

Air Flight Dynamics

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# 1. ANALYSIS AND OPTIMIZATION OF AIRCRAFT FUEL CONSUMPTION AND EMISSIONS

# 1.1 Abstract:

This project aims to advance the field of aerospace engineering by proposing a comprehensive mathematical model and an advanced algorithm for the analysis, optimization, and dynamic planning of aircraft fuel consumption, emissions, and flight trajectories.

The mathematical model provides a closed-form formula expressing the aircraft’s weight variation over time, and hence, the fuel flow rate, as a function of aerodynamic and engine parameters. It also yields closed-form expressions of the aircraft’s main performance parameters, such as lift, drag, thrust, and specific air range. The model is validated using MATLAB, showing a high degree of accuracy and reliability. It is then applied to improve the calculation of carbon dioxide emissions for four example routes, enabling a more precise estimation of the pollutant mass emitted and a sensitivity analysis of the emissions with respect to the aircraft’s initial weight, Mach number, the ratio of velocity of a fluid to the velocity of sound in that fluid, and altitude.

Simultaneously, the project explores the intricate dynamics of air flight and its efficiency, focusing on fuel utilization. It proposes an advanced algorithm for dynamic planning of optimized flight trajectories based on the concept of Flexible Use of Airspace (FUA). This algorithm considers parameters like air traffic, political airspace, airport capacity, weather data, and aircraft performance. It divides the airspace into four-dimensional cubes (Latitude, Longitude, Altitude, and Time - 4D-T) and calculates a dynamic score for each cube, representing the estimated weather, aerodynamic drag, and air traffic within that cube. The project also explores the impact of flexible airspace structures on flight efficiency, with a detailed analysis of their use in Europe, particularly the availability and utilization of conditional routes (CDR).

The objective of this research is to enhance an aircraft’s fuel efficiency, mitigate emissions, optimize performance parameters, and contribute to global well-being by addressing concerns like air pollution and global warming. It aims to elevate the standards of aerospace engineering vehicles through the continual improvement of their characteristics, shedding light on the potential for enhancing efficiency through flexible use of airspace and optimized flight trajectories. This project contributes to the environmental and economic sustainability of the aviation industry by providing a comprehensive and efficient tool for the analysis and optimization of aircraft fuel consumption and emissions.

# 1.2 Introduction:

The field of flight dynamics studies the performance of an aircraft in flight, analyzing how aerodynamic, propulsive, and gravitational forces affect an aircraft. It provides mathematical models of the aircraft’s state variables as a function of time during different flight phases, such as fuel consumption analysis. Fuel consumption has been a critical issue of aircraft design and performance since the early days of modern aviation. Flight planning involves estimating the trip fuel required for a certain mission profile, meeting the standards set by safety and regulatory agencies (EASA, FAA, ICAO, etc.), and the requirements of Air Traffic Control (ATC) to ensure the optimal and safest route to the destination airport.

The global airline industry has seen significant growth, driven by technological advancements and globalization, leading to peak airspace congestion. This growth has resulted in increased fuel consumption, greenhouse gas emissions, and scheduling issues, exacerbated by changing socio-political scenarios. These challenges necessitate long-term international planning and dynamic planning of optimized flight trajectories.

This project proposes a comprehensive approach to address these challenges. It introduces a mathematical model for fuel consumption analysis and an algorithm for trajectory planning. The mathematical model estimates the fuel required for each segment of the mission through iterative computational procedures that depend on the aircraft’s take-off weight, performance characteristics, and atmospheric conditions. The proposed algorithm for trajectory planning identifies cost-effective flight plans for optimal fuel utilization. It considers parameters like air traffic, political airspace, airport capacity, weather data, and aircraft performance.

Simultaneously, this project explores the impact of flexible airspace structures on flight efficiency. The concept of Flexible Use of Airspace (FUA) proposes a shift from rigid division to a more fluid, continuum-based approach. According to FUA, airspace should be allocated and used daily, with temporary segregation carried out as per real-time operational requirements.

This project aims to improve fuel saving strategies and search for more efficient ways to mitigate atmospheric pollution. In 2019, jet fuel combustion in the aviation industry produced 915 million tons of CO2, which accounted for 2% of all human-induced CO2 emissions and 12% of the general transport emissions. The potential benefits of this project extend beyond individual advancements, shedding light on the potential for enhancing efficiency through flexible use of airspace and optimized flight trajectories. This research aims to elevate the standards of aerospace engineering vehicles through the continual improvement of their characteristics.

This project delves into the impact of flexible airspace structures on flight efficiency, with a detailed analysis of their use in Europe. The study scrutinizes the availability and utilization of conditional routes (CDR), which are implemented through the flexible airspace structures (TSA / TRA).

Through this project, we aim to shed light on the intricate dynamics of air flight and the potential for enhancing its efficiency through flexible use of airspace and optimized flight trajectories. This project is a comprehensive exploration of the dynamics of air flight, its efficiency, and the potential enhancements through innovative approaches.

The resolution of this problem opens a wide range of possible applications such as:

• Calculation of pollutant emissions (CO2, NOx, Hydrocarbons) by means of the aircraft’s fuel flowrate closed-form formula and validated emissions indices.

• Knowing the fuel fraction that has been invested during the cruising flight phase and the aircraft’s weight at any moment in time.

• Knowing the closed-form formula of the relationship between the aircraft’s weight and the engine’s fuel consumption.

• Performance analysis with different types of jet fuel.

• Optimal aircraft selection for a certain route in terms of fuel consumption.

• Optimal engine selection for a certain aircraft type and route in terms of fuel consumption.

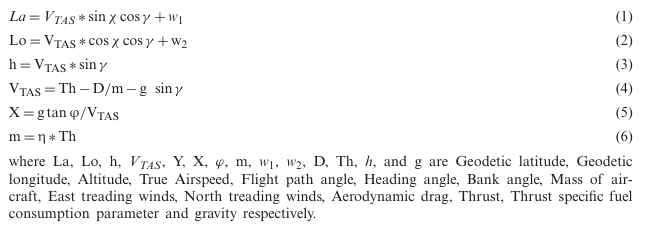
In this project, we focus on the first application, that is, we calculate the pollutant emissions by means of the closed-form formula of the aircraft’s fuel flow rate. Such emissions, unlike here, are usually obtained under the assumption of a constant value of the fuel flow rate.

## 1.3 Objective:

The objective of this project is to develop an efficient algorithm for four-dimensional trajectory planning (4D-TP) that optimizes fuel utilization and mitigates the challenges of airspace congestion in the global airline industry. This algorithm will consider various parameters such as air traffic, political airspace, airport capacity, weather data, and aircraft performance. Additionally, the project aims to explore the impact of Flexible Use of Airspace (FUA) on flight efficiency and scrutinize the availability and utilization of conditional routes (CDR) in Europe. The project seeks to enhance flight efficiency through innovative approaches and provide insights into the complex dynamics of air flight.

## 1.4 Flight Dynamics:

An aircraft needs to follow an Aircraft Dynamic Model (ADM). ADM enlists three degrees of freedom point mass model (PMM) with variable mass. PMM represents all the intricacies of an aircraft movement as shown in Equations. (1) – (6).



## 1.5 Path Constraints:

A flight needs to conform to certain path constraints which arise due to military procedures and other socio-political constraints. There are specific no-fly zones declared globally. Such zones act as deterrent in fixing the optimal path. This deterrence is considered as a constraint in 4D-TP planning.

# 1.6 Problem Statement:

The physical system under consideration is akin to a modern jet engine aircraft during the cruising flight phase. The focus is on analysing fuel consumption for such a physical system. To achieve this, the fuel consumption relationship is combined with the equations of motion and the aerodynamic expressions of lift, drag, and drag polar of the aircraft during the cruising flight phase.

These equations can be considered under the following flight configurations:

* Cruise at constant altitude and Mach number.
* Cruise at constant altitude and lift coefficient.
* Cruise at constant Mach number and lift coefficient.

In this paper, we propose a mathematical model for the first configuration, that is, cruise at constant altitude and Mach number. The following assumptions are made to obtain the mathematical model:

* The aircraft is considered a variable-mass system: fuel is being consumed over time, and weight varies consequently.
* Fuel consumption is only considered for the aircraft’s engines and under ideal conditions, i.e., engines consume equal fuel quantity, and their degradation effects are not considered.
* Static atmosphere and ideal gas conditions enable thermodynamic parameters such as pressure, temperature, and air density to be expressed only as a function of altitude.

Regarding aircraft flight mechanics:

* The aircraft is considered as a physical system that follows a rectilinear trajectory contained in a horizontal plane, meaning that its velocity vector remains constant both in magnitude and direction.
* A vertical mass symmetry plane exists along the longitudinal axis, and all the interacting forces are contained in the same plane, including the aircraft’s velocity vector.
* Wind effects are not considered.

Regarding the aircraft performance parameters:

* The thrust-specific fuel consumption (TSFC) is considered a constant parameter since the flight configuration studied implies constant altitude and Mach number, and the parabolic drag polar approach is employed.

This approach allows for a more nuanced understanding of fuel consumption during flight, contributing to more efficient and environmentally friendly aviation practices

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# 1.7 Background of the project:

Here is a conceivable way to make the text more readable and understandable:

This section gives an overview of previous research and relevant information for evaluating how efficient airport arrivals are.

## 1.7.1 Previous Research:

EUROCONTROL has a method to measure how efficient flights are when they climb and descend. They also checked how well air traffic management works in Europe in 2018, and looked at how punctual and efficient flights were at the top 30 European airports, including Stockholm Arlanda. They also have online data sources that anyone can use to check their results.

Some researchers used a formula to estimate how much extra fuel is wasted when flights are not efficient, mostly for the part of the flight that is between airports. We use a similar method to estimate the extra fuel for the part of the flight that is near the airport.

Other researchers measured how much fuel is used in various parts of the airport area, and how much of it is due to air traffic management delays or inefficiencies. They also compared how much fuel can be saved by using Continuous Descent Operations (CDO), which means flying down smoothly without leveling off. They found that CDO can save 25-40% of fuel. Correia did a detailed analysis of how efficient and how much fuel was used at Lisbon Airport for four years, and compared it to other European airports, including Stockholm Arlanda, for one year.

Many researchers have also tried to find out what causes airport delays. Some of the early studies said that weather changes are a big reason for delays. Another reason is that air traffic management cannot handle the increasing number of flights.

This research can help us to study how other factors, such as air traffic management automation or different weather conditions, affect the delays and the extra fuel at airports

## 1.7.2 Vertical Flight Efficiency:

In this paper, we focus on the analysis of vertical flight efficiency (VFE) within the TMA, as it is a critical phase of flight that affects the overall flight efficiency and the airport capacity. VFE is measured by the level-off during descent KPI, which quantifies the deviation from the ideal CDO.

To calculate the VFE KPI, we need to identify the level segments during the descent phase of the flight trajectory. We follow the techniques proposed by EUROCONTROL in, with some adaptations to suit our data and objectives. We use the data from the ICAO’s Global Air Navigation Plan (GANP), which provides the flight trajectory data in four dimensions: latitude, longitude, altitude, and time (4D-T).

We first identify the point of entry to the TMA for each flight and use it as the starting point for the VFE calculation. The point of entry is determined by the intersection of the flight trajectory and the TMA boundary, which is defined by the ICAO’s regional air navigation plan (ANP). We then detect the level segments by applying a threshold of 300 feet per minute for the vertical speed, as suggested by EUROCONTROL. A level segment is considered a segment where the aircraft flies at a vertical speed below this threshold for at least 30 seconds. This duration is based on the recommendation of the Continuous Climb/Descent Operations (CCO/CDO) Task Force, which is a group of air traffic management (ATM) stakeholders that established general definitions for measuring CCO and CDO in Europe. The task force suggested that a single level segment of up to 30 seconds be allowed in the CDO measurement, as it may not significantly affect flight efficiency. Therefore, we exclude the level segments that are shorter than 30 seconds from the VFE calculation. For example, if a flight has a level segment of 45 seconds before intercepting the glide slope, we only count 15 seconds of level flight for the VFE KPI. Table II shows the indicators that we use to calculate the VFE KPI.

The pressure ratio and temperature ratio, along with the speed of sound at Mean Sea Level (MSL) in standard atmosphere (ae), the fuel's lower heating value (LHV from the Propulsive Forces Model (PFM)), and the fuel coefficient (CF), which depends on thrust for non-idle ratings, are all used in the calculation of fuel consumption. Each aircraft model is accompanied by an XML file provided by BADA, containing the corresponding aircraft performance data. This includes the coefficients used to compute the thrust coefficient CT in the thrust equation. With these equations and XML files, we can compute the fuel consumption of a trajectory. The process involves the following steps:

• Thrust Computation: If the aircraft is climbing, the maximum climb rating is selected and the corresponding thrust formula is applied based on the engine type. If the aircraft is descending, an idle rating is assumed. During level-offs, the total-energy model is used to compute the aircraft thrust (with drag).

• Fuel Consumption Computation: For non-idle ratings, the previously computed thrust is used to obtain the fuel coefficient CF. For descents, an idle rating is assumed for all aircraft.

To generate the optimum trajectories, five input parameters are used: aircraft model, cruise altitude, distance to go (i.e., the distance remaining to the metering fix by following a given route), speed (i.e., the true airspeed of the aircraft in cruise), and the cost index. Moreover, we use the aircraft performance model from EUROCONTROL'S BADA v4. In the case the aircraft model does not correspond to any of the BADA models, a comparable aircraft in terms of performance and dimensions is used

# 1.8 RESULTS:

This section presents the results of the flight efficiency evaluation for arrivals at Stockholm Arlanda airport during 2018.

## 1.8.1 Data:

We use two independent databases that provide air traffic data: the Demand Data Repository (DDR2) hosted by EUROCONTROL and the Historical Database of the Opensky Network, a crowd-sourced ground sensor network collecting air traffic data from transponder signals that are continuously transmitted by aircraft.

EUROCONTROL offers data in SO6 format that is delimiter-separated values files which store flight trajectories (the lists of waypoints containing aircraft position, barometric altitude, and identity). DDR2 has two types of these files: SO6m1 and SO6m3. The first one provides the last submitted flight plans, while the second one consists of the actual trajectories.

We obtain flight plans from the SO6m1 DDR2 files, but for the historical flight trajectories, we use both DDR2 (SO6m3 file format) and the Historical Database of the Opensky Network.

Opensky supports two types of data: state vectors and tracks. The aircraft state vector is a summary of all tracking information at a certain point in time. This format can provide precise information but is very memory-consuming and for that reason not suitable for analysis of the full end-to-end trajectories. Opensky tracks do not contain all information about the flights the database keeps, but rather show the aircraft’s general movement pattern as a list of waypoints, like EUROCONTROL’S DDR2; however, the choice of waypoints in Opensky and DDR2 does not match. Opensky data is available to third parties through online databases and APIs.

To estimate the impact of vertical and horizontal flight inefficiencies on the fuel waste we use BADA v4.

## 1.8.2 Data analysis:

Next, we compare vertical flight profiles obtained from DDRm3 data and Opensky data. An example of a vertical flight profile according to the Opensky and DDRm3 data is presented in Figure 2. The Opensky states data is perfectly accurate as it provides altitudes for each second. Calculations based on such dense data are very memory-consuming; still, in the end, we used Opensky states to calculate VFE inside TMA, as it only represents a short portion of the total flight.

We use the techniques proposed by EUROCONTROL except for the calculation starting point. We find the point of the trajectory at which the aircraft enters the TMA and use it as a starting point of the trajectory instead of the top of the descent. The results are summarized in Table IV (for the notations, please, refer to Table II above), and illustrated in Figure 2.

We compare the actual trajectories of the Arlanda arrivals (from origin to destination) with the corresponding flight plans in terms of fuel consumption. Two data sources are used: DDRm1 files correspond to the traffic flight plans, while DDRm3 correspond to the trajectories flown. We compare fuel consumption for all the trajectories from the m1 and m3 files.

Figure 3 shows the difference in fuel consumption (in percents) between m1 and m3 trajectories. We observed that computations with m1 data (flight plans) result in a slightly higher fuel consumption than the same calculations with m3 (flown), in most of the cases. This effect can be explained by the shortcuts that controllers tend to give to the flights which decrease the total distance flown and, in most cases, the fuel consumption as well.

Another example of the extra fuel consumption due to flying inefficient descent trajectories is shown in Figure 4, where fuel consumption for actual trajectories (DDR2m3) and CDO (computed with the trajectory optimization technique described), are shown for the same callsign AFL2386 during the month of December 2018.

The total values of 8277 kg (about the weight of a school bus) and 3773 kg (about 8318.03 pounds) of fuel are estimated for actual trajectories and CDO respectively during this month, which demonstrates an improvement of around 120% in terms of efficiency when flying CDO. However, it is not representative enough to analyze only what happens with the same flight over the whole month. To understand the result better, we looked at the fuel consumption per day. As can be observed in Figure 2, there are two days (more specifically 03/12 and 06/12), where the fuel consumption of the actual trajectories is exceedingly high. This is caused by long-level segments at low altitudes, which are avoided with CDO. And that is the reason this high reduction in fuel burn is obtained. During the rest of the days, however, the additional fuel burn remains in the range of 30%-70%.

VFE INDICATORS AND KPIS CALCULATED FOR THE YEAR 2018 BY MONTHS:

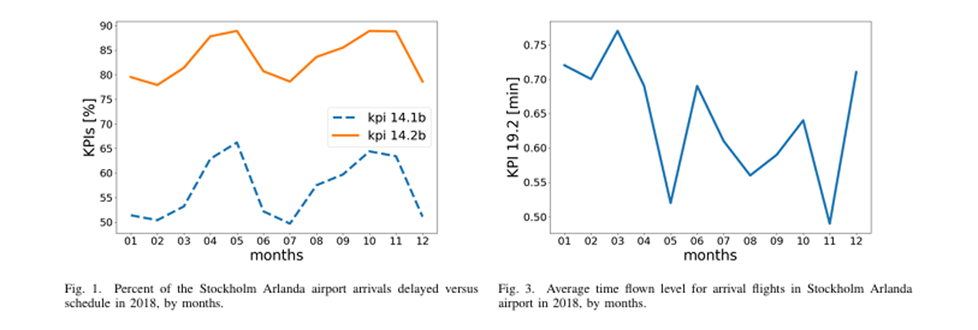
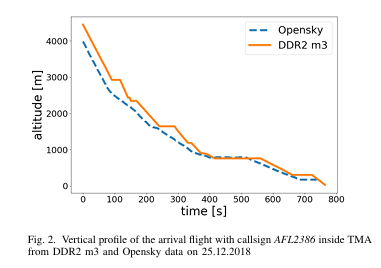


Figure 2

Figure 1

COMPARISON OF AIRPORT VFE STATISTICS FOR 2017 AND 2018:

A graph with numbers and lines

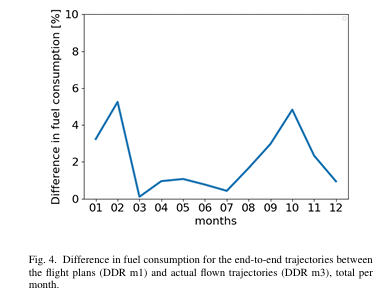
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Figure 3

Figure 4

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# 1.9 Conclusions and future work:

In this work, we quantified the impact of the deviations from the flight plans in terms of fuel burn and calculated how much extra fuel is wasted due to vertical flight inefficiency within Stockholm TMA.

We investigated Opensky Network data comparing it to EUROCONTROL’s DDR2. Although Opensky has certain problems with data integrity and additional methods to detect and filter the diverse kinds of integrity breaches are needed, it provides the data of high density in form of state vectors with accurate three-dimensional aircraft positions along with precise timestamps for the signal arrivals. A drawback of the Opensky data is the lack of a flight identifier, which is critical for flight identification, and aircraft type information, needed for the calculation of fuel consumption. We resolved this problem by merging the data with DDR flight plans (SO6 m1 files).

Overall, we recommend Opensky state vectors as a valuable data source for research with high accuracy demand.

The results of this work create a base for future research; for instance, for the studies of the impact of weather on the flight trajectories (i.e., using the statistics obtained in this work), or for studies focusing on the correlation between the different weather conditions (wind, convective weather, visibility), the arrival delays and associated fuel waste.

# 2. MATHEMATICAL MODEL FOR FUEL CONSUMPTION

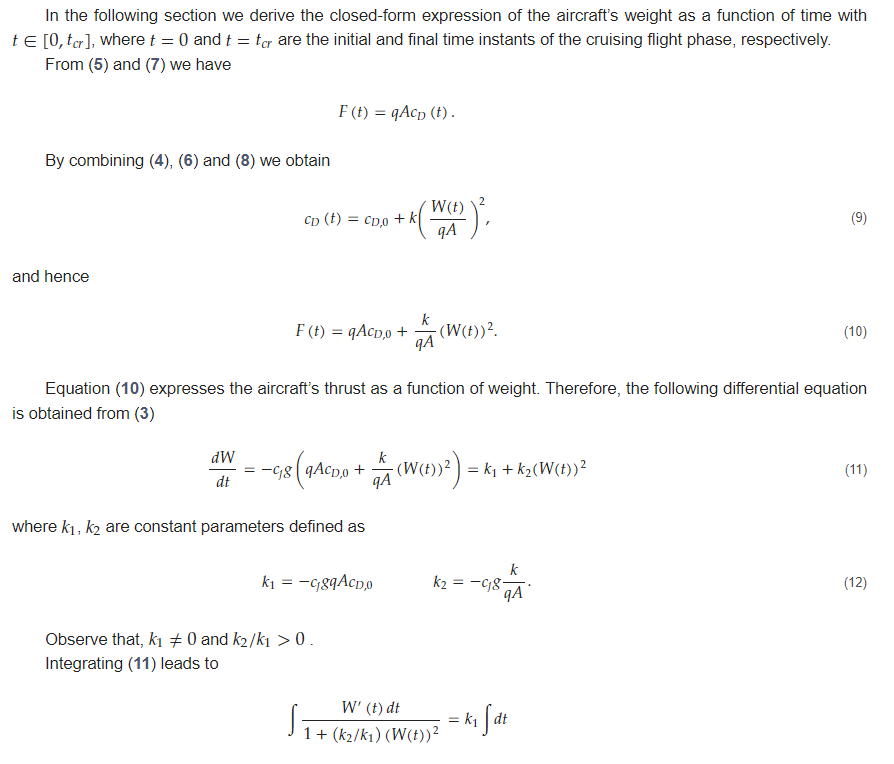
## 2.1 Introduction:

For our mathematical model to visualize the fuel consumption of a standard commercial aircraft, we took the Boeing Airbus A320. We took the drag coefficient for an altitude of approximately 10,000 m (about the cruising altitude of a commercial jet), the surface area of the plane as 122.6 m, and air density 0.366 kg/m³. From here, we considered the velocity as 230 m (about twice the height of the Statue of Liberty)/s, and the mass of the aircraft as 72,000 tons.

2.2 Differential Equation and Derivation:

A paper with text and numbers

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## 2.3 Code:

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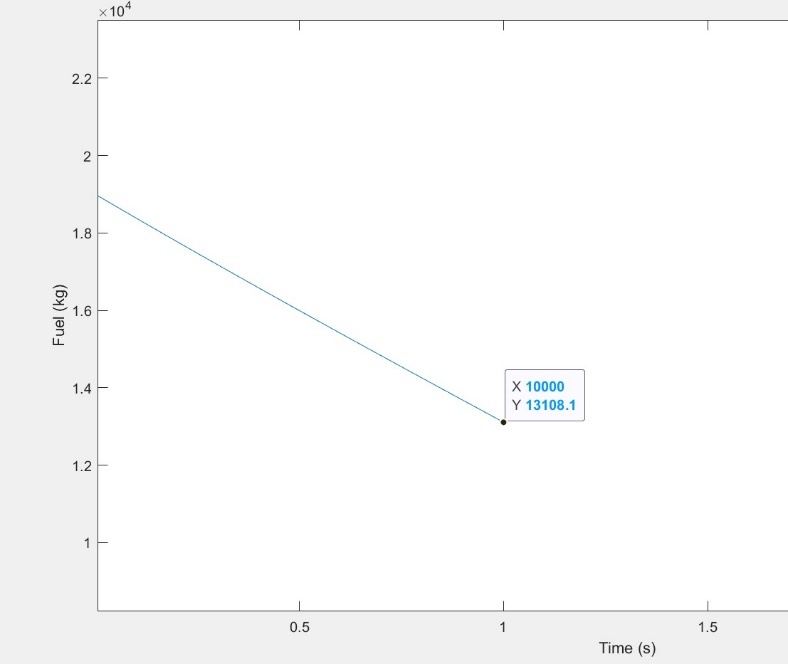
## 2.4 Graphs:

A graph with a line and a point

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Mass 72000, Velocity 200

A graph with a line

Description automatically generated

Mass 72000, Velocity 230

In these graphs, all the values except for the velocities have been kept constant. The mass is 72,000 kg and the velocity values are 200 m/s, 230 m/s, and 300 m/s, where 230 m/s was our initial value. As we can see from the graphs, the change in velocity has a dramatic effect on the fuel values after 10,000 seconds.

Mass 72000, Velocity 300

## 2.4 Graphs:

A graph with a line and a point

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Mass 65000, Velocity 200

A graph with a line

Description automatically generated

Mass 65000, Velocity 230

In these graphs, all the values except for the velocities have been kept constant. The mass is 65,000 kg and the velocity values are 200 m/s, 230 m/s, and 300 m/s, where 230 m/s was our initial value. As we can see from the graphs, the change in velocity has a dramatic effect on the fuel values after 10,000 seconds. From these two sets of graphs, we can start to form an assumption that the change in velocity significantly affects the rate of fuel consumption and that the change in mass doesn’t significantly affect the rate of fuel consumption

Mass 65000, Velocity 300

## 2.4 Graphs:

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Mass 80000, Velocity 200

## 

Mass 80000, Velocity 230

A graph with a line and numbers

Description automatically generatedIn these graphs, all the values except for the velocities have been kept constant. The mass is 65,000 kg and the velocity values are 200 m/s, 230 m/s, and 300 m/s, where 230 m/s was our initial value. As we can see from the graphs, the change in velocity has a dramatic effect on the fuel values after 10,000 seconds. From these three sets of graphs, our assumption that the change in velocity significantly affects the rate of fuel consumption and that the change in mass doesn’t significantly affect the rate of fuel consumption is proving to seem true.

Mass 80000, Velocity 300

# 3.FUTURE AIRCRAFT CONCEPT

## *We have selected a research paper from December 2017, that contains the results of multiple studies performed. The reason for selecting a relatively out of date paper, is that the field of aviation hasn’t had much mainstream innovation regarding alternative fuels, and implementation and experimentation of other types of systems, such as electric ones.*

## 3.1 Introduction:

In the contemporary landscape of aviation, the significance of aircraft efficiency has become increasingly pronounced, spurred by the escalating costs of jet fuel. Recent years have witnessed a comprehensive exploration of various aircraft concepts, encompassing diverse fuel types and even the integration of electricity. Among these alternatives, hydrogen stands out as the most conspicuous fuel type. This report is based on a research paper that employs a multi-criterion scoring method to compare traditional aircraft, more electric aircraft, and liquid hydrogen-fueled aircraft. Notably, a future-oriented proposal emerges, advocating for a novel aircraft concept tailored for long-distance flights.

This innovative approach amalgamates the more electric concept with the utilization of liquid hydrogen, demonstrating superior efficiency, cost-effectiveness, and reduced environmental impact in comparison to traditional aircraft. As the aviation sector grapples with the imperative to enhance energy efficiency and mitigate harmful environmental effects, this research asserts that embracing such forward-thinking concepts is an unavoidable choice for shaping the future of aviation.

## 3.2 Aircraft Efficiency and Energy Consumption:

The nexus between the annual surge in air travel and the parallel increase in energy consumption and environmental impacts is undeniable. As the aviation industry expands, so do the associated challenges of fuel consumption and emissions. Long-range transportation takes precedence over other ranges due to its higher fuel consumption and cost implications. The imperative to address energy consumption is underscored by the significance of energy efficiency in aircraft across all modes of transportation.

Energy efficiency in aviation is synonymous with fuel efficiency, a critical consideration given the escalating costs of jet fuel. Approximately 3% of the total worldwide fossil fuel usage corresponds to fuel consumption in aviation, leading to 3% of total carbon dioxide (CO2) emissions attributed to aircraft. To combat this, a two-pronged approach is proposed: the development of new, more fuel-efficient aircraft and the modification of existing ones to adhere to sustainability goals.

## 3.3 Alternative Fuels and Aircraft Concepts:

The depletion of fossil fuels in the coming decades necessitates a proactive approach in seeking alternative fuels for aviation. This involves a meticulous examination of the costs, efficiencies, and potential hazards associated with various fuel types. The crux of the matter lies in improving fuel efficiency by evolving aircraft systems and diversifying fuel types. The paramount goal is to reduce fuel consumption, a crucial aim for commercial aircraft, with the understanding that the importance of efficiency is directly proportional to the range of transportation.

To streamline these efforts, the Advisory Council for Aeronautical Research in Europe (ACARE) was established with the ambitious aim of reducing fuel consumption and CO2 emissions by 75%, NOx emissions by 90%, and perceived noise by 65%. This comprehensive agenda encompasses not only the reduction of emissions during flight but also emission-free movements during aircraft taxiing, and the establishment of centers focusing on sustainable alternative fuels.

## 3.4 More Electric Aircraft (MEA) and Hydrogen as Fuels:

MEA emerges as a promising paradigm shift in the quest for fuel efficiency. The MEA system seeks to replace pneumatic, mechanical, and hydraulic systems with electrical ones, ushering in benefits that extend beyond traditional aircraft. Comparisons between MEA and traditional aircraft showcase the former's superior efficiency, lower fuel consumption, and reduced environmental impact. The Boeing 787-8 Dreamliner stands as a prime example, with a 20% reduction in fuel consumption, lower CO2 emissions, and a smaller noise footprint.

Hydrogen, recognized as the most abundant element in nature, takes center stage as a formidable alternative fuel. Despite its abundance, hydrogen does not exist freely in nature and must be produced through methods like gasification and electrolysis. The integration of hydrogen as a fuel source in aircraft has gained traction in recent years, driven by the need to reduce harmful emissions. Liquid hydrogen (LH2) emerges as a particularly promising alternative, especially for long-distance flights. Its advantage lies in its lightweight nature, a critical factor influencing maximum take-off weight. However, the adoption of hydrogen in aircraft necessitates ingenious technology and design, presenting a crucial challenge for future implementation.

## 3.5 Exploring Other Alternative Energy Sources:

Beyond MEA and hydrogen, other alternative energy sources are under investigation, including solar-powered aircraft, fuel-cell-powered aircraft, and biofuels. While solar-powered aircraft face technological constraints for long-range flights, fuel-cell technologies show promise but are currently limited to small aircraft with short ranges. The adoption of biofuels, although a potential solution for emissions reduction, faces challenges related to price differences and the requirement for blending with kerosene, making it less suitable for this study's focus.

## 3.6 Liquid Hydrogen: Challenges and Advantages:

Liquid hydrogen's potential as an alternative fuel is explored in-depth, acknowledging its benefits and challenges. Studies like the Cryoplane project assess the feasibility of LH2 as a fuel for aircraft, revealing a potential range of take-off gross weight changes based on transportation distance. Challenges related to storage, delivery, and refueling times are acknowledged, with the study indicating that the negative effects of LH2 tanks can be mitigated with longer transportation distances.

The advantages of using LH2 are manifold, with higher energy content per weight, increased efficiency for long-range transportation, and reduced direct operating costs. However, drawbacks, such as lower energy content per volume, higher production costs, and storage challenges, prompt a comprehensive evaluation of LH2 as a viable alternative to traditional fuels.

## 3.7 Economic Considerations and Environmental Impact:

The cost of LH2, a critical factor in its viability, is contingent on the production method. While LH2 can be derived from renewable energy resources, petroleum, electrolysis, coal, and natural gas, the choice of production method significantly influences initial investment costs and operating costs. The reduction of CO2 emission rates in LH2 production is a consideration, especially in the context of renewable energy-based production.

Comparisons between the efficiency of aircraft using hydrogen and kerosene highlight the economic and environmental advantages of LH2 for long-range transportation. While the efficiency of LH2 is currently smaller for short and medium-range flights, its potential for substantial benefits in long-range transportation, both in terms of cost and environmental impact, is evident.

## 3.8 Comparative Studies and the Unique Contribution of This Study:

The research delves into existing comparative studies in the literature, emphasizing that most comparisons focus on environmental effects by changing either the propulsion or the fuel type of aircraft separately. The unique contribution of this study lies in its holistic approach, aiming to identify the best future aircraft concept by suggesting changes to both fuel types and propulsion. ACARE performance criteria, H2O emissions, and fuel prices are considered concurrently, providing a comprehensive evaluation framework.

Additionally, the study expands its evaluation beyond the cruise phase to include taxi operations, offering a more nuanced understanding of energy efficiency and environmental effects throughout the entire flight. The contributions of the paper are threefold: evaluating three selected aircraft concepts simultaneously, utilizing a multi-criterion scoring method to choose the best available aircraft concept, and proposing a future aircraft concept aligned with ACARE's targets, encompassing both cruise and taxi stages.

## 3.9 Historical Perspective and Evolution of Aircraft:

Before delving into the intricacies of alternative fuels and advanced aircraft concepts, it is essential to appreciate the historical evolution of aviation. Sir George Cayley's fundamental concept of traditional airplanes, articulated in 1799, laid the groundwork for fixed-wing aircraft with propulsion and control systems. The Wright brothers, pioneers in aviation, not only built but successfully flew the first controlled aircraft in 1903. The first commercial flight in 1952 marked a transformative moment in aviation history.

Traditional aircraft, primarily powered by kerosene, have been the stalwarts of aviation. However, their derivative nature from crude oil raises environmental concerns. Kerosene combustion not only emits nitrogen oxides (NOx) and water vapor (H2O) but also releases carbon dioxide (CO2), contributing to the industry's environmental footprint. The study selects the Boeing 747-400 as the representative traditional aircraft for its fuel efficiency and noise data, crucial parameters in the comparative analysis.

## 3.10 Comparative Analysis and Environmental Impact:

The study undertakes a comprehensive comparative analysis, considering factors such as fuel efficiency, noise levels, and emissions for traditional, MEA, and LH2-fueled aircraft. The incorporation of ACARE performance criteria, H2O emissions, and fuel prices into the multi-criteria scoring method enhances the depth and scope of the evaluation.

Noteworthy is the study's expansion beyond the cruise phase to encompass taxi operations, providing a holistic assessment of energy efficiency and environmental effects throughout a flight. The proposed future aircraft concept is subjected to scrutiny, considering its performance during both the cruise and taxi stages. This nuanced approach contributes to a more robust understanding of the potential environmental impact and energy efficiency of various aircraft concepts.

## 3.11 Economic Considerations of Liquid Hydrogen:

Economic considerations play a pivotal role in determining the viability of LH2 as an alternative fuel. The cost of LH2 is contingent on the production method, ranging from renewable energy-based to natural gas-based approaches. The study underscores that the cost of LH2, being three times higher than kerosene prices, poses a challenge for short and medium-range flights. However, for long-range transportation, the advantages in terms of cost, environmental impact, and efficiency become evident.

The study acknowledges the dynamic nature of LH2's economic viability, dependent on factors such as production methods, initial investment costs, and operating costs. The emphasis on renewable energy-based production underscores the potential for reducing CO2 emission rates in the production process.

## 3.12 Hydrogen vs. Kerosene:

Comparisons between hydrogen and kerosene as fuel sources reveal a nuanced landscape. While hydrogen offers benefits such as higher energy content per weight, potentially more efficient flights for long-range transportation, and reduced take-off gross weight, challenges such as lower energy content per volume, higher production costs, and storage complexities must be addressed.

The study highlights the efficiency trade-off between hydrogen and kerosene for short and medium-range flights, emphasizing that hydrogen's advantages become more pronounced for long-range transportation. Zero CO2 emissions and reduced NOx emissions position LH2 as a viable alternative, especially considering the environmental concerns associated with traditional kerosene usage.

## 3.13 Conclusion and Future Directions:

In summary, this research paper has successfully navigated the intricate landscape of aircraft efficiency and alternative fuels, highlighting the pressing need to address environmental challenges within the aviation industry. The comprehensive comparative analysis, encompassing traditional, More Electric Aircraft (MEA), and liquid hydrogen (LH2)-fueled aircraft, and incorporating ACARE performance criteria and environmental considerations, has yielded invaluable insights into the pursuit of sustainable aviation.

The proposed future aircraft concept, which integrates the more electric and liquid hydrogen-fueled paradigms, emerges as a promising trajectory. The expanded evaluation, now including taxi operations, provides a nuanced understanding of energy efficiency throughout the entire flight. The examination of economic considerations for LH2, contingent on production methods and costs, emphasizes the dynamic nature of alternative fuel viability.

As the aviation industry endeavors to meet the ambitious targets set by ACARE for 2050, this research contributes significantly to the ongoing discourse by advocating for a holistic approach. Looking ahead, future research endeavors should delve deeper into the technological advancements necessary for LH2 adoption, specifically addressing challenges in storage, refueling, and infrastructure. Furthermore, the exploration of alternative energy sources, including solar, fuel-cell, and biofuels, remains a promising avenue for enhancing aviation sustainability.

In essence, achieving sustainable skies demands a collaborative effort from researchers, industry stakeholders, and policymakers. This research paper, acting as a guiding compass, points the way toward a future where aircraft efficiency and alternative fuels harmonize to create a greener and more sustainable aviation landscape. Considering the information gleaned from the multi-criteria scoring method, it becomes evident that the selected aircraft concepts—MEA and LH2-fueled aircraft—outperform traditional aircraft in terms of scoring values. This underscores the potential of these innovative concepts to lead the aviation industry toward a more sustainable and environmentally conscious future.

1. References:

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