared by several users whereby any segregation can only be temporary and based on real-time usage. As established by the International Civil Aviation Organization (ICAO) [3], airspace under the FUA concept is no longer classified as entirely civil or military, but is allocated according to airspace user requirements, such that these are met to the best possible extent. Presently, FUA practices are not as ideal as the concept definition implies, yet innovation in ATM continues to develop FUA into more advance forms, as it has since it was first introduced in the ECAC area in 1996 [4].

This first section aims to give an overall introduction to the FUA concept. For this, FUA is first dissected in Section 2.1.1 into the several forms it can appear as. Next, the role of FUA as a pillar of civil-military coordination is explained in Section 2.1.2, which introduces the dichotomy between plannability and flexibility of airspace. Lastly, this is followed by a review of academic literature on FUA in Section 2.1.3, where the main research fields within FUA are considered.

2.1.1. FUA Structures

Flexible Use of Airspace is enabled by a series of airspace structures created to be used temporarily, based on reservations or other conditions. While each country has their own specific set of FUA structures, the following serve as a common denominator outlined by Eurocontrol [4]:

- **Conditional Route (CDR):** non-permanent Air Traffic Service (ATS) routes complementing the permanent route network, which can be planned and used with a reservation or specific conditions. There have been three types historically, outlined below, which are to be replaced by a single CDR category.
  - **CDR 1**: permanently plannable CDR during the times published in the Aeronautical Information Publication (AIP), with amendments made the day before operations on the Airspace Use Plan (AUP) and Updated Use Plans (UUP). Examples of these are M90, UN852, Z708 and Z733.
  - **CDR 2**: non-permanently plannable CDR. Contrary to CDR 1, flights may be planned for these routes only according to conditions published on a daily basis, and they are not used in Amsterdam FIR.
  - **CDR 3**: non-plannable CDR, which civil traffic can only use when a tactical clearance is given. In other words, flights cannot be planned on these routes, as they are only available during the tactical phase when the military decide they do not want to make use of them.

- **Temporary Segregated Area (TSA):** airspace temporarily segregated for the exclusive use of an airspace user during the interval of time reserved. As oppose to the later mentioned Temporary Reserved Airspace, a TSA does not enable the possibility of giving ATC clearance to other users while the airspace is segregated. Examples of TSA in Amsterdam FIR are for instance EHTSA1A and EHTSA1B (De Peel A and B). It must be noted that the rest of TSA regions are significantly small in comparison to other FUA airspace structures, and some are only activated during holidays.
- **Cross-Border Area (CBA):** Temporary Segregated Area spanning different countries. Despite the fact that the availability of some CDRs depends also on military activity in Belgium, the only CBAs formally implemented in Amsterdam FIR are shared with Germany (EUCSEA1 and EUCSEA1L).
- **Reduced Coordination Airspace (RCA):** used when Operational Air Traffic (OAT) is of low density, therefore allowing General Air Traffic (GAT) to operate outside the route structure without requiring coordination between OAT and GAT controllers. These are not implemented in Amsterdam FIR.
- **Restricted areas:** these are defined as areas where the aircraft transit is not prohibited but may be used if specified conditions are complied with. An example of such structure in Amsterdam FIR is EHR8 (Den Helder).
- **Danger Areas:** these are defined as regions of airspace where potential danger exists at specified times. In practice, this also leads to their restriction due to military activity. Examples of such areas are the FUA in the north of Amsterdam FIR, e.g. EHD01 to EHD09.
- **Temporary Reserved Airspace (TRA):** similar FUA structure as the TSA, where the airspace is given to the user that made the reservation. Nonetheless, while the TSA was used exclusively by the user reserving the region, the TRA may still be used by other users subject to ATC clearance. An example of such structure is EHTRA10, located in Nieuw Milligen TMA A.

2.1.2. The Role of FUA in Civil-Military Cooperation

The concept of Flexible Use of Airspace is at the very core of civil-military ATM cooperation and coordination. This is because it enables a shared airspace continuum to be used by each party according to their needs and objectives. On the one hand, the objective of civil aviation is to support the economic interests of both business and customer stakeholders. On the other hand, military aviation aims to train efficiently to develop defence capabilities and thus protect national and international security [5]. Despite both of their interests can be summarised as striving for efficiency, their requirements on FUA are very different. In the following, the distinction is made between availability and plannability of FUA. While availability is whether the airspace is usable or not by an airspace user, plannability represents the time in advance the airspace was planned to be available.

FUA Availability

The availability of FUA for civil use brings the following benefits. First, the distance flown is minimised, as the trajectories become more optimal, thus reducing fuel burnt and emissions. Further, the larger the volume of the airspace, the more aircraft can fly through the corresponding sector while maintaining a reasonable level of ATCO workload, thus increasing capacity and reducing delays.

For military use, the availability of FUA is required for the successful completion of the training curriculum and other missions. This availability is not only relevant in terms of volume but also in terms of the interval of time the airspace remains segregated. Further, the segregated airspace needs to also be available sufficiently close to the base, as the longer the time it takes to reach the training site, the less time is left for training [6].

FUA Plannability

On the one hand, plannability of the airspace plays a major role in the operation of civil traffic, as it allows to optimise trajectories well in advance, predict the demand in sectors and distribute better the flow. It is therefore desirable to plan as far in advance as possible and adhere to these plans during the day of operations.

On the other hand, efficiency in the operations of military aviation comes from a good flexibility. Due to the dependence of military missions on the availability of equipment, weather conditions, mission specific objectives, geographical aspects and support resources on land or sea, it is beneficial for them to have as much airspace available until the day of operations [6]. The more airspace is reserved, the better the chance of having the desired conditions and with them a successful training, for which the RNLAF benefits from keeping the airspace for as long as possible and making it available for civil use only when they are sure they do not need it.

One Concept, Contradicting Requirements
In summary, while the aforementioned concept of FUA is to allocate airspace on the basis of user requirements, it has been found that these requirements actually contradict one another. When it comes to FUA availability, each user benefits from having as much airspace as possible, while the other hinders its efficiency because of it. For FUA plannability, the military user benefits from flexibility, which opposes the plannability desired by the civil user, and vice-versa. This results in a civil-military cooperation that utilises the same tool under inherently conflicting interests.

2.1.3. Survey of Academic Literature on Flexible Use of Airspace
The vast majority of the academic literature considering the current FUA system focuses on studying the decision support tools and Collaborative Decision Making (CDM) infrastructure to improve the allocation of the airspace to different parties. For instance, Krozel [7] investigates a novel mechanism to streamline the airline user preferences into an amended flight plan such that a more dynamic communication structure between parties is achieved and thus the airspace is better utilised. It also explains that a significantly higher benefit for civil traffic is achieved if the right of transit through a FUA is given prior to loading the fuel, an idea which will be further explored in the following section. A tool for the similar purpose of making the airspace more dynamic is proposed by Torres [8], where contingency plans are created to update the flight plan such that these can be used in case a FUA becomes inactive. The closer the civil aircraft is to the FUA that is turning inactive, the less optimal the contingency plan will be. Further, Kodera [9] suggests how the current Network Manager function could be used to implement changes on the flight plan en-route to utilise recently given up FUA while the aircraft was in transit, under the Free Route Airspace concept. Lastly, Birdal [10] considers machine learning algorithms for a strategic allocation of the airspace given airspace user needs.

While these studies focus on improving operational aspects of the communications and logistical infrastructure, they indicate, together with Mihetec [11], that the decisive levels of airspace management for FUA are pre-tactical and tactical. The benefits for civil aviation attained there are twofold. First, if it known that the FUA is deactivated after the aircraft has fuel has been loaded, this may still benefit from more direct routing thus saving some fuel (tactical phase). Nonetheless, the aircraft had no right of transit through the FUA when the fuel was loaded, for which extra fuel had to be carried to fly the expected detour. This extra fuel increased the weight of the aircraft, increasing the amount of thrust needed and thus fuel was burnt simply to carry the surplus fuel. If it is known that the FUA is inactive before loading the fuel, however, the greatest fuel benefit can be achieved as the aircraft carries only the fuel needed.

2.2. FUA Plannability
The requirements and benefits of FUA plannability of civil and military users have been introduced in Section 2.1.2. This section serves as an explanation on how the planning process works, and its consequences. For this, the current practices of FUA plannability in the Netherlands are first outlined in Section 2.2.1, to which an example from historical data is given in Section 2.2.2 to illustrate the reservation and usage process. Finally, the effects of plannability on civil traffic are outlined in Section 2.2.3.

2.2.1. Current Practices of FUA Plannability and Usage
The idea of FUA plannability is that reservations can be made by the different stakeholders, from months to hours in advance, such that these are always updated according to the user requirements. These requests or changes in reservations are sent to the Airspace Management Cell (AMC), currently the FUA Cell LVNL (FC-L) and FUA Cell MUAC (FC-M), staffed by the Royal Netherlands Air Force. This cell carries out the allocation based on the Booking Procedures and Priority Rules (BPPR). These BPPR are the rules under which a stakeholder has priority for reserving an airspace region, which may vary depending on the time of the reservation, and establish which booking process is applicable to each area [6].

Nonetheless, the current BPPR establish that the military user has priority over the civil one, and there is no requirement for a plannability horizon in which they must give up the unused airspace. Given that, as explained in Section 2.1.2, keeping the airspace works in the benefit of the military user, they currently have no reason to do otherwise. This results in three main stages of FUA plannability, outlined in the following.

- Six months in advance (D-180): the standard times of reservation are laid out. It is common that the military reserve all areas they can for as long as possible. These standard schedules remain the norm throughout the following months and are published in the Aeronautical Information Publication (AIP).

- The day before operations (D-1): the availability of the conditional routes is published in the Airspace Use Plan and Updated Airspace Use Plans (AUP and UUPs). There, it usually appears that the Conditional Routes traversing the FUA at hand are closed for a smaller period of time, meaning that the FUA is closed for less time than that which was formerly established in the AIP.
- The day of operations (D-0): the FUA closing period of the AUP/UUPs are further detailed into smaller intervals as the day progresses and the military user decides not to use the region during specific periods of time. This results in transit around these intervals which was only announced throughout D-0.

2.2.2. Example: EHTRA10 Plannability

To illustrate the stages of FUA plannability outlined above, a historical scenario can be used. For this, September 6^{th}, 2021 was examined, combining radar data with the reservations of EHTRA10, one of the most reserved areas in Amsterdam FIR. The reservation data is taken from the AIP, the AUP and the AAA (Amsterdam Advanced Air traffic control) system log of map activations. These correspond to the three reservations made at three different stages: six months in advance (D-180), the day before operations (D-1) and the day of operations (D-0), respectively. Note that the original reservation is referred to as AIP, although this reservation is made with six months in advance and the AIP is published with a higher frequency. Nonetheless, since usually no changes are made to this original reservation from D-180 to when the AIP is published, this is referred to as the AIP reservation. Further, note that the logging of map activations from the AAA system is not further used for the experiments of the research. This is because, as it will be explained in Section 5.2, the reservation of the Alpha and Delta sectors overwrite those of the smaller ones. Nonetheless, in order to better illustrate the problem of plannability, it is necessary to present the reader with the logging time at which the reservations took place, for which this system is used for illustrative purposes.

For EHTRA10, the AIP currently establishes its activation from 0600-2200 Monday to Thursday, and 0600-1500 on Fridays, UTC time, and this is assumed to hold for the sample at hand. As aforementioned, this is the original reservation, usually made six months in advance (D-180) by the Royal Netherlands Air Force, although the AIP is published much later. The AUP published for the fifth of September (the day before operations, so D-1) announced the closure of Z708 and Z733, the routes traversing EHTRA10, only from 0600 to 1500, i.e. allowing the transit between 1500 and 2200 which was not guaranteed before D-1. Lastly, the AAA map activation log for the 6th of September (the day of operations, so D-0) shows the logging times summarised in Table 2.1 for EHTRA10.

Logging time	Start time	End time
2021-09-06 06:16:10	07:00	10:30
2021-09-06 10:10:02	11:30	14:30

Table 2.1: EHTRA10 reservation time intervals (UTC) as logged in the AAA system

This shows that it was first decided to use the region from 0700 to 1030, and only later in the morning another interval was detailed as 1130-1430. In this manner, three intervals have been left for civil use: 0600-0700, 1030-1130 and 1430-1500, yet they were only known throughout D-0. More importantly, even if a D-0 reservation is made, this does not guarantee the transit through the FUA at a later time, as another D-0 reservation could still be made. This information can then be illustrated as shown in Figure 2.1.

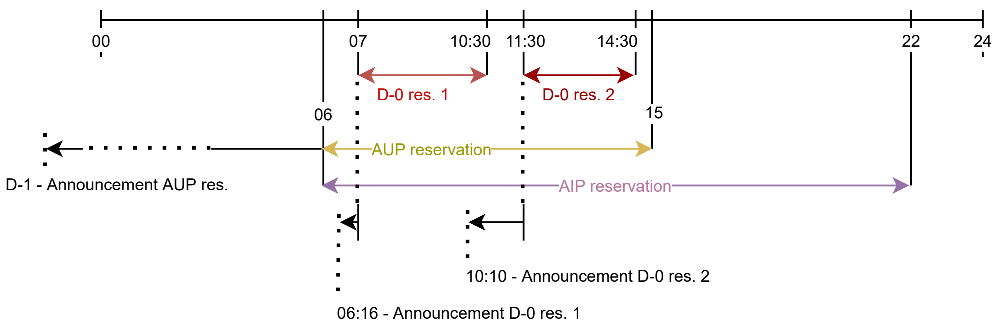


Figure 2.1: Illustrated AIP, AUP and D-0 reservation intervals

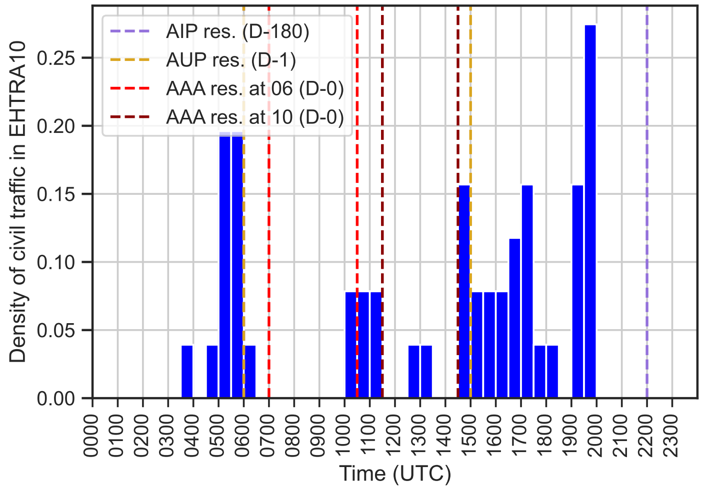


Figure 2.2: Normalised frequency of traffic entry times in EHTRA10, 6th of September

Once the sets of reservations are known, historical traffic data was used to know the actual usage of the region. For this, the open source air traffic simulator BlueSky, developed by Hoekstra [1] was used in combination with the plugin sectorcount.py and historic traffic data from radar, as provided by LVNL. The entry of each aircraft in the region was recorded and their frequencies are shown in the histogram of Figure 2.2.

Several conclusions can be drawn from this histogram. Firstly, even within the final reservation times there is civil traffic traversing EHTRA10. This mainly occurs at the start or end of the reservation intervals, as trainings start later or end sooner than expected, shown by the traffic between 10:00 and 10:30. This may also occur sporadically as a result of the military training taking place in another region for a certain time, resulting in ATC clearance given to civil traffic, shown in the traffic between 12:30 and 13:30. These show that civil-military coordination takes place at all times. Secondly, outside the reservation intervals of D-0 but within the reservation interval of the AUP (i.e. the intervals of 0600-0700, 1030-1130 and 1430-1500, are those flights transiting the FUA without a previous guarantee of transit, as having it would eliminate the military flexibility to add another interval, for which only the tactical benefits could be attained. Thirdly, outside the AUP reservation but within the AIP reservation (i.e. 1500 to 2200) are those flights that gained the guarantee of transit only after D-1.

This comes to show that although civil-military coordination allows some civil traffic to traverse the FUA as long as it is not used by the military user (even within the final reservations), a significant number of civil flights do so without a previous guarantee of transit. The following subsection outlines the effects of this plannability.

2.2.3. Effects of FUA Plannability on Civil Traffic

Even if the trajectories of flights through the FUA may eventually end up as the same, the time at which the guarantee of transit is given has effects on the performance of civil aviation. The following outlines the main performance areas in which FUA plannability has an effect.

Fuel Efficiency

Even if transit through the FUA is tactically enabled, the aircraft is loaded with the fuel required to fly the route specified by the last flight plan, issued three hours before the time at the gate (H-3). If the right of transit through the FUA is given after H-3, the detour route is assumed and the fuel is loaded accordingly. From interviews with ATC Operators, it is understood that transit through the FUA is usually allowed as soon as the FUA is delegated for civil traffic, for which the trajectory flown by the aircraft may be assumed the same regardless of when the right of transit is guaranteed. In other words, the penalty of a low plannability may be assumed to be captured by analysing the effect of flights taking the surplus fuel under identical trajectories. For flights not transiting the FUA during the intervals delegated to civil traffic, the penalty is taken as problem of route efficiency and contained within the aspect of FUA availability. The plannability penalty can thus be represented by the loading of a surplus fuel for the flights the last flight plan of which was issued before the guarantee of the transit was given. Else, if the guarantee of transit is given before H-3, the aircraft has a strategic benefit and carries only the fuel needed for the shortcut, i.e. no surplus fuel. A surplus fuel increases the aircraft weight and thus the thrust needed, leading to an increase in fuel burnt and emissions.

Sector Demand Predictability
If the uncertainty in whether a FUA is open or not is included in the uncertainty of the trajectory of a flight itself, then the possible entry times of an aircraft into a later sector can differ greatly. If the sector demand is modeled probabilistically, the larger the uncertainty in demand the larger the maximum possible demand in a sector. Once the FUA availability is clear, the range of possible entry times shrinks, reducing the maximum possible demand, even if the expected demand increases. The higher the FUA plannability, the earlier the demand forecast jumps in accuracy. It is this maximum possible demand which may exceed the declared demand in a sector and, in consequence, ATFM measures are applied to smoothen the demand, which result in a loss of efficiency.

Sector Capacity
The larger the airspace available in a sector, the higher the number of aircraft that can be safely handled by the ATCOs. If the availability of a route is known well in advance, a consistent number of additional flights could be scheduled through that sector. On the contrary, if the airspace is assumed to be closed until a few days before the day of operations, these additional flights which could have eventually taken place cannot be offered due to the lack of guarantee of sufficient airspace, thus risking considerable delays. In summary, a better FUA plannability can assist in solving demand and capacity inbalances by integrating the concepts of Airspace Management and Air Traffic Flow and Capacity Management.

Air Navigation Service Provider/ Network Manager Cost Efficiency
The earlier the FUA availability is known, and therefore the sector capacity, the earlier the Air Navigation Service Provider (ANSP) and the Network Manager (NM) can schedule the roster of ATCOs and optimise their productivity.

2.3. Advanced Flexible Use of Airspace (AFUA)

The main inefficiencies found in the current FUA system are the allocation of airspace, often resulting in more airspace being segregated than the military user truly needs, and the inability of the civil user to fully take advantage of new opportunities arising within a short notice. These are all inherent to today's ATM infrastructure. Advanced Flexible Use of Airspace (AFUA) essentially consists of making optimal use of FUA, enabled by tools making relevant and transparent information available to all stakeholders in real-time [12]. AFUA therefore implies a fully dynamic airspace management in the planning and execution phase of every flight, from strategic to tactical phases. It is thus a centralised information sharing enabling dynamic, real-time and transparent collaboration where both civil and military users have a common situational awareness [13], which results in the seamless integration of the airspace management phases. Therefore, a reconfiguration of the airspace division can occur without significantly hindering ATM performance as a result of low predictability [12]. In summary, AFUA would make use of CDM and real-time collaboration to connect Airspace Management and Air Traffic Flow and Capacity Management and thus improve the balance between demand and capacity.

This section is structured as follows. First, Section 2.3.1 outlines the enabling technologies and concepts needed to realise AFUA. Second, Section 2.3.2 delves in greater detail into the last enabler, which may also be understood as the result of all the prior ones: Dynamic Airspace Configurations.

2.3.1. AFUA Enablers

AFUA is, rather than a new concept in itself, the expansion of the current FUA system with advanced technology and concepts. These enablers are outlined in the following.

Trajectory Based Operations
All elements enabling AFUA are all provided by, if not inherent to, a Trajectory Based Operations (TBO) environment enabling System Wide Information Management (SWIM). On the one hand, the SWIM concept can be taken as an intranet for ATM providing all the information relevant to the airspace users in a timely and reliable manner [13], thus enhancing their collaboration. On the other hand, the TBO concept consists of characterising each flight as a series of four-dimensional coordinates: latitude, longitude, altitude and time. In such an environment, a precise knowledge of every flight trajectory is known to all parties. Although this is best exploited with a high plannability, allowing strategic de-confliction of the trajectories, this common situational awareness also means that changes occurring at any moment of the flight planning and execution process can be accommodated and the airspace can still be optimally used by all parties.

Collaborative Decision Making
Further, advanced and extensive Collaborative Decision Making (CDM) will enhance FUA by performing airspace allocation with a better adherence to the objectives of specific airspace users, such as civil flight economy and military mission effectiveness (MME). Moreover, a centralised communication infrastructure will also provide a common situational awareness of the planned trajectories of all airspace users, therefore enabling a continuous and iterative planning over the different airspace management phases. This is known as the rolling process [12].

The Rolling Process
As outlined by Eurocontrol, the increase in predictability that forms the basis of TBO is of key importance for enabling the seamless planning through all airspace management phases that AFUA can benefit from. By having a detailed knowledge of every planned trajectory, the airspace can be optimised for that actual (expected) use. This poses a complete change in paradigm from today's operation, where the airspace configuration is laid out in advance based on a vague plan of the real use and the trajectories are then flown within those bounds. In this manner, an AFUA enabled environment would segregate the airspace as needed based on the trajectories accepted.

This process of requesting, de-conflicting and accepting trajectories is known as the rolling process [12]. It starts with the request of an airspace user to fly a trajectory, known as the Business Development Trajectory (BDT). The BDT is the trajectory the user deems optimal for their own interests, yet does not account for other BDTs from other stakeholders. Once this request is sent to the ATM system, the BDT becomes a Shared Business Trajectory (SBT), as the optimal preference of the airspace user is now subject to changes when considering the rest of trajectories requested to be flown. By means of CDM and de-confliction techniques, the SBTs are changed into feasible trajectories that are de-conflicted and account for the available resources in ATC and airports. Once this general agreement has been reached between airports, ANSPs and the airspace user, the SBT becomes the Reference Business Trajectory (RBT), which is the trajectory to be followed in-flight [14]. This process is to take place continuously in every airspace management phase. Therefore, sudden changes in the plans of the airspace users can be accommodated, if deemed acceptable, up to tactical level.

LARA+
The aforementioned Airspace Management Cell (AMC) allocates airspace based on the BPPRs. Currently, the reservations are submitted under the planning tool LARA: Local And Regional Airspace Management Supporting System. This tool schedules the reservations of the different users, visualises the expected airspace segregation for a better situational awareness, and finally provides a post-operational analysis of the bookings [15]. LARA+ is thus the next generation planning tool expected to be used by the AMC in the future, making use of the possibilities that AFUA and dynamic airspace configurations offer.

2.3.2. Dynamic Airspace Configuration (DAC)
The last AFUA enabler, resulting at the same time by the deployment of all other concepts discussed above, is the use of a wide variety of airspace configurations, both by civil and military users. In the future, all airspace civil and military is expected to be flexible, for which the airspace configurations of AFUA refer both to civil and military configurations, while the current FUA system is used only to reference the airspace of the military user.

This overarching research is contained within the Dynamic Airspace Configuration (DAC) project of Eurocontrol, SESAR PJ08 [1], which concerns both military and civil airspace configuration concepts. On the one hand, elements such as the Variable Profile Area (VPA) and Dynamic Mobile Areas (DMAs) (see below) are expected to be used to tailor the segregated airspace to the true needs of the military user, minimising the airspace used and thus the burden on the performance of the civil user. On the other hand, dynamic sectorisation of the civil airspace is expected to be used more extensively; not only to adapt sector capacity with the traffic flow but also to optimise the sectors given the different dynamic segregations.

DAC for the Military User
Barring the previously mentioned tactical permission of transit that may be given to civil traffic if the FUA is underused, current FUA reservations are static, i.e. during the time the FUA is reserved, the entire block of airspace is deemed as segregated during the specified times of reservation.

In the future, however, it is expected for the military airspace reservation building blocks to be more complex. These consist of the Variable Profile Area (VPA) and Dynamic Mobile Areas (DMAs). These are expected to be

[1] https://www.sesarju.eu/projects/aam

used flexibly, i.e. accommodating AU needs as much as possible, and dynamically, i.e. allowing adaptation to a continuously evolving demand, based on CDM mechanisms [5]. The following serves as an introduction to these, as taken from the Eurocontrol AFUA concept [12].

- **Variable Profile Area (VPA):** consists of subdividing a reserved block of airspace into smaller volumes. In this manner, once the actual use is determined to require only a certain region within the greater reserved area, only a few subdivisions of the airspace are actually blocked for civil traffic, and the rest of subdivisions are given up. Although not formally implemented in the Netherlands as of now, the essence of this permeates in airspace blocks of the same area but divided over different altitudes, such as EHD41A to EHD41D, or simply as the subdivisions of the danger areas (EHD01 to EHD09) [16].
- **Dynamic Mobile Area 1 (DMA 1):** DMA 1 consists of a block of airspace of constant volume and time of reservation, the position of which may vary within an acceptable range to the base based on civil and military user preferences. This range ought not to be too great, as this would result in a longer time taken to arrive at the training region and thus less training time [5].
- **Dynamic Mobile Area 2 (DMA 2):** DMA 2 segregates the airspace with several blocks at different locations which are activated and deactivated at different times. In this way, a mission that has different parts at several locations and times can be segregated with different blocks activating at different periods, instead of blocking an airspace region as large as the entire mission for its full duration.
- **Dynamic Mobile Area 3 (DMA 3):** DMA 3, the most advanced type of segregation and still in exploratory research at SESAR [12], is a segregation that encloses the aircraft to be segregated rather than a region, with a horizontal and vertical separation from other trajectories larger than the regular separation standards, effectively making the segregation move along with the mission.

These advanced concepts for military segregation would not only reduce the segregation volumes of airspace, resulting in benefits for the civil user (capacity, route and fuel efficiency benefits, etc.), but could also improve the flexibility of the military user, as well as potentially reduce the transit time to the training areas [5].

DAC for the Civil User

As aforementioned, all airspace is expected to be flexible in the future, and the form taken of AFUA by the civil user is that of dynamic sectorisation, used to better match capacity with demand. As of today, this is limited to the division and merging of sectors. In the future, however, dynamic sectorisation is expected to expand and be a key enabler for the better implementation of AFUA as the segregation is done in a more dynamic manner.

Dynamic sectorisation is extensively researched in literature. A simple approach is proposed by Kaltenhaeuser [13], in which the shape of dynamic segregations can be used as input to the dynamic sectorisation process. In this manner, the sizes and shapes of the civil sectors are optimised to better adapt to the segregations. Further, Gerdes [17] proposes AutoSec, a tool that uses fuzzy clustering, Voronoi diagrams and evolutionary algorithms to optimise time dependent sectors and balance controller task load. The objectives to optimise for may be multiple, such as the case of the research by Tang [18], which combined the previous methods with a multi-objective optimisation approach that minimises the variance of the controller workload, maximises the average sector flight time, and minimises the distance between sector boundaries and the traffic flow crossing points. The efforts done by SESAR on dynamic sectorisation are encapsulated in Solution 66 [19]. This project has developed a tool a supervisor may use to determine the sector planning more efficiently based on the resources available. The expected benefits of such a tool are an increase in safety and capacity and an improvement in cost efficiency.

2.4. The Dutch Airspace Redesign Programme

With FUA being an essential concept of civil-military airspace cooperation and coordination, it becomes a key element of the Dutch Airspace Redesign Programme (DARP), a redesign of Amsterdam FIR aimed at improving the efficiency of all airspace users. This section gives an overview of the DARP and the role of FUA in it, as well as its challenges within this context. In this manner, Section 2.4.1 explains the reasons behind such a redesign, with Section 2.4.2 translating these into objectives. To realise these goals, the main changes proposed are presented in Section 2.4.3, and subsequent challenges are identified in Section 2.4.4, contextualising this research within the Dutch Airspace Redesign Programme.

2.4.1. Rationale

The Netherlands has one of the busiest hubs of air traffic in the world and is predicted to further grow in the future [2]. Good international accessibility by air is of the utmost importance to the economic development of the country, and is achieved by the quality of the network connections [20]. This network quality must be enhanced by improving the accessibility to Schiphol mainport and other airports of significant importance, which at the same time is to be done considering the living quality of the airport surroundings and the safety of the traffic.

Further, the military user requires of a significant part of the airspace for the purposes of ensuring national and international security, monitoring Dutch airspace and to train for their deployment in possible conflict situations. These duties result from national and international agreements from the United Nations and the North Atlantic Treaty Organization [20]. Extensive training purposes and new systems such as the F-35 make their airspace demand also grow with time. Their efficiency and success in carrying out these activities, which in turn enables the military to operate as they would in a real conflict situation, is determined by the Military Mission Effectiveness (MME), which is given by accessible, well-situated and sufficiently available airspace [6]. On top of that, other uses from the flight of manned and unmanned civilian vehicles to shooting areas or even large wind turbines greatly limit the regions that civil traffic may fly [6]. This, combined with the relatively small size of the country, make airspace an extremely scarce and valuable resource.

So far solely airspace user requirements have been discussed, yet the development of ATM new innovations and procedures such as the further implementation of Free Route Airspace (FRA) and Continuous Descent Operations (CDO) also require of major changes in the airspace structure. The significance of these changes that are to take place for a more optimal use of the airspace is so great that a revision is needed, leading to the Dutch Airspace Redesign Programme. This aims to design a new airspace structure that satisfies the requirements of the many stakeholders, with a time span expected to go from 2023 to 2025 [6].

2.4.2. Objectives

The user requirements driving this airspace redesign have been summarised as the following objectives, as taken from [6]. First, a more efficient utilisation of the airspace is needed by all users. This not only includes the actual use but a better management of its reservation and allocation. Essentially, given the scarcity of the airspace, it is imperative for the airspace users to reserve based on actual use and to do so as soon as possible. Secondly, the DARP aims at reducing the burden of air traffic on the environment, both in terms of noise nuisance and emissions. This can be achieved not only by a more extensive use of FRA and optimal trajectories in the TMA, but also with the aforementioned better management and allocation of airspace. Lastly, the DARP is set out to increase the capacity of civil traffic and the MME of the armed forces.

2.4.3. Main Changes in Airspace Structure

In order to achieve these top level objectives, the following main changes are being considered [6]. First, the training areas to the east and south-east of Amsterdam FIR may be partially removed and redesigned, respectively. This is done for the aforementioned requirement to increase the accessibility to Schiphol mainport and increase capacity. With the current structure, a bottleneck is created between these regions, which if solved would enable a better air access from the the east. Secondly, in order to maintain the training opportunities of the armed forces given the reduction of area in the east and south-east of the Netherlands, the northern region is to be expanded to the south-east. This is also done on the basis that the F-35 requires more training overland. In summary, the new structure aims to optimise the northern region for military use and the southern one for civil use and reducing the impact of air traffic on the environment.

2.4.4. FUA Challenges

Within the many challenges of the DARP, identifying those related to FUA and its plannability sets the context and the motivation for the research at hand. Firstly, in order to steer the considerations about the removal or redesign of the areas, it is desired to have a precise understanding of the effects of the availability of the airspace on the efficiency of civil traffic. Secondly, the other task of the DARP in terms of FUA is to propose new Booking Procedures and Priority Rules (BPPRs), i.e. new rules of reservation and priority, such that the delegations of airspace to civil traffic can be better planned. In order to propose this new set of BPPRs, new concepts of plannability and its benefits for civil traffic efficiency need to be investigated.

3 Motivation

From the background surveyed and the corresponding literature reviewed, key pieces of information can be extracted that serve as the motivation for the research at hand. Such a rationale will be used in the next chapter to unravel specific research objectives and questions.

Firstly, the complexity of the operation and the user requirements has been understood. Amsterdam FIR accommodates airspace for different users, which have opposing requirements that become more demanding with time. For civil traffic, international accessibility, efficient routing and plannability of operations are of the utmost importance to sustainably and efficiently support the growth of the aviation industry. For the Royal Netherlands Air Force, availability and flexibility of airspace within a reasonable range to the bases are required to carry out effective missions and training exercises, which in turn make use of increasingly demanding systems such as the F-35. To suffice all of these different requirements, the Ministry of Infrastructure and Water Management started the Dutch Airspace Redesign Programme (DARP), aiming to redesign the airspace route system, segregations and procedures. A key component to airspace design and, in particular, to civil-military cooperation and coordination, is the use of Flexible Use of Airspace (FUA). FUA is to take a major role within the DARP, as the Alpha and Delta sectors are to be redesigned both in terms of airspace volume and plannability policies.

It is therefore required to have a good understanding of the effects of FUA availability and plannability in all relevant areas such that the best compromise can be reached between stakeholders. While FUA availability can be defined as having the airspace accessible for civil traffic or not, FUA plannability considers the time in advance the availability is made known. These affect airspace user aspects such as Military Mission Effectiveness, fuel efficiency of civil traffic, optimal ATCO allocation for ANSP cost-efficiency, predictability of sector occupancy and others. For civil aviation, the most pressing of these performance areas is that of fuel efficiency, which indicates the performance of civil traffic (cost-)efficiency and the burden of civil aviation on the environment.

On the one hand, understanding the effect of FUA availability on fuel efficiency of civil traffic is valuable for several purposes. Firstly, such an analysis would better inform the DARP on some of the considerations of the FUA redesign. These are for instance the partial removal of the southern region and the expansion of the northern one. Secondly, the study is also motivated from a more academic standpoint by investigating the effects of the horizon at which the direct route transiting the FUA may be enabled.

On the other hand, an investigation on the effects of FUA plannability on fuel efficiency is motivated to develop new Booking Procedures and Priority Rules (BPPRs) such that all stakeholders can make use and benefit from FUA equitably. The current BPPRs do not guarantee the transit of civil traffic through the FUA during the intervals of time the airspace has been delegated for civil traffic, which has been identified to be a source of efficiency loss. The DARP also aims to develop a new set of more equitable BPPRs that better align with a modern airspace and technology, and the first step to inform such a new policy is to investigate the effects of plannability on civil fuel efficiency. If a framework is developed to model such effects, new plannability horizons of FUA can be tested and its results can inform a new policy. Further, different concepts can also be investigated to combine an eventual guarantee of transit while maintaining military flexibility as much as possible, such that the most optimal compromise between stakeholders can be found.

4

Research Plan

Having identified the research gap and motivated the operational need, the research building blocks can be proposed. First, the research questions in Section 4.1 specify what the research aims to solve. To focus the research and construct it in a logical order, sub-questions are also laid out. These are then used to establish the research objective and sub-goals in Section 4.2, yielding tangible tasks to undertake. There, an overview of the stakeholder interests for this research project and a note on the scope is also provided. Finally, hypotheses to the research questions are given in Section 4.3, and the Gantt chart of the project is given in Section 4.4.

4.1. Research Questions

The previous chapters outlined the current state of operations of FUA and the future challenges, as well as the motivation for this study. This can be summarised in the following research questions and corresponding sub-questions.

- RQ-1: How much fuel consumption is saved by making FUA completely available for civil use?
  - RQ-1.1: What are the benefits in fuel consumption of enabling a GCR trajectory at different ranges from the FUA?
  - RQ-1.2: Given the current route system, what are the actual effects of FUA availability on fuel consumption?
  - RQ-1.3: What is the yearly estimation of the benefits, extrapolated from the sample scenario results?
- RQ-2: How much fuel consumption is saved by making FUA available for civil use with a higher plannability?
  - RQ-2.1: What is the baseline fuel consumption of flights affected by a FUA for a given time period?
  - RQ-2.2: How much would this fuel consumption reduce by increasing the FUA planning horizon?
  - RQ-2.3: What is approximately the largest FUA planning horizon affecting fuel efficiency?
  - RQ-2.4: What is the yearly estimation of the benefits, extrapolated from the sample scenario results?

4.2. Research Objective

The main research objective of this work is:

"to assess the effects of Flexible Use of Airspace (FUA) availability and plannability on fuel efficiency by comparing the fuel consumption of transit/no transit through the FUA, and to compare scenarios where the right of transit is given at different planning horizons".

4.2.1. Research Sub-goals

This main objective is to be reached by achieving the following sub-goals. These milestones will be the basis of the Gantt chart in Section 4.4. For the first set of research questions, the sub-goals are as follows:

- Develop a model to create direct trajectories for flights which historically deviated away from the FUA.

- Acquire a BADA license and use it to quantify the fuel efficiency of a given flight.
- Combine the two prior goals to develop a framework quantifying fuel efficiency based on flight trajectories of historical data, given different ranges at which the GCR is enabled.
- Quantify the benefits of enabling the direct trajectory at different ranges from the FUA (RQ-1.1).
- For each flight not making use of the FUA, find a similar one (same departure-destination airports) which did, and compare their fuel consumption (RQ-1.2).
- Determine an extrapolation method to obtain yearly estimations of the fuel benefits (RQ-1.3).

For the second set of research questions, the sub-goals are as follows:

- Develop a framework to determine whether a flight takes the surplus fuel depending on a hypothetical FUA plannability concept, using flights which historically traversed the FUA.
- Implement a relation between an increase in range and its corresponding increase in fuel required.
- Implement the addition of a surplus fuel into the fuel consumption model.
- Quantify the baseline fuel efficiency of a no plannability scenario (RQ-2.1).
- Quantify the benefits of different plannability horizons and concepts (RQ-2.2).
- Determine the largest FUA plannability horizon affecting fuel efficiency (RQ-2.3).
- Determine an extrapolation method to obtain yearly estimations of the fuel benefits (RQ-2.4).

4.2.2. Research Project Stakeholders

This research is aimed at understanding the effects of FUA availability and plannability on fuel efficiency, such that new standards of Booking Procedures and Priority Rules can be proposed from the perspective of fuel efficiency benefits. The acquisition of this knowledge has therefore several stakeholders with different interests.

- **LVNL/DARP:** the knowledge required to make a well-informed decision for a new set of BPPR from the perspective of fuel consumption.
- **Airlines:** proposing a better plannability standard is hypothesised to bring significant fuel efficiency benefits, which is of interest for airline cost efficiency.
- **General public:** the improvement of fuel efficiency results also in the reduction of fuel burnt and thus greenhouse gas emissions.
- **Scientific community:** the relevance of the research for the part of FUA availability is a direct routing study where the distance enabling a GCR is an independent variable. For the part of FUA plannability, the relevance lies in obtaining an insight on the effects of plannability of airspace on fuel efficiency. As surveyed in Chapter 2, all airspace is expected to be flexible in the future, for which the effects of airspace plannability need to be studied.
- **Koninklijke Luchtmacht:** the proposal of new concepts of plannability for their consideration and assessment, and an understanding of the effects of the plannability of their reservations to the other stakeholders.

4.2.3. Scope

The main limitation of this scope is that it is restricted to study the effects of FUA plannability solely on fuel efficiency. As described in Section 2.2.3, other aspects that would experience a benefit are sector demand forecasting, sector capacity and ANSP cost efficiency. A holistic approach accounting for all of these aspects would yield a much better informed proposal of new Booking Procedures and Priority Rules. Nonetheless, fuel efficiency remains the most important aspect to consider. Not only does it best encapsulate the environmental and economic interests of civil users, but fuel efficiency benefits come with the least demanding plannability. Other aspects affected by plannability, such as the ATCO roster allocation or the sector occupancy forecasting, are hypothesised to yield the desired benefits with a much greater horizon of plannability, in the order of days instead of hours. Such horizons are more demanding and thus more difficult to be adopted by the military user. Fuel efficiency, on the contrary, would be the least demanding aspect for the military user and the most beneficial for the civil one.

4.3. Hypotheses

This section provides the reader with preliminary hypotheses for the research questions in Section 4.1, with Section 4.3.1 and Section 4.3.2 concerning Research Questions 1 and 2, respectively.

4.3.1. Research Question 1 Hypotheses

Although it is clear that the greater the range at which the GCR is enabled, the greater the benefits in fuel consumption are, it is difficult to offer a hypothesis for a quantification of the fuel benefits of varying this range, let alone the total fuel benefits. For a general idea of the benefits direct routing may bring, one can refer to the study by Pappie [21]. Here it is found that optimising the cruise phase of European flights above 10,000 ft can realise an average of 1.8% total fuel savings.

To hypothesise about RQ-1.2, the current route structure must be examined, as the actual effects of FUA availability depend on it. From interviews with ATCOs, and by looking at the Amsterdam FIR charts, the Conditional Routes (CDRs) going through Alpha and Delta can be identified. For Alpha, these are M90, Z733, Z708. For Delta, this is N852. The waypoints where permanent routes diverge between these CDRs and other permanent routes are therefore the bifurcation points for EHAM outbounds. These are BERGI, ANDIK and KEKIX for Alpha and LOPIK for Delta. Outside of the subset of EHAM outbound flights, and in particular for transcontinental flights, the bifurcation and merging points of the directs are considerably more difficult to identify.

4.3.2. Research Question 2 Hypotheses

Before hypothesising over the influence of plannability, it is important to remember why does plannability affect fuel efficiency. As oppose to FUA availability, where the flights historically not transiting the FUA are considered, the flights which have a plannability penalty are those which made use of the FUA yet they were expecting not to do so, so the time in advance the announcement was made determined whether each flight took a surplus fuel.

In this manner, the fuel consumption reduction comes not from a different route but by reducing the number of aircraft that issued the last flight plan before the right of transit through the FUA was guaranteed to them. For this reason, it can be hypothesised that the maximum planning horizon affecting fuel efficiency is approximately 20 hours, as this is usually the time it takes for the flight taking off the earliest from issuing the last flight plan to crossing the FUA. From no plannability to around 20 hours in advance, more and more flights will not carry a surplus fuel. The rate at which this occurs depends on the usual schedules in which flights arrive at Schiphol, as different jumps in plannability may affect different traffic (e.g. an inbound or outbound peak) and thus benefit from covering the corresponding number of flights. Furthermore, the benefits in fuel efficiency may not necessarily go hand in hand with the number of flights not taking the surplus fuel. This is because the flights benefiting from the earliest planning horizons are the longest ones: although their surplus fuel might be small when compared with their total fuel weight, they carry it for the longest trajectories.

4.4. Gantt Chart

By first establishing the main milestones of the project (Midterm review, Green light review, etc.) the aforementioned sub-goals composing the research objective can be organised into a series of high-level tasks in order of execution, shown in the Gantt chart of Figure 4.1. The first thing to notice is that the literature review and project proposal have already taken a large part of the thesis. This is because, although the topic at hand is not built upon extensive literature, it is a problem deeply rooted in the operation of airlines and the RNLAF, for which a significant amount of time was needed to get acquainted with the policy, processes and data logging. Given the importance of data analysis for this research, time was reserved also for an introduction to pandas. Further, this was used for a preliminary data acquisition of historical traffic to understand the benefits and limitations of using each traffic database (ADS-B, radar and Eurocontrol data) for a well-informed decision. Once the viability of the thesis presented in this plan was asserted in terms of the operational context, data available and technical knowledge required, the final project was proposed and the research questions defined, ending the Preparation Phase. The Experiment Phase starts by defining the methodology: designing the experiment and choosing the metrics. Once this is taken to a mature point, all steps of the thesis become tangible and the preliminary thesis can be presented. The steps after the Midterm review are those mentioned in Section 4.2.1, going from implementing the fuel computation models to extrapolating the results. Lastly, the final steps are also laid out. It is important to mention that the planning provided is still preliminary and subject to change to complications or other developments throughout the project. For example, this Gantt chart has been updated to account for the usage of the ATM simulator BlueSky as a tool to compute fuel consumption, as reasoned by the discussion in Section 5.6.

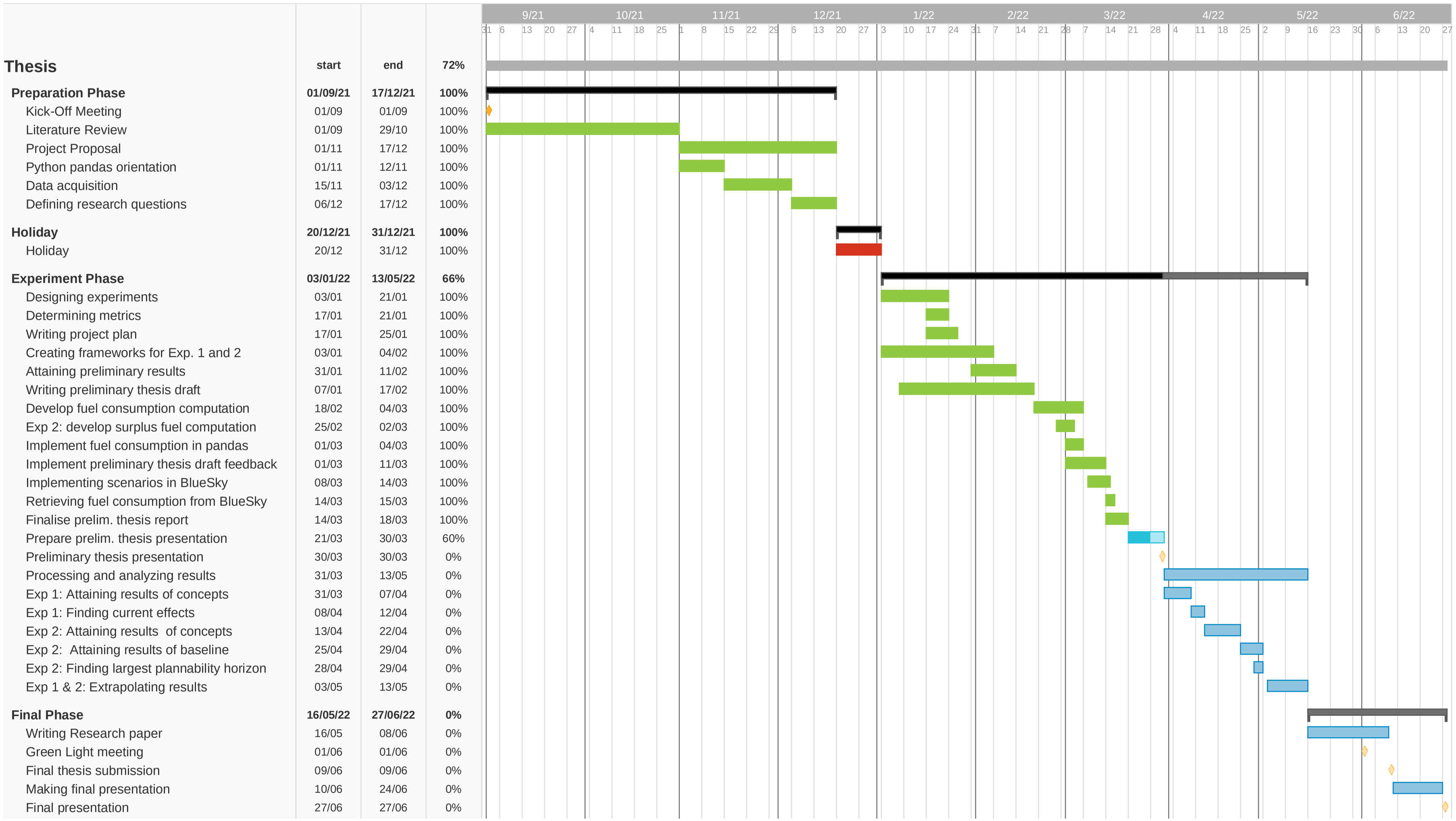


Figure 4.1: Gantt chart of the research project

5

Methodology

This chapter contains the methodology used to carry out the research plan outlined in Chapter 4. Before delving into it, it must be clarified that the two main research questions (RQ-1 and RQ-2) are very different in essence, for which each has its own corresponding experiment. The first one is to describe the effects of altogether restricting an airspace by investigating those flights which were historically deviated around the FUA and calculating their benefits had they transited it. This is similar to a direct routing analysis, and does not account directly for the plannability of FUA, although it is influenced by it. The second research question, however, investigates FUA plannability by considering the flights affected by plannability, i.e. those which historically made use of the FUA yet were not expecting to do so due to a previous reservation. The earlier the plannability of the final reservation, the more flights will not carry a surplus fuel while traversing it, thus burning less fuel due to a reduced aircraft weight. In this manner, while the FUA availability experiment (answering RQ-1) compares two different trajectories, the FUA plannability one (answering RQ-2) compares the same trajectory with different weights onboard.

This chapter is structured as follows. Firstly, Section 5.1 and Section 5.2 describe the flights and FUA considered for the analyses. Secondly, Section 5.3 and Section 5.4 design the experiment for the research questions of FUA availability and plannability, respectively. Next, Section 5.5 describes the usage of the data, from the data source selection to the sampling, coherence of datasets between experiments and extrapolation of the results. Lastly, Section 5.6 and Section 5.7 discuss the tools used and verification and validation considerations.

5.1. Flights Considered

Before delving into the experiments, the subsets of flights considered need to be clarified. These appear in Figure 5.1, with some subsets bearing the name given in the code, for which they are here explained. First, from all flights from the data source, those flying during a day with FUA reservations are filtered. In case of flights spanning two different days, they are taken if they appear (close to) Amsterdam FIR during a day with FUA reservations. All of these flights are divided between those which historically transited (flights_in_ALPHA, flights_in_DELTA) and not transited the FUA (flights_not_in_FUA). The latter is taken as the input for Experiment 1. For each flight historically not transiting the FUA, it is checked if it would have benefited from it by means of enabling a hypothetical GCR. Those flights with GCRs in the FUA are thus deemed to have lost benefit due to a FUA (flights_lost_benefit_ALPHA, flights_lost_benefit_DELTA). This may occur in one of three periods of time: outside of the AIP reservation, within the final (D-0) reservations or in the interval within the AIP reservation but outside the D-0 reservation: an ATS delegation. Outside the AIP reservation, there had never been a FUA reservation, for which the lost routing efficiency cannot be attributed to the FUA and this subset is not further considered. Both during D-0 reservations and ATS delegations, the loss of efficiency is penalised as a routing problem, yet it is important to remember that while flights not transiting the FUA during a D-0 reservation was because of FUA availability, if a flight did not transit the FUA during an ATS delegation (when there was supposedly no issue in transiting the FUA, simply that the guarantee was given pre-tactically or tactically) , it should be attributed to FUA plannability. Furthermore, even if the number of flights not transiting the FUA during a D-0 reservation and ATS delegation was similar, it must be noted that this was done on the basis of flights with a GCR transiting the FUA, which disregards current flight procedures. In reality, however, ATCOs try to enable transit through the FUA as soon as this is given by the military, regardless of the plannability.

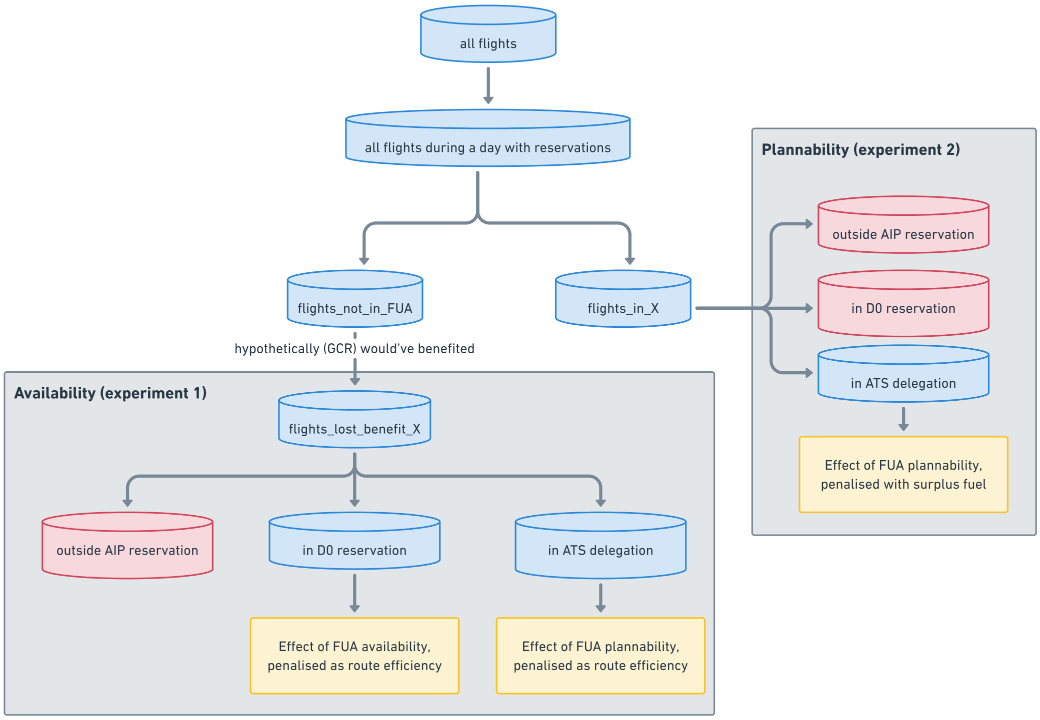


Figure 5.1: Subsets of flights in Experiments

Secondly, the flights found historically to traverse a FUA are also divided depending on the time they transited the FUA. For flights outside of the AIP delegation, there was never a problem of plannability, for which they are disregarded. During a D-0 reservation, however, flights transiting the FUA had taken a surplus fuel which was eventually useless, yet transit during D-0 reservations is not penalised as it is seen as the time the military used the airspace equitably. Finally, flights transiting the FUA during an ATS delegation are those which took a surplus fuel and flew while there was eventually no military usage of the airspace, for which a better plannability could have improved the performance. This latter subset is then taken as the basis of FUA plannability, penalised with the addition of a surplus fuel.

5.2. FUA Considered

Every military airspace in Amsterdam FIR is considered to be Flexible Use of Airspace. These are shown in Figure 5.2, as a custom scenario created within the air traffic management simulator BlueSky [1]. Here, Restricted Areas appear in red, Danger Areas in blue, Temporary Reserved Airspace (TRA) in yellow, Temporary Segregated Areas (TSA) in white and Cross Border Areas (CBA) in green, as published in the Aeronautical Information Publication [16]. The Alpha and Delta sectors, covering the regions highlighted in red in the North and South, respectively, are the higher level of grouping. Once any of the airspaces within them is segregated by the military, the entire Alpha or Delta sector is segregated. Contrarily, segregating Alpha or Delta blocks all airspaces it is composed of. As a consequence, the airspace reservation and segregation is done on the basis of these two regions. Given that all military airspaces outside Alpha and Delta are lower altitude ones, irrelevant to civil commercial traffic, it becomes clear that Alpha and Delta ought to be the airspaces considered for the analysis.

5.3. Experiment 1 Design: FUA Availability

The section at hand discusses the methodologies of RQ-1.1 and RQ-1.2 in Section 5.3.1 and Section 5.3.2, respectively. Next, the fuel efficiency metrics common to both experiments are outlined in Section 5.3.3. Lastly, the variables and assumptions are stated in Section 5.3.4 and Section 5.3.5.

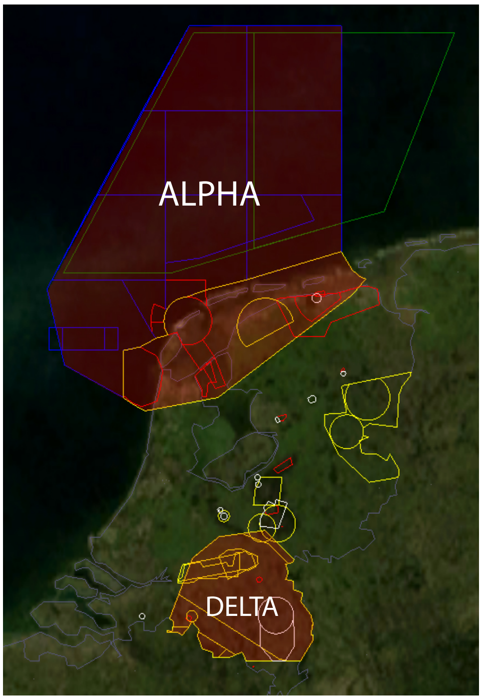


Figure 5.2: FUA in Amsterdam FIR

5.3.1. Methodology of RQ-1.1

As briefly mentioned above, this experiment is set to answer RQ-1.1: *"How much fuel consumption is saved by making FUA completely available for civil use?"*. The aim is to compute the benefits in fuel efficiency of the flights the trajectories of which did not transit the FUA, yet they would have benefited from it, had the airspace been available. It is only those flights that ought to be examined. This yields two scenarios: no FUA transit and hypothetical FUA transit for a number of historical flights which would have benefited from it, for a given period of time. These are the baseline and concept scenarios, respectively. Later it will be seen that multiple concept scenarios can be obtained depending on the horizon of distance the Great Circle Route (GCR) is enabled and the speed chosen. Once these have been found, the experiment proceeds by computing the benefits in fuel efficiency as shown in Section 5.3.3. In summary, the steps to answer RQ-1.1 are as follows:

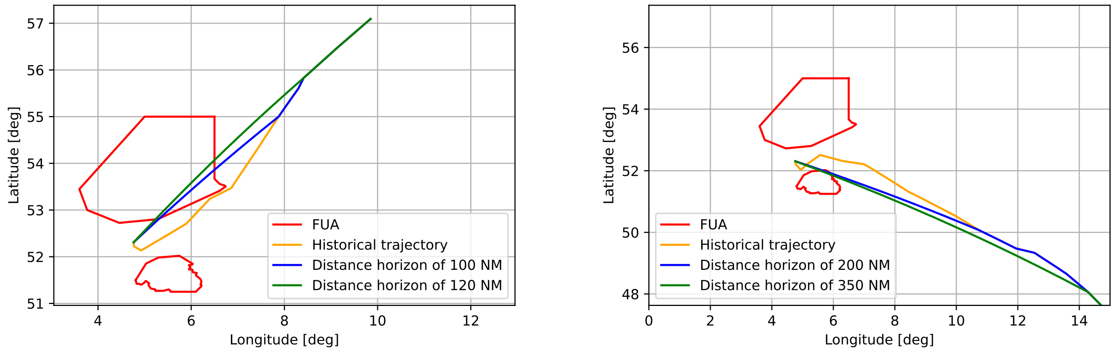
- Step 1: Filtering the flights not traversing the FUA historically.
- Step 2: For the remaining flights, create GCR trajectories and check if they traverse the FUA
- Step 3: Compute the fuel efficiency metrics.

Step 1: Filtering the Flights not Traversing the FUA Historically

Before considering the flights which could benefit from the FUA, it is necessary to filter out the flights which historically traversed it. This can be done in a straightforward manner by first filtering out all flights with data points lying within the FUA volumes defined, which are the coordinates of the Alpha and Delta sectors, shown in Figure 5.2, above FL 95. Nonetheless, when using the historical traffic data from the Eurocontrol R&D data archive, which has a lower frequency of reported coordinates than ADS-B or radar data, an extra step must be done. It may occur that the data points of a flight lie outside the FUA, yet connecting the points linearly shows how the flight actually crossed the FUA. Assuming the flight goes directly from one reported coordinate to another, intermediate points can be interpolated between the historical data points registered around the FUA. If these intermediate coordinates are within the FUA, it can therefore be concluded the flight traversed it. Once all flights have been found for which their original coordinates (or their interpolated points in between) lie within the FUA, they are filtered out to have all flights which did not traverse the FUA.

Step 2: Creating GCR Trajectories

From the subset attained in Step 1, each flight is checked whether it would have actually benefited from traversing the FUA. This is done by checking whether hypothetical GCR trajectories substituting (part of) a flight trajectory actually traverse the FUA.



(a) Aalborg (EKYT) - Amsterdam (EHAM) flight

(b) Athens (LGAV) - Amsterdam (EHAM) flight

Figure 5.3: Effect of different ranges (distance horizons) at which the GCR is enabled

If a fully direct routing analysis was done, such as the one presented by Pappie [21], the Great Circle Route (GCR) generated would hold for the entire flight. Nonetheless, this study aims to understand the impact of Dutch FUA, for which these ought to be the sole sources of inefficiency of the hypothetical trajectory proposed. In other words, deviations in the route caused by factors external to Dutch FUA should be present in both hypothetical and proposed trajectories for a fair comparison. In this manner, the range away from the FUA at which the GCR can be generated becomes a critical factor, for which it is used as an independent variable. The larger this horizon, the greater the section in the flight plan substituted by a GCR concept, and thus the more optimal the proposed flight. This horizon also affects the number of flights found to benefit from the FUA, as the resulting GCR trajectory is dictated by the horizon at which it starts and ends. These notions are illustrated in Figure 5.3. On the one hand, Figure 5.3a clearly shows how the GCR becomes more optimal given a greater horizon at which the GCR is enabled. On the other hand, Figure 5.3b presents a flight whose GCR traverses a Dutch FUA only when the horizon is increased to a 200x200 NM region around Delta. Note that the low frequency of the Eurocontrol data makes the merging and bifurcation points of the proposed GCR not necessarily at the horizon specified.

Furthermore, in order to provide a fairer comparison between baseline and concepts, the hypothetical GCR segment should only substitute (part of) the cruise phase of the flight. Not only does this greatly simplify the definition of the concept trajectory, as a cruise flight level and airspeed may be assumed throughout the fictional (GCR) flight points, but it also gives a more realistic alternative by respecting the Standard Arrival Routes and Standard Instrument Departures. As shown in Figure 5.3, disregarding the descent procedures results in a more optimal solution, yet these are unrealistic trajectories in terms of airport procedures and routes.

For a given GCR horizon, the procedure of checking whether a historical trajectory could make use of the FUA is the following:

- 1) Given a range of distance (distance horizon) in NM, a square around each FUA is defined.
- 2) For each flight and FUA (of those which did not traverse the FUA historically), check if it contains points within the square defined above. If not, discard it. Otherwise, the GCR trajectories are created as follows.
- 3) First, select the last historical flight point within the square. This becomes the point the GCR ought to merge with the historical trajectory. Next, the points are selected in historical order as the bifurcation where the GCR starts, and the GCR is created between the bifurcation and the merging point. Once a point is found to create a GCR that traverses a FUA, the most optimal GCR traversing the FUA is found. This is selected as the concept the baseline (historical) trajectory is compared with.

These steps are summarised in Algorithm 1. When all flights are analysed for the given distance horizon, those with lost efficiency are saved and used as a concept to be compared with the baseline. This implies that the concepts contain only flights with lost efficiency. Two same flights are only compared if the hypothetical GCR concept traverses the FUA, while more optimal trajectories than the baseline yet not crossing the FUA are not compared. This is done such that less flights are considered for a reduction of computation times, and to compare only those flights where the FUA affected the route efficiency. As a result, each concept can only be compared with the baseline by considering the same number of flights, for which the baseline used in Step 3 will have less flights than the historical sampled time had.

While this method is to answer solely RQ-1.1, it also relates to RQ-1.2: investigating the effects of FUA availability due to the current route system. This is because the flights seen to lose efficiency due to the greatest distance horizon are all investigated to find historical trajectories with the same departure-destination pair that did transit through the FUA. RQ-1.2 may thus start only after completing Step 2 of RQ-1.1.

Algorithm 1 Experiment 1, Step 2

```
for each distance horizon:
  Calculate the distance from each FUA at which the GCR is enabled, creating a square around the FUA.
  for each flight:
    Select only the cruise phase of the flight, found by filtering the flight points using Rate of Climb and
    altitude.
    if flight trajectory has points within the square:
      Save the last trajectory point within the square: here the GCR and historical trajectories will merge.
      for each point within the square, in historical order:
        Use this point as the bifurcation point between GCR and historical trajectories.
        Create a GCR trajectory between the bifurcation and merging points.
        if the GCR traverses the FUA:
          Route efficiency was lost due to the FUA. Save this flight and trajectory.
        else:
          Continue to the next historical point.
    else:
      Continue to the next flight.
  Having found all flights with lost efficiency for the given distance horizon, save them as a concept.
```

Original and Optimised Speed Settings

Lastly, another aspect exclusive to RQ-1.1 may be considered. Although this experiment is posed to understand the fuel benefits of a hypothetical scenario where historically deviated flights around the FUA make use of it, this framework allows to consider another angle. Given that a deviation around a FUA and a shortcut are compared, the benefits could be examined considering two scenarios. Firstly, a scenario where the shortcut had been taken at the original speed of the substituted trajectory segment, thus arriving sooner to the destination given the shorter distance flown. Secondly, a scenario where the flight follows the shortcut at an optimal airspeed to minimise the fuel consumed with the same distance flown.

In this manner, for each historical trajectory deemed to have lost efficiency due to the FUA, whether it is during a D-0 reservation or an ATS delegation, two hypothetical concepts are proposed for the comparison, with identical trajectories (the same GCR) but different speeds, for which the two hypothetical concepts are named Original and Optimised speed settings. For a better comparison, airspeed is kept constant per concept. For the historical trajectory, the speed chosen is the average of the ground speed of the historical entries, calculated from the timestamp and coordinates. Assuming no wind, this is taken as the airspeed. This same average airspeed is used for the Original speed setting. For the Optimised speed setting, on the other hand, the airspeed is chosen to minimise fuel flow per airspeed.

As taken from [22] and shown in Equation 5.1, $\frac{V_{TAS}}{f}$ can be interpreted as the specific range, i.e. distance that can be flown for 1 kg of fuel. Its inverse, outlined in Equation 5.2, would therefore be the amount of fuel burnt per meter of distance, which is in fact what must be minimised to optimise the fuel consumption over a constant distance.

$$\frac{V_{TAS}}{f} = \frac{[m/s]}{[kg/s]} = [\frac{m}{kg}] \quad (5.1)$$

$$\frac{f}{V_{TAS}} = \frac{[kg/s]}{[m/s]} = [\frac{kg}{m}] \quad (5.2)$$

With this relation, a curve is created for each specific flight, using as inputs the altitude to calculate air density and thus C_L, and the aircraft type with its corresponding coefficients from BADA. The airspeed yielding the minimum of this curve is thus used for the Optimised speed setting, and results in the least fuel consumed for the distance given. It was first hypothesised that this would be a smaller airspeed in the vast majority of cases, given the

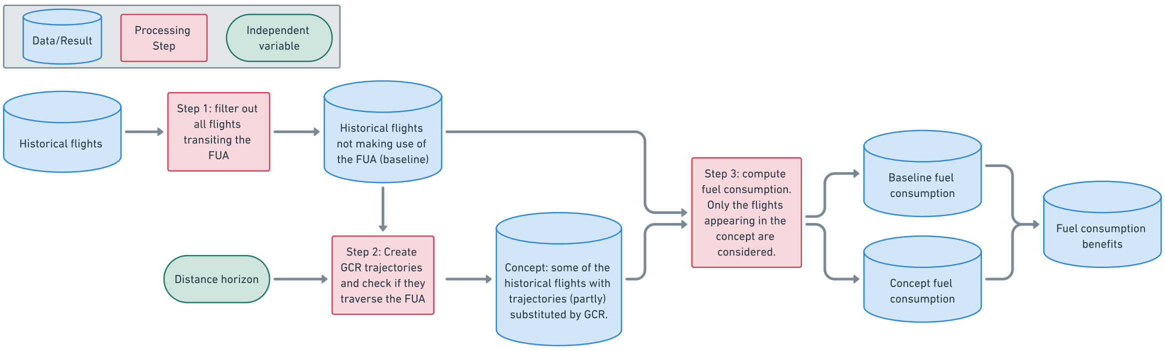


Figure 5.4: Flowchart of Experiment 1 RQ-1.1 methodology

presence of V_{TAS}^2 in the Drag force formula and Equation 5.9 also increasing with airspeed. However, a larger V_{TAS} decreases C_L and in consequence C_D and D. This usually results in a marginal difference between the fuel flows at each instant of the simulation, for which the total consumption greatly depends on the flown time. For this reason, as well as the fact that minimising $\frac{f}{V_{TAS}}$ simply favours a larger airspeed, minimising the fuel flow per distance using the inverse of the specific range usually results in the optimal airspeed to be larger than the historical one, with a slightly increased consumption at each instant but compensating by flying for less time. Despite a noticeable decrease in total fuel consumed, the increased airspeed increases thrust and thus work done. Since the latter does not directly depend on time but rather on the distance flown, the Optimised speed setting generally results in a greater work done.

RQ-1.1 Methodology Summary

Having described the steps to accomplish RQ-1.1 of Experiment 1, their order and logic appear summarised in the flowchart of Figure 5.4. Note that since the number of flights found to hypothetically benefit from using the FUA depends on the distance horizon, the performance of each benefit is compared with its own baseline and not other concepts. In other words, Figure 5.4 illustrates the process for a single choice of the independent variable.

5.3.2. Methodology of RQ-1.2

As briefly mentioned above, this experiment is set to answer RQ-1.2: *"Given the current route system, what are the actual effects of FUA availability on fuel consumption?"*. The aim is to compare the fuel efficiency of historical trajectories where flights did not go through the FUA with similar flights that made use of it. For this, the subset of flights and the identification of the similar flights must be chosen carefully.

Flight Subset Used

The first step is thus to get the flights which were deemed to have lost benefit due to a FUA, i.e. those historically not transiting Alpha nor Delta, but which would have benefited from doing so, during either a D-0 reservation or an ATS delegation. This is a direct output of RQ-1.1 Step 2, and the flights used are those for which the GCR was enabled with the greatest horizon. This results in having a basis of flights where a more optimal routing was found, yet much of the region covered by the GCR is not necessarily due to the FUA, which results in an overestimation of the flights affected. It is thus expected for the number of flights affected by FUA in reality to be significantly less, yet all flights affected ought to be contained from the subset.

Finding Similar Flights

In order to find the effects of actual FUA usage, instead of creating more optimal trajectories in the fashion of RQ-1.1, only historical trajectories are compared for RQ-1.2. That is, for each flight of the subset identified, a similar flight is found traversing the FUA. A similar flight is here defined as another historical flight with the same departure-destination or vice-versa. In this manner, for each flight with lost efficiency, the similar flights going through the FUA are identified, as taken from the subsets flights_in_ALPHA and flights_in_DELTA previously found which form the basis of Experiment 2 (see Figure 5.1). After identifying all similar flights, they are examined one by one to find a good candidate.

Although all flights examined go through the FUA, many do so for a very small distance. Since it is desired to find a representative alternative, the candidate is found by one of the following strategies. First, if a similar flight is

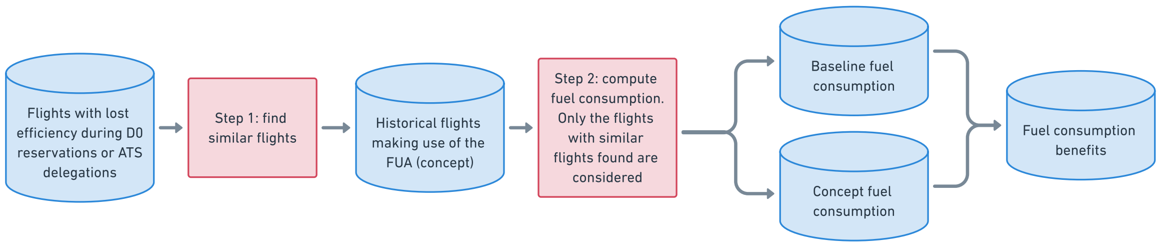


Figure 5.5: Flowchart of Experiment 1 RQ-1.2 methodology

found to contain a significant number of data points within the FUA, it is already taken as a possible candidate. Else, the data points within the FUA of all similar flights seen are counted to find the one with the largest number. Furthermore, the search is limited to e.g. 80 to 100 similar flights to reduce process time when considering the most common departure-destination pairs. After finding the best candidate, it is checked that the routing is indeed more optimal by computing the total distance flown within a range around the FUA. If it is indeed smaller, then the candidate is taken as the flight's similar flight.

Same as for RQ-1.1, the trajectories of the baseline and concept (in this case two historical flights) are translated into BlueSky scenarios to analyse the fuel efficiency metrics outlined in Section 5.3.3.

RQ-1.2 Methodology Summary

The methodology used to answer RQ-1.2 appears summarised in the flowchart of Figure 5.5. Without the independent variable enabling GCRs, RQ-1.2 simply becomes a problem of finding a suitable alternative to each flight chosen. When these are found, the same number of flights are considered to compute the benefits, i.e. disregarding the flights for which no similar flight was found.

5.3.3. Fuel Efficiency Metrics

After the baseline and concept trajectories have been formalized for each flight, the fuel efficiency of each is calculated in the same manner for both research sub-questions. This can be done with different metrics: work done, fuel consumed and CO_2 emissions. Existing studies with the purpose of fuel consumption computation have for instance been carried out by Inaad [23], Klapwijk [24] and Adriaens [25] under the context of Continuous Descent Approaches, Continuous Climb Operations and an assessment of the delay absorption capabilities of MUAC for Schiphol inbounds.

Work

The work done by the aircraft is a measure of the force it must overcome along the distance flown, and therefore an indication of the fuel that must be burnt. Compared to the metric of fuel consumption, work done has the benefit of being more robust to new engine types, yet the derivation below can only be used for cruise condition.

Work done, here written as E, is thus the thrust T exerted to move the aircraft over the distance flown d as shown in Equation 5.3. In cruise, lift balances weight ($L = W$), for which $\frac{L}{W} = \frac{W}{L} = 1$. Further, thrust balances drag during cruise ($T = D$), for which the work formula can be rewritten to $E = D \cdot d$, and thus $E = D \cdot \frac{W}{L} \cdot d$. This is then reduced to the non-dimensional coefficients as shown in Equation 5.4.

$$E = T \cdot d \tag{5.3}$$

$$E = \frac{C_D}{C_L} \cdot W \cdot d \tag{5.4}$$

More generally and regardless of the flight configuration, work done can be computed with Equation 5.3 within BlueSky. The thrust at each step can be multiplied by the increase in distance between timestamps (calculated with the timestep and airspeed) to yield the work done for the step at hand. This is logged and then integrated to yield the total work. Lastly, preliminary results show that, although work is correlated with fuel consumption, major differences are seen when comparing the Original and Optimised speed settings for RQ-1.1. This is because to optimise fuel consumption a higher airspeed is generally used, which increases fuel flow at each instant marginally, but reduces the number of instants to integrate. Nonetheless, the work done is not directly affected by time but rather distance, which is the same for both speed settings. The difference thus comes from the thrust exerted throughout this distance, which generally increases with airspeed. As a result, the Optimised speed setting will have a reduced total fuel consumption but increased work done.

Fuel Consumption

Fuel consumed can be calculated to provide a direct indication of fuel efficiency, as well as giving a more complete overview than work done by accounting for all phases of the flight, as enabled by different fuel flow coefficients. Nonetheless, it is this reliance on a variety of coefficients which makes fuel consumption a more sensitive metric to approximations in the BADA coefficients and new engine types. The relations laid out below are given following the BADA User Manual [26] and are valid for jet and turboprop engines.

In essence, the fuel consumed is computed by integrating the fuel flow f over time, as depicted in Equation 5.5. To calculate the fuel flow, the Thrust-Specific Fuel Consumption (TSFC) η is multiplied by the Thrust T, as shown in Equation 5.6. This formula changes if cruise or descent is considered, as shown below.

$$F_{burnt_i} = \int_{t_0}^{t_i} f dt \tag{5.5}$$

$$f = \eta \cdot T \tag{5.6}$$

Firstly, let us discuss TSFC. This is given as a linear function of the airspeed, as shown in Equation 5.7. Here, V_{TAS} is the true airspeed and C_{f1} and C_{f2} are the TSFC coefficients 1 and 2, respectively. Equation 5.6 and Equation 5.7 can be used together in all flight phases except during idle descent and cruise [26]. For idle descent, a minimum fuel flow is directly calculated based on the geopotential pressure altitude H_p as shown in Equation 5.8. For cruise, Equation 5.9 is used with Equation 5.7. $\mathrm{C_{f3}}$, $\mathrm{C_{f4}}$ and $\mathrm{C_{fcr}}$ are all coefficients given by the aircraft performance database BADA.

$$\eta = C_{f1}\left(1 + \frac{V_{TAS}}{C_{f2}}\right) \tag{5.7}$$

$$f_{\mathrm{min}} = \mathrm{C_{f3}}\left(1 - \frac{\mathrm{H_P}}{\mathrm{C_{f4}}}\right) \tag{5.8}$$

$$f_{\mathrm{cr}} = \eta \cdot \mathrm{T} \cdot \mathrm{C_{fcr}} \tag{5.9}$$

Secondly, let us consider the Thrust component of Equation 5.6. This is taken from the total energy equation shown in Equation 5.10. Here, m is the mass of the aircraft, $g_0 = 9.80665 m/s^2$ is the gravitational acceleration, h the altitude and D the aerodynamic drag. The latter is given by Equation 5.11, with ρ and S the air density (kg/m^3) and wing reference area (m^2), and C_D the drag coefficient. This is then given by Equation 5.12, composed of coefficients C_{D_0} and C_{D_2} for a given flight condition e.g. cruise, approach or landing, and the lift coefficient C_L. This is in turn given in Equation 5.13 if the flight path angle is zero, once again using the aircraft mass.

$$T = \frac{mg_0}{V_{TAS}}\frac{\mathrm{d}h}{\mathrm{dt}} + m\frac{\mathrm{d}V_{TAS}}{\mathrm{dt}} + D \tag{5.10}$$

$$D = C_D \cdot \frac{1}{2}\rho V_{TAS}^2 \cdot S \tag{5.11}$$

$$C_D = C_{D_0,X} + C_{D_2,X} \cdot C_L^2 \tag{5.12}$$

$$C_L = \frac{m \cdot g_0}{\frac{1}{2}\rho V_{TAS}^2 \cdot S} \tag{5.13}$$

Contrary to Experiment 2, where the same trajectory is flown with two different fuel weights depending on whether the right of transit was guaranteed before the fuel was loaded, Experiment 1 has no surplus fuel. Nonetheless, a few nuances about the weight have been identified. First, it can be tested whether assigning different fuel weights based on different mission ranges has a significant effect on the results. As for Experiment 2, a difference in fuel mass could be determined based on a difference in mission range, thus considering the effects of the trajectory shortcut not only in the distance flown. Nonetheless, given that it is differences between concepts that ought to be considered, changing the absolute mass would only offset both results, thus having a small effect on the difference between baseline and concepts. Further, it is also desired to test whether the burning of fuel mass in-flight affects the results, although in the case of the ATM simulator BlueSky, this is already implemented.

CO_2 Emissions
Having calculated the kg of fuel consumed, the corresponding emissions of CO_2 can be calculated. Given its emission index EI of 3150 g/kg, as given in [27], it can be approximated for every kilogram of fuel burnt to generate 3.15 kg of CO_2.

5.3.4. Summary of Experiment Variables

Having explained the methodology of the main sub-question of Experiment 1, the independent and dependent variables of the analysis are summarised as follows.

Independent Variables

- **FUA sectors:** Alpha and Delta.
  Given the possible removal of Delta in the near future, the effects of each FUA are to be considered separately to extract individual conclusions.
- **Distance horizon:** in nautical miles around each FUA (only for RQ-1.1).
  This range is the horizon at which a hypothetical GCR trajectory is enabled. A greater horizon will result in a more optimal concept, both affecting the GCR trajectory itself and the number of flights making use of the FUA. Given the sensitivity of the results to this factor, it is investigated as an independent variable.

Dependent Variables
The following variables will be calculated for both historical and concept trajectories, such that the benefits can be extracted.

- **Work:** in Joules.
- **Fuel consumption:** in kilograms.
- CO_2 **emissions:** in kilograms.

5.3.5. Assumptions

This analysis is carried out based on the following assumptions common to both research sub-questions:

- The flights are assumed to have flown directly from point to point registered in the historical data.
  This assumption is used to establish whether a flight historically crossed a FUA even if its points do not fall within the FUA. This is needed for Eurocontrol data, as the frequency of position reports is much lower than for radar data. It may occur that the historical points reported are outside the FUA, yet the line connecting them does cross the FUA. In most cases this crossing is clear, yet in others the points lie in the corners of FUA and it is not so clear if the flight traversed it. For these, this assumption may indicate the FUA was used while this was not the case. This is deemed acceptable for two reasons. First, for the flights where this occurs (around corners of the FUA) their deviation around the FUA would have been minimal, so the benefits associated are not significant. Secondly, given that the study aims to understand the impact of FUA and the benefits of its use, labeling more flights to have used the FUA than in reality only makes the findings more conservative.
- No wind is assumed, enabling ground speed to be set equal to airspeed. Ground speed can be calculated from the trajectory data using the coordinates and timestamps of each entry. By assuming ground speed to be equal to airspeed, the latter can be converted into the calibrated airspeed used by BlueSky.
- International Standard Atmosphere (ISA) is assumed. The calculation of the calibrated airspeed is done using the ISA model along with the ideal gas law. This assumes a linear relation of temperature with altitude for each of the layers in which this model divides the atmosphere.
- For RQ-1.2 only: if no similar flight is found, it is assumed that the current route system and flight procedures do not enable the departure-destination pair at hand to make use of the FUA. The validity of this assumption lies in the percentage of flights for which a similar one is not found, yet how the problem is posed make this largely acceptable. This is because the subset chosen contains the flights for which a GCR would travel through the FUA enabled at a large range, disregarding flight procedures. It is thus understandable that far from all flights benefiting from the FUA with a hypothetical GCR enabled from e.g. 200 nautical miles could in reality go through the FUA. Nonetheless, such a large range ensures that all possible flights are covered.

5.4. Experiment 2 Design: FUA Plannability

The second experiment is set to answer RQ-2: *"How much fuel consumption is saved by making FUA available for civil use with a higher plannability?"*. The aim is to compute the benefits in fuel efficiency of the flights that historically traversed the FUA, yet the plannability at which the FUA was announced determined whether they carried a surplus fuel or not.

As illustrated in Figure 2.2, FUA is preemptively reserved months in advance for a large timeslot. This reservation period is shrank the day before operations as established in the AUP, and finally shrank again as one, two or three reservation intervals are made during D-0. Although tactical use may be made during the reservations made at D-0 (from here referred to as D-0 reservations), these are assumed to be the real usage of the FUA. All flights traversing the FUA outside of the D-0 reservation(s) but within the original reservation are those for which the carrying of a surplus fuel depended on the plannability. It is this set of flights which are considered for this experiment. Although FUA plannability may also result in flights losing route efficiency, this is quantified in Experiment 1 as shown in Figure 5.1.

The concepts proposed in Experiment 2 are different plannability horizons of the FUA, with respect to the D-0 reservation(s). The baseline is the scenario with no plannability. In this manner, the earlier the plannability, the higher the number of flights not carrying the surplus fuel. The trajectory of each flight is not subject to change, yet its fuel carried is. Once it has been identified whether the aircraft carries a surplus fuel or not, the experiment proceeds by computing the consequent benefits in fuel efficiency. In summary, the steps of this analysis given a certain period of interest are as follows:

- Step 1: Identifying the flights traversing the FUA.
- Step 2: Establishing the baseline and concept scenarios.
- Step 3: Identifying the flights in the FUA within the ATS delegations.
- Step 4: Identifying the flights (not) carrying the surplus fuel.
- Step 5: Determining the deviated route.
- Step 6: Calculating the surplus fuel needed based on the additional range.
- Step 7: Computing the fuel efficiency metrics.

This section is structured as follows. First, Section 5.4.1 to Section 5.4.7 describe in detail the steps above. Finally, the methodology and variables are summarised in Section 5.4.8 Section 5.4.9, respectively. Lastly, the assumptions are given in Section 5.4.10.

5.4.1. Step 1: Identifying the Flights Traversing the FUA

The first step is done in the same way as Section 5.3.1. Contrary to Experiment 1, here the flights considered for the following steps are those found to traverse the FUA.

5.4.2. Step 2: Establishing the Baseline and Concept Scenarios

As illustrated in Figure 2.2, the original reservation consists of one large interval throughout the day (e.g. 06-22). This interval is reduced a day in advance with the submission of the AUP. This step can be understood as a plannability concept, as it gives a better indication of the real usage of the airspace some time in advance. The concepts of plannability proposed with respect to the D-0 reservation(s) effectively substitute the need for an intermediate, historical step, for which the AUP is not accounted for historically within the concepts. The reasons and repercussions of this are explained in more detail below.

The concepts proposed by the experiment consider two reservation types: the original (months in advance) and D-0 reservations. The periods outside the final intervals but within the original contain those flights which initially had no guarantee of transiting the FUA yet they eventually transited it. The plannability at which they have this guarantee of transit determines the fuel loaded. As a result, the benefits of different concepts in plannability can be compared, effectively overriding the need for the intermediate reservation interval and plannability of the AUP.

The reservation intervals of the analysis can thus be defined as follows, with Figure 5.6 showing an example.

- **Original reservation:** preemptive reservation of the airspace, occupying a large part of the day (e.g. 06:00-22:00). Flights planned to cross the FUA outside of this interval always have the guarantee of transit, and are thus not affected by FUA plannability.

These reservations are made months in advance and published in the AIP, yet remain somewhat constant. Given the existence of the AUP as an intermediate step, taking the original reservation as a baseline of today's performance is not representative. Nonetheless, this allows for a better generalization of the framework presented. The true impact of today's operational practice can be investigated as a separate baseline.

- **D-0 reservation(s):** eventual reservations of the airspace made during the day of operations. Can be one, two or three throughout the day and are logged into internal systems of LVNL.
  For eventual instances where the training is in another region or has just finished at the end of the reservation, civil traffic may make use of this airspace during this interval. For the simplicity of the analysis, it is decided for such occurrences not to be deemed as lost efficiency.
- **ATS delegations:** periods of time within the original reservation interval yet outside the D-0 reservation(s). In other words, intervals of time where civil traffic initially had no guarantee of transit but traffic was eventually allowed through the FUA.
- **Planning horizon:** relative time with which a D-0 reservation is established, e.g. 4 hours in advance. The experiment will explore several concepts: with each D-0 reservation having a corresponding planning horizon, or having both D-0 reservations the same announcement time.
- **Announcement time:** absolute time at which the D-0 reservation interval is established, i.e. time during the day at which the D-0 reservation is made.

Baselines
Currently, D-0 reservations are made to enable transit of civil traffic through the FUA outside of them. However, there is no real guarantee that another D-0 reservation will not be made later on, for which all flights wanting to cross the region within the AUP reservations will still take the surplus fuel. This is therefore the baseline of the analysis, where no plannability is given and the flights still take a surplus fuel when crossing within the original reservation time. Note that, if this is done using the original reservations (e.g. 06:00-22:00) and not the AUP (e.g. 07:00-15:00), this baseline scenario results in plannability having worse effects on fuel efficiency than in reality (as the time during which the inefficiency occurs is larger than when considering the AUP). This makes the baseline the concepts are built upon to not be representative of reality. To gain an insight of today's impact, the AUP reservations can be considered as a separate baseline, created with the sole purpose of analysing today's impact in a representative manner. In summary, two baselines can be considered. First, Baseline 1 is based on the AIP reservations, which makes it the best candidate for the baseline the concepts are built upon. Secondly, Baseline 2 is based on the AUP reservations, which provides a more representative view of the impact of today's operation yet, given that the AUP is already a plannability concept, it is not used as the basis of the concepts proposed. These are summarised in Figure 5.10.

Concept Sets
In the concepts proposed, the guarantee of transit must be given during the ATS delegations with some plannability. This however depends on the number of intervals: as shown in Figure 5.6, there may be one, two or even three D-0 reservations. This poses a problem: since historically these reservations are made at different times, how can it be known that the first D-0 reservation made will be the last one of the day? As seen in Figure 5.6, it can be known in hindsight that the day had one or two reservations, but if the reservations are made at different times, during the day of operations one could expect a second reservation that eventually does not take place, resulting in not giving the guarantee of transit to civil traffic unnecessarily. In practice, reservations today are made at different times, but as explained they do not guarantee the transit outside of them, for which more intervals can still be added. The concepts proposed are however based on giving the guarantee of transit with a better plannability, for which something must be assumed to enable reserving more than one interval at D-0.

To solve this problem, different ways of planning this guarantee are considered. Each of these is here referred to as a Concept Set, with each having concepts of their own in the form of plannability horizons. These are summarised in Figure 5.10. The first Concept Set solves the problem of transit guarantee in the simplest, yet most favourable way for civil traffic. Concept Set 1 allows only one announcement of D-0 reservations per day, regardless of the number of reservations. For example, if three D-0 reservations are made, Concept Set 1 establishes the plannability horizon relative to the start of the first ATS delegation, making the military user compromise on the entire day of operations early in the morning at the latest, restricting its flexibility considerably and yielding great benefits to the civil user. In order to maintain the guarantee of transit through the FUA outside the reservations, no changes can be made after the first and only announcement time. This proposed concept is shown in Figure 5.7, where

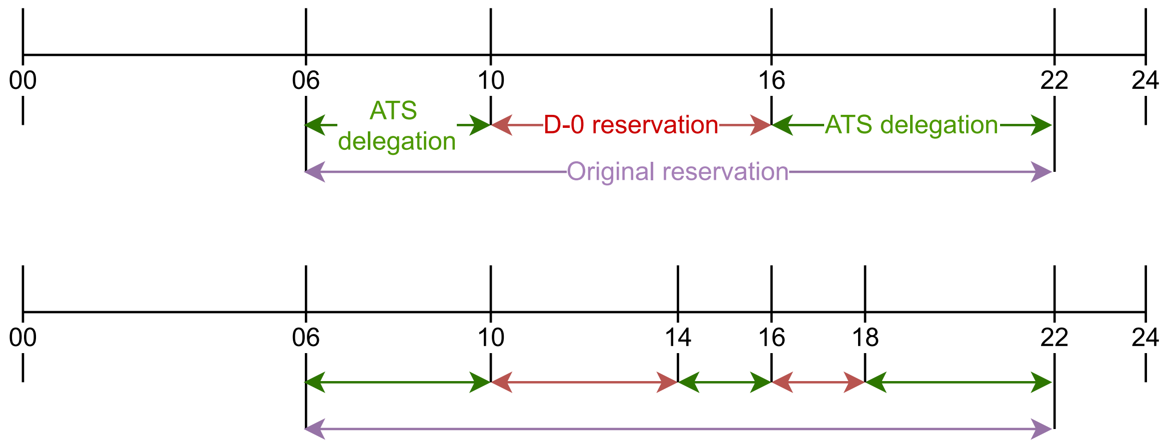


Figure 5.6: Example arrangement of reservations and resulting ATS delegations for one (above) and two (below) D-0 reservations

independently of the number of ATS delegations, these are decided upon with some plannability relative to the ATS delegation preceding the first D-0 reservation.

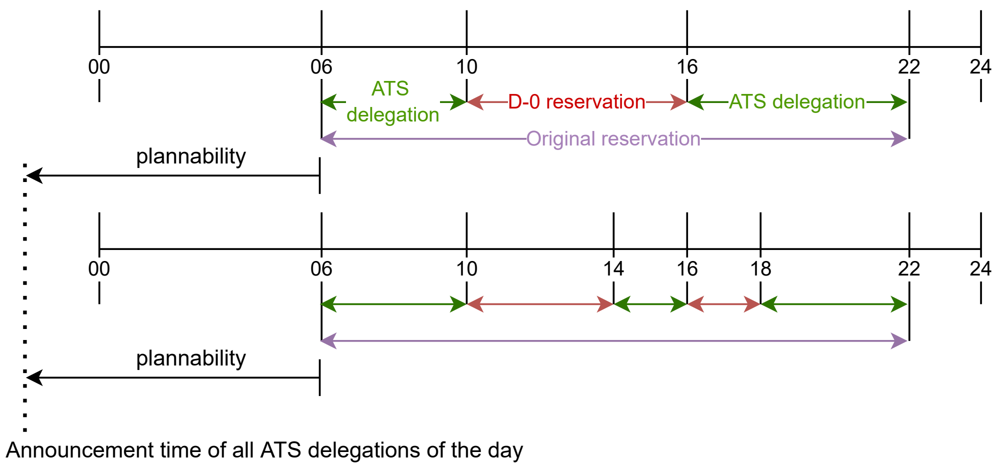


Figure 5.7: Concept Set 1 policy

Secondly, Concept Set 2 proposes a more flexible alternative for the military user and consequently yields lesser benefits to the civil user. This allows different announcement times for different final reservations, yet setting a maximum allowable time to make more final reservations. Without this constraint, the current situation would be given again, where no guarantee of transit can be given during the entire original reservation. In this manner, each D-0 reservation has its corresponding announcement time, when transit is guaranteed for the ATS delegation before the D-0 reservation at hand, but not after it. If it also guaranteed the transit after the D-0 reservation, this would mean that no more D-0 reservations could be made later throughout the day. In order to give an eventual guarantee of transit, a maximum time to make a reservation can be used. D-0 reservations can be made up until that time, but not later. At that time, transit is guaranteed from that point to the end of the original reservation, barring the periods of D-0 reservations already made. For example, if the maximum time a reservation can be made is at 17:00, any reservation made previously (up to 16:59) is still valid after 17:00, but outside of these (and in the case of no reservation) civil traffic has the guarantee of transit through the FUA from 17:00. In summary, Concept Set 2 guarantees the transit through the FUA in two manners. First, at each announcement time corresponding to a D-0 reservation, transit is guaranteed for the ATS delegation preceding it. Secondly, at the cutoff time e.g. 17:00, transit is guaranteed within any ATS delegations remaining after this time. This cutoff time can therefore become a second independent variable to analyse the benefits of. The later this maximum allowable time, the less time civil stakeholders have a guarantee of transit through the FUA while this is not used. This proposes a new dimension of flexibility to Dutch FUA that the military user can still benefit from without excessively burdening on the civil user. This is shown in Figure 5.8, where each D-0 reservation made guarantees transit to the preceding ATS delegation, and new reservations can be added up until the cutoff time, shown at 17:00 in the example. Before this, new reservations can be made, but at the cutoff time the transit through the FUA is guaranteed for all remaining ATS delegations thereafter. For simplicity, all plannability horizons relative to each D-0 reservation share the same value in the experiment (yielding different announcement times). These, together with the cutoff time, are the independent variables of Concept Set 2.

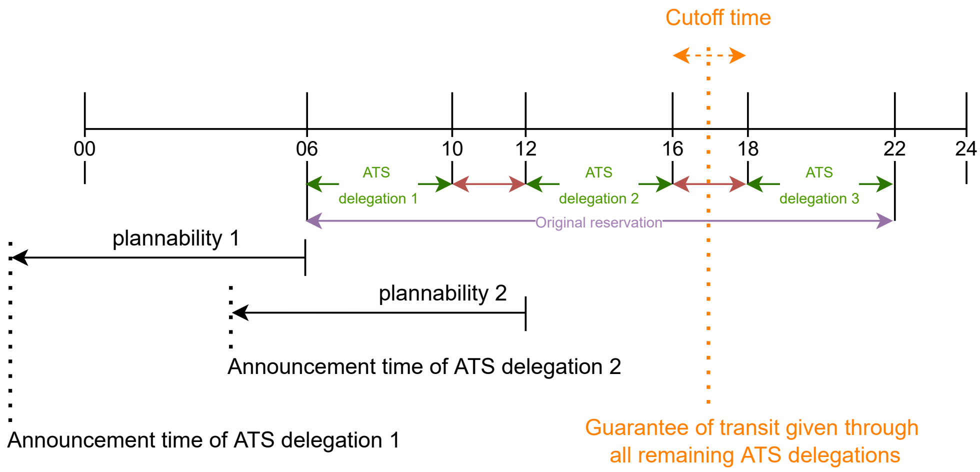


Figure 5.8: Concept Set 2 policy

Lastly, Concept Set 3 proposes an extension of the current procedure of the AUP, where the original reservation interval is shrank with some plannability. Instead of doing so only once a day in advance, it is proposed to do so in a more continuous manner. While this is also the idea of the UUP, Concept Set 3 proposes the guarantee of transit and higher plannability horizons. The idea behind Concept Set 3 is that the military user becomes more confident about the D-0 reservations the smaller the plannability. In practical terms, this means that the reservation interval evolves from the original reservation to the D-0 reservations in a gradual approach. The expected usage of the FUA thus shrinks with time, with each stage guaranteeing transit through a larger ATS delegation outside of the times during which the military may still want to use it. The independent variables of this Concept Set are twofold. A first parameter steering the performance must be the rate at which the FUA is delegated to ATS, e.g. the amount of minutes delegated per frequency of update. This captures how conservative or generous the policy of the military user is. For simplicity, the frequency of update is fixed at one hour, and thus this variable becomes the amount of time, in minutes, delegated at each hour. The greater the amount of time delegated per hour, the faster the FUA is delegated and thus the more flights end up not taking the surplus fuel. Naturally, this also depends on the time at which the FUA starts to be delegated. A slow delegation of e.g. 10 minutes per hour does however not matter if it starts four days in advance, for which the absolute time at which the delegation starts is also used as an independent variable. For a given delegation start and interval of time delegated per hour, Figure 5.9 shows how the further in time, the larger the ATS delegation intervals are. Lastly, an overview of all Baselines and Concept Sets, along with their key characteristics and independent variables, is given in Figure 5.10.

5.4.3. Step 3: Identifying the Flights in the FUA within the ATS Delegations

Once the ATS delegations have been identified, the flights entering the FUA within them are taken as the flights considered, i.e. those which plannability affected them in taking the surplus fuel or not. While in Concept Set 1 the plannability is guaranteed for all ATS delegations at once, this step becomes more complex for Concept Sets 2 and 3, where different announcement times guarantee the transit to different ATS delegations.

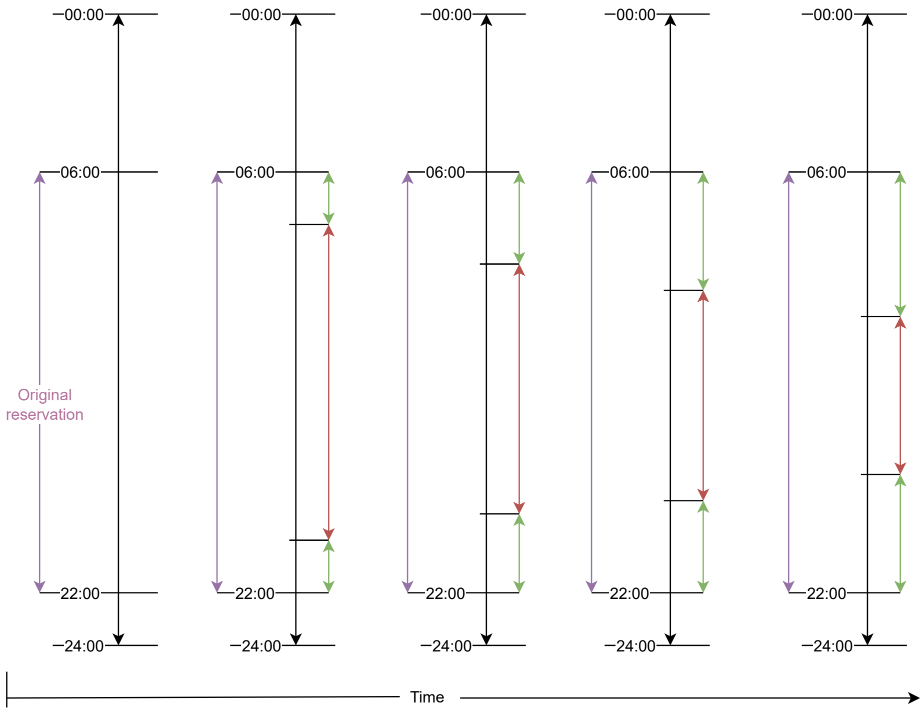


Figure 5.9: Concept Set 3 policy

5.4.4. Step 4: Identifying the Flights not carrying the Surplus Fuel

Having set up the problem of plannability, and during what intervals of time the plannability of FUA affects whether a flight carries the surplus fuel or not, it must be determined how the latter is decided. In other words, it is clear the earlier the plannability the higher the number of flights not carrying the surplus fuel, but the conditions for this must be further specified.

As explained in earlier sections, the problem of plannability comes from loading the fuel according to a longer trajectory than the actual one, as the guarantee of transit through the FUA was lacking. The trajectory according to which the fuel is loaded is given in the last flight plan issued. Based on discussions with KLM representatives, this can be approximated to be at H-3, i.e. 3 hours before the time at the gate. The time at the gate can be taken to be the start of turnaround, so around 45 minutes before the filed (planned) Off-Block Time. In this manner, it can be assumed that for all flights the last flight plan is issued 3 hours and 45 minutes before the filed Off-Block Time, with the latter being available from historical data.

For each flight, the absolute time at which the last flight plan is issued can now be approximated. Knowing also the announcement times of the FUA, which guarantee the FUA final reservation(s) and thus also the ATS delegations, it can be now known whether each specific flight takes the surplus fuel or not. If the corresponding ATS delegation is announced before the flight's last flight plan is issued, then the latter will have the guarantee of FUA and not load the surplus fuel. Else, the flight does not have the guarantee of transit and will need to load the surplus fuel. This logic is summarised in Algorithm 2.

5.4.5. Step 5: Determining the deviated Route

The surplus fuel to be calculated is defined as the difference between the fuel weights required to fly the range of two scenarios. The first of these scenarios is the hypothetical case where the flight is deviated around the FUA, i.e. the planned route before the right of transit through the FUA is guaranteed. The second is the historical scenario, where the flight makes use of the FUA. While the latter route is taken from the historical traffic data, the former one needs to be determined such that the corresponding range can be calculated. In other words, while in Experiment 1 a GCR trajectory was created, a deviated trajectory must be found for Experiment 2.

Several path planning methods to avoid obstacles were considered. For example, graph-search methods finding

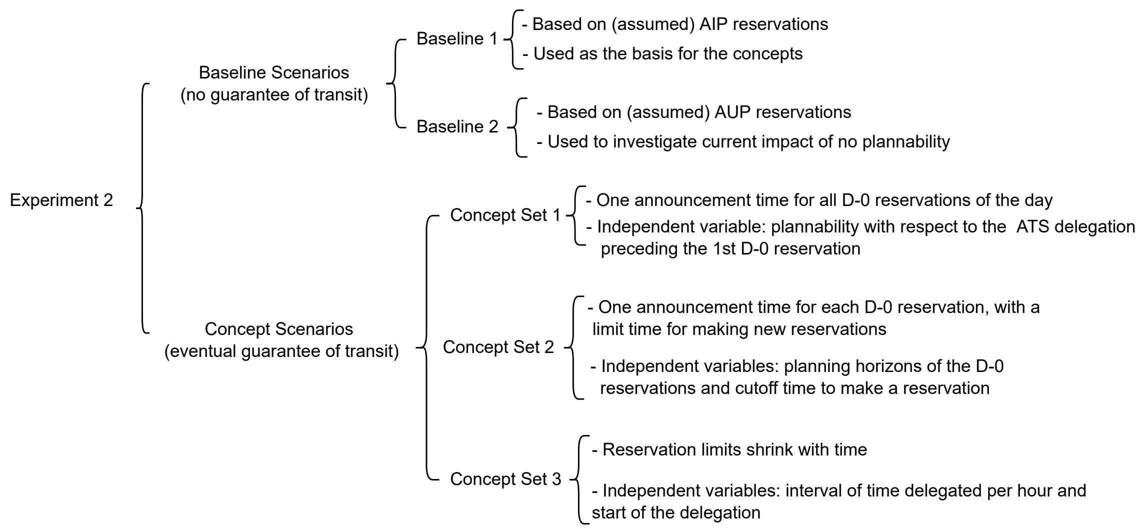


Figure 5.10: Setup of Experiment 2

Algorithm 2 Experiment 2, Step 4

for each ATS delegation:
  Based on the plannability concept, calculate the announcement time of the right of transit.
  for each flight within the ATS delegation:
    Calculate last flight plan issued: 3h and 45 minutes before the filed Off-Block Time.
    if the announcement time is before the time the last flight plan is issued:
      The flight does not take a surplus fuel.
    else:
      The flight takes a surplus fuel.

the cheapest route through a discrete network of vertices and edges could be used, such as Dijkstra's algorithm [28] and A*. Another possibility would be gradient-based methods such as a potential field approach [29] or the Ordered Upwind method [30], consisting of making local searches rather than finding a global optimum, thus moving in the most promising direction. The most promising option would be that of branch-and-bound methods, which circumvent the need to iterate over all possible combinations by directing the search to a number of feasible solutions and comparing each to the best one known. The hypothesis that such a method would be an acceptable alternative to the Ordered Upwind Method in terms of the quality of the solution, yet with much more efficient computational times, was proven by Rein-Weston [31]. The model developed is able to find an optimal 2-dimensional path between origin and destination avoiding obstacles and in the presence of wind, with similar results to that of Girardet's baseline model.

This method was chosen for its implementation but a series of problems were found. Firstly, it is important to note that making use of such an algorithm yields the most optimal deviated trajectory around the obstacle, which implies for this route to travel along the edges of the FUA. To circumvent this issue, the obstacle given as input to the branching planner could have a certain margin with respect to the true FUA coordinates. Secondly, this tool is contextualised as a 4-dimensional trajectory planner for TBO, for which it assumes direct routing from origin to destination. In contrast, the research at hand is to use this tool to substitute only the segment of the trajectory within the FUA, for which the optimal route yielded by the tool is used to connect the last historical point before entering the FUA with the first one after leaving it. When connecting the deviated segment to the other historical segments (before and after the FUA) this yields in many cases a sub-optimal and unrealistic deviation, as in reality a flight would go to a couple more waypoints downstream to reduce the distance flown. This issue could be partially solved by the aforementioned strategy of inputting an obstacle larger than the FUA, as the most immediate waypoints before and after the FUA would not be used.

Given that for the sample size and number of simulations desired this method would result in a major obstacle in terms of computation time and practicality, it is decided to opt for a simpler and more realistic approach. This consists of, in a similar fashion as for RQ-1.2, finding the flights that share the same departure-destination pair than the flight at hand, simply now taking flights that went through the FUA and finding similar ones which did not. After checking that the similar flight has flown a larger distance in the region in and around the FUA, this is taken as the extra range the original flight assumed before being guaranteed the transit. Not only is this method simpler and better integrated with the remaining software modules, but it also provides a more realistic alternative as it is a historical route.

5.4.6. Step 6: Calculating the Surplus Fuel

In order to relate an increase in range to a corresponding increase in fuel weight, a new relation must be developed. The basis is Breguet's range equation, and the derivation is similar to the model proposed by Wink [32], where the relation between fuel and payload weight is examined to develop a flexible passenger demand model. Breguet's equation, shown in Equation 5.14, relates the range R of a mission phase with aircraft parameters and the fuel burnt during the phase. More concretely, V is the aircraft's speed, L, D and c_j the Lift, Drag and specific fuel consumption of the jet engine $[kg/Ns]$, and W_{Start} and W_{End} the weights of the aircraft at the start and end of the phase, respectively. The dimensional analysis is given in Equation 5.15.

$$R = \frac{V}{g_0 c_j} \frac{L}{D} \ln\left(\frac{W_{Start}}{W_{End}}\right) \tag{5.14}$$

$$[m] = \frac{[m/s]}{[m/s^2][kg/Ns]} \frac{[N]}{[N]} \ln\left(\frac{[kg]}{[kg]}\right) = \frac{ms^2Ns}{mskg} = \frac{Ns^2}{kg} = \frac{kg\frac{m}{s^2}s^2}{kg} = m \tag{5.15}$$

The fuel burnt throughout the phase is the unknown of the problem at hand, for which the equation must be rearranged. First, let us subdivide the weights as follows. W_{Start} is to be composed by the fuel burnt before starting cruise $W_{f_{before\ cruise}}$, the fuel burnt during cruise $W_{f_{cruise}}$ and the fuel to be burnt after cruise $W_{f_{after\ cruise}}$, as well as the Operational Empty Weight W_o and the payload weight W_{pl}. Now let us define the end section of this analysis as the end of cruise. At that point, the weight of the aircraft W_{End} consists of the weight for the fuel after cruise $W_{f_{after\ cruise}}$, Operational Empty Weight W_o and the payload weight W_{pl}. For simplicity, let us define W_{remain} as the sum of the fuel weight after cruise, Operational Empty Weight and payload weight, i.e. the weight components which remain after the cruise phase and may be assumed independent of the route taken. Breguet's formula can thus be developed as shown below.

$$R\frac{g_0 c_j}{V}\frac{C_D}{C_L} = \ln\left(\frac{W_{Start}}{W_{End}}\right) \tag{5.16}$$

$$e^{\frac{Rg_0 c_j C_D}{VC_L}} = \left(\frac{W_{Start}}{W_{End}}\right) \tag{5.17}$$

$$e^{\frac{Rg_0 c_j C_D}{VC_L}} = \left(\frac{W_{f_{before\ cruise}} + W_{f_{cruise}} + W_{f_{after\ cruise}} + W_o + W_{pl}}{W_{f_{after\ cruise}} + W_o + W_{pl}}\right) = \left(\frac{W_{f_{before\ cruise}} + W_{f_{cruise}} + W_{remain}}{W_{remain}}\right) \tag{5.18}$$

$$e^{\frac{Rg_0 c_j C_D}{VC_L}} = \frac{W_{f_{before\ cruise}} + W_{f_{cruise}}}{W_{remain}} + 1 \tag{5.19}$$

$$\left(e^{\frac{Rg_0 c_j C_D}{VC_L}} - 1\right) W_{remain} = W_{f_{before\ cruise}} + W_{f_{cruise}} \tag{5.20}$$

Essentially, Equation 5.21 now yields the required fuel weight for the cruise phase given the aforementioned parameters. Again, it is not desired to know the fuel weight given a desired range, but its change given another range. Given that the fuel needed to descend from cruise $W_{f_{after\ cruise}}$, the Operative Empty Weight W_o and the Payload Weight W_{pl} (and therefore W_{remain}) should be independent of the exact mission range, and the fuel needed before cruise $W_{f_{before\ cruise}}$ is also assumed to be independent of the mission range, Equation 5.21 can be used to yield Equation 5.22 when two different ranges are considered, e.g. R_1 going through the FUA sector and R_2 deviating around it ($R_2 > R_1$).

$$W_{f_{cruise}} = \left(e^{\frac{Rg_0c_jC_D}{VC_L}} - 1\right) W_{remain} - W_{f_{before\ cruise}} \tag{5.21}$$

$$W_{f_{cruise_2}} - W_{f_{cruise_1}} = \left(e^{\frac{R_2g_0c_jC_D}{VC_L}} - 1\right) W_{remain} - W_{f_{before\ cruise}} - \left(e^{\frac{R_1g_0c_jC_D}{VC_L}} - 1\right) W_{remain} + W_{f_{before\ cruise}} \tag{5.22}$$

In this manner, the difference between the fuel weights as a function of the different ranges required can be obtained as shown in Equation 5.23.

$$\Delta W_{f_{cruise}} = \left(W_{f_{after\ cruise}} + W_o + W_{pl}\right)\left(e^{\frac{R_2g_0c_jC_D}{VC_L}} - e^{\frac{R_1g_0c_jC_D}{VC_L}}\right) \tag{5.23}$$

Nevertheless it is not trivial to attain C_L and C_D, as these depend once again on the mass and thus fuel taken. In order to approach this problem, the following procedure is used, as taken from Wink [32]. The Breguet equation relates the range to a given mass configuration. If specific weights and ranges are known from a given condition, the parameters to be found can be taken as a constant. In this way, the Breguet equation is formulated as in Equation 5.24, where TPR is the aircraft range at Maximum Take-Off Weight, the W_{start} is taken as the Maximum Take-Off-Weight and the W_{End} is taken as the sum of the Operative Empty weight and the payload. By taking a standard case the weights of which are given by aircraft specifications, the parameters needed can be taken as a constant C holding for any flight of the same aircraft type.

$$C = \frac{V}{g_0c_j}\frac{C_L}{C_D} = \frac{R}{\ln\left(\frac{W_0+W_p+W_{\text{fuel}}}{W_0+W_p}\right)} = \frac{TPR}{\ln\left(\frac{W_{MTOW}}{W_0+W_p}\right)} \tag{5.24}$$

In this way, Equation 5.23 can be further simplified into Equation 5.25. The variables needed are then the operative empty weight, the payload weight (given by BADA), an assumption of the fuel needed for the descent phase, the maximum take-off weight and the corresponding maximum range. With these, the extra fuel needed based on the different mission ranges R_1 and R_2 can be found. These ranges are calculated from the deviated (hypothetical) trajectory found in Section 5.4.5 and the actual one from historical traffic data.

$$\Delta W_{f_{cruise}} = \left(W_{f_{after\ cruise}} + W_o + W_{pl}\right)\left(e^{\frac{R_2}{C}} - e^{\frac{R_1}{C}}\right) \tag{5.25}$$

This increase in fuel can then be added to the assigned weight of every aircraft (e.g. the reference mass taken from BADA) as the surplus fuel. In other words, the plannability of FUA changes only the mass of the aircraft in this experiment. The earlier a FUA deactivation is planned in advance, the higher the number of aircraft that will know about this delegation before loading the fuel. The flights whose fuel was loaded without the right of transit will still traverse the FUA once delegated, yet carrying the extra amount of fuel given by Equation 5.25.

5.4.7. Step 7: Computing the Fuel Efficiency Metrics

For each baseline and concept proposed, which as aforementioned differ only in the fuel weight taken and not in the trajectory flown; the work done, fuel consumption and CO_2 emissions are calculated throughout the entire flight. This is done in the same way as for Experiment 1, using then relations shown in Section 5.3.3.

5.4.8. Experiment 2 Methodology Summary

Having described all the different steps to accomplish the main sub-question of Experiment 2, their order and logic appear summarised in the flowchart of Figure 5.11. Note that the flow chart shows the procedure of only one concept, i.e. given a certain Concept Set and concept of plannability or the corresponding independent variables.

5.4.9. Summary of Variables

The following summarises the dependent and independent variables, with the latter differing per Concept Set.

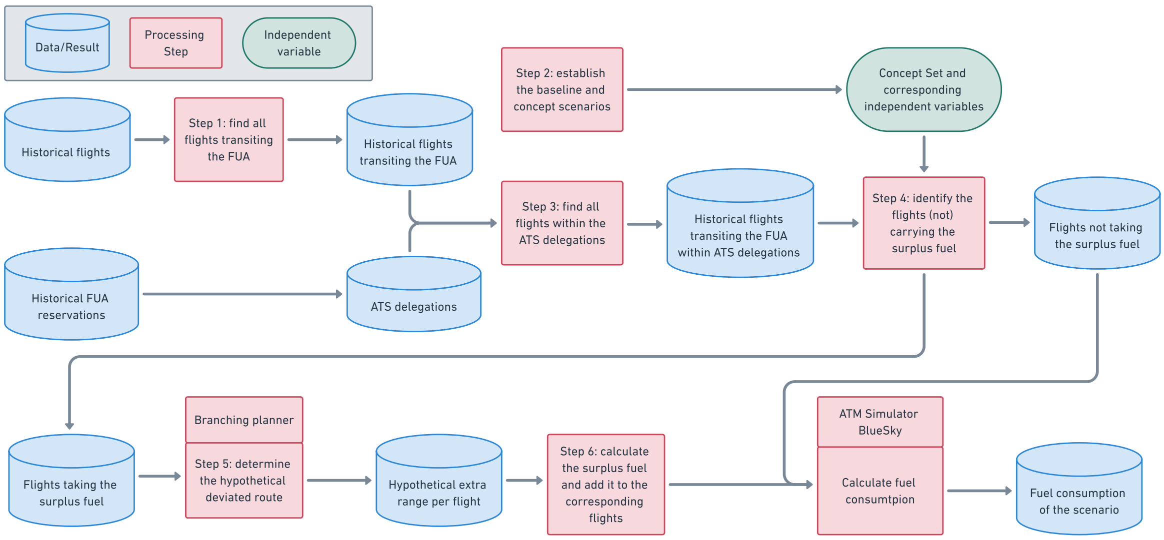


Figure 5.11: Flowchart of Experiment 2 RQ-2.2 methodology

Independent Variables
For all Concept Sets:

- **FUA sectors:** Alpha and Delta. As for Experiment 1, Alpha and Delta are to be considered separately.

For Concept Set 1:

- **Plannability horizon:** in hours relative to the ATS delegation preceding the first D-0 reservation. The corresponding announcement time guarantees transit for all ATS delegations of the day.

For Concept Set 2:

- **Plannability horizon for each D-0 reservation:** in hours relative to the ATS delegation preceding each corresponding D-0 reservation. For simplicity, the same plannability can be used for all reservations. Their announcement times guarantee the transit through the ATS delegation before the corresponding D-0 reservation.
- **Cutoff time for making new reservations during D-0:** absolute time during the day of operations. New D-0 reservations can be made up until that time. Then, transit is guaranteed for all ATS delegations remaining.

For Concept Set 3:

- **Interval of time delegated per hour:** amount of time, in minutes, the airspace is delegated to the civil user each hour.
- **Start of the delegation:** time relative to the first ATS delegation, in hours, at which the intervals start to be delegated to the civil user.

Dependent Variables
The following variables are calculated for the baseline and every plannability concept, such that its benefits can be investigated.

- **Number of flights not carrying the surplus fuel:** the first effect of a given plannability horizon is the number of flights not carrying the surplus fuel. All metrics below are a direct consequence of this.
- **Work:** in Joules.
- **Fuel consumption:** in kilograms.
- CO_2 **emissions:** in kilograms.

5.4.10. Assumptions

- Flights traversing the FUA during the D-0 reservations (and hence carrying a surplus fuel regardless of the plannability concept) are not considered lost efficiency.
  As seen in Figure 2.2, a small number of flights may traverse the FUA even during the D-0 reservations. This is because the training may start later or end sooner than expected, or take place in a certain region while leaving much of the FUA free. In these cases, transit is cleared for civil flights through the FUA for a small window of time within the D-0 reservations. Irrespective of the plannability concept, these flights are to carry surplus fuel. Nonetheless, given that this is the D-0 reservation itself, this transit is not deemed as lost efficiency but rather equitable. In this manner, only the flights transiting the FUA during the ATS delegations are considered.
- No wind and ISA are assumed, as reasoned for Experiment 1 in Section 5.3.5.

5.5. Data Selection and Sampling

This section provides the reader with the rationale behind the databases used and the sampling. First, an overview of the data sources available for the historical civil traffic and D-0 reservations is given in Section 5.5.1 and Section 5.5.2, respectively. Knowing the strengths and weaknesses of each database, a decision on the selection is made in Section 5.5.3. Finally, the database selected requires of an extrapolation method to provide yearly estimations of the analysis, the challenges of which are introduced in Section 5.5.4.

5.5.1. Data Availability: Historical Traffic

The experiments of this study are to make use of historical traffic data. This is because it is desired to gain a concrete understanding of the effects of specific FUA structures in Amsterdam FIR, as well as wanting to compute the fuel efficiency of traffic in a representative manner. For such historical data, three main sources are available: ADS-B, radar data from LVNL and the Eurocontrol R&D data archive, as described below. Their characteristics with respect to the criteria of relevance to this study are summarised in Table 5.1.

ADS-B

First, Automatic Dependent Surveillance Broadcast or ADS-B consists of broadcasting via datalink the aircraft's callsign, latitude, longitude, altitude, velocity, heading, etc. Any user within range can receive and process the data, allowing all users to have access to the same data [33]. According to FlightRadar24, around 80% of all European flights are equipped with an ADS-B transponder [1]. Databases of such information are publicly available, and these can be accessed through Python APIs, enabling the use of worldwide historical traffic data for research purposes. A good example of such a tool is pyOpenSky, a Python library developed by Sun [34] [35] which decodes Mode-S messages from the OpenSky database [36]. The advantage of this process is the ability to gather any period and region of historical data as desired. The main disadvantage is that the scraping process may become extremely time consuming for large regions of airspace and sample times.

LVNL Radar Data

Secondly, use could be made of radar data from LVNL. This is an accurate data source of the traffic within Amsterdam FIR. It contains not only civil flights but also most of the military ones, except for the F-35 due to current issues with the surveillance of this aircraft type. Nonetheless, some civil commercial flights above FL245 do not appear in the database, nor their flight plans as these were not shared with LVNL. Contrary to ADS-B, the data is readily available i.e. does not take time to collect it, and as for ADS-B any day of the last few years can be investigated. The critical disadvantage of this data source, apart from missing flights above FL245, is that the data points are limited to Amsterdam FIR, making it impossible to compute benefits for full trajectories. Further, this data is not openly available, limiting the reproducibility of this study.

Eurocontrol R&D Data Archive

Thirdly, Eurocontrol has made openly available an R&D data archive of all commercial flights operating in and over Europe [2]. It contains a list of flights with their essential information, filed and actual flight trajectory, etc. It also contains the complete trajectory of all civil commercial flights traversing Europe. The main disadvantage of this data archive is the limited database of 4 months per year, for which an extrapolation method needs to be chosen and reasoned if the results are desired on a yearly basis. Further, the airspeed is not available, which is

[1] https://www.flightradar24.com/how-it-works
[2] https://www.eurocontrol.int/dashboard/rnd-data-archive

Criteria	ADS-B	Radar	Eurocontrol
Complete trajectories?	Yes, worldwide data	Only in Amsterdam FIR below FL245	Yes, for flights in and over Europe
Number of flights covered?	About 80% of European flights	All civil flights below FL245	All civil commercial flights in Europe
Readily available data?	No, scraping needed	Yes	Yes
Openly available?	Yes	No	Yes
Possible sampling available per year?	No limit	No limit	For 2015-19: March, June, September and December

Table 5.1: Possible sources of historical traffic data

needed in order to compute the fuel consumption. In order to suffice for this, the ground speed can be assumed as true airspeed, and calculated by using the time and position between entries.

5.5.2. Data Availability: FUA Reservations

The results of Experiment 2 greatly depend on the number of flights flying through the FUA during the ATS delegations. For this reason, it is as important to know the historical traffic for a given day as it is to know its ATS delegations. To determine these, data on the reservations made at D-0 for Alpha and Delta is needed. The data used for the Experiment 2 must therefore match between historical traffic and D-0 reservations data.

This data is saved for the last 30 days in an internal system of LVNL. Nonetheless, it is desired to have a greater sampling of data, such that the study can be done for months previous to the COVID-19 pandemic, with a higher (or nominal) traffic density. To have this sampling, the historical records in paper of the military ATC supervisors have been retrieved, going as far back as 2019.

5.5.3. Data Sampling

On the one hand, the most ideal database for Experiment 1 is the Eurocontrol R&D data archive. This is because it has the complete trajectories of the flights that may benefit from the FUA with a GCR trajectory. This is important for mainly two reasons. First, it allows to quantify the benefits over the entire trajectory. Secondly, whether a flight can benefit from the FUA or not is given by the distance horizon chosen, for which the complete trajectory is needed.

On the other hand, Experiment 2 requires the aforementioned match between historical traffic and reservation sampling. Given the availability of up to 2019 from the historical records of the military ATC, the four months available in the Eurocontrol R&D data archive (March, June, September and December) can be used. The drawbacks of using this database, mainly the lack of airspeed and the limited sampling, far outweight the drawbacks of using radar data, which inherently limits the number of flights attainable and has limited trajectories. Further, ADS-B is not a feasible option for the sampling times (months) desired due to the long scraping times.

In summary, while Experiment 1 is to use the Eurocontrol R&D data archive with no preference for the sampling from the years available (2015-2019), Experiment 2 requires of 2019, as full records of D-0 reservations were retrieved. 2019 is also the preferred year, as it is the last and thus busiest year of civil traffic before the COVID-19 pandemic. In this manner, both Experiments will share the same sampling, to be chosen between March, June, September and December from 2019.

It must be however noted that, given the large number of independent variables to be considered, processing times need to be carefully examined. Take Experiment 1, for example. In order to answer RQ-1.1, two FUAs are examined, three scenarios may be considered (historical trajectory and two GCR speed settings), and four distance horizons can be taken for example. Their combinations already result in 24 scenarios per day. As explained in Section 5.6, BlueSky is to be used to compute fuel consumption for each of these scenarios. Given that for both experiments a single scenario means running an entire day of trajectories, which has been seen to take around 25 minutes, this creates a bottleneck in computation time. It is desired to investigate as many days as possible, but doing several in this manner is entirely unfeasible. To solve this problem, use can be made of the built-in batch simulations of BlueSky, which allow to run as many scenarios in parallel as logical processors available. Despite this great advantage, doing several months from the available sampling would still be challenging, given the two experiments and the different Concept Sets, two of them driven by not one but two independent variables.

5.5.4. Data Extrapolation

The results of the sampled time need to be extrapolated if a yearly estimation of the benefits is desired. For this analysis, and in particular for Experiment 2, this becomes a challenging task for the following reason. When considering an analysis on e.g. Continuous Climb Operations or any other concept where all flights adhere to, computing the yearly benefits is straightforward. By computing the average benefits for each aircraft type for e.g. a new climb concept, attaining yearly benefits is only a matter of knowing the total number of flights of that aircraft type which took off in Amsterdam FIR or Schiphol, and doing so for all aircraft types. Such an extrapolation is presented by Klapwijk [24]. Nonetheless, the study at hand presents concepts which affect only a selected number of flights, for which what must be extrapolated is not only the fuel efficiency benefits but primarily the number of flights which are estimated to have them. Not only that, but the D-0 reservations are also a deciding factor, as they determine the actual usage of the FUA by civil traffic. It is expected for this extrapolation to rely on the results of the sampled time of 2019 and to extrapolate the number of flights benefiting from each concept using as a basis the D-0 reservations made throughout the entire 2019. Further, if the benefits for more than a month are found, the extrapolation method could be tested by separating the results in different datasets. In this manner, using the results from one of the sampled months, the other(s) could be estimated, and then compared with the actual results found for that sample.

5.6. Experiment Tools

The main tools of this research are discussed in this section. If each of both experiments was to be divided into two general parts, it would be a first part on data processing and a second on the computation of fuel efficiency metrics. For the first part, consisting mainly of the filtering of flights and the creation of hypothetical trajectories, the main tools used are the libraries pandas for database filtering, shapely to check if a point lies within a polygon of coordinates and pyProj for the cartographic projections and distance computations.

For the second part, the fuel computation logic outlined in Section 5.3.3 was first implemented directly with the pandas DataFrame infrastructure, i.e. calculating the fuel flow for each point or entry of the trajectory DataFrame. Nonetheless, this provided extremely coarse results, largely insensitive to nuanced changes in the performance of the flights. As aforementioned, the Eurocontrol R&D data archive contains a small number of points per trajectory, e.g. from 20 for domestic flights up to 150 for transcontinental ones, which results in a frequency of one data point per each five to ten minutes. Furthermore, each flight has only one or two climb and descent entries. This is an extremely coarse basis to integrate the fuel flow from, as the one calculated for each entry must be assumed constant for the entire interval.

This coarse quantification of the fuel consumption results in inherently incorrect results when comparing concepts with nuanced performance settings. For instance, and as explained in Section 5.3.3, the hypothetical GCR concept created for Experiment 1 could be constructed using two different methods for the speed. On the one hand, the original velocity could be maintained, and thus the flight would arrive to the destination earlier given the shorter distance to fly. On the other hand, the speed could be optimised to minimise fuel consumption. The coarseness of computing the fuel flow directly from the database entries transpires to an inherently incorrect computation when the former concept is seen to have a lower consumption than the latter. This is because small changes in the performance are insignificant compared with the inaccuracies given by the low frequency entries. More concretely, the thrust calculation is very sensitive to values of airspeed and altitude, which cannot be accurately represented with such low frequency entries. The objective of this thesis is to quantify fuel consumption to a sufficiently accurate level such that concepts with slightly different performance settings in airspeed or mass are seen to make a difference, for which another framework is needed.

The solution to this problem is having more entries at which the variables are accurately represented. Creating more entries by interpolating the existent ones would be of no use, as the problem lies in the fact that the points available are already too sparse. In order to create high-frequency and consistently propagated data points, a simulation environment must be used. Although no higher order behaviour is to be investigated, the rationale behind simulation lies in the need to propagate accurately an initial condition. For this, use will be made of the software tool BlueSky, created by Hoekstra et al. [1]. The historical trajectories can be converted into scenario files and fed into the simulator, which then propagates the initial conditions given. Finally, BlueSky itself can be used to calculate the fuel consumption, as previously done by Inaad [23], Klapwijk [24] and Adriaens [25].

As mentioned in Section 5.5.3, BlueSky creates a bottleneck in processing times when trying to compute the fuel consumption of many scenarios. This makes it necessary to use its batch simulation functionality, enabled by a multi-CPU core computer. For this, the 36-logical processor computers at the Innovation LABs of LVNL will be used, such that 36 different simulations can run in parallel.

5.7. Verification and Validation

The main model to be used for this thesis is the fuel consumption computation. This uses the formulae outlined in Section 5.3.3 and the coefficients from BADA 3.12 to compute the performance of civil aircraft. These have been validated by Eurocontrol and other independent studies, e.g. Nakamura [37]. This model is already present within BlueSky in perfbada.py, implemented and validated within the simulator by Metz [38].

Secondly, the implementation of the surplus fuel computation can be verified by using the results of Wink [32]. There, the values of the variable C, which enables the calculation of fuel weights irrespective of the specific mass of each scenario, are found per aircraft type. By using the same aircraft type and performance settings, the results may be compared with those of Wink and the implementation of the model verified.

Furthermore, no wind was assumed for both experiments. This was done such that the ground speed calculated between flight points, as given by the time between the points and their coordinates, could be used as airspeed, which is later converted to calibrated airspeed to be used by BlueSky. By adding wind to the scenarios, the sensitivity to the results in fuel efficiency to the assumption of no wind could be assessed. Similarly, the effects of assuming a standard atmosphere could be judged by adding different temperature offsets. Nonetheless, these assumptions affect the absolute performance of the scenarios, creating an offset in the results that is cancelled when finding the relative benefits in fuel efficiency metrics between scenarios.

6

Preliminary Results

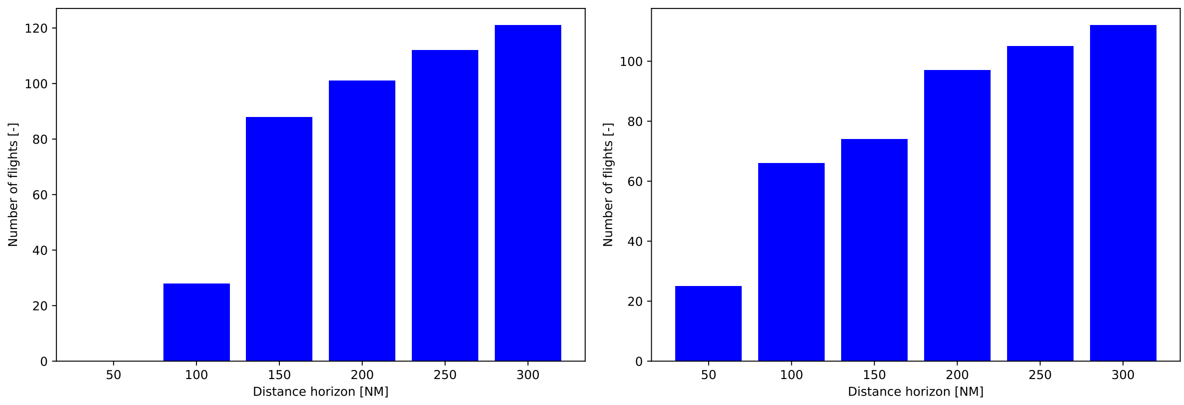
This chapter contains the preliminary results of the research project. These aim to provide an understanding of the principles of the experiments and the effect of their corresponding independent variables. For both experiments, the preliminary results here focus on identifying the number of flights fulfilling the conditions of interest (e.g. flying through the FUA or not taking the surplus fuel), thus leaving the fuel consumption computations as future work. In this manner, this chapter presents the preliminary results for Experiment 1 and 2 in Section 6.1 and Section 6.2, respectively. In both of these, the results were determined by making use of the Python libraries pandas for database filtering, shapely to check if a point lies within a polygon of coordinates, and pyProj for the cartographic projections. Lastly, the results attained are used to propose a reasonable range of values for the independent variables to have, as described in Section 6.3.

6.1. Experiment 1

For Experiment 1, it is first important to see how the distance horizon variable affects the number of flights which would benefit from the FUA. Only after can RQ-1.2 be started, for which the only results shown are for RQ-1.1. By enabling the GCR at a greater range (increasing the distance horizon), more flights can benefit the transit. Below is shown the number of flights which would have benefited from traversing the FUA, yet they historically did not, at different distance horizons at which the GCR is enabled. The results are considered separately for the Alpha and Delta sectors in Figure 6.1a and Figure 6.1b, respectively.

These results were determined as explained in Chapter 5 and summarised as follows. First, all flights historically making use of the FUA are filtered out. All remaining flights are considered with each different distance horizon, defined as the range in nautical miles from the center of each FUA at which a direct route is enabled. If a flight has points within the square created by this range, it is further considered as possibly benefiting from a GCR route. For each point within this square, a GCR route is created, bifurcating the historical trajectory, and merging back to it at the last historical point within the square. If this hypothetical trajectory crosses the FUA, it is deemed as lost efficiency. If the GCR does not traverse the FUA, the following historical points are checked in the same manner. In this way, increasing the range at which the GCR is enabled results in more flights being able to use the FUA while also containing those which benefited already from a previous, smaller range. For each distance horizon input, the number of flights which traversed the FUA was counted and shown in Figure 6.1a and Figure 6.1b. The data source used is the Eurocontrol R&D data archive for Tuesday 5th of March, 2019, as both regions had similar D-0 reservation intervals (08:00-15:00).

As expected, it can be seen how the number of flights which would have benefited from the FUA increases with the range from the FUA at which the GCR is enabled. Although it could have been hypothesised that a higher number of flights could benefit from Delta than for Alpha if this was made completely available, based on the significantly higher traffic density in the south of Amsterdam FIR, it is seen that the number of flights benefiting from both FUA is similar at each distance horizon. That is, except for 50 NM in the case of Alpha, an airspace larger in most its dimensions than that range, for which no GCR segments are possible. This similarity in the number of flights benefiting from the FUA may be explained by the fact that, although the traffic around Delta is denser, Alpha is much larger in size, thus allowing for more possible direct trajectories. In this manner, Figure 6.1 allows to



(a) Alpha sector

(b) Delta sector

Figure 6.1: Effect of the range (distance horizon) from the FUA at which the GCR is enabled on the number of flights benefiting from traversing the FUA. Note that for this, all flights are considered regardless of the period they would have transited the FUA.

hypothesise that both FUA hold similar potential benefits for the civil user if it is made available more often. This notion is however sensitive not only to the fact that smaller distance horizons are of particular benefit for Delta, but also given the inherent D-0 reservation intervals of the sample used. Even if they are not accounted for here, the D-0 reservation intervals determined the number of flights making use of a FUA, for which the more the FUA was historically reserved in the sample, the more flights avoided it and thus the greater the potential benefits.

6.2. Experiment 2

For Experiment 2, the key result of a proposed plannability concept is the number of flights that do not take the surplus fuel. The higher this number, the larger the fuel efficiency benefits. Whether each individual flight is deemed to take the surplus fuel or not is determined by the process explained in Section 5.4 and outlined in the following. First, for a given sample (when both the historical civil traffic and military reservation data are available), all D-0 reservation intervals are identified. By assuming an original reservation of 06:00 to 22:00 for both the Alpha and Delta sectors, the ATS delegations are determined. Note that this applies only to weekdays, as no reservations are made during the weekends. Furthermore, days with cancelled reservations, which occur sparingly and mainly due to adverse weather conditions, are disregarded, as these result in many more aircraft flying through ATS delegations: no D-0 reservations took place eventually, so the entire day would have been considered an ATS delegation, yielding a much greater loss of efficiency than usual.

With the ATS delegations now known for the days considered, the historical flights making use of the FUA during these can now be found. A flight is deemed to make use of the FUA during an interval if it enters the airspace within the corresponding period of time. All flights considered in Experiment 2 are those making use of the FUA within the ATS delegations, irrespective of the Concept Set or plannability concept.

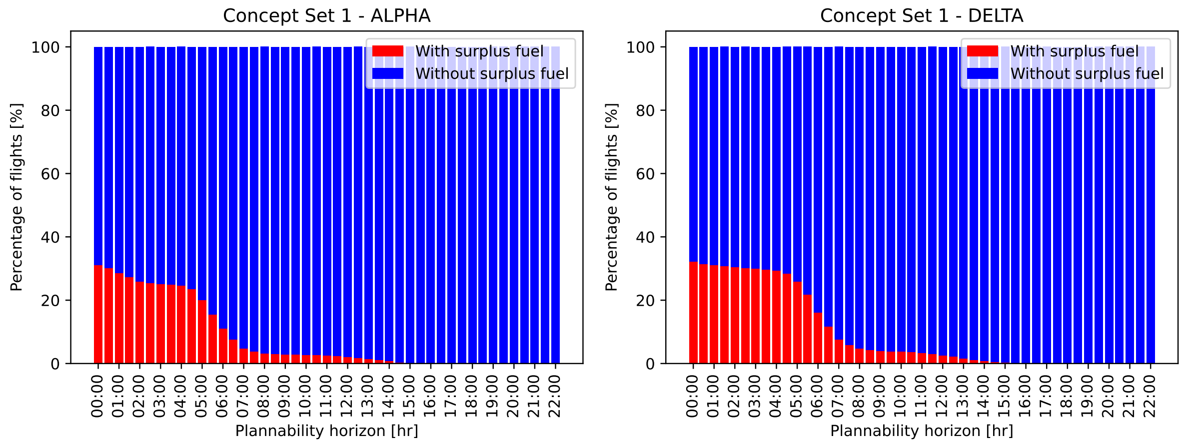
These plannability concepts, explained in Section 5.4.2 with results shown in Section 6.2.1 to Section 6.2.3, influence the number of flights that take a surplus fuel or not. Nonetheless, they are all done on the basis of the same number of flights, that is, those making use of the FUA during the ATS delegations. Each plannability concept yields a different announcement time, and depending on the Concept Set, each ATS delegation may have its own announcement time. This announcement time is the absolute time at which the transit through the corresponding ATS delegation(s) is guaranteed. This is calculated depending on the hypothetical plannability concept or horizon used as input. Whether each individual flight takes a surplus fuel or not is then determined by the calculated time at which the last flight plan is issued, assumed to be three hours and 45 minutes before the filed Off-Block Time as explained in Section 5.4.4. If this time is before the announcement time of the corresponding ATS delegation, this means that the flight did not have the guarantee of transit when issuing the flight plan, thus loading a surplus fuel. On the contrary, if the flight's last flight plan is issued after the announcement time, the guarantee of transit was known and therefore the flight did not load a surplus fuel.

As a summarising note, it is important to remember that the D-0 reservations and civil traffic is taken from historical data, while the original reservations have been assumed to be 06:00-22:00. However, all concepts of plannability, and therefore the flights taking or not taking a surplus fuel, are hypothetical scenarios. Further, it must be noted that the historical D-0 reservations used are actual use and not a planned interval: since the Royal Netherlands Air Force currently does not need to guarantee the ATS delegations, the intervals are logged by the minute, as e.g. 14:32-16:53, which are not realistic planning intervals as would for instance be 14:30-17:00.

In this manner, the preliminary results are given for the Concept Sets 1, 2 and 3 in Section 6.2.1 to Section 6.2.3, respectively. The data sampled for all is the entire month of March, 2019.

6.2.1. Concept Set 1

As explained in Section 5.4.2, Concept Set 1 guarantees the transit of civil traffic to all ATS delegations of the day with a plannability relative to the ATS delegation preceding the first reservation. This creates a large buffer of time for the later ATS reservations of the day, for which this Concept Set presents the most favourable results for civil traffic. As shown separately for the Alpha and Delta sectors in Figure 6.2a and Figure 6.2b, the number of flights carrying a surplus fuel decreases with plannability until it reaches zero.



(a) Concept Set 1: Alpha

(b) Concept Set 1: Delta

Figure 6.2: Effect of different plannability horizons on the percentage of flights taking the surplus fuel, under Concept Set 1

Concept Set 1 with a plannability of 0 hours means that the guarantee for the transit through all ATS reservations of the day is given at the start of the first ATS delegation. Although this is not a fixed time axis, and for Concept Set 1 an absolute time could be used, it is consistent with the other Concept Sets, where each ATS delegation has a corresponding announcement time, and thus an absolute time cannot be used as independent variable. Further, even if the military currently understands plannability relative to the D-0 reservations, it is decided to use a datum for the purposes of the civil stakeholders, for which all plannability horizons should be meaningful and useful, which is not the case with 1 or 2 hours of plannability relative to the D-0 reservation, as (some interval of) the ATS delegation becomes useless.

This yields a very different scenario (and much more favourable for civil users) than the current operation. This results in Figure 6.2 starting off with a considerable number of flights already not taking the surplus fuel, as the announcement time given by zero plannability still allows for most flights taking off after noon to benefit from the announcement. A noticeable increase in the number of flights not taking the surplus is seen after five hours of plannability, which given the average start of the morning training between 06:00 and 07:00 means an announcement time of after midnight. With this, a Schiphol inbound peak in the morning of short haul flights is covered. A minority of flights needing up to around 14 hours of plannability, i.e. an announcement time of around 4p.m. on the day before, covers the long haul, transcontinental flights arriving to Schiphol in the morning.

6.2.2. Concept Set 2

As oppose to Concept Set 1, the second proposed concept set does not guarantee the transit for some ATS delegations until a certain point of the day. As explained in Section 5.4.2, in order to maintain military flexibility each D-0 reservation made guarantees transit only in the ATS delegation preceding it, such that the military can still make more D-0 reservations after it. For an eventual guarantee of transit through the FUA, a 'cutoff time' is selected at which the remaining ATS delegations have a guarantee of transit. As it can be seen in Figure 6.3 to Figure 6.5, the main trait of Concept Set 2 when compared with Concept Set 1 is a percentage of flights taking the surplus fuel which remains somewhat constant irrespective of the plannability horizon. This is because of the cutoff time, the time at which transit is guaranteed for the remaining ATS delegations. Until that time during the day, transit for the remaining ATS delegations is not guaranteed, resulting in a percentage of flights not taking the surplus fuel largely independent of the plannability variable. The effects of the cutoff time variable are thus shown in the size of the band of somewhat constant percentage throughout the different plannability horizons, but changing throughout the different cutoff times used as input. By examining the plots in Figure 6.3 to Figure 6.5 vertically, it can be seen how the later the cutoff, the more flights take a surplus fuel.

6.2.3. Concept Set 3

For Concept Set 3, once again the preliminary results presented here focus on understanding the effects of the independent variables on the percentage of flights taking and not taking the surplus fuel. As explained on Section 5.4.2, the independent variables of Concept Set 3 are the interval of time delegated to ATS per hour (in minutes) and the start of the delegation, in hours relative to the first D-0 reservation. Once again it is important to note it is fixed to have one update each hour, for which at each hour said interval of time is delegated. As shown in Figure 6.6 and Figure 6.7, the x-axis contains the interval of time delegated per hour. The higher the interval of time delegated at each update, the faster transit is guaranteed through the final ATS delegation, representing a generous policy of the military user in which they compromise to give up the airspace rather sooner than later, and thus the smaller the percentage of flights taking the surplus fuel. For each FUA, each of the different plots in Figure 6.6 and Figure 6.7 is made for a different start of the delegation. When examining them vertically, it can be seen that the later the start of the delegation (so the smaller the delegation start variable), the more flights carry a surplus fuel, as this is equivalent to a smaller plannability or, in this case, a later time at which the airspace starts to be delegated. Further, it can be seen that even at the latest delegation start, around 70% of flights still do not take the surplus fuel. This is because, much like for Concept Set 1, this concept set was defined in a way that all ATS delegations are determined at the start of the first D-0 reservation at the latest. This leaves plenty of time for most flights of the ATS delegations in the afternoon not to take the surplus fuel, once again at the expense of military flexibility. In order to provide a more attractive concept for the military, notions of Concept Set 2 could be implemented to this one such that not all ATS delegations need to be specified at the start of the day.

6.3. Selection of Independent Variables

The preliminary results attained in Section 6.1 and Section 6.2 can be used to propose the values of the independent variables. Each combination of day, airspace, trajectory, plannability horizon and other independent variables leads to a different scenario to be ran within BlueSky. As explained in Section 5.5.3, the number of scenarios ought to be limited for reasonable running times, for which not all independent variables shown in this chapter can be further used. Using such a great resolution in the independent variables did however allow to gain a clear view on their most informative values. These are to be selected to lower the resolution of independent variables and thus make the processing of the results manageable for BlueSky within reasonable processing times. The following proposes, albeit subject to changes, sensible ranges of values for the independent variables of the experiments.

First, for Experiment 1, the independent variable of the distance horizon to the FUA may be limited to 100, 150, 200 and 250 nautical miles for Alpha, and 50, 100, 150 and 200 for Delta. Note that since Delta is considerably smaller, the bifurcation and merging would also be closer, for which a value of 250 nautical miles is not further considered. For Alpha, a value larger than 250 nautical miles is simply too far outside of Amsterdam FIR for it to be earnestly considered. These two factors, FUA and distance horizon, are also combined with the sampling time or days used and the concept of historical or GCR trajectories. For Experiment 2, both FUAs has been seen to have a similar behaviour, for which the independent variables will be the same for FUA and sample time, with each combination thus giving a different number of flights taking the surplus fuel and thus scenario to run in BlueSky. For Concept Set 1, the independent variable is the planning horizon and can be taken every two hours from 0 to 16 hours relative to the first D-0 reservation, thus in 9 possible values. As seen from Figure 6.2a, this would capture all possibilities with a reasonable resolution. For Concept Set 2, although the planning horizon behaves identically as for Concept Set 1, investigating the cutoff time becomes more interesting. To reduce process time, the plannability concept can be examined at a lower resolution, in steps of 8 hours, and the cutoff time as 08, 10 and 12 hours. Finally, for Concept Set 3, the interval delegated per minute considered can be reduced to 30 and 60 minutes, and the delegation start variables may be 16 and 8 hours before the first D-0 reservation. From the results shown in this chapter, these limited sets of variable values are expected to capture the most informative scenarios.

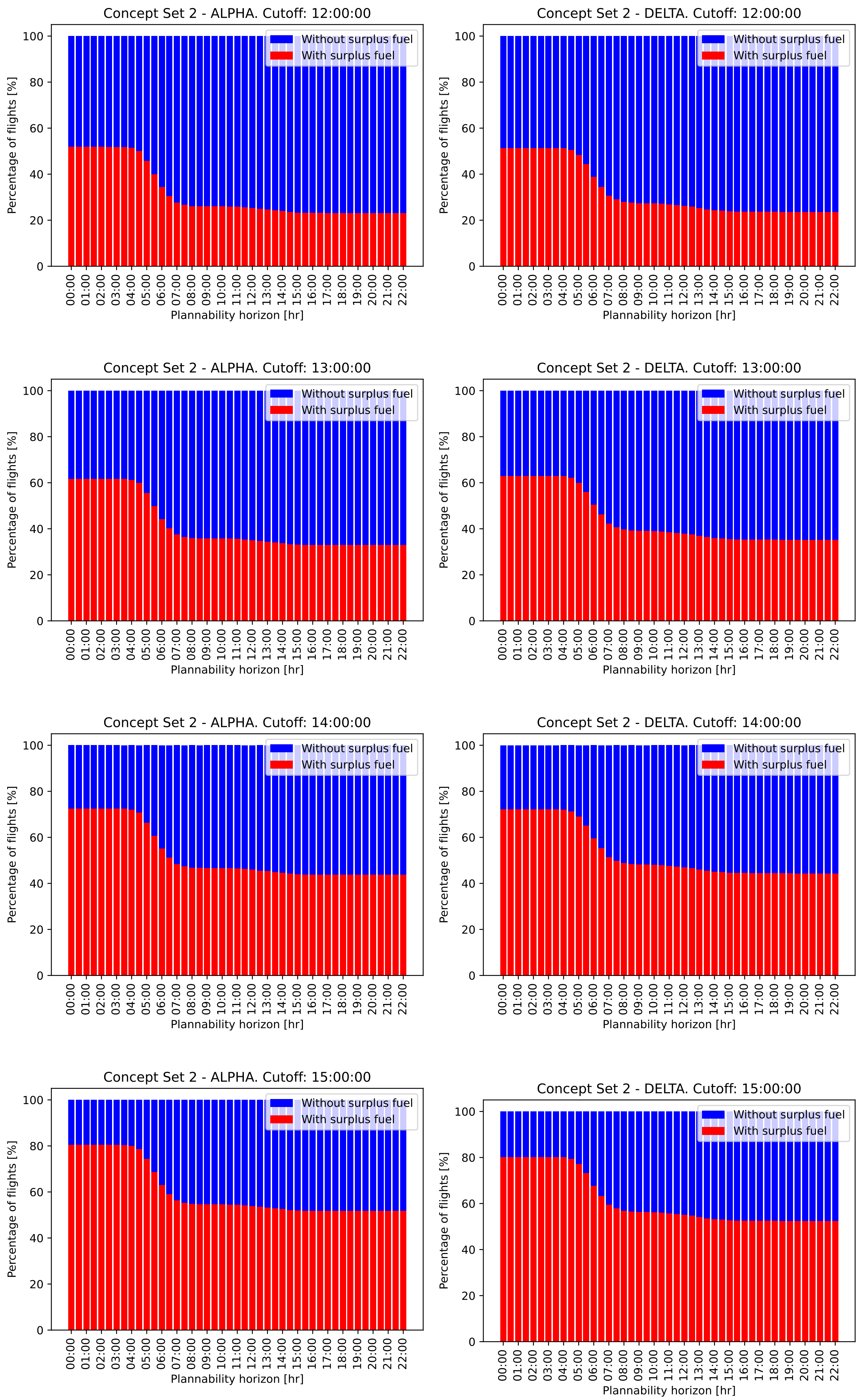


Figure 6.3: Effect of plannability on the percentage of flights taking the surplus fuel, under Concept Set 2 with cutoff times 12:00 to 15:00.

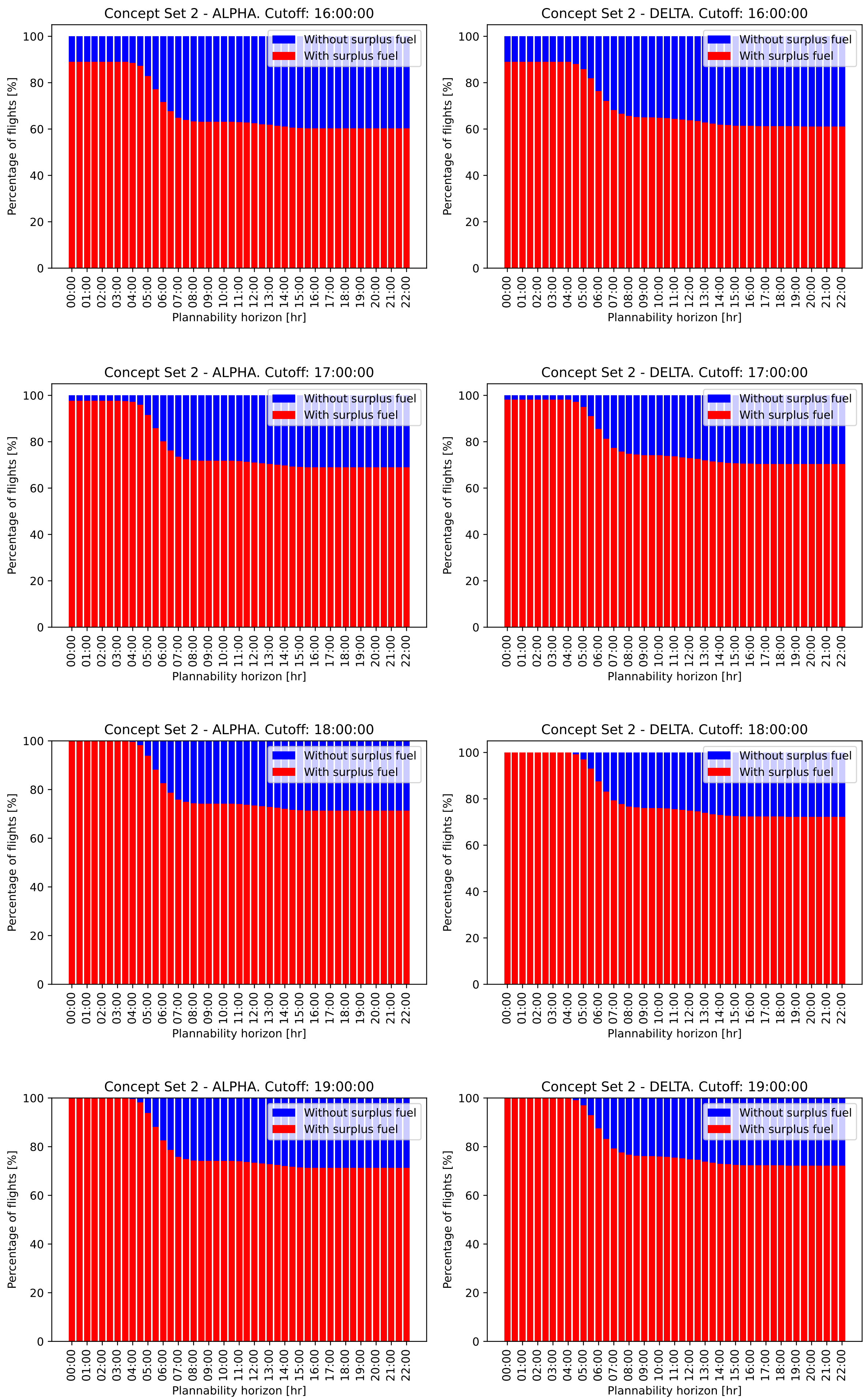


Figure 6.4: Effect of plannability on the percentage of flights taking the surplus fuel, under Concept Set 2 with cutoff times 16:00 to 19:00.

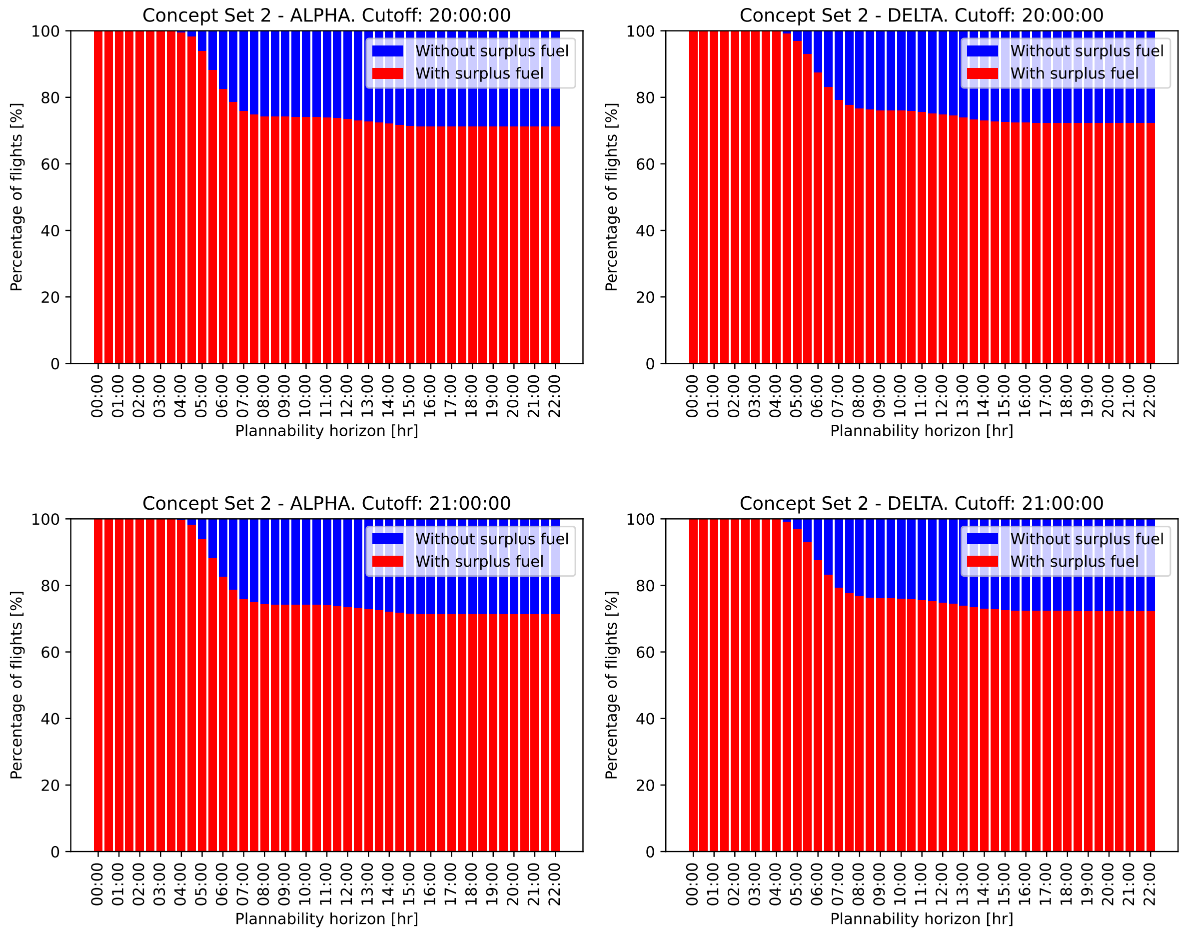


Figure 6.5: Effect of plannability on the percentage of flights taking the surplus fuel, under Concept Set 2 with cutoff times 20:00 and 21:00.

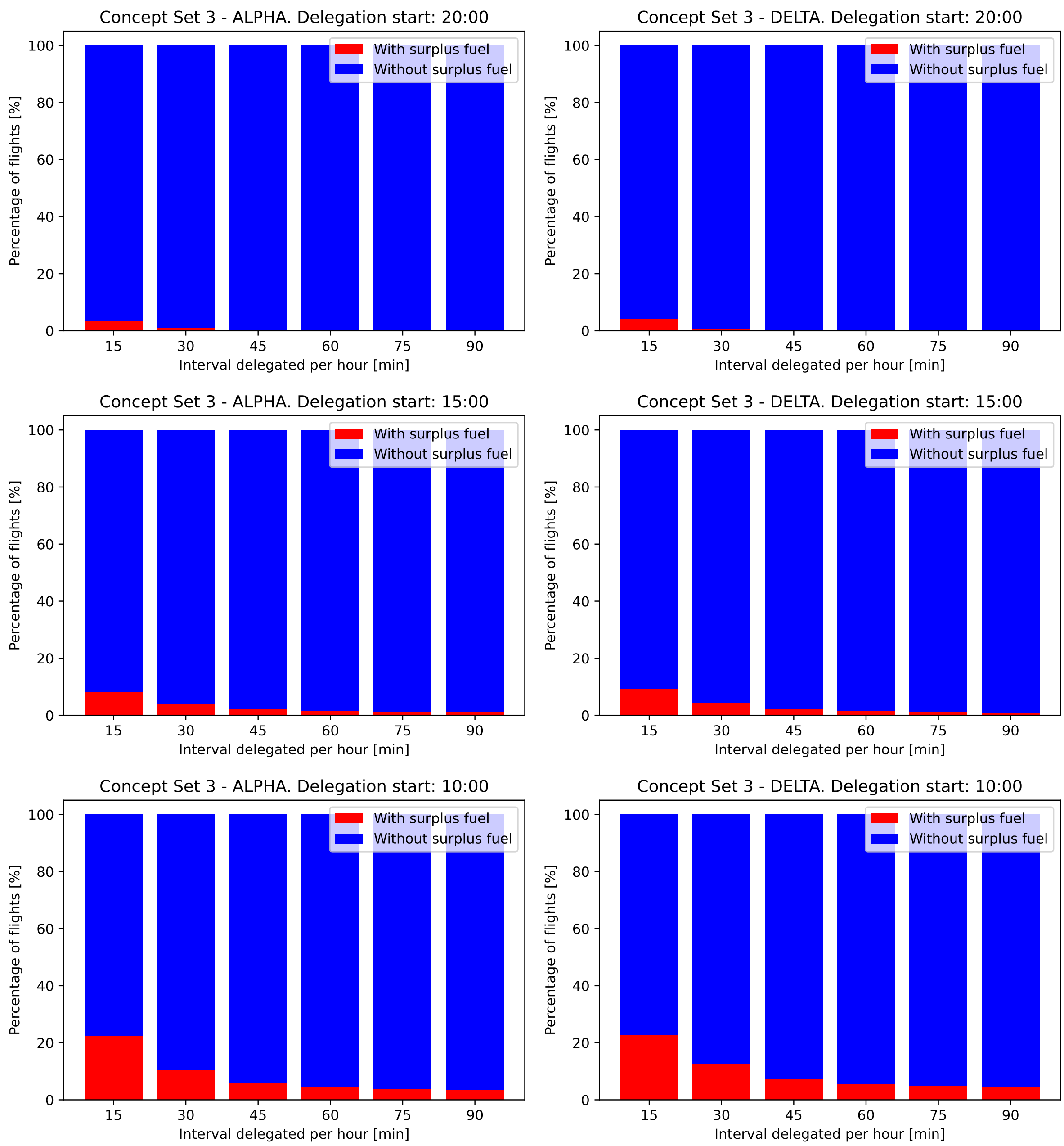


Figure 6.6: Effect of the interval of time delegated per hour on the percentage of flights taking the surplus fuel, starting the delegation at 20, 15 and 10 hours relative to the first D-0 reservation

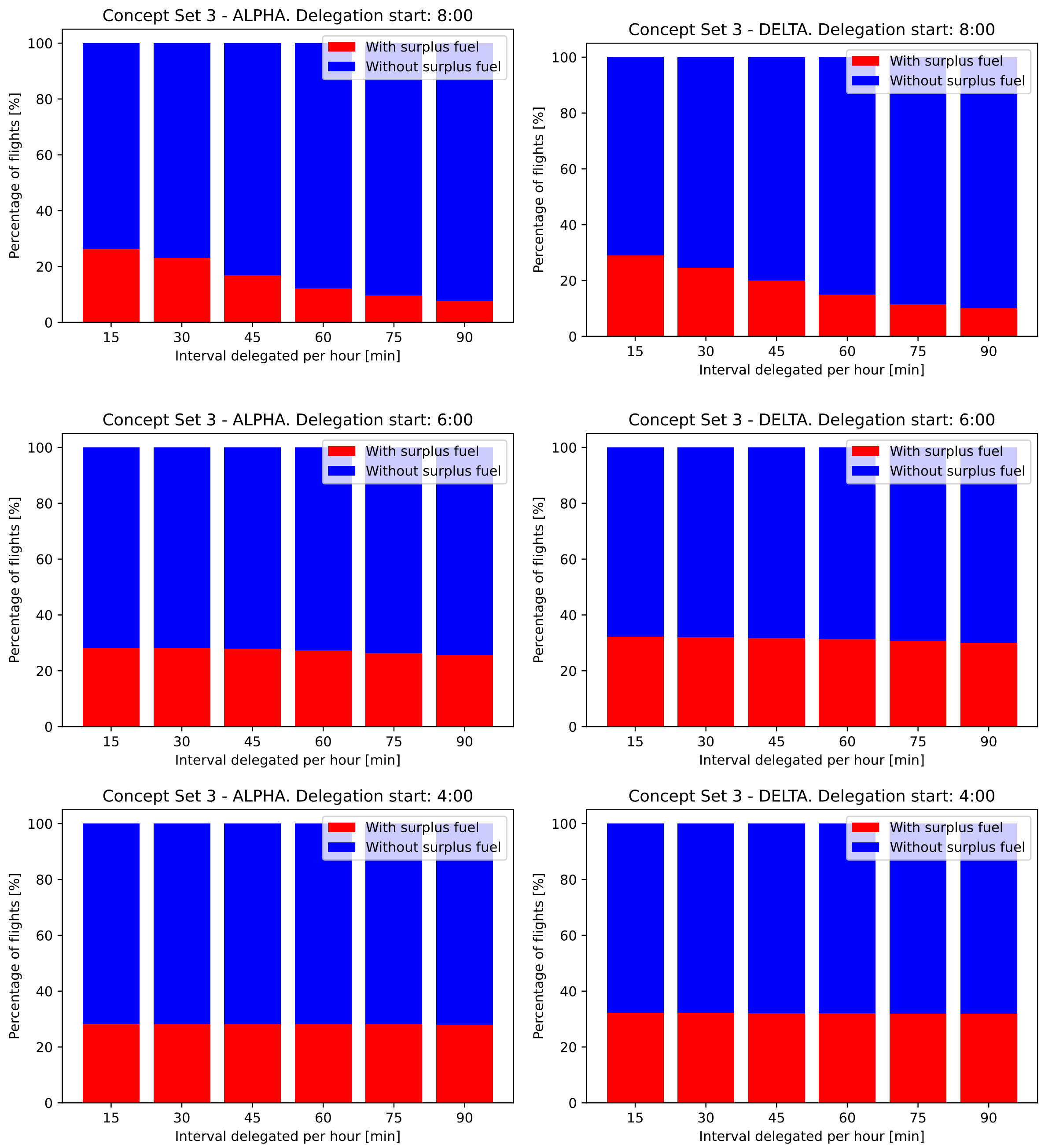


Figure 6.7: Effect of the interval of time delegated per hour on the percentage of flights taking the surplus fuel, starting the delegation at 8, 6 and 4 hours relative to the first D-0 reservation

7
Future Work

As shown in Chapter 6, preliminary results have been obtained to gain an understanding of the number of flights affected by each concept proposed. This already proves there is room for improvement of the current operation, but the main analysis is to consist of the computation of fuel efficiency metrics given each concept.

The first major aspect to be done following the work presented in this report is the computation of the work done, fuel consumption and CO_2 emissions, which are to be carried out using the Base of Aircraft Data (BADA) of Eurocontrol. This also contains nuanced components varying per experiment. For Experiment 1, it can be investigated how the fuel consumption further reduces when choosing a speed to minimise it. For Experiment 2, the fuel consumption metrics will vary based on another module of the experiment, the computation of the surplus fuel. Furthermore, and as reasoned in Section 5.6, given that a preliminary implementation of the fuel consumption computation directly on the pandas databases has seen to be too coarse to capture the nuances in the performance inputs such as airspeed and mass, it has been decided to carry out the fuel consumption computation in the air traffic simulator BlueSky.

Apart from these computation steps, several other aspects of the research must be undertaken to complete the project research questions as laid out in Chapter 4. For RQ-1.2, a realistic concept must be created by for instance comparing flights with the same departure-destination airports yet differing in the usage of FUA, such that the true impact of today's FUA system is assessed. For Experiment 2 RQ-2.1, a sensible estimate for the possible AUP reservations of the months sampled needs to be attained, in order to have a realistic baseline estimating the true impact of the current reservation system on the fuel efficiency of civil traffic.

For both of these experiments, a way to extrapolate the results of the sampled days must be investigated to yield a yearly estimate. The difficulty of this task lies in the fact that the basis that must be extrapolated is a number of flights, irrespective of their aircraft type, which greatly depends on the specific days considered. For this reason, not only patterns in number of flights but also in the reservations will need to be investigated to find a common basis they can be extrapolated upon.

Furthermore, verification and validation techniques for the different modules used could be further investigated. Despite this study focuses on finding a relative benefit between concepts, which would eliminate any absolute error of the computations, it would however improve the validity of the results.

Lastly, given that the core of this thesis is to provide new concepts of FUA plannability, these are to be further assessed. Firstly, it is desired to inquire about their qualitative feasibility with military operational experts to understand what the consequences might be for each of these on their operations. Secondly, the concepts proposed may be combined to achieve a better compromise between civil fuel efficiency and military flexibility. So far, the concepts proposed and in particular Concept Set 1 and 3 significantly benefit the civil user, as all D-0 reservations are assumed to be laid out early in the morning at the latest. Several strategies could be proposed to improve military flexibility by implementing changes in the logic of the concepts. For example, the notion of a shrinking reservation of Concept Set 3 can be done separately for morning and afternoon ATS delegations, and Concept Set 2 may be tested with different plannabilities for each D-0 reservation.

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