ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

FREE ROUTING IN HIGH-COMPLEXITY AIRSPACE: IMPACT ASSESSMENT FOR ENVIRONMENT AND AVIATION STAKEHOLDERS

M.Sc. THESIS

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Department of Aeronautics and Astronautics Engineering

Aeronautics and Astronautics Engineering Programme

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To my family,

FOREWORD

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June 2022

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TABLE OF CONTENTS

Page

FOREWORD ..... **ix**
TABLE OF CONTENTS ..... **xi**
ABBREVIATIONS ..... **xiii**
LIST OF TABLES ..... **xv**
LIST OF FIGURES ..... **xvii**
SUMMARY ..... **xix**
ÖZET ..... **xxi**
1. INTRODUCTION **1**
1.1 Free Routing Airspace 2
1.2 Literature Review 3
1.3 Purpose of Thesis 5
2. DATA SOURCES AND INPUTS FOR THE MODELLING ENVIRONMENT **7**
2.1. Base of Aircraft Data 7
2.2. ALLFT+ Data 8
2.3. Weather and Wind Data 11
3. MODEL **13**
3.1. Aircraft Dynamics 13
3.2. Trajectory Tracking Guidance 14
3.3. Simulation 15
3.3.1. Direct routing 15
3.4. Emission Model 16
3.4.1. Emission calculations 17
3.4.2. Fuel Flow Method2 17
4. KEY PERFORMANCE INDICATORS **19**
4.1 Air Traffic Control 19
4.1.1 Air traffic controller workload 20
4.1.2 Number of movements 24
4.1.3 Number of conflicts 25
4.2 Airlines 25
4.2.1 Routing efficiency 26
4.2.2 Fuel consumption 26
4.2.3 Travel duration 27
4.2.4 Direct operating cost 27
4.3 Passenger 28
4.4 Climate / Emissions 29
4.4.1 CO2 emissions 30
4.4.2 NOx emissions 31
4.4.3 H2O emissions 31
5. SIMULATION AND RESULTS **33**
5.1 Airspace Selection 33
5.2 Simulation 36
5.3 Results 36
5.3.1 ATC workload 36
5.3.2 Non-climate KPIs 40
5.4 Emissions 40

5.4.1 CO_2 emissions 41
5.4.2 H_2O emissions 42
5.4.3 NOx emissions 43
6. CONCLUSION 45
REFERENCES 47
CURRICULUM VITAE 51

ABBREVIATIONS

ACARE **:** Advisory Council for Aviation Research and Innovation

ACE **:** ATM Cost Effectiveness

ACM **:** Aircraft Characteristics Model

AEM3 **:** Advance Emission Model

ANSP **:** Air Navigation Service Provider

APM **:** Aircraft Performance Model

ARPM **:** Airline Procedure Model

ATC **:** Air Traffic Controller

ATR **:** Average Temperature Response

BADA **:** Base of Aircraft Data

CLIMOP **:** Climate Assessment of Innovative Mitigation Strategies Towards Operational Improvements in Aviation

CORSIA **:** The Carbon Offsetting and Reduction Scheme for International Aviation

DDR2 **:** Demand Data Repository

DFS **:** Deutsche Flugsicherung GmbH

DOR **:** Direct Operating Cost

DR **:** Direct Route

EC **:** European Council

ECAC **:** European Civil Aviation Conference

FRA **:** Free Routing Airspace

GFS **:** Global Forecast System

HDIF **:** Horizontal Different Interacting Flows

ICAO **:** International Civil Aviation Organization

KPI **:** Key Performance Indicator

NCEP **:** National Centers for Environmental Prediction

NextGen **:** Next Generation Air Transportation

RF **:** Radiative Forcing

SDIF **:** Speed Different Interacting Flows

SESAR **:** Single European Sky ATM Research

TGT **:** Trajectory Generation Tool

VDIF **:** Vertical Different Interacting Flows

LIST OF TABLES

Page

Table 4.1: 2018 Part 121 Passenger Air Carriers Filing Schedule P-5.2 Operating and Fixed Costs per Block Hours. **27**
Table 5.1: Grid options taken into account. **36**
Table 5.2: Non-Climate KPI Results for Baseling and Direct Route Scenarios. **40**
Table 5.3: Greenhouse Gas Emission Results for Baseline and Direct Route Scenarios. **41**

LIST OF FIGURES

Page

Figure 2.1: Structure of the BADA Model [24]. **8**
Figure 2.2: An example for Wind Fields (m/s) obtained from NCES GFS. **11**
Figure 3.1: Direct Routing in FRA [32]. **16**
Figure 4.1: Air Traffic Control Workload Chart [35]. **20**
Figure 4.2: Passenger-Kilometers Performed, Total Scheduled Traffic [40]. **29**
Figure 4.3: Temperature Change caused by the emissions during the years [41]. .. **30**
Figure 5.1: Conflicts in ECAC Region [35]. **33**
Figure 5.2: Airspaces plot based on adjusted density and complexity [36]. **34**
Figure 5.3: Complexity Scores in the ECAC area [36]. **35**
Figure 5.4: Air Traffic Densities in US and Europe [9]. **35**
Figure 5.5: Adjusted Density and Complexity Scores for Baseline and Direct Route Trajectories. **37**
Figure 5.6: Adjusted Density values calculated for different scenarios. **38**
Figure 5.7: Complexity Score values calculated for different scenarios. **38**
Figure 5.8: Structural Index values calculated for different scenarios. **38**
Figure 5.9: VDIF values calculated for different scenarios. **39**
Figure 5.10: HDIF values calculated for different scenarios. **39**
Figure 5.11: SDIF values calculated for different scenarios. **39**
Figure 5. 12: Heatmap for CO_2 Emissions for Baseline and DR Scenarios. **42**
Figure 5.13: Heatmap for H2O Emissions for Baseline and DR Scenarios. **42**
Figure 5.14: Heatmap for NOx Emissions for Baseline and DR Scenarios. **43**

FREE ROUTING IN HIGH-COMPLEXITY AIRSPACE: IMPACT ASSESSMENT FOR ENVIRONMENT AND AVIATION STAKEHOLDERS

SUMMARY

Global warming is an important phenomenon that is threatening the Earth and the living beings on it. It is affected by the human factors such as fossil fuels, exploitations of forests and livestock. Aviation industry has a part on producing the greenhouse gases causing the climate change. The industries contribution is around 5% to the global warming and it is expected to increase over time regarding its growth.

Which is why many organizations are taking action to reduce and mitigate the effects of the aviation to earth temperature. Flightpath 2050 is a documentation for targets defined to reduce the aviation sector's contribution to the climate change. NextGen, SESAR can be counted as initiatives found for the aim. CLIMOP is a project that is coming up with operational improvements aiming to mitigate the climate effects of aviation.

There are diverse studies and ideas focusing on reducing aviation's involvement in the long term and short term. While long term mitigations take time for implementation, short term improvements take an important role for reducing overall impact on the climate.Free Routing Airspace is one of the operational improvements that can be counted. Free Routing Airspace (FRA) is a concept introduced by SESAR as an operational improvement and it is defined as an airspace where the users can fly flexible routes with only entry and exit points defined. Evident option to choose in a FRA is the Direct Routes, where the direct path between the entry and exit points is followed by the aircraft.

In this study the difference the Direct Route concept makes is assessed considering diverse stakeholders in aviation.

Firstly, a high complexity airspace in the ECAC area is selected: EDUU controlled by DFS. It is observed that the air traffic is dense and complex in the area. It is selected as a demonstrative sample of flights to do the comparison.

Second, baseline and direct route trajectories are generated using the Trajectory Generation Tool. For the baseline trajectories, ALLFT+ data from EUROCONTROL's DDR database is used and for the direct routes the trajectories are generated directly from the entry and exit points.

Then, the different KPIs affecting multiple stakeholders in aviation are determined. The stakeholders are counted as the airlines, passengers, ATC officers and evidently the climate. The KPIs are defined as ATCo workload, number of movements, number of conflicts, routing efficiency, fuel consumption, travel duration, direct operating cost and the greenhouse gas emissions. Emissions of CO2, NOx and H2O are taken into account for the study considering their long-term effects on the earth temperature.

Once the KPIs are calculated using the models constructed for the baseline and direct route trajectories, the results are compared. It is seen that applying the direct route concept is beneficial for all stakeholders in aviation and it is also better for the climate effects of the industry.

This thesis, assesses and compares the impact of the Direct Route application to a high-complexity air space and it demonstrates the improvements that are possible through the practice. It is hoped to serve as a guidance point following the path of optimizing for climate in aviation.

YÜKSEK KARMAŞIKLIKTA SERBEST HAVA SAHASI UYGULAMASI: ÇEVRE VE SİVİL HAVACILIK PAYDAŞLARI ÜZERİNDEKİ ETKİLERİN İNCELEMESİ

ÖZET

Küresel ısınma günümüzde, dünya ve üzerinde yaşayan canlıların geleceğini tehdit eden önemli bir konu haline gelmiştir. İnsan faktörü iklim değişikliğinin ilerleyişinde önemli bir rol oynamaktadır. Fosil yakıt tüketimi, ormanlık alanların azaltılması ve hayvancılık gibi insan faaliyetleri bu konuda önemli bir rol oynamaktadır. Havacılık sektörü, iklim değişikliği hususunda ihmal edilemeyecek bir paya sahiptir. Bu pay güncel olarak 5% olarak belirtilse de, sektörün ilerleyişi göz önünde bulundurulduğunda önemli ölçüde artacağı öngörülmektedir.

Bu sebepten, birçok organizasyon ve kurum havacılığın iklim üzerindeki etkisini azaltmak ve bu konuda önlem almak amacıyla girişimlerde bulunmaktadır. FlightPath 2050 havacılığın iklim üzerindeki etkilerini azaltma amacıyla oluşturulmuş bir hedef dokümanıdır. Burada amaç, 2050 yılında yolcular için daha konforlu ve verimli yolculuklar sağlamak, Hava Trafik kontrolünü verimli hale getirmek ve tabi ki iklim ve insanlık için de havacılığın negatif etkilerini azaltarak daha parlak ve güvenli bir gelecek sağlamaktır. NextGen ve SESAR da aynı amaçla varolmuş inisiyatiflere örnek gösterilebilir. CLIMOP ise havacılığın iklime olan etkilerini azaltma amacına hizmet eden operasyonel iyileştirmeler üzerine kurulu bir projedir. Amacı, CO2 emisyonlarında 75%, NOx emisyonlarında ise 90% azalmayı sağlayarak FlightPath2050 hedeflerine katkı sağlamaktır.

Havacılığın iklim üzerindeki etkisine yönelik uzun veya kısa vadeli çeşitli çalışmalar ve inisiyatifler bulunmaktadır. Uzun vadeli çözüm önerilerinin uygulanma ve sonuç gösterme süreleri de göz önünde bulundurulduğunda, iklime olan etkiyi kısa vadede azaltacak çözümlerin bulunması da öncelikli bir hal almaktadır. Havaaraçlarının belirli bir giriş ve çıkış noktası arasında esnek ve serbest bir rota izlemesini mümkün kılan Serbest Hava Sahası (FRA), SESAR tarafından öne atılmış operasyonel iyileştirme konseptlerinden biridir. Havaaracının bu giriş ve çıkış noktaları arasında direkt bir yol izlediği Direkt Rota konsepti bir Serbest Rota Sahası senaryosunda göz önünde bulundurulan ilk seçenek olarak öne çıkmaktadır. Serbest Hava Sahasında kullanıcılar belirlenmiş giriş ve çıkış noktaları arasında esnek bir şekilde belirleyebilirler; bu sırada rotalar aralarda belirlenmiş noktalardan geçebilirler. Giriş ve çıkış belirlenmiştir ancak takip edilen yollar serbest bırakılmıştır. Direkt rota konseptinde ise bu giriş ve çıkış noktaları arasındaki direkt mesafenin uçulduğu varsayılır.

Bu tez çalışmasında, Direkt Rota konsepti uygulamasının havacılıktaki farklı paydaşlar ve iklim değişikliği üzerindeki etkileri ve olası iyileştirmeleri analiz edilmektedir. Bu paydaşlar havayolları, yolcular, hava trafik kontrolörleri ve iklim olarak belirlenmiştir. Direkt rota konseptinin uygulanmasıyla bütün paydaşlar için

değerlendirme kriterlerinde değişiklik gözleneceği ve bu değişimin toplam etkisinin olumlu yönde olacağı tezi öne sürülmüştür.

Öncelikle, ECAC bölgesi içerisinde yer alan karmaşıklık seviyesi yüksek bir havasahası seçilmiştir. Farklı çalışmalardan yola çıkarak, hava trafiğinin yoğunluğu ve çok katmanlılığı da göz önünde bulundurularak, EDUU bölgesi bu çalışma için örneklem olarak seçilmiştir.

Ardından, Trajectory Generation Tool kullanılarak referans ve direkt rota uçuşlarının rota bilgileri oluşturulmuştur. Referans olarak, bölgede belli bir günde gerçekleşmiş uçuşların uçuş bilgisi EUROCONTROL tarafından sağlanan ALLFT+ verisiyle oluşturulmuştur. Direkt rota senaryosu içinse, giriş ve çıkış noktaları belirtilerek rotalar oluşturulmuştur.

Daha sonra, farklı paydaşlar göz önünde bulundurularak temel performans göstergeleri belirlenmiştir. Havayolları, yolcular, hava trafik kontrol çalışanları ve iklim bu konudaki paydaşlar olarak göz önünde bulundurulmuştur. Bu hususta temel performans göstergeleri Hava Trafik Kontrolörü iş yükü, hareket sayısı, çakışma sayısı, rota uzunluğu, yakıt tüketimi, yolculuk süresi, operasyon masrafı ve sera gazı emisyonları olarak belirlenmiştir. Dünyanın yüzey sıcaklığında uzun vadedeki etkileri göz önünde bulundurularak CO2, NOx ve H2O gazlarının emisyonları bu çalışma kapsamında incelenmiştir.

Referans ve direkt rotalar için performans göstergeleri kurulan modeller ile hesaplanmış ve sonuçlar karşılaştırılmıştır. Direkt rota uygulaması sonucunda, göstergeler göz önünde bulundurulduğunda bütün paydaşlar için bir iyileşme sağlandığı ve kapsamdaki gaz emisyonlarının da azaldığı gözlenmiştir.

Bu tez çalışmasında Direkt Rota konseptinin havacılığın farklı paydaşları ve iklim değişikliği üzerinde sağlayabileceği olumlu değişiklikler bir yüksek karmaşıklıkta hava sahası üzerinden incelenmiştir. Çalışmanın, havacılıkta iklim amaçlı iyileştirmeler yolunda bir fayda sağlaması amaçlanmıştır.

1. INTRODUCTION

Climate change has been one of the most alarming issues that the world and the human race are facing. People and organizations are prioritizing to find a solution to slow down or mitigate the effects of the climate change on our lives; ironically this is only possible by finding a solution for the human practices that are causing the climate change and making the end of the world become nearer. By the report of the European Commission [1]; the temperature on earth and the climate is hugely affected by human practices such as fossil fuel usage; deforestation and livestock farming. All these activities cause the greenhouse effect and adds to the global warming. According to the EC report; greenhouse effect is the main cause for the climate change. The increased density of several gases such as carbon dioxide, methane, nitrous oxide, fluorinated gases by the human activities contribute the most to the greenhouse effect.

Aviation industry is one of the sectors to blame for the increased greenhouse gasses. Carbon dioxide (CO2), water vapour (H2O), nitrogen oxides (NOx), sulphur oxides (SOx), soot, and sulphate aerosols are all released by the aviation sector, contributing to human-made emissions. Aviation currently contributes for about 2% of global CO2 emissions. In 2005, airplane emissions (excluding produced cirrus clouds) contributed 3.5 percent of total anthropogenic forcing (in a range of 1.3 percent to 10%, which is a 90% likely range). When aviation-induced cirrus cloud impacts are factored in, the size rises to 4.9 percent [2]. The impact of aviation to the climate is expected to gravely increase over the next decades if no counteractions are taken. With projected growth in aviation, aircraft emissions are expected to rise, resulting in increased environmental impacts unless scientifically based mitigating measures are applied [2].

Important organizations and institutions have been working on projects to come up with actions that could decrease aviation's impact on climate change. Several strategies were developed. In Flightpath 2050, the Advisory Council for Aviation Research and Innovation in Europe (ACARE) has established emission reduction

targets. By 2050, the goal is to reduce CO2 emissions by 75% and NOx emissions by 90% per passenger-kilometer [3]. The United Nations' International Civil Aviation Organization (ICAO) has agreed on a global market-based measure scheme to reduce CO2 emissions from international aviation. The Carbon Offsetting and Reduction Scheme for International Aviation is the name of this program (CORSIA). According to this plan, the sector's expansion after 2020 must be offset so that net carbon emissions do not increase [3]. CLIMOP is one of the projects that is initiated to mitigate climate effects considering different stakeholders. The total anthropogenic radiative forcing caused by aviation emissions (CO2 and other emissions) is estimated to be 5% of total anthropogenic radiative forcing. Although the aviation sector has made tremendous efforts in recent years to stabilize CO2 emissions at 2020 levels through a combination of technological improvements and regulation, much more needs to be done to minimize aviation's total climate effect. ClimOP intends to study which operational changes may have a positive impact on climate in a sound research framework, taking non-CO2 effects from NOx and water vapour emissions, as well as contrail production, into account for a greener aviation [4].

1.1 Free Routing Airspace

Free routing airspace (FRA) is a concept introduced as a part of the Single European Sky Airspace Research program (SESAR) [5]. The SESAR 3 Joint Undertaking is a formalised European cooperation involving business and public sector partners, established to speed the delivery of the Digital European Sky through research and innovation. To do so, it is leveraging, creating, and speeding up the use of cutting-edge technological solutions for managing conventional aircraft, drones, air taxis, and vehicles flying at greater altitudes [6]. Users in a FRA can arrange their own route between the defined Entry and Exit fixes, with the option of passing through intermediate sites. There are Arrival and Departure fixes accessible in a FRA, but no airways. For separation provisions and flight level change authorizations, free route flights are still subject to air traffic control (ATC) [7].

The main change coming from the implementation of FRA is that the flight trajectories are straightened and expectedly shortened. This would also raise the expectation to

reduce flight time and cost; emissions produced by the engines. Additionally, by reducing the number of manoeuvres it is expected to reduce the ATC workload.
The goal of establishing free route airspaces is to address some of aviation's concerns, such as efficiency, capacity, and the environment. According to EUROCONTROL, the European Organization for the Safety of Air Navigation [8], the use of FRAs has the potential to reduce flying distances by 7.5 million nautical miles per year, saving 45, 000 tons of fuel and 150, 000 tons of pollutants. In addition, compared to the current fixed route network, FRAs offer less conflicts in terms of aircraft collision avoidance because aircrafts are more uniformly spaced out across the airspace. In Europe, inefficiency in the en-route phase of actual trajectories dropped somewhat between 2015 and 2017. The gradual deployment of Free Route Airspace, which attempts to remove the restrictive route network and provide airspace users more options for filing flight plans, has contributed to the improvement in Europe [9].

1.2 Literature Review

There are many aspects to focus on the civil aviation operations in order to perform optimizations based on different factors. The sector involves many stakeholders such as airlines, passengers, air traffic operators and the climate. Many studies were performed focusing on different areas.

In [10] Chapman proposes methods to mitigate the aircraft environmental pollution such as increasing the fuel tax, modifying the aircraft design and changing the transportation systems. Howe-Veenstra studies the opportunity that can be provided by removing some of the restrictive constraints from ATC systems. Efficiency of ATC procedures were assessed and a new concept with less restrictive ATC systems is used to optimize the commercial aircraft trajectories [11]. Zillies et al creates a 4D optimization model for a trajectory-based air traffic management. They define the fuel flow, time, distance and aircraft performance as the factors of the cost function [12]. The study by Sridhar et al focuses on the new trajectory planning concepts while aiming for the ATC system improvements and also considering climate effects [13].

In “Flight Planning in Free Route Airspaces”, Jensen et look into the subject of determining the best path across a free route airspace between two entry/exit points while considering wind conditions. A data structure is brought up to create discrete regions with constant wind and the problem is solved with a geometric algorithm. The study aims to minimize the cost for the airlines [14]. In [15], Aneeka and Zhong focuses on Southeast Asia region and calculate the total quantity of emitted greenhouse gases per day by current air traffic demand in the ASEAN region, as well as the reduction in such emissions, using the free route airspace concept. It is shown that there is a potential for huge reduction in such gas emissions with the application of FRA.

The paper by Lai et al [16] took a multidisciplinary approach to analyzing the problems and prospects for decreasing aviation's climate effect through mitigation measures, presenting new viewpoints and pointing to topics for additional research. The review focuses specifically on Sweden. In “Reducing global warming by airline contrail avoidance: A case study of annual benefits for the contiguous United States” by Avila et al. avoidance of specific regions that are causing the contrails is studied. Flight plans are modified to avoid to contrail-conducive areas in United States and the results are discussed [17]. Ng et al works on Trans-Atlantic flight trajectories to avoid contrails and reduce the emissions causing the greenhouse effect in [18]. [19] by Tian et al. provides a method for 4D commercial flight trajectory optimization to evaluate and analyze the relationship between environmental and conventional costs in green civil aviation.

In [20] Lührs et al applied optimal control techniques in order to create optimal flight trajectories. The study focused on flights selected from North Atlantic region. The team looked for reducing the climate impact while considering the cost optimization. Dahlman, Lührs et al., a similar team, in [21] develops an aircraft model to reduce the climate effects and studies the potential improvements. In [22] Niklaß, Lührs et al. comes up with an interim strategy to reduce the climate effects considering the fact that the time required for previous strategies to come to action might not be short enough. Paper focuses on defining Climate Restricted Airspaces(CRA), regions that are temporarily closed for aircraft when the climate effects are too high.

1.3 Purpose of Thesis

As explained above, climate change is an alarming issue for the planet and the living beings; and the aviation sector has a part on the increasing density of the greenhouse gases causing the global warming. Free routing airspace is a concept which is suggested firstly as a solution for the Air Traffic Control issues; however, the opportunity is seen that it may have a contribution to the better trajectories for climate change. In this work, the objective is to provide a detailed and comprehensive assessment of the effects of Direct Route concept in FRA implementation for a high-complexity area. The concept is considered as a possible operational improvement for the climate effects of aviation but the impact of such a modification on other stakeholders such as ATC and airlines must not be negliged.

The opportunity is; with less complex and shorter trajectories the fuel consumption and the emissions would be reduced. Free Routing Airspace makes it possible for users to plan the trajectories effectively considering different factors. With less constraints and fewer waypoints that are predetermined, trajectory planning is more flexible. The routes can be optimized considering factors such as climate, cost and duration. The influence on the ATC should be borne in mind since it is a change on the essential aspects of the system. With Direct Route concept, the effect on the ATC is expected to remain beneficial with less complex routes and less maneuvers. For the airlines point of view, the expectation is to reduce the fuel consumption and the travel duration that are factors to direct operating cost; for which is looked for ways to decrease. Additionally the passengers, they expect to fly with cheaper flights and shorter durations with most comfort. Last but not the least; emissions are a priority for the study. The greenhouse gas emissions that are produced by the flights are calculated and evaluated to see the overall effect of the Direct Route concept.

Previous studies focus on different specific aspects of improvements to optimize flight trajectories to mitigate climate effects or reduce cost. The works assessed the optimized trajectories based on different specific metrics affecting different stakeholders such as airlines, passengers and climate. We see studies that are providing methods to optimize trajectories for climate; there are studies that are coming up with

strategies for Air Traffic Control systems. Cost efficiency has been always an issue that was worked for in aviation. However, studies focusing on solutions attacking different aspects of aviation and assessing the diverse stakeholders are limited.

This study focuses on the Free Route Airspace implementation in a high-complexity area. FRA is a concept that is already in application for restricted areas and ATC systems. One of the trivial solutions that can be thought of in the application of FRA is the direct route trajectories where the only entry and exit waypoints are defined. A comprehensive approach is followed for the assessed metrics and all stakeholders in aviation are taken into account while selecting the KPIs to study. Airlines, passengers, ATC and climate effects are all included to the solution.

For this aim; a representative number of flights passing a specific high-complexity airspace in the ECAC area was selected. For the flight data selected; the baseline trajectories with the existing waypoints were created as the baseline trajectories. Using the Trajectory Generation Tool (TGT), direct routing trajectories were also generated implementing the FRA concept. Selected KPIs were assessed for both sample of trajectories. Results are compared to assess the impact of the free routing concept on the environment and the key stakeholders.

2. DATA SOURCES AND INPUTS FOR THE MODELLING ENVIRONMENT

2.1. Base of Aircraft Data

"The Base of Aircraft Data (BADA) is an Aircraft Performance Model (APM) developed and maintained by EUROCONTROL, with the active cooperation of aircraft manufacturers and operating airlines." [23] It helps simulating and forecasting the trajectories of aircraft for research and operational purposes. BADA contains information to calculate the performance parameters and trajectories. In order to create operational and research based accurate models and simulations, all real aircraft needs a model. BADA contains information that is designed for utilizing in aircraft trajectory prediction and simulation. It represents a fundamental hub for ground-based operational ATM systems in trajectory prediction and tools for air traffic modelling and simulation.

The Aircraft Performance Model (APM) specifies the operating boundaries of an aircraft's performance parameters. The Aerodynamic Forces and Configurations Model (AFM) is used to calculate drag and lift coefficients, the Propulsive Forces Model (PFM) is used to calculate thrust and fuel coefficients, and the Aircraft Limitation Model (ALM) is used to identify geometric, kinematic, dynamic, and environmental operation limitations. Transition time is defined by the Operation of Configuration Parameters Model (OPM) for both high-lift devices and landing gear configurations [MU-49]. Figure 2.1 depicts the interactions between these various models.

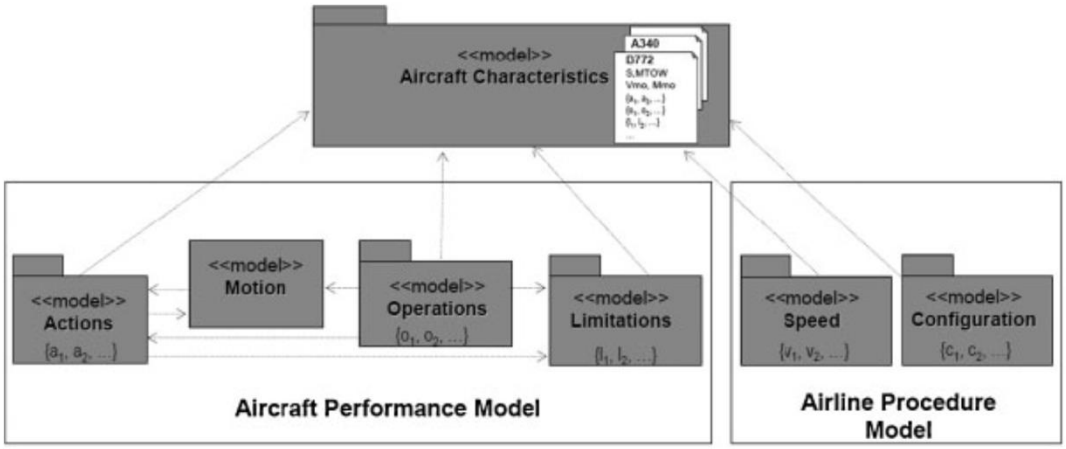

Figure 2.1: Structure of the BADA Model. [24]

According to the BADA fact sheet "BADA's Aircraft Performance Model is based on the Total Energy Model, which equates the rate of work done by forces acting on the aircraft with the rate of increase in potential and kinetic energy. It can be considered as a reduced point-mass model."

For this study BADA 4 is utilized. BADA Family 4 has the intention of meeting the requirements in an advanced and precise way. It covers 70% of the aircraft types operating in the ECAC airspace [23]. The goal of BADA 4 is to precisely represent aircraft performance across the whole flight envelope, including all phases of flight and aircraft in all configurations. The mathematical models in BADA 4 are developed using an investigation of the physical laws that govern aircraft movement and the physical variables that would be used to describe the aircraft performance are identified. Modeling accuracy is improved by using adequate physical relationships and selecting appropriate mathematical models to connect them. In BADA 4, physical relationships are expressed in terms of dimensionless variables. The dimensionless relationship enables analysis and comparisons, prevents errors, and allows for the discovery of physical similarity relationships, assuming an acceptable selection of dimensionless words.

2.2. ALLFT+ Data

As Network Manager, EUROCONTROL offers operational stakeholders with the most up-to-date view of past and future pan-European air traffic demand from many years ahead to the day before operations. This comprises data on the environment,

analytical reports, and tools such as (SAAM and NEST). The Demand Data Repository manages and provides access to all of this information (DDR). EUROCONTROL anticipates future traffic trends using information from previous traffic flows and thousands of travel intents provided by airlines and airports. This data is collected, stored, analysed and processed daily to support strategic, seasonal and pre-tactical planning, as well as special events and large air traffic management (ATM) evolution initiatives.

DDR provides past traffic data, past and pre-ops environment data, strategic traffic forecasts, pre-tactical traffic forecasts, NEST and SAAM tools, DCT use and DCT mapping to wide range of users such as air navigation service providers, airlines, airspace management actors and airports. Past traffic data contains the most recent documented flight plan trajectories and actual trajectories.

DDR Project Phase 1 is the initial implementation of the data repository concept. It is designed to be reached and used by the Airlines and ANSPs inside the European Civil Aviation Conference (ECAC). Users could pick and download demand data according to their own specifications using the DDR web interface, and several formats are offered so that the DDR can be utilized with existing EUROCONTROL tools as well as users' own tools [25]. Repository provides filtered, projected and historical traffic data. DDR Project Phase 2 is an upgraded version of the Phase 1. It delivers better demand projectoions based on airline schedule and airport slot data that spans the strategic planning phase and the pre-tactical phase; also including the DDR Phase 1's features. Flight intention data is often accessible 6-9 months prior to the day of operations and the forecasts are provided for the entire European airspace. Furthermore, up until the day of the operation, the statistics are kept up-to-date and enhanced [26].

There are numerous data file types accessible for download in the DDR project, and all files are compressed using the 7za tool. The most recent flight plan that was filed and the 4D flight trajectories are available in the SO6 m1 files; an the SO6 m3 provides the aforementioned data with the radar data updated. The demand with routings is represented by these two file formats. Flow Demand, FLD, indicates the number of flights available for each city pair. The EXP2 file format has no trajectory information and is condensed to supply traffic demand with flight information. Lastly, with routings and intersected sectors, the ALL FT file format generates demand [27].

The PRISME (Pan-European Repository of Information Supporting the Management of European Air Traffic Management Master Plan) group manages the ALL FT+ data collection, which provides an integrated set of data for the development and maintenance of an integrated ATM datawarehouse [28]. A variety of different sorts of information for individual flights that took place in European Airspace; intercontinental flights that fly over the ECAC area is also included.

There are 143 fields in the data set structure, with 46 of them containing numerical parameters, 18 representing numerical values related to time, 12 being Boolean, and 32 being made up of grouped parameters. The letter ";" is used to identify each field from the others, while the sign ":" is used to segment the 32 composite fields internally. The ALL FT+ dataset contains regulated information (RTFM), information on the precise point at which an aircraft changes its flight plans in terms of planned information (FTFM), and information prior to flying (CTFM). Furthermore, the ALL FT+ dataset has the CPF-REF field, which contains information about the points where the flight passed through. Flight level profiles, point profiles, and airspace profiles exist in all flight models, and all of these profiles are compound properties. The vertical description of the flight route is depicted by flight level profiles, which include centesimal barometer measurement, cruise speed, and start distance, which represents the distance over the trajectory measured from the departure Aerodrome/Airport.

For this study ALLFT+ [29] data acquired from the DDR system is used. The point profile data in the ALL FT+ dataset is utilized to obtain the flight plans for the aircraft that fly in the focused airspace on that day, December 3, 2018. The point profile data is filtered to acquire the aircraft operating in the airspace with their flight plans inside the airspace after pre-processing the flight records to eliminate and fix data anomalies. The superfluous waypoints in the point profiles are also deleted in order to produce flight plans with the fewest possible waypoints for improved trajectory tracking in the simulation environment. A series of waypoints described in terms of longitude, latitude, and altitude are generated for each aircraft flying in the area to show its flight plan.

2.3. Weather and Wind Data

The Global Forecast System (GFS) is a weather forecasting model developed by the National Centers for Environmental Prediction (NCEP) that generates data for dozens of atmospheric and land-soil variables such as temperatures, winds, precipitation, soil moisture, and atmospheric ozone concentration. To accurately describe weather conditions, the system combines four independent models (atmosphere, ocean model, land/soil model, and sea ice) [30]. It is a global numerical weather forecast system that includes a global computer model and variational analysis. The GFS is updated four times every day and can forecast up to 16 days ahead of time. The wind and weather information that is used in the simulations for this study is obtained from NCEP's GFS data.

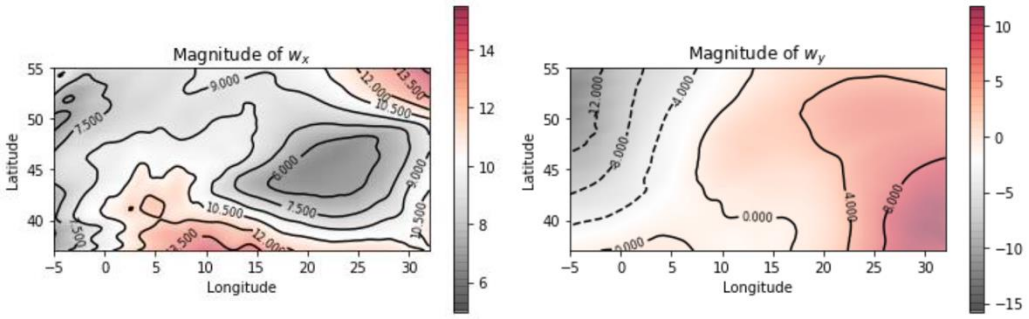

Figure 2.2 An example for Wind Fields (m/s) obtained from NCES GFS.

3. MODEL

3.1. Aircraft Dynamics

The aircraft models provided by BADA are characterized by Aircraft Characteristics used in APM and ARPM; which actually define the set of coefficients used in the model equations. There are four sub-models forming the Aircraft Performance Model which are actions, motion, operations, and limitations. Actions define the acting forces on the aircraft motion such as gravitational, aerodynamic, and propulsive forces. Coefficients affecting the weight, lift, drag, and thrust are also given by this sub-model as well as the fuel consumption factors which is an agent on the aircraft mass. Motion sub-model provides the system of equations representing the aircraft motion. Different operating manners are given in the operations sub-model and the Limitations part defines the limitations for realistic behavior of the aircraft.

The aircraft model used for the study is the B737-800 provided by BADA 4.

Time-invariant general form for the aircraft dynamics is defined as:

$$\dot{x}(t) = f\big(x(t), u(t)\big) \qquad x(0) = x_0 \tag{1}$$

where,

$$x(t) \in X \subseteq \mathbb{R}^n \quad , \quad u(t) \in U \subseteq \mathbb{R}^m$$

such that,

$n, m \in \mathbb{N}$ and the state $x_0 \in X$ is the initial state of the aircraft.

A point mass model of the aircraft that is derived from basic aerodynamics is used for the simulation. It is a nonlinear dynamical system defined by three control inputs and six state variables.

Motion equations for the aircraft are defined as:

$$\dot{x} = v\cos(\psi)\cos(\gamma) + w_1 \tag{2}$$

$$\dot{y} = v\sin(\psi)\cos(\gamma) + w_2 \tag{3}$$

$$\dot{h} = v\sin(\gamma) \tag{4}$$

$$\dot{v} = -\frac{C_D S\rho v^2}{2m} - g\sin(\gamma) + \frac{T}{m} \tag{5}$$

$$\dot{\psi} = \frac{C_L S\rho v}{2m}\frac{\sin(\phi)}{\cos(\gamma)} \tag{6}$$

$$\dot{m} = -F \tag{7}$$

Where x and y are the state variables for the horizontal position, h for the altitude, v for the true airspeed, ψ for the heading angle and m for the mass of the aircraft. Engine thrust (T), bank angle (ϕ) and the flight path angle (γ) are the control inputs.

$W = [w_1, w_2]$ models the wind speed; which also acts as a disturbance to the aircraft motion. The altitude has no impact on the wind components; wind can be expressed as a function of longitude and latitude.

C_L and C_D denotes the coefficients for the lift and drag, S is the total wing surface area. Air density and the fuel consumption are indicated by ρ and F, respectively. All necessary parameters and corresponding coefficients are obtained from BADA 4.

3.2. Trajectory Tracking Guidance

Trajectory Tracking is the process where the required control inputs to follow for the aircraft are created in order to realize the reference trajectory. Two functions of control are combined for motions: lateral where the straight-line controller, turn controller, and heading controller are included and the longitudinal defining the desired velocity and the required flight path angle for reaching the target altitude. A speed controller is also present for the thrust adjustment to preserve the desired speed.

Longitudinal controller provides the required flight path angle using the equation for the climb and descent phase:

$$\gamma = \max\left\{\gamma_{min}, min\left\{\gamma_{max}, \left(\frac{T-D}{m} - \frac{V_d - v}{\Delta t}\right)\frac{1}{g}\right\}\right\} \tag{8}$$

And for the cruise phase a proportional controller is used:

$$\gamma = \max\{\gamma_{min}, min\{\gamma_{max}, k_a(H_d - h\}\} \tag{9}$$

Lateral controller works with a switching process between two different controllers which are straight line controller and the turn controller.

Straight line controller follows the equation:

$$\phi = \max\left\{-\phi_{max}, min\left\{\phi_{max}, arctan\left(\frac{\dot{\psi}v}{g}\right)\right\}\right\} \quad (10)$$

And the turn controller is defined by:

$$\phi = \max\left\{-\phi_{max}, min\left\{\phi_{max}, arctan\left(\frac{\dot{\psi}v}{g}\right)\right\}\right\} \quad (11)$$

Detailed information of the approach that is used to model the aircraft which is also referred as Trajectory Generation Tool in this study can be found in "Optimization-Based Autonomous Air Traffic Control for Airspace Capacity Improvement" by Başpınar et al. [31]. The method was used to create the trajectories for the baseline and the direct routing concept.

3.3. Simulation

The simulation process includes every aircraft in the environment considering their flight plans.The tool generates a trajectory for the aircraft crossing the given waypoints. The user can make changes on the trajectory by modifying the waypoint inputs. Based on the waypoints given as inputs, a trajectory is generated passing through these waypoints. Trajectory can be modified and different factors can be applied by changing the number or attributes of the waypoints. For this study, all actual waypoints that the aircraft in the sample are used to generate the baseline trajectories and only entry and exit waypoints are used to generate the direct route trajectories.

3.3.1. Direct routing

Trajectory Generation Tool (TGT) enables the user to generate trajectories with different options and concepts. In the given case, the default option for the user is the direct route. For the Free Route Airspace concept, with less restrictive constraints the trivial option would be to generate direct routes with only two waypoints.

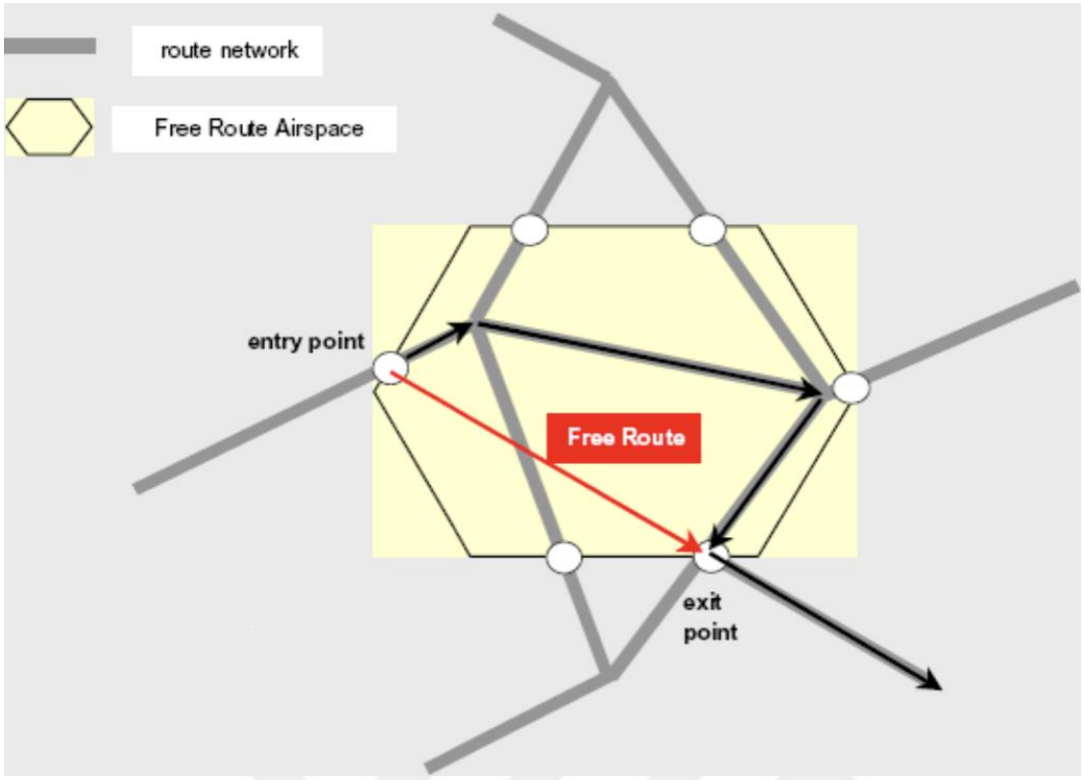

Figure 3.1: Direct Routing in FRA. [32]

3.4. Emission Model

For the emission model, the approach of the Advanced Emmision Model is followed. The Advanced Emission Model (AEM3) [33] is an independent and self-contained system used to estimate aviation emissions which are water vapour, sulfur oxides, corbon dioxide, Benzene, nitrogen oxides, hidrocarbons, TOC, VOC and fuel burn. Analysing the flight profile data for different air traffic scenarios on a flight-by-flight base is within the capabilities of the AEM3. Air traffic and the flight data are the inputs of the model.

For the fuel burn calculations, Landing and Take-off Cycle (LTO) defined by the ICAO Engine Certification specifications is used for flights below 3000 ft. Above 3000 ft Base of Aircraft Data (BADA) is used for fuel burn calculations.

3.4.1. Emission calculations

Convenient to the fuel burn calculations, ICAO Engine Exhaust Emissions Data Bank is used for below 3000 ft. For above 3000 ft, the calculation takes the ICAO Engine Exhaust Emissions Data Bank as a base, but the fuel flow and the emission factors are adapted to the altitude using the Boeing Method 2 [34].

CO_2 and H_2O emissions are directly caused by the oxidation of carbon in the fuel and the oxygen present in the atmosphere. Sulphur content of the fuel directly effects the SO_2 emissions. For emissions of NO_x, HC, CO Boeing Method 2 is used. All of the mentioned emissions are proportionally dependant to the fuel burn.

For this study, CO_2 emissions are calculated. With ALLFT+ data input the results were obtained.

3.4.2. Fuel Flow Method2

P3T3 method, which is a preferred method to calculate engine emissions requires internal gas parameters of the engines as inputs. This makes the method unusable for the people and institutions who does not have access to the engine internal data.

The fact that P3T3 method is not useful for everyone working on emissions, created the need for a method to calculate the emissions without knowing the engine internal data. Fuel Flow Method2, also known as the Boeing Method2 is a method developed by Doug DuBois and Gerald C. Paynter. The method introduces a way to correlate the T3 and the fuel flow and a pressure correction.

The method uses the energy balance across the combustor to define a correlation between the T3 and the fuel flow at the sea level condition. Then a pressure correction is introduced to adapt the calculations to the corresponding altitude. NO_x and H_2O emissions are calculated using the Boeing Method 2.

4. KEY PERFORMANCE INDICATORS

Trajectory planning methods impact multiple stakeholders in aviation. These are airlines, passengers, authorities, and climate. Future air traffic management systems will be designed to improve the safety and efficiency of air traffic operations while meeting demand. The environmental impact of aircraft emissions and contrails adds a new dimension to aircraft trajectory planning [13]. Free Route Airspaces and Direct Routes are operational improvements that are suggested to reduce the climate impact of aviation. However, modified trajectory planning methods require conveniency to multiple aspects of aviation operations to be applicable and efficient.

This study aims to analyse the direct routing concept outcomes in terms of different stakeholders in the field including airlines, passengers, ATCo and climate. Which is why KPIs selected for the study targets the defined stakeholders. Airlines look for ways to optimize the flight trajectories to have more aircraft availability, shorter flight durations, less fuel consumption, less cost and more ticket sales. Passengers are customers of airlines. It is expected from them to choose faster and cheaper flights. It must also be bore in mind that ATCo workload is an important factor for feasibility and improvement.

4.1 Air Traffic Control

Over the last decade, the demands on the commercial flying sector and its outmoded Air Traffic Control (ATC) infrastructure have risen dramatically. The ATC system has already reached its capacity, resulting in widespread flight delays during peak demand periods, and passenger throughput is likely to continue to rise in the future, putting more strain on the system [11].

Implementation of Free Route Airspace means great change for current ATC systems. The operator will have to adjust to a new way of planning flight routes.

For the best fuel economy, the operator must design routes based on the most up-to-date airspace information [32]. ATC must have their systems updated to be convenient with the FRA concept. This means an effort for the change that is going to be implemented. That is why at the same time, the new system must provide the ATC with beneficial improvements in the workload. In this study, the workload of ATCo is studied based on several metrics.

4.1.1 Air traffic controller workload

Air Traffic Controller Workload is an important metric considering a project suggesting a change on the method of how the trajectories are planned and affecting the air traffic concept. Although the main purpose of the suggested change is to optimize the trajectories based on reducing the environmental impact, different stakeholders must be taken into account. One of them is the ATC; suggested method for the air traffic must be feasible and even making the ATCo's job easier. The controller's workload, and hence the ACC productivity, are directly and quantifiably affected by complexity.

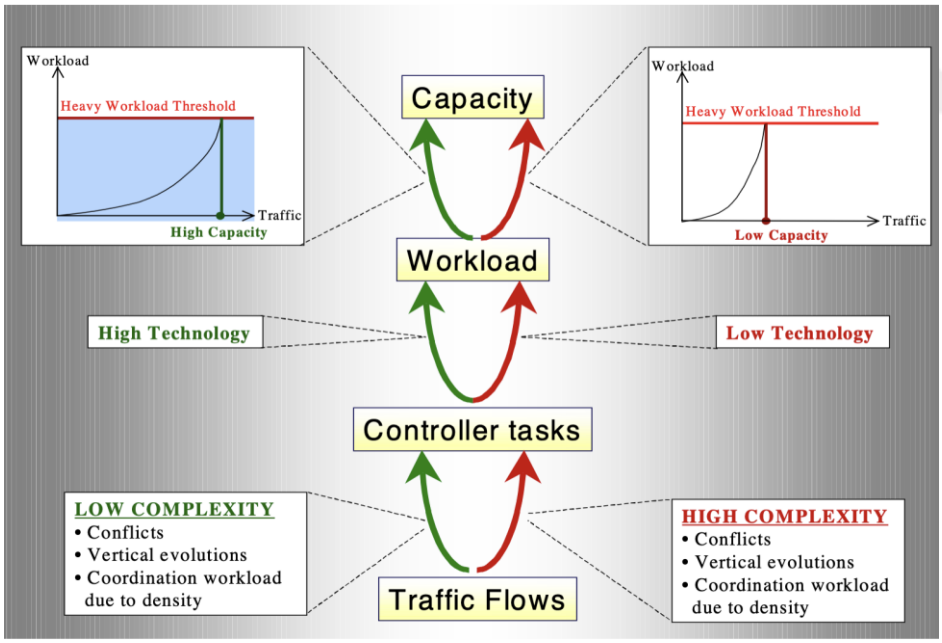

Figure 4.1: Air Traffic Control Workload Chart. [35]

Therefore, complexity metrics were studied to assess how the ATC workload is affected by the change in the trajectory plans. Although the term "complexity" is commonly used to describe "degree of difficulty," there is no globally accepted definition for ATM. According to "Complexity Metrics for ANSP – Benchmarking

Analysis" report prepared by the ACE Working Group on Complexity in April 2006 [36], the definition of complexity depends on the intentions of its used scope. In these studies; complexity is used for benchmarking and comparison; therefore, defining it by capturing the external factors of the controller workload and the difficulty of the ATC task is convenient. The working group defined the complexity on a range of complexity dimensions which are formulated in detail. The dimensions and metrics defined in the document [36] are used for complexity calculations in this study.

First one of the dimensions that are defined is; traffic density which is indicated by adjusted density and described as the potential number of interactions between aircraft in a given volume of airspace. The other is the traffic in evolution; capturing the potential interactions between different phases of flights and indicated by the potential vertical interactions (VDIF). Flow structure which is the measure of potential interactions based on the heading of the aircraft is indicated by the potential horizontal interactions (HDIF) is the third dimension for complexity. And the final one is the traffic mix; indicated by the potential speed interactions (SDIF), assessing the potential interactions based on the aircraft speeds. The consistency of the defined indicators is applied by the concept of an interaction between two aircraft in a cell of 20x20 nautical miles and 3000 feet in height.

4.1.1.1 Interactions

The presence of multiple aircraft in the same area at the same time adds complexity, especially if the aircraft are in different flight phases, have different headings, or are traveling at different speeds. The definition of an interaction is the presence of two aircraft in the same cell at the same time, as seen from the perspective of each aircraft. The technique simply analyses how long each aircraft is in the cell throughout the hour, and each aircraft might have passed through at any point during the hour.

If t_a and t_b are the observed durations of aircraft (a) and (b) in the cell during the hour, then the product is the expected duration of the interaction between aircraft a and b.

$$T_k = \sum_{i \in cell_k} t_i \tag{12}$$

Is the total time flown in the cell k per hour

$$D_k = \sum_{i \in cell_k} \left(\sum_{j \in cell_k} t_i * t_j \right) \quad (13)$$

Is the expected duration of potential interactions.

4.1.1.2 Adjusted density & concentration

Adjusted density is defined as the ratio between the hours of interactions and flight hours. It is the indicator of the traffic density which is a measure of the amount of traffic that exists within a given volume over a given time.

Concentration is adjusted density divided by raw density and it provides the information for the traffic distribution in space and time.

$$AdjDens = \frac{\sum_{Cells} D_k}{\sum_{Cells} T_k} \quad (14)$$

4.1.1.3 Vertical interactions

The Vertical Different Interacting Flows (VDIF) indicator is a measure of the complexity resulting from interactions between aircraft at different stages of flight. It is calculated as the number of potential vertical encounters per flight hour (in hours). When two aircraft are present in the same cell at the same time and have different attitudes, they are considered to interact vertically (climbing-cruising-descending). The attitude of each aircraft is set when it enters the cell. If the rate of climb/descent is less than 500 feet per minute, the aircraft is considered in cruise.

VDIF is expressed as the hours of vertical interactions divided by flight hours.

$$V_k = \sum_{i \in cell_k} \left(\sum_{j \in cell_k} t_i * t_j \right) \quad (15)$$

Is the hours of vertical interactions, where i and j have different attitudes.

And

$$VDIF = \frac{\sum_{Cells} V_k}{\sum_{Cells} T_k} \quad (16)$$

4.1.1.4 Horizontal interactions

The Horizontal Different Interacting Flows (HDIF) is a measure of the complexity originating from interactions between flights with different headings and is given as the potential horizontal interactions' duration (in hours) per flight hour.

A horizontal interaction occurs when two airplanes with different headings are present in the same cell at the same time. The heading utilized in the calculation is the same as when the plane entered the cell. When the difference between the headings of two aircraft is larger than 20 degrees, one interaction is recorded.

HDIF is expressed as the hours of horizontal interactions divided by flight hours.

$$H_k = \sum_{i \in cell_k} \left(\sum_{j \in cell_k} t_i * t_j \right) \quad (17)$$

Is the hours of horizontal interactions, where i and j have different headings.

$$HDIF = \frac{\sum_{Cells} H_k}{\sum_{Cells} T_k} \quad (18)$$

4.1.1.5 Speed interactions

The SDIF indicator, which is represented as the duration of potential speed interactions (in hours) per flight hour, is a measure of the complexity emerging from the interactions between aircraft with various speeds.

When the difference between the speeds of two aircraft is higher than 35 knots, it is called a speed interaction. The speed utilized in the computations is the value from the BADA performance table for the type of aircraft evaluated at the cell's flight level.

SDIF is expressed as the hours of speed interactions divided by flight hours.

$$S_k = \sum_{i \in cell_k} \left(\sum_{j \in cell_k} t_i * t_j \right) \tag{19}$$

Is the hours of speed interactions, where i and j have different speeds.

$$SDIF = \frac{\sum_{Cells} S_k}{\sum_{Cells} T_k} \tag{20}$$

4.1.1.6 Complexity score

The structure of traffic flows and traffic volume have an impact on the ANSP complexity scores. These components can be separated with the use of the r_DIF indicators.The traffic volume is represented by adjusted density, whereas the traffic flow structure is represented by the structural index.

The structural index is expressed as:

$$Structural\ Index = \left(\frac{VDIF}{AdjDens} + \frac{HDIF}{AdjDens} + \frac{SDIF}{AdjDens} \right) \tag{21}$$

And complexity is the structural index multiplied by the adjusted density.

$$Complexity\ Score = AdjDens \left(\frac{VDIF}{AdjDens} + \frac{HDIF}{AdjDens} + \frac{SDIF}{AdjDens} \right) \tag{22}$$

4.1.2 Number of movements

Number of movements indicates the amount of aircraft present in the airspace for a given second. It is an important metric to understand the concept's impact on the ATCo workload. The more aircraft is present in the area the more aircraft and movements the ATCo is required to manage. Increased number of movements may have results such as an operator needing to work more or more efficiently during their workday or it might mean that there needs to be more operators hired to manage the present aircraft. This can have an important impact on how the ATC system works.

That is why number of movements is selected as a KPI to assess the impact of Direct Routing concept. The amount of aircrafts that is passing by the selected airspace is calculated per second. It is evaluated in terms of ATC workload.

4.1.3 Number of conflicts

Conflict is defined as a form of position between two aircraft. When the horizontal distance between the two aircraft is less than 5 naval miles and the vertical distance is less than 1000 ft; the two aircraft are considered to have a conflict. Alongside the amount of aircraft present in the airspace, their locations according to each other are very important considering the ATC operations. The distance between aircraft needs to remain greater than the safety requirement in order to avoid any safety concern or incident. Conflict is a concern for safety as well. Issues emerge when aircraft come very close to each other. It is something to avoid regarding the safety of the aircraft and the passengers.

Number of conflicts is an important metric in terms of ATC workload. Every conflict requires the attention and effort of the ATCo. For every instance, air traffic controller needs to intervene to solve the conflict. Increased number of conflicts might affect the efficiency of the ATCo in a negative way. Therefore, number of conflicts directly impacts the ATC workload.

4.2 Airlines

While flight plan calculations are required for safety and regulatory compliance, they also allow airlines to save money by allowing them to estimate the best route, altitudes, speeds, and amount of fuel to put on a plane.

Flight plans that are accurate and optimized can save airlines millions of gallons of fuel each year without compromising schedules or service.

Airlines can reap the benefits of investing in a higher-end flight planning system with advanced optimization capabilities, then ensuring accuracy by comparing flight plan values to actual flight data, identifying the source of discrepancies, and updating the parameters used in the flight plan calculation [37].

4.2.1 Routing efficiency

Routing efficiency can also be expressed as the length of the trajectory for a specific flight. The distance traversed by an aircraft is a metric that is important for airlines and the ATC.

Total distance crossed effects the duration of flight, the fuel consumption which are important criteria for airlines and also the ATC workload. The more distance is traversed it is expected to burn more fuel which means cost and the more time aircraft spends crossing the distance. Aircraft are expected to spend optimal time flying since it affects their availability and overall route plannings for the airlines.

4.2.2 Fuel consumption

Users look for the cheapest flight between their departure and arrival airports while booking a trip. The cost of a route is affected by the amount of fuel used and the amount of time spent flying [14].

Commercial airlines' operating costs include jet fuel as a significant component. Furthermore, high fuel costs are forcing carriers to raise ticket prices, a move that most airlines have avoided due to the sluggishness in air travel demand over the last years. With the current political situation, fuel prices are unlikely to fall anytime soon. This drives most airlines to look for cost-cutting fuel-saving strategies [38]. According to IATA's Fuel Price Monitor, current jet fuel price is 136.8 $ per barrel and in May 2018 this price was 94$ [39].

Airlines are using methods to plan their flight trajectories considering different metrics that they have. One of the important factors is the fuel consumption. It takes a significant place in dispatchers' decision process. Direct routing is also expected to provide a drop for the fuel consumption since it is providing a change that is possible shortening the routes that are followed by the aircraft. With less distance to go the aircraft is expected to consume less fuel. With airlines being a stakeholder, fuel consumption is also assessed. On the other hand, since emissions are mostly caused by the fuel consumed by the engine, less fuel consumption might also act as a factor to reduce the emissions.

4.2.3 Travel duration

Airlines and passengers are important stakeholders for any change to be made in the trajectory planning methods. The greatest problem aviation solves is the time saving it provides for traveling. Shorter flight durations are preferred by the passengers. Airlines prioritize the flight duration since it has an effect on other metrics such as fuel consumption and aircraft availability. Travel duration is a compound of the direct operating cost that is a metric used by airlines. The more time the aircraft spends in the air means more cost to the airline. It also means that the aircraft and the engine life are spent more and it spends more time in the air for a reserved route. Aircraft availability affects the route planning process for airlines.

4.2.4 Direct operating cost

A study has been made for the estimates of variable and fixed aircraft operating expenses. Direct operating cost affects airlines directly and air service consumers indirectly through higher or cheaper ticket prices or taxes.

Fuel and oil, maintenance, and personnel expenditures are terms of variable costs that change in response to aircraft utilization. In 2018, passenger air carriers' average total operating cost per block hour was $8,916 and all-cargo air carriers' average cost was $28,744 [40].

Table 4.1 2018 Part 121 Passenger Air Carriers Filing Schedule P-5.2 Operating and Fixed Costs per Block Hours. [40]

Aircraft Category	Cost Per Block Hour									
	Fuel and Oil	Maintenance	Crew	Total Variable	Depreciation	Rentals	Insurance	Other	Total Fixed	Total
Wide-body more than 300 seats	$5,411	$1,331	$2,356	$9,097	$845	$406	$4	$1	$1,254	$10,351
Wide-body 300 seats and below	$4,080	$1,289	$1,857	$7,227	$685	$366	$4	$4	$1,058	$8,285
Narrow-body more than 160 seats	$2,054	$718	$1,152	$3,925	$355	$217	$3	$7	$582	$4,506
Narrow-body 160 seats and below	$1,741	$737	$1,034	$3,512	$306	$215	$5	$7	$533	$4,045
RJ more than 60 seats	$115	$431	$444	$991	$131	$252	$1	$13	$397	$1,388

RJ 60 seats and below	$92	$479	$470	$1,041	$58	$227	$1	$7	$293	$1,334
Turboprop more than 60 seats	$0	$880	$360	$1,241	$439	$103	$0	$2	$544	$1,785
All Aircraft	$1,681	$727	$1,012	$3,420	$314	$239	$4	$7	$564	$3,985

Considering different compounds that are causing expense to the airline operators, direct operating cost is calculated as:

$$DOR = 0.748\, Fuel\ Consumption + \frac{1870}{60} Travel\ Duration(\text{min}) \qquad (23)$$

Effective planning of flights and trajectories are important to optimize the crew schedules and aircraft availability. Airlines look for ways to optimize their route planning in order to reduce the operating cost attacking different aspect that is affecting the cost. In this study, direct operating cost and its factors are selected as KPIs to assess the Direct Route concepts effect on the airlines.

4.3 Passenger

Passengers is an important bullet point for the aviation sector. They are the customers of the airlines and also of the aviation sector as a whole. The humans' need to travel distances faster and quicker and in a more comfortable way made the aviation one of the most important and needed sectors in the world. Aviation is a safe, quick and comfortable way to reach a point from another. According to ICAO's report for 2018 [41]the number of passengers carried by airlines is 4.3 billion. This number increases every year.

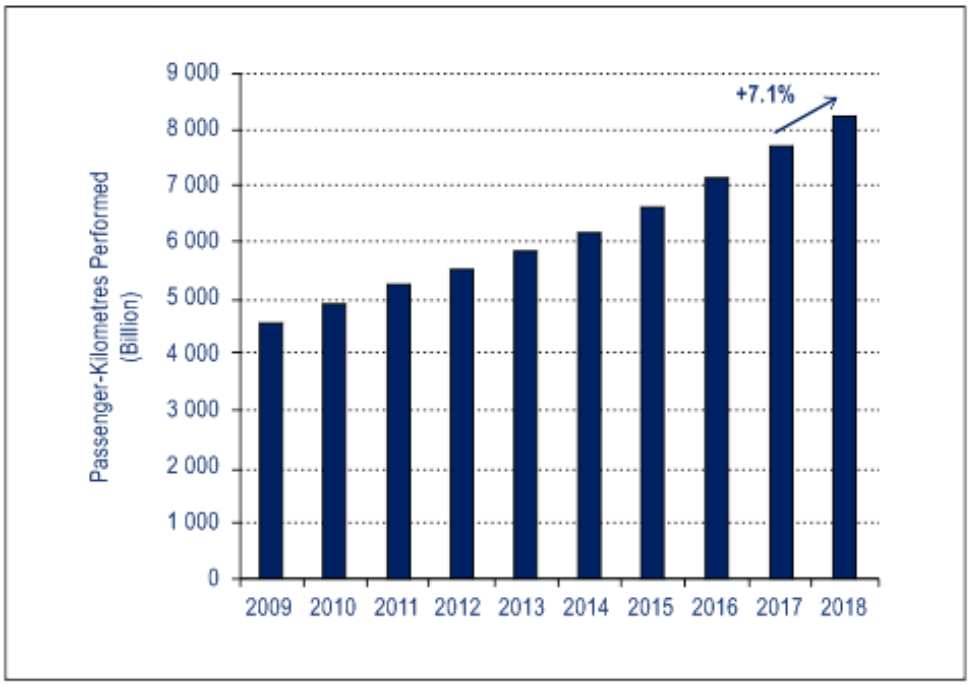

Figure 4.2: Passenger-Kilometers Performed, Total Scheduled Traffic. [41]

Ticket prices, travel durations, arrival and departure locations and the comfort of the flight are the criteria for the passenger using air transport. On that account, performing and suggesting operational improvements to the ATC systems, travel duration and cost are important KPIs affecting the passenger experience.

4.4 Climate / Emissions

Carbon dioxide (CO2), water vapor (H2O), nitrogen oxides (NOx), sulfate aerosols, incomplete combustion products (unburnt hydrocarbons, UHC), and particulates are all released by aviation (soot). The released species are carried through the atmosphere, affecting a variety of atmospheric processes such as contrail generation, ozone depletion, and methane depletion [3].

CO2, NOx, and H2O emissions are selected as KPIs to assess the effectiveness of the direct routes. According to [42] these are the greenhouse gases that have a major effect on the surface temperature.

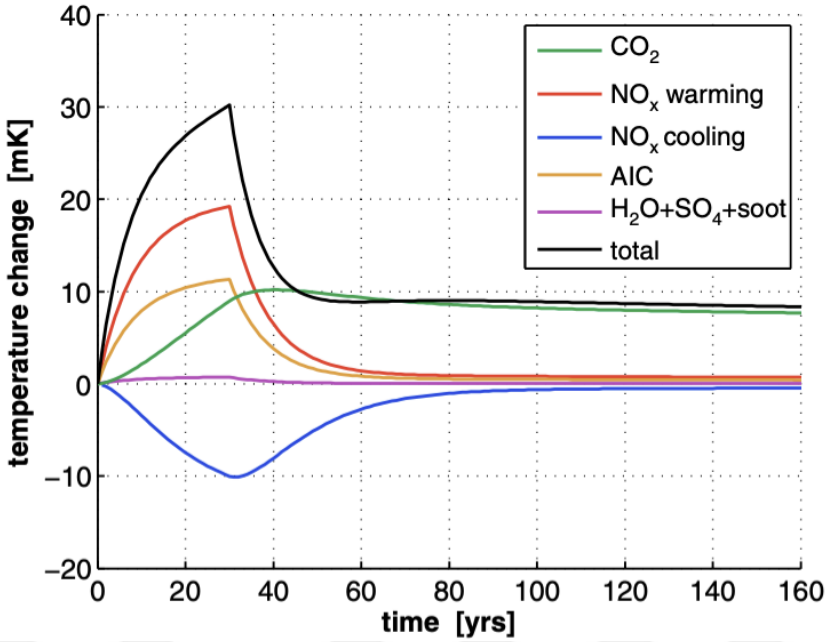

Figure 4.3: Temperature Change caused by the emissions during the years. [42]

In [42] a metric called the Average Temperature Response (ATR) is proposed to measure the effects of gas emissions on the global warming and it is based on the temperature change in the long term.

The goal of ATR is to quantify the climate impacts realized from emissions during operation as well as the climate impacts that occur from perturbations that linger in the Earth-atmosphere system after the airplane's operating lifetime has finished for a specific aircraft [42]. In this study, gas emissions' contributions are also considered according to the ATR approach.

4.4.1 CO2 emissions

Aviation accounts for approximately 2% of all anthropogenic CO2 emissions, with a major fraction occurring at altitudes where emissions last longer than if emitted at ground level [18]. CO2 has a long-term impact on global warming.

The United Nations' International Civil Aviation Organization (ICAO) has agreed on a global market-based measure scheme to reduce CO2 emissions from international aviation.The Carbon Offsetting and Reduction Scheme for International Aviation is

the name of this program (CORSIA) [43]. According to this plan, the sector's expansion after 2020 must be offset so that net carbon emissions do not increase [3].
Changes in the climatic system are caused by CO2 emissions and non-CO2 aviation effects. Surface warming is caused by both aircraft CO2 and the sum of quantifiable non-CO2 components. The increase in CO2 concentration, which is the principal driver of observed global warming in recent decades, makes the highest contribution to anthropogenic climate change across all economic sectors. Aviation impacts a variety of physical processes in the atmosphere, including plume dynamics, chemical transformations, microphysics, radiation, and transport [44].

4.4.2 NOx emissions

NOx emissions from aircraft cause photochemical changes that promote the development of global ozone (O3) while decreasing the lifetime and quantity of methane (CH4) [44]. Exhaled nitrogen oxides (NOx) mix with hydroxyl radicals (HOx) to generate ozone, which contributes to the decrease of atmospheric methane.
As a result, nitrogen oxide emissions enhance ozone levels while decrease methane levels at the same time. Changes in ozone and methane concentrations cause positive changes in the RF, resulting in warming [3]. Over long timescales, NOx enhances the destruction of the greenhouse gases methane (CH4) and ozone (O3L), which are cooling effects [42].

4.4.3 H2O emissions

The stratosphere accounts for a significant portion of annual aviation emissions from the global fleet, particularly in the northern hemisphere [45]. The concentration of water vapor emissions disturbs the lower stratosphere's low background humidity and alters the water vapor radiative balance [44], [46].
Water vapour emissions contribute to the humidity and the contrail generation caused by the aircraft. This has a short term yet important effect on the global warming. Total yearly anthropogenic Net Radiative Forcing (NRF) is estimated to be 2.38 W/m2 by the Intergovernmental Panel on Climate Change, with aviation contributing 0.090 W/m2 (3.7 percent) [46]. The yearly NRF of contrails, which are predicted to cover

0.1 percent of the Earth's surface, is 0.05 W/m2. In this sense, even while contrails contribute only about 2% to global warming, they account for 55% of aviation's overall anthropogenic NRF [47]. The percent contribution of contrails is predicted to increase in lockstep with the expansion of aviation. Contrary to CO2 emissions, which have a 20–40 year influence on global warming, the impact of contrails on global warming is immediate.

5. SIMULATION AND RESULTS

5.1 Airspace Selection

For the airspace selection of the sample flights, it was pursued to choose a high complexity airspace. There are existing studies assessing generic airspaces for specific criteria. This work aims to assess the KPIs for all possible stakeholders and to perform the analysis for a high-complexity airspace.

There are 37 separate en-route ANSPs throughout Europe, covering varied geographical locations [9]. Multiple sources and reports are screened to pick a convenient airspace including [35], [36], [9].

In the "Investigating the Air Traffic Complexity" report by EUROCONTROL PRF, different methods were followed to calculate the Air Traffic Complexity of air space regions. The conflicts that were found are plotted as:

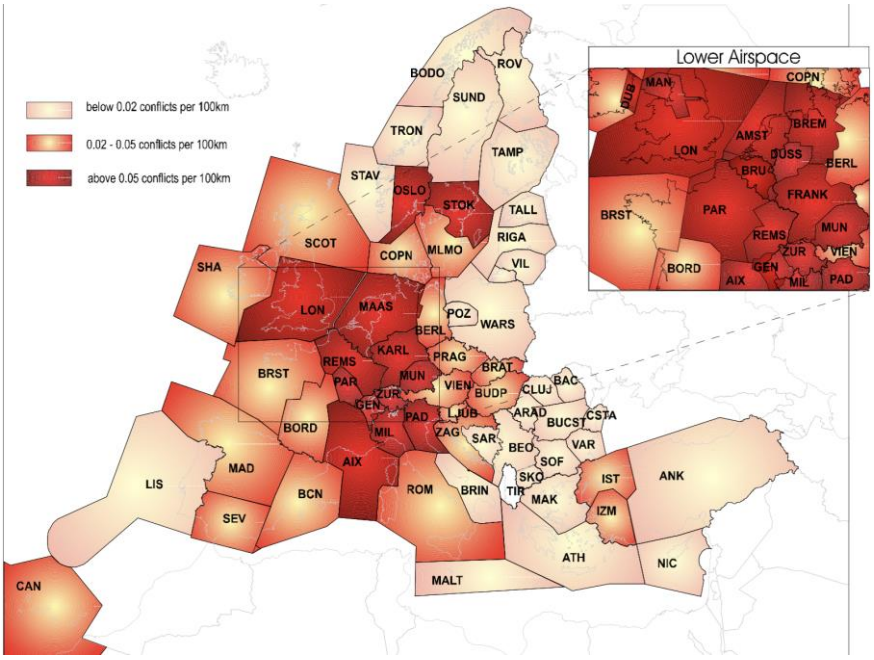

Figure 5.1: Conflicts in ECAC Region. [35]

In [36], complexity metrics and dimensions were defined. The definitions that are published are used for the hereby study. The dimensions were calculated for all ECAC areas and published.

Adjusted density values are plotted as:

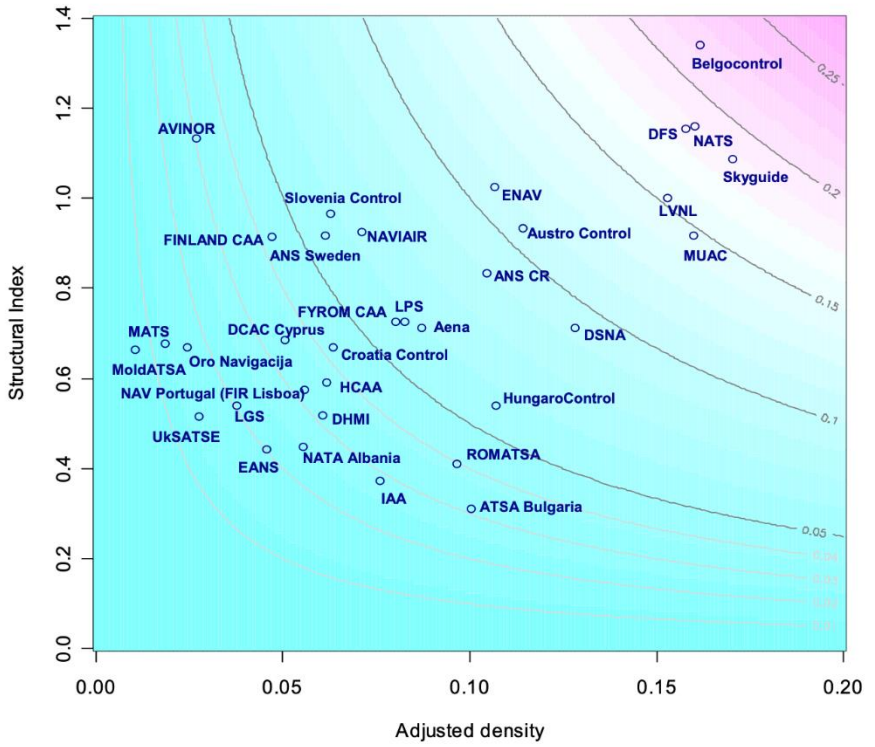

Figure 5.2: Airspaces plot based on adjusted density and complexity. [36]

And the complexity scores are found as:

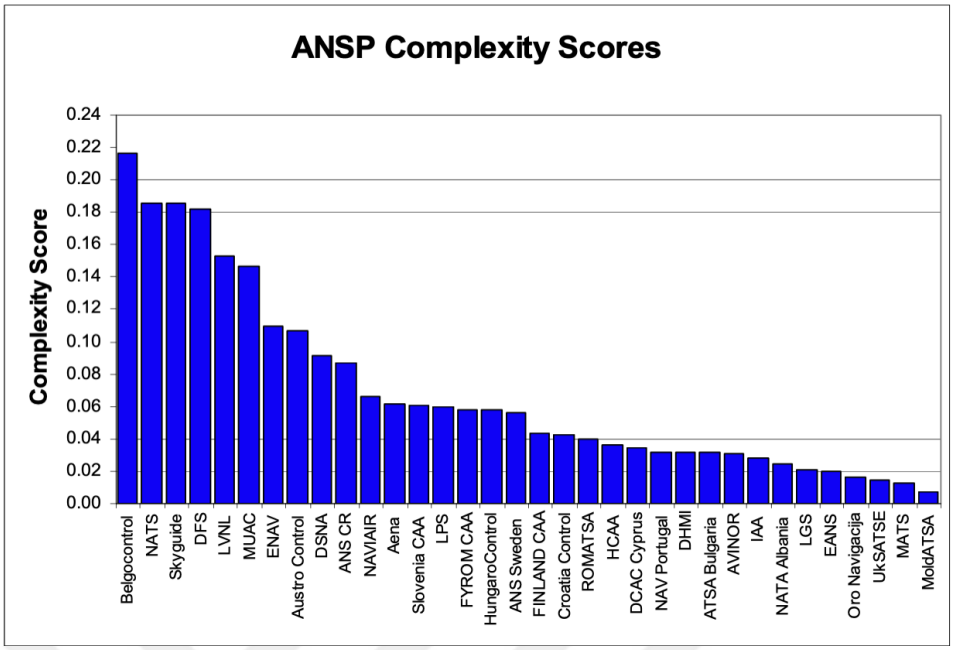

Figure 5.3: Complexity Scores in the ECAC area. [36]

[9] aims to calculate the complexity metrics to perform a comparison between US and Europe airspaces. The density results were shared as:

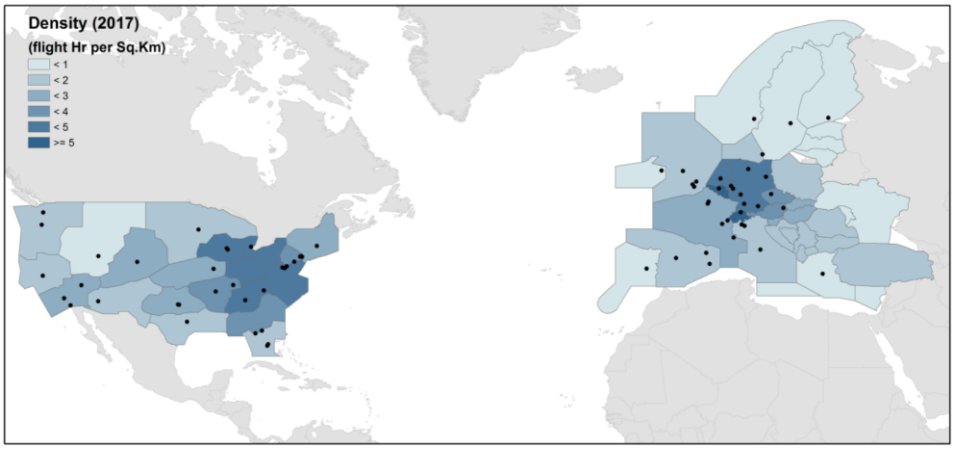

Figure 5.4: Air Traffic Densities in US and Europe. [9]

The "core area," which includes the Benelux States, Northeast France, Germany, and Switzerland, is Europe's most crowded and complex airspace [9].

Considering data availability and the results that were published on different sources EDUU area controlled by DFS was chosen as the sample airspace region for the calculations of this study.

5.2 Simulation

Trajectory Generation Tool (TGT) is used to generate the trajectories for two different scenarios. Baseline trajectories are obtained by giving the existing waypoints from the actual flight plans to the TGT. The real flight plan data for December 3rd, 2018 is obtained from EUROCONTROL's DDR2 database. A windy and dense day is selected for reliable impact assessment. With the obtained data and waypoints the actual trajectories are generated through TGT. For the Direct Route scenario only entry and exit waypoints were given to TGT. The output trajectory data was used to calculate the values for the defined KPIs and compared to determine the impact of applying the direct route concept.

5.3 Results

5.3.1 ATC workload

To represent the ATC workload, ATC complexity dimensions are calculated for both Baseline and DR trajectories. To minimize the effect of grids; 12 different grid origin options were considered getting the results. The average value of 12 different scenarios is taken as final result.

Table 5.1: Grid options taken into account.

Grid Option	X Starting Point (nm)	Y Starting Point (nm)	Altitude Starting Point (ft)
1	0	0	0
2	0	0	1000
3	0	0	2000
4	0	10	0
5	0	10	1000
6	0	10	2000
7	10	0	0
8	10	0	1000
9	10	0	2000
10	10	10	0
11	10	10	1000
12	10	10	2000

The values calculated for the Adjusted Density and Complexity score for both cases are shown in Figure 5.5. It is seen that overall complexity score in the area visibly drops when the direct routes are applied. Complexity is the KPI that is determined to

evaluate the ATCo workload. Decrease that is observed on the complexity score means that the operator's workload also drops since the airspace becomes less complex. This would be also interpreted as the operator's efficiency is increased.

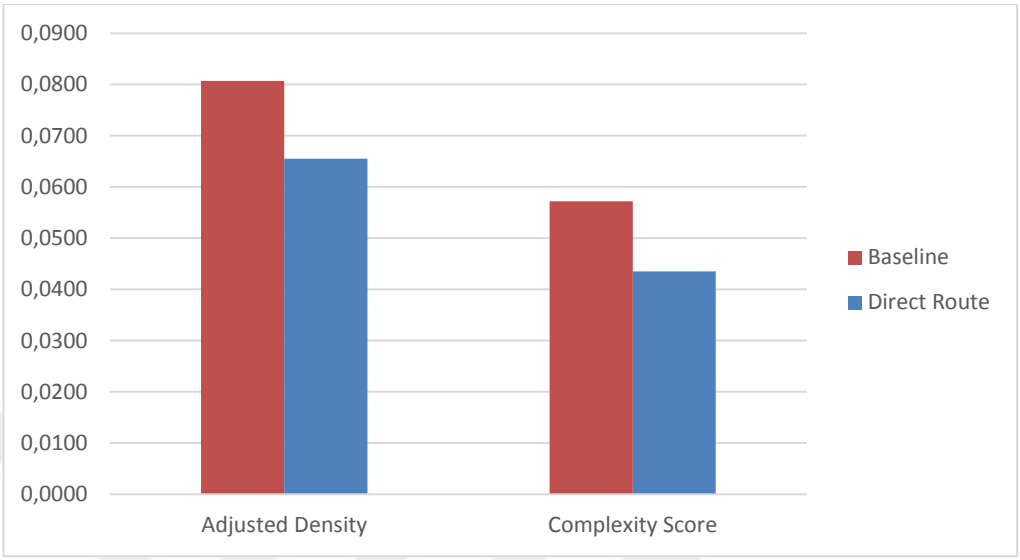

Figure 5.5: Adjusted Density and Complexity Scores for Baseline and Direct Route Trajectories.

The detailed results for the complexity dimensions for different grid options are given below. It is seen that for all dimensions except for the SDIF; the complexity values are decreased for all grid options. Overall complexity score appears to be decreased; however this could also be possible by some dimensions getting lower or higher. When the dimensions are calculated and plotted seperately it is observed that all dimensions of the complexity are dropped except for the SDIF.

For the SDIF; the results appear to be slightly increased for the Direct Route option. This is not unexpected considering the fact that for the simulation a specific aircraft model was used so the speed profiles would be the same. The change on the SDIF is negligable considering the assumptions made in the assessment.

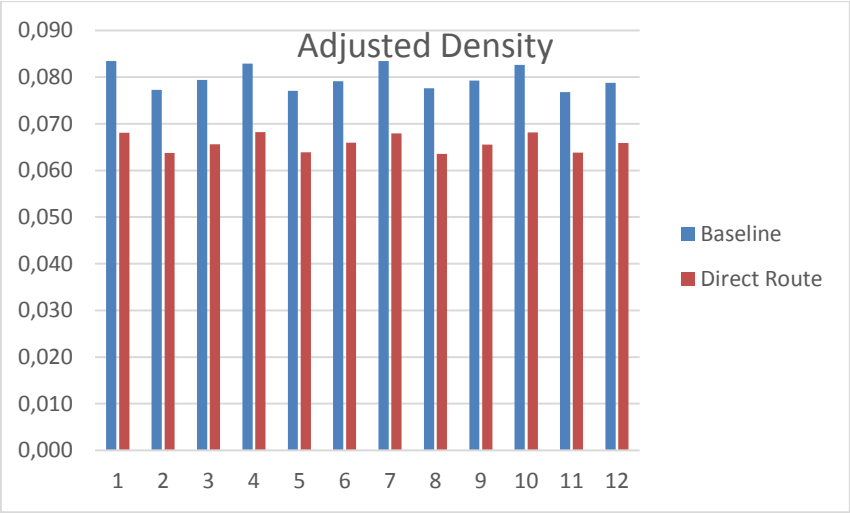

Figure 5.6: Adjusted Density values calculated for different scenarios.

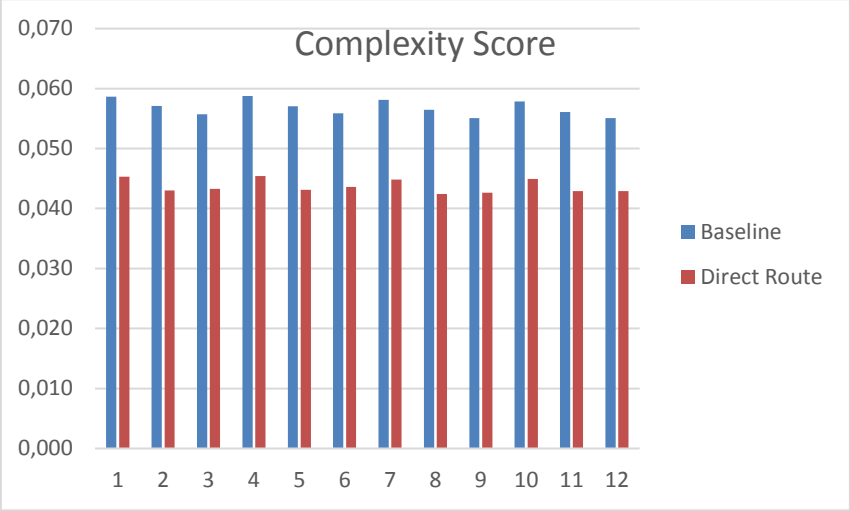

Figure 5.7: Complexity Score values calculated for different scenarios.

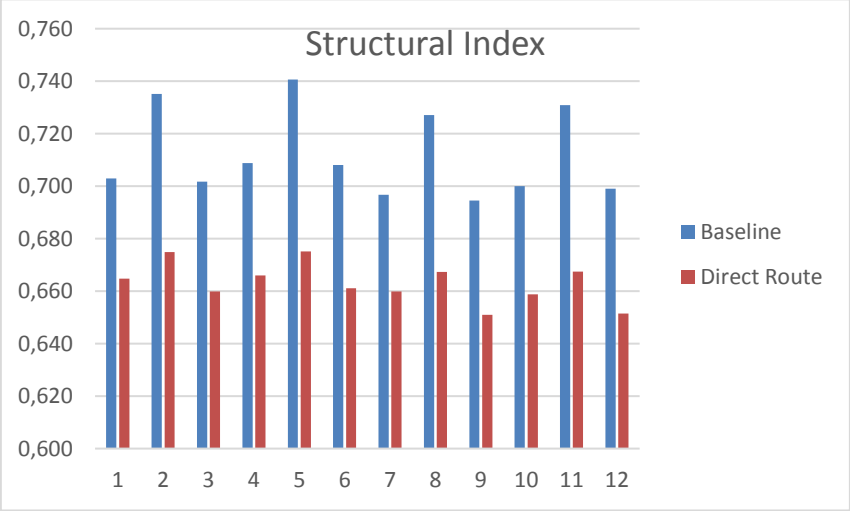

Figure 5.8: Structural Index values calculated for different scenarios.

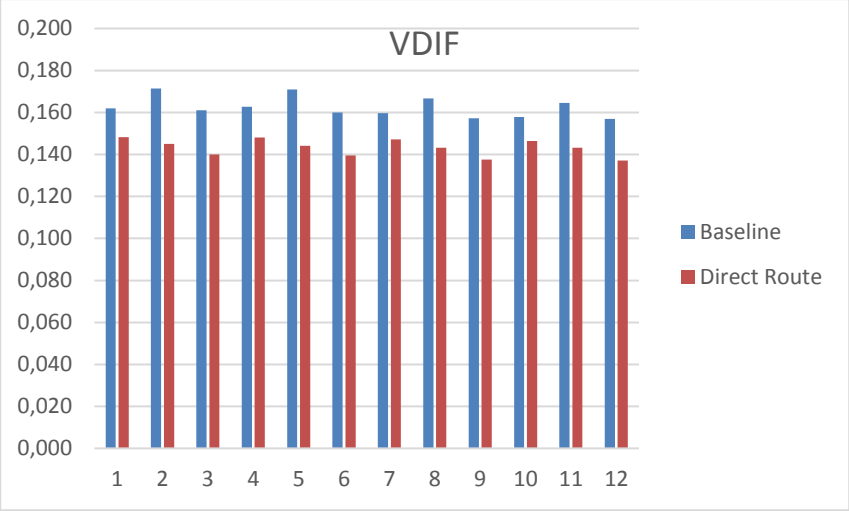

Figure 5.9: VDIF values calculated for different scenarios.

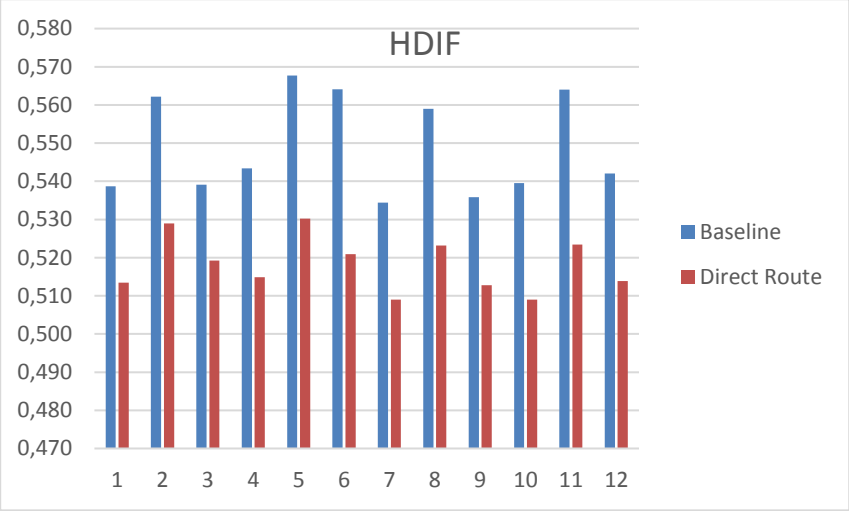

Figure 5.10: HDIF values calculated for different scenarios.

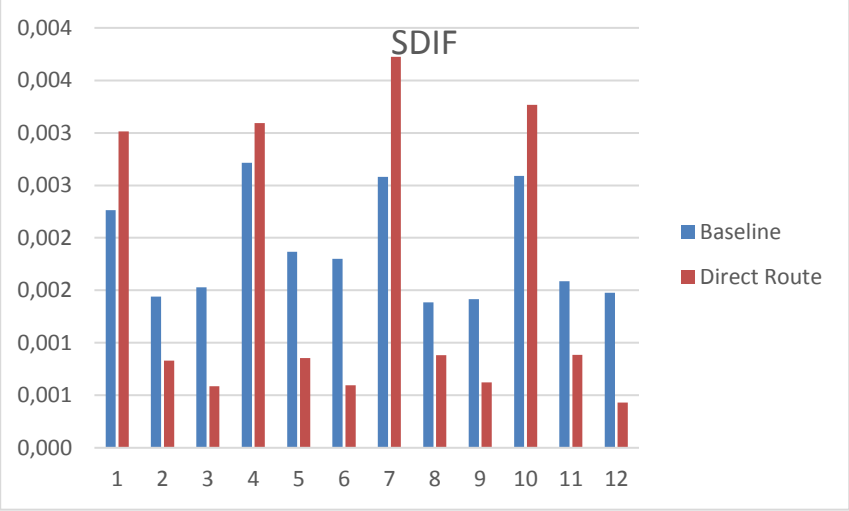

Figure 5.11: SDIF values calculated for different scenarios.

5.3.2 Non-climate KPIs

Results are tabulated in Table 5.2. It is observed that for all the KPIs in the scope there is an improvement. The largest improvement is seen on the Complexity Score which is decreased by 23% and the number of conflicts is decreased 21%. KPIs defined for the airlines however, are improved by around 1 or 4%.

Table 5.2: Non-Climate KPI Results for Baseling and Direct Route Scenarios.

KPI	Baseline	Direct Route	% Improvement
Complexity Score	0.0572	0.0435	23%
Number of Movements	68.86	68.19	0.10%
Number of Conflicts (per flight hours)	0.55	0.43	21%
Routing Efficiency (km)	243.86	240.06	1.50%
Fuel Consumption (kg per flight)	797.42	737.26	7.50%
Travel Duration (sec per flight)	1088.86	1078.09	0.10%
Direct Operating Cost ($)	1161.6	1111.5	4%

It can be concluded that the application of Direct Route concept is most beneficial for the ATC point of view. As it was expected, with direct routes application in the DFS ara the trajectories get shorter, aircraft travel shorter distances and they spend less time in the airspace even though it is a minor change. Number of conflicts and the complexity show a major decrease making the ATCo officer workload smaller. Fuel consumption is decreased by 7,5%; the change can be highly beneficial for larger scales. It is also known that airlines are look for ways to decrease the fuel consumption for any amount. Direct operating cost is observed to drop by 4%. It shows great opportunity for savings.

5.4 Emissions

Boeing Method 2 approach is followed to calculate the gas emissions produced by the aircraft throughout the generated trajectories. The results are plotted on a heatmap for both baseline and direct route scenarios. Additionally, emissions per flight values are also calculated and compared.

It is seen that for CO_2 and H_2O emissions, there is a decrease by 7,5% and NO_x emissions are dropped by 23,9% with the application of Direct Route concept. This can be evaluated as a major positive outcome of the Direct route application. NO_x emissions are observed the decrease by 23,9% which is a significant quantity considering the cumulative and long-term effects of NO_x. CO_2 and H_2O emissions also drop by 7,5%. Their emissions are directly dependent to the fuel consumption. Considering the ATR approach, what is important for the gas emissions selected for the study is their long-term cumulative effects. The results show the change in the emissions for a given day for a specific area. For a larger scale area and for the long-term this change can result in major improvements for the climate and the earth's surface temperature.

Table 5.3: Greenhouse Gas Emission Results for Baseline and Direct Route Scenarios.

Emissions	Baseline	Direct Route	% Improvement
CO2 (kg per flight)	3030.0235	2801.4104	7,5%
H2O (kg per flight)	1183.5277	1094.2314	7,5%
NOx (kg per flight)	12.946	9.8498	23,9%

5.4.1 CO_2 emissions

The distribution in the EDUU area of CO2 emissions are shown on the Figure 5.12. It is seen that the maximum values of emissions have dropped with the application of DR. Decrease in the CO_2 emissions is directly related to the drop of the fuel consumption. Although, it is not directly observable on the map, the quantity of the CO_2 that is produced by the aircraft is decreased by 7,5%. The gas' contribution to the increase of the surface temperature is major. For the long-term considerations this change in the emission can have positive responses for the mitigation of the climate change effects.

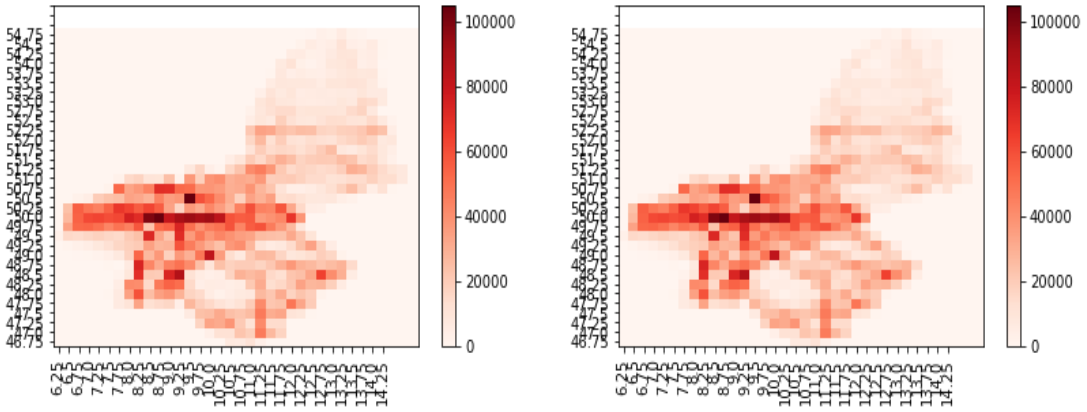

Figure 5. 12: Heatmap for CO_2 Emissions for Baseline and DR Scenarios.

5.4.2 H_2O emissions

H_2O emission distribution for the EDUU area is shown on the Figure 5.13. Maximum observed value per grid is dropped and the total emissions also decreased. The total value of H_2O emissions decreased by 7,5%; this value is calculated for a specific day in a specific area. The cumulative effect on the humidity is expected to decrease as well when a larger scale is considered.

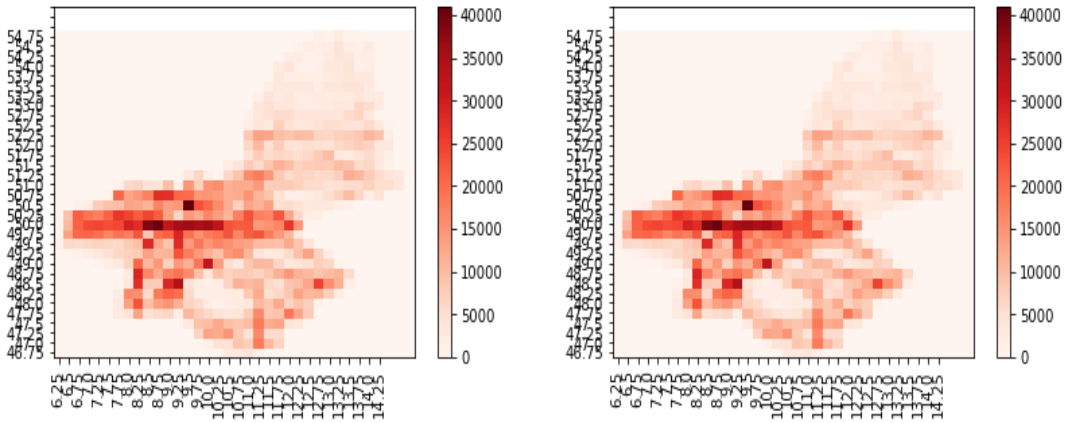

Figure 5.13: Heatmap for H2O Emissions for Baseline and DR Scenarios.

5.4.3 NOx emissions

NO_x emissions distribution is plotted in Figure 5.14. A significant drop can be seen on the heatmaps. The emissions dropped by 23,9% with the Direct Route application. The impact of NO_x on the other gas present in the earth's atmosphere such as ozone effects directly and indirectly the change of the surface temperature and global warming. Considering the cumulative impact of this improvement a significant amelioration can be expected in terms of climate can be expected by the application of the Direct route and FRA concept.

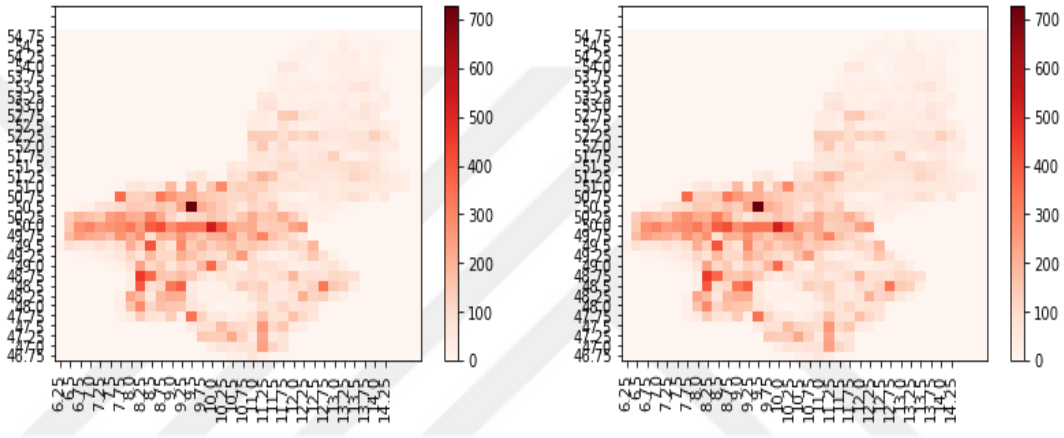

Figure 5.14: Heatmap for NOx Emissions for Baseline and DR Scenarios.

6. CONCLUSION

This thesis analyzes the impact of direct routing in the free route airspace concept. Possible results that can be obtained from switching to the direct routing in trajectory planning with less restrictive ATC systems are assessed.

Direct routing implies a planning system with more flexible constraints and it is suggested as an operational improvement for reducing aviation's effect on climate change. In this study, the difference direct routing can make on climate change is investigated. While performing the assessment, all stakeholders in the aviation sector were considered; therefore multiple KPIs were defined to comprehensively present the applicability and the overall possible benefit of the concept.

Firstly, KPIs are determined as the ATC workload, Number of Movements, Number of Conflicts, Routing Efficiency, Fuel Consumption, Travel Duration, Direct Operating Cost, and the Greenhouse Gas Emissions. These are representative indicators for the present stakeholders in aviation: airlines, passengers, ATCo, and the climate. Second, an indicative sample of flights are selected to perform the comparative assessment. The airspace was chosen as the EDUU area in ECAC. It is a high-complexity region where the density and ATC workload is high. Data of the 4505 flights that are passing by the area on December 3^{rd,} 2018 are acquired from the DDR2 database of EUROCONTROL.

Then, using the Trajectory Generation Tool, baseline and direct route trajectories are generated. With the trajectory data that is obtained, defined KPIs and emissions of CO_2, H_2O, and NO_x are calculated and compared for both scenarios. After assessing the results it was seen that for the selected ECAC area, the application of Direct Routing visibly improves the KPI values. The ATCo workload and operation cost are shown to be dropped while the emissions of the greenhouse gases are declining as well. The metrics defining the ATCo workload are dropped by around 23%; for passengers and airlines the KPI results show less than 5% improvement and for the greenhouse gases 23.9% for NO_x, 7.5% for H_2O, and CO_2 is shown. In conclusion, it can be said

that the Direct Routing concept not only improves the trajectory plans in terms of climate change effects it also impacts the other stakeholders positively. This positive effect is visible for climate and ATCo.

The contribution of this thesis is that the Direct Routing concept is analyzed for a high-complexity area for the first time. Also; in this specific study, all key stakeholders are taken into account while coming to conclusions. The climate impact is assessed based on the emission quantities of the selected gases. For future work, the assessment of climate impact is planned to be made directly by a model simulating the surface temperature change in the long period following the ATR approach. This study can be expanded to larger airspace areas to observe the demonstrative characteristic of this work. Moreover, direct routing, as the name implies, is a direct idea for an operational improvement in the Free Routing Airspace concept. This study can be followed by more complex trajectory planning methods that are optimized for climate, for winds, or for other critical factors.

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