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ALBATROSS

THE MOST ENERGY EFFICIENT FLYING BIRD

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Abstract

Air travel is one of the fastest and most progressive branches of the transportation sector. It is exposed to large visibility and strong European and worldwide pressure on sustainability. ALBATROSS is an initiative of major European aviation stakeholders to demonstrate how the technical and operational innovations delivered by SESAR in the past years can further reduce the environmental footprint of aviation towards a more sustainable mode of transportation.

This document describes “the methodologic approach towards green flights” as defined by project ALBATROSS. The scope of the methodology is to create a structured approach for flight operations optimization and ATM improvements in order to help those users that would face the problem of flight optimization on a given new city pair. The idea is to create a set of reference examples and lessons learnt that could be used by future users as guidelines to initiate similar initiatives on any other route in Europe or anywhere else in the world.

To achieve the objective this methodology starts introducing the overall approach of the project, based on extended coordination, improved dynamicity of the constraints, support by new kind of analytic data based tools and the enhancement of the ground segment operations. Afterwards, it gives a general overview of the existing processes and operations, defining then what is supposed to become the reference for Performance and Benefits assessment of the different solutions, the Optimum Flight (OF). The second part of the document focuses then on the existing ATM (and not) constraints affecting the most efficient flight and it gives some recommendations and concrete examples of applications of workaround to counteract those.

This methodology clearly paves the way for a pragmatic and systematic approach that could help stakeholders move from tactical improvements to strategic ones. Improved predictability, enhanced dynamicity and systemized analytic approach were the key pillars of the ALBATROSS proposed approach. In line with these concepts, this methodology aims at providing the ATM community with concrete guidelines and examples to foster, even more, the application of this technique.

Table of Contents

List of Tables

List of Figures

1 Executive Summary

The purpose of ALBATROSS methodologic approach is twofold:

1. Specify requirements providing the most CO2 optimum flight trajectory from origin to destination without any imposed ATM constrains.
2. Provide ALBATROSS technique to remove or relieve ATM constrains counteracting the most CO2 optimum flight trajectory.

Combining this, the methodology can serve as a reference handbook for aviation stakeholders aiming to introduce prompt airspace environmental improvements, specifically targeting a reduction in CO2 emissions.

The aim of ALBATROSS approach is to put focus on the short-term possibilities to swiftly make the current operational environment more CO2 efficient, by introducing changes that are ready to deploy in specific local airspace and under specific circumstances. In ALBATROSS, this is concluded as many small but tangible improvements executed in daily operation. This may seem trivial and obvious, but it is ALBATROSS methodology clear understanding there are many inefficiencies in today's airspace possible to solve without exhaustive effort and using technology that is readily available, thereby decreasing CO2 emissions in small increments, but altogether making a difference.

The improvements can be derived from more advanced solutions (for example, SESAR catalogue of Solutions) or relatively simple and locally developed improvements. In either case, they are operationally oriented possible to be utilized on short-term basis.

ALBATROSS methodology is not a projection of future technologies and ATM systems or a new concept of operations. It is as statement of Best Practices and Lessons Learnt from ALBATROSS demonstration project lifetime with focus on operational improvements possible to implement in today's operation.

Initial conclusions from the ALBATROSS activities:

1. The shortest ground distance (2D) trajectory is not a sufficient metric when defining the Optimum Flight (OF). The vertical profile is fundamental in evaluating the efficiency of a flight, and the horizontal profile should be evaluated in terms of "equivalent still-air distance" (that considers the effect of winds distribution).
2. ALBATROSS exercises have, in several cases, demonstrated that ATM constraints can be managed dynamically, and be relaxed during time periods when they are not necessary.
3. The albatross exercises have demonstrated that existing technology allows the dynamic management of ATM constraints and provides adequate notification to airspace users to consider any ATM improvements offered to improve the trajectories at planning level.
4. The ALBATROSS exercises have demonstrated as well that existing technology allows for an ad-hoc optimization of the flight trajectory (specific to the tactical conditions or aircraft/flight characteristics), while still complying with the necessity for the ANSPs to be able to predict the behavior of the flight(s).

Note:

For consistency with ALBATROSS project in general and for transversal understanding and comparison with all specific WPs, the document uses CO2 emissions as the recognised KPI to identify possible constrains, solutions and overall airspace optimisation. CO2 emissions is also the reference indicator used by states, authorities, and general public outlining greenhouse emissions in general.

In practice, however, CO2 emissions are very difficult – or even impossible – to measure on airborne aircraft. WP2 (and ALBATROSS project in general) therefore uses fuel consumption as the quantitively indicator to measure relative differences (i.e., before and after flights demonstrating improvements) and converts the fuel burn to CO2 emissions using factor 3.15, as recognised by EU Emission Trading Scheme (ETS).

2 Introduction

2.1 Purpose of the document

WP2 Deliverable 2.4 (hereafter named “Methodologic Approach towards Green Flights”) is intended to server the following purpose(s):

1. Provide a reference document – handbook – for aviation stakeholders’ targeting to introduce swift operational improvements aiming to reduce CO2 emissions.
2. Provide the so called “ALBATROSS Technique” which not only includes the technical aspects of finding improvements for a given or set of flights, but also provides best practices in the non-technical domain (e.g., stakeholder collaboration, teamwork etc.).
3. Try to achieve the most coherent and comprehensive definition of a trajectory for a generic flight from A to B, eliminating all sub-optimal constraints not directly linked to the aircraft envelope, flight crew procedures and/or specific safety regulations (where necessary).
4. Endeavour to identify constraints counteracting the optimal trajectory, whether they are ATM or non-ATM constraints, or a combination of both.
5. Endeavour to identify improvements or solutions overcoming identified constraints. The improvements or solutions should be directly, or partly, linked to the SESAR Catalogue of Solutions but they may also have been locally developed outside SESAR scope. In either case, the prerequisite for the methodology is that the solution is mature enough to be implemented in a foreseeable future, i.e., it must not be solutions in the early stages of R&D.

2.2 Scope

The scope of the methodology is to create a structured approach for flight operations optimization and ATM improvements in order to help those users that would face the problem of flight optimization on a given new city pair. The idea is to create a set of reference examples and lessons learnt that could be used by future users as guidelines to initiate similar initiatives on any other route in Europe or anywhere else in the world.

The most complicated part in the process of a “Gate to Gate” operations optimization, is to effectively evaluate the benefits of the proposed improvements. It is important to assure a harmonized and agreed reference model to follow in order to make consistent calculations and be able to compare two different solutions when it comes to CO2 emissions reduction. That is the reason why the ALBATROSS project proposed the “Optimum Flight” as a theoretical ideal reference; by doing this, the potential gain, if the flight would happen in an unconstrained idealistic world, becomes the basis to assess any other improvement both at technological or operational level. This reference is then used as model towards which to strive for those “Baseline flights” that will be enhanced by any ATM operational or technological solution. Also, the Optimum Flight would work as a metrics to evaluate how inevitable constraints (i.e. for separation or safety) are affecting the efficiency of the flight in normal operations.

This methodology clearly paves the way for a pragmatic and systematic approach that could help stakeholders move from tactical improvements to strategic ones. Improved predictability, enhanced dynamicity and systemized analytic approach were the key pillars of the ALBATROSS proposed approach. In line with these concepts, this methodology aims at providing the ATM community with concrete guidelines and examples to foster, even more, the application of this technique.

2.3 Intended readership

The intended readership for this document is the ATM Community at large. The project participants, the SESAR Joint Undertaking and any other ATM stakeholder that might be interested to understand, up to a significant level of detail, the methodologic approach created by the ALBATROSS project to optimize flight operations from a “Gate to Gate” holistic point of view.

More particularly, the member, affiliate or associate having access right to this document and taking part in SESAR3 DSD HERON or to other granted projects like CICONIA or CONCERTO that also deals with in flight emissions optimization.

2.4 Structure of the document

Chapter 1 and 2 are template chapters outlining general information about the document including Executive Summary (ES).

Chapter 3 briefly describes the project's approach, by introducing the context, the focus and the set of available tools and procedures that represented the starting point of the ALBATROSS developed methodology

Chapter 4 gives a snapshot of today's operation for all stakeholders (airline, ANSPs, airport and Network Manager) with the quest to compile these snapshots into a single and comprehensible all-stakeholder timeline.

Chapter 5 identifies Optimum Flight (OF) requirements, constrains and possible solutions including all associated justifications focusing **only** on reducing CO2 emissions, i.e., less fuel usage.

Chapter 6 gives an overview on the different existing ATM (and not ATM) constraints that degrade the efficiency of a flight.

Chapter 7 will give a short description on the methodology usage for WP3 including demonstration feedback and concrete examples.

2.5 Glossary of terms

Term	Definition	Source of the definition
4DTM	"4D Trajectory Management" is the name of SESAR Project PJ18 during the SESAR2020 wave 1, that hosted in particular the Solution 18-06 focussed to the enhancement of Trajectory Prediction computation based on information extracted from the ADS-C flight data (notably EPP).	Summary based on PJ18 Final Project Report
ADS-C	A means by which the terms of an ADS-C agreement will be exchanged between the ground system and the aircraft, via a data link, specifying under what conditions ADS-C reports would be initiated, and what data would be contained in the reports. ADS-C content includes among others: position, altitude, speed, managed modes, estimation to waypoint, elements of navigational intent and meteorological…	SESAR Concept of Operations Step 1, Edition 2015
Authorization	the security mechanism to determine access levels or user/client privileges related to system resources including files, services, computer programs, data and application features	
EPP	Specifies the aircraft predicted trajectory up to 128 waypoints including for each waypoint, Latitude, Longitude and when available, Fix, Level, ETA, Airspeed, Vertical type(s), Lateral type(s), Level constraint, Time constraint, Speed constraint. When available, provides the relevant data for the trajectory as Current gross mass and EPP trajectory intent status. It indicates the date and time these values were computed.	Baseline 2 ATS Data Communications Standard: ED-228 march 2014 edition
CWP	Controller Working Position, i.e.: the operator (ATCO/AFISO) work station including necessary ATS systems.	06.09.03 – D09 – Contingency TWR trial 1 validation report
FMS	An integrated system, consisting of an airborne sensor, receiver and computer with both navigation and aircraft performance databases, which provides performance and RNAV guidance to a display and automatic flight control system.	ICAO, Technical Committee of the Regional Safety Oversight Cooperation System, ADVISORY CIRCULAR, AC : 91-008

Table 1: Glossary of terms

List of acronyms

Acronym	Definition
ACMS	Aircraft Condition Monitoring System
ACS	Area Control Surveillance
ADS-B	Automatic Dependent Surveillance–Broadcast
ADS-C	Automatic Dependent Surveillance–Contact
ANSP	Air Navigation Service Provider
ASM	Airspace management
ATM	Air Traffic Management
ATN	Aeronautical Telecommunication Network
ATN-B2	Aeronautical Telecommunication Network Base 2
ATCo	Air Traffic Controller, Air Traffic Control Officer
ATFCM	Air Traffic Flow and Capacity Management
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
ATS	Air Traffic Services
ATS-B2	Air Traffic Services Base 2
AU	Airspace User
CANSO	Civil Air Navigation Services Organization
CCO	Continuous Climb Operation
CDA	Continuous Descent Approach
CDO	Continuous Descent Operation
CP	Common Project
CPDLC	Controller–Pilot Data Link Communications
CWP	Controller Working Position
DAR	Digital ACMS Recorder Data
EASA	European Aviation Safety Agency
EC	European Commission
ECTL	Eurocontrol
EFB	Electronic Flight Bag
EPMB	Extended Project Management Board
EPP	Extended Projected Profile

ETA	Estimated Time of Arrival
EU	European Union
FDR	Flight Data Recording
FMS	Flight Management System
GRRT	Ground ReRouting Toll
H2020	HORIZON 2020 (research and innovation programme of the EU, 2014-2020)
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IP	Internet Protocol
IR	Industrial Research project
LNAS	Low Noise Augmentation System
MUAC	Maastricht Upper Area Control
OF	Optimum Flight
PEG	Programme Execution Guidance
PM	Project Manager (is used as synonym for SGA coordinator [SESAR] as well as for Action Coordinator [H2020; PPP Membership Agreement Appendix E] in this proposal)
PMB	Project Management Board
QAR	Quick Access Recorder
RAD	Routes Availability Document
RNP	AR Required navigation performance with Authorization Required
RNP	Required navigation performance
RRP	ReRouting Proposal
SESAR	Single European Sky ATM Research
SJU	SESAR Joint Undertaking
SPD	Single Programming Document
STAM	Short Term ATFCM Measures
TA	Transversal Action
TBO	Trajectory Based Operations
TMA	Terminal Manoeuvring Area
ToC	Top of Climb
ToD	Top of Descent
TRA	Temporary Restricted Area

TTO	Target Time of Overfly
VLD	Very Large Demonstration
WAN	Wide Area Network
WP	Work Package
xBAS	SBAS (Satellite Based Landing System) or GBAS (Ground based landing system)
xLS	Landing System (ILS, GLS or SLS)

Table 2: List of acronyms

3 The ALBATROSS Approach

3.1 General

The ALBATROSS project demonstrated several improvements that bring a reduction of CO2 emissions in the operational processes of aviation, particularly those involving ATM/ATC.

Carbon neutrality of aviation will come from (i) new more efficient aircraft and engine technology; (ii) the usage of alternative fuel; (iii) the optimization of operations. This third component is the main focus of ALBATROSS (although an activity dedicated to SAF has also been carried out). The carbon reduction contributed by optimized operational processes is estimated at 10-15% of the total reduction.

The approach that was successfully followed in the ALBATROSS demonstrations, carried out by different stakeholders in different locations, can be adapted to (any?) other operational contexts. The ambition of the present "Methodology" is to collect the key aspects underpinning the "ALBATROSS exercises" and distil them into a reference document – a handbook of sorts – for aviation stakeholders to reduce CO2 emissions. Most, if not all, of the applied improvements required relatively reasonable efforts and limited, progressive investment; they can therefore be considered "quick wins".

The "Smart innovation" showcased by ALBATROSS relies on:

- Concepts having sufficient maturity to quickly become ready for real operations and bring immediate benefit. SESAR has contributed to turn several "New enablers" from research concepts into deployable solutions;
- Selection of those mature concepts for which the local context is "ready", operationally and organizationally;
- Unitary improvements that may seem small, but accumulate into a significant benefit when applied to a large number of flights.

Going into more concrete detail, the operational principles applied in the ALBATROSS demonstrations are listed below. These reinforce one another, and constitute a framework that can be used to inspire local environmental improvement initiatives in the European airspace/aviation community at different scales.

At the end of this section concrete examples from the ALBATROSS demonstrations will further illustrate the method.

<u>Collaboration of all involved stakeholders, at the right scale</u>

<u>In the Strategic phase</u>: In order to identify which inefficiencies could be reduced, and how, in a given portion of airspace, the needs and constraints of all involved stakeholders must obviously be known. Processes of continuous improvement of the "ATM System", involving all concerned stakeholders, are

in place at many levels (NM steering and working groups; national aviation instances; CDM communities; industry associations; etc.) and they cover the range from daily operations to long term strategy.

But concrete opportunities for change seem to emerge more swiftly when working with the right balance of detailed local operational knowledge and vision of the available innovation possibilities.

In the Planning phase: Identification of ATM constrains and processes to allow their management in planning phase are key improvements to enhance the predictability of the traffic demand as well as to allow AUs to increase the effectiveness in the fuel management. Both of them, directly or indirectly, contribute to the reduction of CO2. Better fuel management is driven by the reception and processing in the planning phase of the information related to any ATM improvements available according to the pre-tactical CDM process conclusions. This information will enable the preparation and submission of FPLs addressing more efficient trajectories therefore a better fuel management. This will contribute to improve traffic predictability therefore to exploit ATM capacities, normally not used to cope with uncertainties of the traffic evolution. Better capacity means less ATM constrains (e.g. rerouting, level capping) to the traffic that can fly a better trajectory.

In the Execution phases: The increasing availability of Information sharing channels (ground-ground and air-ground) facilitates the involvement of all actors concerned in coordinated decision making. This allows the operational stakeholders to be aware of each other's "intentions and preferences", so that each flight is conducted in the most optimized way.

Dynamic Management of ATM constraints

Air Traffic Management (ATM) is the dynamic, integrated management of air traffic and airspace including air traffic services, airspace management and air traffic flow management - safely, economically and efficiently - through the provision of facilities and seamless services in collaboration with all parties and involving airborne and ground-based functions. (ICAO definition)

The general objective of ATM is to enable aircraft operators to meet their planned departure and arrival times and to adhere to their preferred flight profiles with the minimum constraints, without compromising agreed levels of safety.

Constraints can be of different nature. Some of them have a permanent nature (e.g. orography limiting optimum approach/departure), others are introduced (e.g. RAD restrictions) to enable States/FABs/ANSPs to maximise capacity and reduce complexity by defining traffic flow rules and flight planning facilitation options that prevent disruption to the organised system of major traffic flows through congested areas with due regard to Aircraft Operator requirements.

The objective of Albatross was to focus on those “ATM constraints” that allow the CDM process to move from "always sized for the worst case" to "dynamically adapting to the operational circumstances", when the reasons that require those constraints do not materialize in a constant way (as is often the case).

Depending on the specific cases, the dynamicity (in space and time) can be more or less fine-grained (ranging from one single waypoint to entire airspaces; and from a few hours per day to permanent restructuring).

It must be pointed out that the possibilities of improvement are very specific to local circumstances, depending on the local traffic patterns.

New CNS capabilities that are becoming commodity

The widening installed base of several new Communication, Navigation and Surveillance capabilities enable flights to operate in a more precise and predictable way, allowing more exact performance calculations/optimizations and a reduction of buffers.

Air-ground connectivity also facilitates information sharing, so that exact flight conditions are downlinked (both to ATC and AU backoffice) and advanced optimizations, complex clearances or awareness on network conditions can be uplinked. (Toddler-steps towards Trajectory Based Operations).

New tools and techniques of advanced Data Analytics

The field of data analytics has seen, in recent years, spectacular advances in terms of improved methods and algorithms and cheap access to automation and computing power that allows to collect, store and process very large amounts of data. The environmental optimization of aviation takes advantage of these novelties.

In Post-ops data analytics: The analysis of large bases of historic data (flown trajectories, crossed with the operational circumstances) provide detailed knowledge about inefficiencies existing in a specific location or on a certain process, and can suggest ways to overcome them.

In the "execution loop": calculations driving operational decisions can use models that are more accurate and more specific to the specific circumstances, first and foremost by using the exact parameters of an individual flight on a specific aircraft as opposed to a generic model per aircraft-type and using average values.

Improvements in the "Ground" segment

ALBATROSS has investigated, and partially demonstrated, some "green taxiing" possible improvements, namely TaxiBot vehicles, that allow the aircraft to taxi with the engines off, and single-engine-taxiing, a process already applied, but which may offer margins f further improvement. The attention on these concepts, in the present document, is only partial, because the main focus is put on improvements that concern the airspace and the flight phase, and the techniques used to optimize flight and airspace do not apply to taxiing (for one thing, on the ground the aircraft could stop and wait with engines off!). Nevertheless, improvements in the pre-takeoff phases should not interact with the flight phases in a way that could be detrimental to the reduction of the environmental footprint.

"Optimum Flight" as an investigation tool

The concept of "Optimum Flight", having "zero excess of CO2", can be used as a detailed investigation tool by compare real flights to their optimums:

- Measure what margin for "improvement of CO2 emissions" exists on a given origin-destination;

- Identify which constraints in the airspace deoptimize the fuel-efficiency of the flight, causing an excess of CO2 emissions.

The concept of "Optimum Flight" looks at the full 4D profile, not just the "shortest ground distance". Following an optimized vertical profile is paramount for CO2-optimization, besides obviously following the shortest horizontal path, also considering the effect of wind (favourable or contrary).

In a few words and in a schematic view, this is how the ALBATROSS exercises put those principles in practice.

		Collaborative process / Strategic	Collaborative process / Tactical	Dynamic constraints mgmt	Advanced CNS	Aircraft- /Flight-specific CDM	Air-Ground info sharing
EXE-01	- Gate-to-gate approach - Dynamic RAD	X	X	X			
EXE-02	Big-Data analysis of ESSA TMA	X					
EXE-03	LNAS-CDA along closed-path PBN-to-ILS		X		X	X	X
EXE-04	Big-Data analysis of German TMAs	X					
EXE-05A	PBN-to-ILS Vienna				X		
EXE-05B	"DPO/IFO" profile optimization tools					X	
EXE-06A	PBN-to-ILS Paris-CDG				X		
EXE-06B	"Green Descents" Paris-CDG	X		X			
EXE-06C	"OptiClimb" climb optimization		X			X	X
EXE-07	TaxiBot at Schiphol	X	X				

EXE-01

Dynamic RAD: By individually analyzing each RAD restriction in place, identify which ones could be dynamically relaxed in certain conditions. The ANSPs selects the more suitable ones, where the relaxation has more “benefits" (number of flights, amounts of CO2 reduced, …) Use existing processes and procedures to coordinate between ASNSPs and NM the dynamic relaxation and to share the information with the airspace users to allow them the planning of more efficient trajectories.

Gate-to-gate: Combination multiple improvements available locally, as long as they don't introduce any side effects, negating each other.

EXE-02 and EXE-04

Data Analysis techniques have been used to find patterns in historic data.

In both cases, the correlation of flight efficiency with ATC clearances has been investigated.

In the approach of EXE-02 a notion similar to the OF is used ("ideal descent").

In the approach of EXE-04 advanced AI/ML methods have been applied.

EXE-03

Knowledge of the instantaneous flight conditions, in terms of weather and aircraft parameters, is used to calculate the best descent profile, adjusted in real time.

RNP arrival procedures determine a closed trajectory that the flight is guaranteed to follow; this allows for an even more precise calculation of optimum.

Implementation designed in the specific context of Zürich by Swiss International Airlines and Skyguide.

PBN-to-Final approach procedures are also studied and deployed in EXE-05A and EXE-06A; although the loop to the crews has not been closed, these are facilitators of future wider improvement of the descents. The same applies to the multiple locations where PBN / RNP deployment is taking place.

EXE-05B

Aircraft-specific flight parameters (ie. per serial number) are derived from "big data" collected from the aircraft history. The calculated optimum profile is therefore more accurate ("more optimum").

EXE-06B

Multiple possibilities of altitude relaxations have been investigated in the specific airspace structure os CDG arrivals. Three "scales" have been analyzed and implemented when possible: Final approach / STARs / Full descent ToD-to-landing.

EXE-06C

Registration-specific flight parameters, derived from "big data" from the aircraft history.

A (simplified) loop with ATC, to communicate that flight-specific parameters are applied.

4 Current Operations

4.1 General

One of the indirect and underlying objectives of this methodology is to ensure a common understanding among ALBATROSS stakeholders of its operational objectives and how the proposed Solutions have been selected and combined to form a seamless operational concept capable of supporting the implementation of optimal flight trajectories.

To facilitate this, this document will eventually provide a comprehensive but digestible overview of the very complex processes involved in executing a flight (or set of flights) from the departure airport to the arrival airport within the European ATM infrastructure.

4.2 Airline Processes

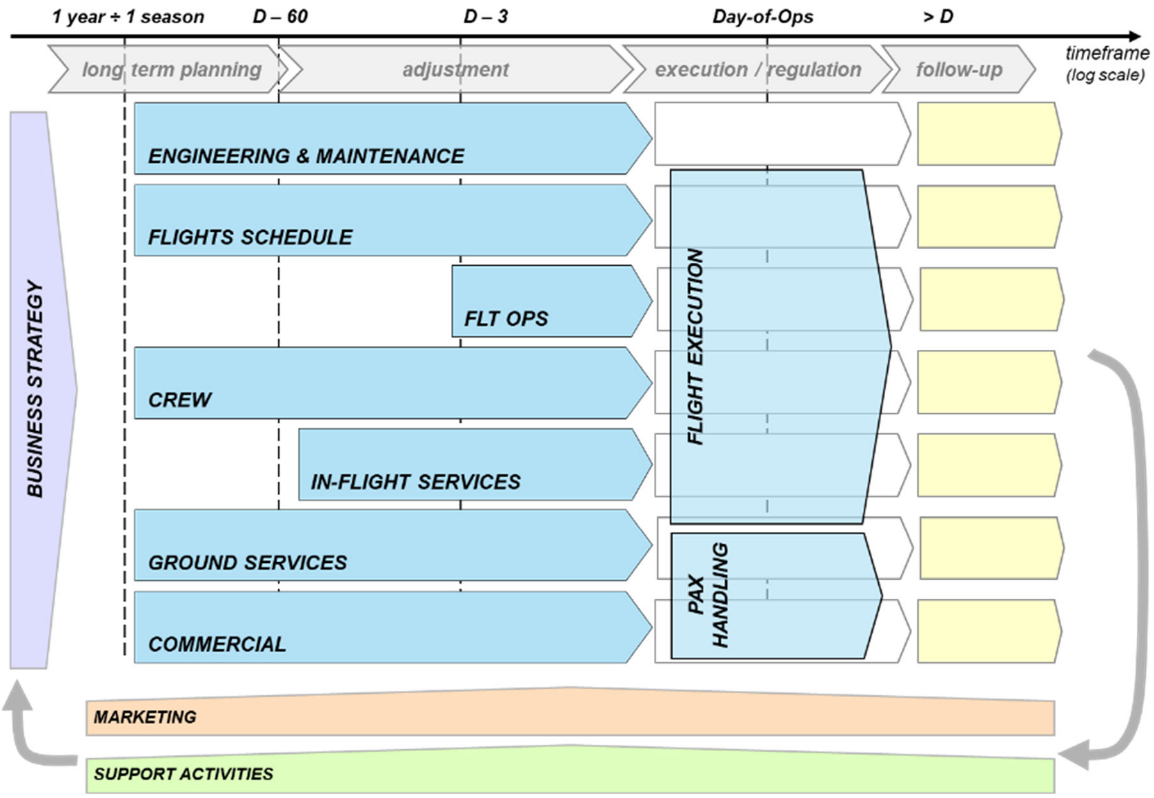

Figure 1: Airline Processes

4.2.1 Long Term

The Flight Schedule or Programme is developed at the rhythm of the IATA Seasons.

Based on available fleet of aircraft, trained flight- and cabin crew, traffic rights, available airport infrastructure and commercial/network strategy, the set of scheduled flights is constantly kept up to date. Seats are sold to passengers (via several distribution channels) starting approximately one IATA season in advance.

4.2.2 Medium Term

The current schedule (approximately 1 month before departure) is adjusted on minor aspects, depending on the availability of specific medium-term information. For example, whether a smaller or larger aircraft should execute the flight.

A so-called chained view is produced, based on aircraft and crew rotations. These sequences of flights are then further detailed via rostering of individual aircraft pared with qualified flight- and cabin crew later conducting the flight(s).

4.2.3 Short Term

On day-of-operations, the schedule of day is followed by the Operations Control Centre.

Flight Dispatch

Flight Dispatch is the function in charge of Flight Preparation and Planning and Flight Following for the flights executed by an operator (for example an airline).

Flight Preparation and Planning consists of calculating, before departure, the parameters of a flight (route, fuel requirements, load, and balance, etc.) and making sure that they are compatible with the aircraft performance (maximum takeoff weight, study of flight performance, etc.) based on the weather conditions and operational circumstances of the day.

Flight Following consists of monitoring the progress of the flight after departure and during its entire duration and assisting/advising the crew of any change that may affect the flight, in particular safety. For this task, Flight Dispatch and flight crews can establish direct contact via radio or datalink worldwide (rarely necessary for medium-haul flights, however).

Flight Dispatch also monitors ATC/ATM conditions over the network and is in contact with ANSPs and the Network Manager to participate in collaborative decision making. This is especially relevant during the planning phase, but for flights of longer duration may require actions also in the execution phase.

Flight Dispatch at an airline is typically organized in multiple teams in charge of different aspects (as relevant for the model of operations of each airline): by geographical region (usually at the scale of a (sub-)continent) or by fleet/aircraft type, and usually supported by a specialized "Network and ATC" team. A dedicated team oversees ensuring that the aeronautical information available to the Flight Dispatch is up to date (infrastructures, routes, NOTAMs, etc.)

Flight Preparation

Regulation requires that an Operational Flight Plan (OFP) - actually part of a more extensive Flight Brief information package - is produced for each flight, with the following purposes:

- Ensure that the flight and the aircraft comply with all relevant regulations.
- Provide all necessary information to the pilots in order to operate the flight in a safe and efficient manner.

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- Inform Air Traffic Control (ATC) of the mission/intent of each flight, so that traffic can be orderly and safely managed.

Flight plans are calculated using computerized systems. The vendors of these software products are sometimes called Computerized Flight-planning Service Providers (CFSP). The terms stress the fact that as part of the software usage license, additional services may be provided. The vendor typically ensures that the most up-to-date weather and aeronautical information is available to the users (flight dispatchers) from the most appropriate external sources (weather providers, AIPs and Aeronautical Databases, NOTAM providers, etc.).

By extension the term CFSP sometimes is also used to indicate the calculation software itself.

In addition to ensuring compliance with regulation, CFSP packages also provide optimization capabilities, to determine flight plans (ground track, altitudes, speeds, amount of departure fuel) that result in minimum fuel burn (to limit emissions, besides fuel costs) and minimum time-based costs and fees, while ensuring revenue from the payload that can be carried in the operational conditions of the day.

The first calculation of each flight plan is typically performed automatically.

It is usual for large European operators to perform flight planning for medium haul flights in an almost fully automated way. The result from the CFSP software is only checked manually, and adjusted, if necessary, if the system produces an alert (e.g., due to non-respected tolerances or regulations, or when an appropriate plan cannot be found at all).

Long haul flights are usually prepared by a flight dispatcher by directly evaluating, manually with the support of the CFSP software, the most suitable solution.

The final flight plan is calculated a few hours before departure (weather conditions are known more precisely closer to the time of departure and may influence the choices for a flight). It is then filed to Air Navigation authorities and forwarded to the crew (together with a Briefing Package that includes additional operational and commercial information). These actions are also automatic.

Manual intervention may also take place in case of:

- Reaction to a penalizing departure regulation, to try a non-regulated route.
- Rerouting due to adverse weather
- Modification of alternates and routes if airport and airspace accessibility conditions have changed.
- Last minute variations in the technical parameters of the flight, for example the payload or an aircraft swap.

Finding an optimized flight plan is quite challenging, from the computational point of view:

Optimization involves physics (airplane performance and weather) that may use some non-linear or non-continuous equations and highly dynamic state changes.

It also involves airspace and route structure (regulatory rules and restrictions necessary for ATC to perform its tasks) accumulated over the flight distance, and thereby increasing the complexity of computing.

For these reasons, the calculation of a single flight plan may take several/many minutes, even with the computing powers currently available.

Airlines sometimes still use fixed "company routes", that are pre-defined routes complying with specific restrictions and company policies on certain origin-destinations. Only weather information and the specific aircraft, payload, and cost parameters are dynamically included in the optimization, while the compliance to the restrictions is ensured structurally without repeating a demanding calculation.

Because of the complexity of the calculations, a full 3D/4D optimization is not yet a widely available function in commercial flight planning software.

More precise trajectory optimization can be performed by specialized tools, developed for example by aircraft/engine/avionics manufacturers or research institutions. However, these tools are not built for daily operational usage at the scale of the fleet and schedule of a commercial airline, both in terms of performance and in terms of supporting the information and processes required by regulation (e.g., full integration of up-to-date aeronautical information and weather; interactions with ANSPs for validating and filing flight plans; fuel regulations; integration with fleet management for the monitoring of aircraft parameters; etc.)

CFSP providers improve and update their products with additional functionality, evolving towards the support of more fine-grained optimization, while still integrated in the regulatory ATM/ATC ecosystem.

The current state-of-the art flight planning products usually proceed by partially optimizing different segments of the flight in a "2D-2D" fashion, usually identifying one or very few candidates' horizontal routes (using simplified wind/weather information over the vertical layers), and then calculating the best vertical profile only for the selected 2D candidates. This is one reason why long-haul flights are not left to fully automatic calculation.

The steps typically followed to determine the flight plan are the following:

- Selection of the runways for departure, arrival, and alternates, based on aerodrome accessibility at the planned times, worst-case winds within thresholds (infrastructure, aircraft limitations, AIP, etc.), local ATC runway usage constellations, availability of at least one SID or STAR, approach within weather minima, aircraft capabilities corresponding with available infrastructure.
- Calculation of maximum take-off weight, based on precise airplane performance characteristics. Rules of contingency fuel are also taken in consideration (defined by a percentage of flight time or planned fuel burn, depending on regulators – see section 4.1).
- Calculation of the horizontal profile (if the flight is dynamically optimized and not using company route-catalogue, in which case the calculation was done in advance).
- Application of the relevant restrictions (that may only be active during specific time periods), for example, airway or airspace closed by NOTAM, restrictions from company policy, RAD restrictions, conditional routes etc.
- Choice of the route (if multiple possibilities exist). The planning tools can be configured to choose for each flight the optimum fuel, or time, or shortest distance or total cost.
- Vertical optimization for the cruise phase (both for dynamic and for catalogue routes), based on the aircraft specific performance parameters and calculated between end-of-SID and beginning-of-STAR.

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NOTE: multiple different altitudes may be proposed if the winds at different altitudes are more favorable. Nevertheless, too many flight level changes are to be avoided, so the number or frequency of step-climbs/step-descents are typically limited (unless level-offs are imposed in the airspace structure).

- Calculation of the speed, mainly based on aircraft parameters but possibly adapted for scheduling reasons (need of early arrival for passenger connections), i.e., timetable.

NOTE: Aircraft performance data is provided by the manufacturer and is constantly corrected (for each aircraft) by tracking changes to the configuration / equipment list and by measuring deviations from baseline data, from flight data recorders.

Once the flight plan has been calculated by the airline and validated by NM/ANSPs it can be studied and accepted by the crew, then uploaded to the aircraft flight management system, ready for the execution of the flight.

4.3 ATM Processes

Air Traffic Management is the aggregation of the airborne and ground-based functions required to ensure the safe and efficient movement of aircraft during all phases of operations.

Air traffic management comprises three main services:

- Air traffic services (ATS), with the general purposes of ensuring safe and orderly traffic flow (facilitated by the air traffic control (ATC) service) as well as providing the necessary information to flight crews (flight information service, FIS) and, in case of an emergency, to the appropriate (e.g., SAR) bodies (alerting service). ATS is mostly performed by air traffic controllers. Their main functions are to prevent collisions by e.g., applying appropriate separation standards and issue timely clearances and instructions that create orderly flow of air traffic (e.g., accommodate crew requests for desired levels and flight paths, ensure continuous climb and descent operations, and reduce holding times in the air and on the ground). ATS relies on tactical interventions by controllers and direct communication with flight crews, usually during the entire flight.

- Air traffic flow management (ATFM), the primary objective of which is to regulate the flow of aircraft as efficiently as possible in order to avoid congestion of certain control sectors. The ways and means used are increasingly directed towards ensuring the best possible match between supply and demand by staggering the demand over time and space and by ensuring better planning of the control capacities to be deployed to meet the demand. Supply and demand can be managed by imposing various restrictions on certain traffic flows (e.g., assigning CTOTs or requiring flights matching certain criteria to use specific routes). In addition, supply can be increased by appropriate sector management (e.g., increasing the number of controllers working at the same time). AFTM measures can be seen as pre-tactical, as they do not affect the current situation but rather the near future.

- Airspace management (ASM), the purpose of which is to manage airspace - a scarce resource - as efficiently as possible in order to satisfy its many users, both civil and military. This service concerns both the way airspace is allocated to its various users (by means of routes, zones, flight levels, etc.) and the way in which it is structured in order to provide air traffic services.

The diagram below shows the structure of ATM and illustrates the relationships between ATM, ATS and ATC.

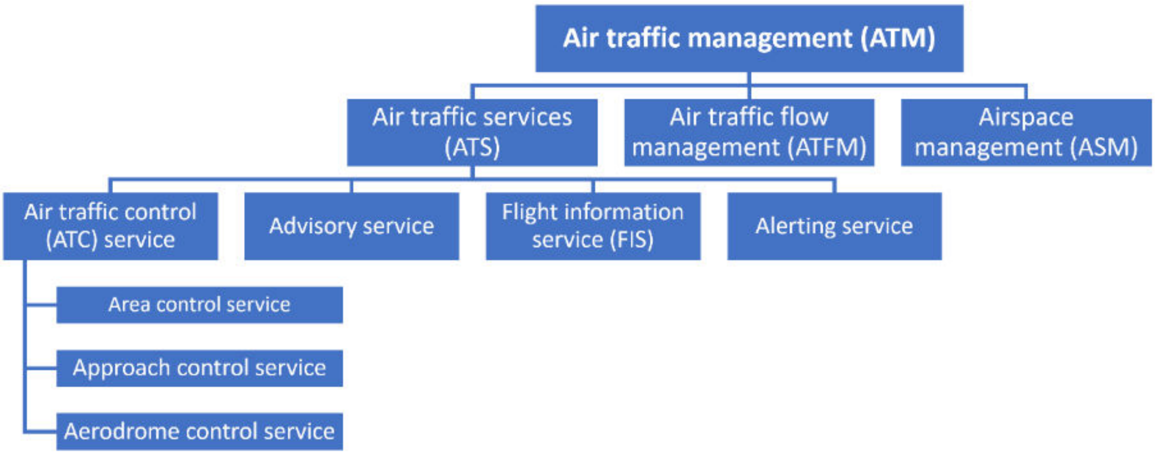

Figure 2: Structure of ATM

The execution of the ATM services involved different stakeholders with clearly defined roles and responsibility to be performed in close cooperation and coordination through agreed processes covering all phases of operations.

"Room for Improvement"

The key successful factor of more efficient flights is the continuous sharing of information among the different relevant stakeholders across the entire ATM lifecycle process. This flow of information facilitates the CDM process among the partners to identify the best options to accommodate traffic demands according to the most efficient trajectories

It’s obvious the granularity of information exchanged during the ATM process varies significantly during the different phases of the ATM process. For example, the sharing of the flight scheduled of the AOs at strategic level doesn’t describe the specific trajectories that will be flown but it is useful to support ANSPs in defining an efficient capacity plan to accommodate the expected capacity. Closer to the time of operations, more precise information is shared and tuning of the ATM capabilities are required.

Dynamicity in the processes and capabilities to adapt the operations to the changes are key requirements for the different stakeholders.

The current processes of the different stakeholders, are designed to cope with the dynamicity and flexibilities required; nevertheless there are still rooms for improvements to take full advantages from the opportunities offered by ATM solutions already available. This can be achieved through a pragmatic approach to exploit the current improvements available for deployment.

Albatross aims to exploit such opportunities through the deployment of the identified improvements and their sustainability in the current operations.

The following chapters provide explanations of how Albatross project demonstrated the feasibility of the approach and the sustainability of the solutions identified.

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5 Optimum Flight (OF)

This section of the Methodologic Approach describes the so called "Optimum Flight" (OF in short).

In this context, optimality only refers to CO2 emissions.

Fuel as a proxy for CO2 emissions

Since CO2 emissions are exactly proportional to fuel burn, the fuel quantity used for a flight will be used as a proxy for CO2 emissions in the reasoning.

Therefore, the "Optimum Flight" ("OF") between a given departure airport (A) and a given arrival airport (B) is a flight burning only exactly the minimum quantity of fuel required to fly from A to B subject only to the laws of physics and to the fundamental regulatory framework and operating procedures, assuming no interactions and interference with any other flight.

ATM vs non-ATM factors

The fuel required for a flight and therefore the CO2 emitted, depends on many parameters.

Since we are focusing on ATM processes, we will make a distinction between factors that ATM can "control" versus those that do not depend on ATM processes. (The meaning and scope of "ATM vs non-ATM" is illustrated in Chapter 4 "Current Operations").

- The physical conditions of the flight are considered fixed and not determined by ATM[1].

  These are:

  - Geography (distance, altitude of the origin and destination locations, surrounding obstacles, etc.; also includes the existing runways, in particular their heading).
  - Meteorological conditions at each point along the flight path, at the moment of the flight (temperature, air pressure, wind).
  - Take-off mass of the aircraft (zero-fuel weight of the aircraft; fuel; payload)
  - Performance of the aircraft and of the engines (aerodynamic performance and thrust/power).
  - Time when the flight takes place. This means, the flight is conducted at a specific time. There is no delay to await better conditions (e.g., more favourable winds).

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[1] Notice that some of these parameters can be controlled by the operators, but not as part of a process that belongs to "ATM". Reduction of CO2 emissions can certainly be achieved from improving those "non-ATM" processes, and aircraft operators have many initiatives revolving around these so-called "Green Operating Procedures". These are not, however, the focus of ALBATROSS and will not be discussed in this project.

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- The conditions that are directly influenced by ATM are:
    - The flight trajectory:
      - lateral path (including turns)
      - vertical path: climb profile, cruise altitudes, descent path
    - The flight speeds

Optimum Flight

The characteristics of the OF will be described in pieces, to understand them individually. A high-level descprition of the resulting flight is given here, and the explanation of each aspect is given in the subsections below.

In extreme summary, minimum CO2 emissions are obtained like this :

trajectory with the **shortest 3D air-distance** from origin to destination,

when flying at the **fuel-optimum airspeed** .

Tools exist to calculate aircraft behaviour, including fuel consumption, when following a given 4D trajectory, based on detailed aircraft models. The minimum fuel is calculated in practice by inputing the optimum trajectory and the aircraft and weather conditions in those tools.

A few remarks before describing the optimum trajectory in some more detail.

Is the OF realistic?

It must be pointed out that ALBATROSS does not expect that flights from A to B can actually operate according to the trajectory described as the Optimum Flight. The practical usage made of the idealized (although physically realistic) Optimum Flight concept is clarified further down.

Some examples of circumstances that limit, in practice, the full application of the ideal trajectory:

- Standard Operating Procedures ("SOP") are mandatory and must be applied by flight crews for safety reasons, even when they do not correspond to absolute minimum fuel. For example, aircraft must be stabilised in landing configuration at 1000 feet above aerodrome elevation. Further optimisation of the trajectory can therefore not be performed below 1000 ft (e.g. idle thrust is no longer possible).
- Constraints put in the airspace for ATM purposes are entirely justified by the presence of other traffic than "only the optimum flight". The typical example concerns the crossing of departure and arrival flows in TMA areas. If these constraints should be, when possible, applied to the

minimum extent necessary, it is certain that they cannot be entirely removed, as traffic will very rarely be limited to "one lonesome flight".

On the other hand, from a physical point of view the OF conditions describe a realistic flight performed by a real aircraft. Therefore it is more than just an abstract reference, when reasoning about "excess of CO2".

Each flight has its specific "OF conditions"

Since the physical conditions described above are specific to each individual flight, ALBATROSS does not describe a single "optimum trajectory" for all flights from A to B. (In particular, the "shortest ground distance" (along a great-circle) is only a rough approximation of the optimal conditions for a flight from A to B.)

A different aircraft, with its own specific age and performances, will be operating "A to B" on a different flight or date. The mass of each flight will be slightly different. The weather conditions in which different "A to B" flights will operate will be different.

Therefore, "the OF" should be understood as the flight trajectory and speed that results in the minimum fuel for the specific parameters of a given flight.

The exact calculation of this four-dimensional trajectory (3D + time) is not easy to perform. Besides the limitations of accuracy in the measurement of all physical parameters, some of them in fact change continuously in space and time (especially atmospheric conditions; but also aircraft weights, performances, etc.) An OF calculation can still be useful in practice when performed with the unavoidable simplifications and approximations.

To a finer level of detail, it should also be pointed out that the aerodromes in "A" and "B" may have multiple runways: a specific different optimum trajectory will result for each combination of departure and arrival runways. "A to B" is used here a shortcut.

Detail of the Horizontal profile: "Shortest Air-Distance"

Air-distance is defined as the product of True Air Speed (TAS) and time (or more precisely the time-integral of TAS).

TAS is the speed of the aircraft relative to the air surrounding it. Airspeed is the physical dimension that determines the aerodynamic behaviour of the aircraft and is chosen as defined further down.

The air mass in which the aircraft moves may itself move relative to ground, in the presence of wind. Therefore, the air-distance of a specific flight from point A to point B is different from the ground distance between A and B and is different from the air-distance of a different flight from A to B.

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In cruise, the OF will consequently follow a trajectory following the airmass with the most favourable movement relative to ground ("strongest tailwind or smallest headwind"). (More on this in section "Atmospheric conditions" below).

The most visible illustration of this kind of path is given by flights following intercontinental "jet streams". To a small scale, the distribution of winds near the shortest path from A to B may result in a ground trajectory longer than the minimum ground distance, while still giving the least fuel usage overall.

Concerning departure and arrival, the OF must use the runways physically existing at origin and destination. For safety reason take-off and landing are always conducted in headwind (given all other parameters are unchanged, aircraft climb performance is increased in headwind compared to tailwind). Therefore, OF uses the runway heading directed towards headwind.

Depending on origin-destination selection, the runway directions will, in most cases, not be aligned with the heading of the shortest air-distance path from origin to destination. Consequently, OF cannot avoid turns during departure and arrival (making the trajectory monger than a "straight line"). Turn characteristics giving the most fuel optimised turn are further analysed in section "Turning during departure and turning approach segments". The OF will include turns giving the most fuel-efficient trajectory.

Detail of the Vertical profile: "Shortest climb time, Cruise at the highest altitude, Idle descent"

The vertical profile will be discussed looking at cruise first, then at climb and descent.

The first order rule for cruise altitude is "the higher the better". Thinner air at higher altitudes requires lower fuel consumption in the cruise phase. On the other hand, aircraft performances, mass and structural limits put limitation on the maximum possible cruise altitude. As the aircraft burns fuel along the cruise phase, its mass decreases and it can continue to climb to a higher altitude. (Notice that in the description of the OF altitudes are not "quantized" to hundreds of feet as is done, for example, in the definition of "Flight Levels FL". Any value of altitude may be the optimum for a flight, whether compatible or not with practical flight in the presence of other traffic.)

A reason for not choosing the highest reachable altitude would be a distribution of winds along the vertical layers that makes flight at lower altitudes more favourable ("strongest tailwind or smallest headwind").

Concerning the climb: The OF should reach its cruising altitude as early as possible, so that the aircraft reaches thinner air as early as possible.

In aerodynamic theory there are two defined speeds to reach the cruising altitude:

Vx = Best angle of climb. Meaning reaching cruising altitude at the shortest **distance**.

Vy = Best rate of climb. Meaning reaching cruising altitude at the shortest **time.**

Vy defines the most fuel optimum climb, as this will give least time to reach cruising altitude.

This may seem contradictory with focusing the OF cruise portion on range (longest distance per fuel, see below "speeds"). The reason is quite simple: climb phase is very fuel consuming because the thrust setting is very high and the most fuel-efficient climb is where cruise altitude is reach as quick (timewise) as possible, i.e., best altitude gained over time (rate of climb). (Vx is used if the aircraft prioritises to clear obstacles, i.e., the best speed to gain altitude over distance no matter the time it will take.)

Notice that Vy will vary during climb to cruising altitude: to maintain best rate of climb throughout the entire climb, the speed needs to be decreased continuously. As of today, aircraft FMS does not fully cater for this requirement. Climb speed is often more a fixed climb speed/Mach being a reasonable compromise between being fixed and providing proper overall performance.

More detail concerning the climb can be found in section "Climb profile" below.

Concerning descent: it should be performed with idle engines without usage of airbrakes, dissipating exactly the accumulated energy (kinetic plus potential) from top-of-descent to touch-down. The exact Top-of-Descent, point of the trajectory where to end cruise and start descending, is set according to this idle descent.

Speed

During cruise, the most fuel-optimal airspeed is maximum range speed.

More on this can be found in section "Cruise flight" below.

In **Summary**

Horizontally: Take-off along the runway heading, turning in the most fuel-efficient manner as early as possible after departure, into the heading of the most fuel-efficient horizontal trajectory.

Vertically: Cruise along the most fuel-efficient trajectory (most favourable wind trajectory close enough to the great-circle trajectory). Start descending at the point that allows to reach stabilization altitude with the engines at idle, without applying airbrakes; turning in the most fuel-efficient manner as close to the runway as possible to be stabilised at 1000 ft above aerodrome elevation.

Speed (Time): Apply Maximum range speed.

Usage of the Optimum Flight

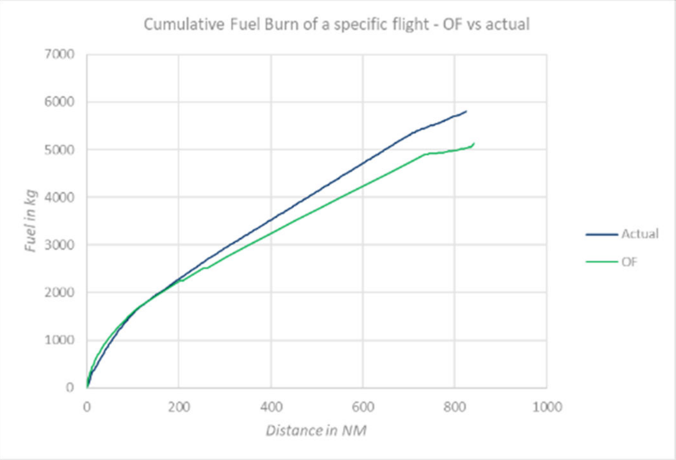
1. The OF is a practical tool to materialize the notion of "CO2 waste", or "the excess of CO2 emissions that could have been avoided on a flight". The CO2 excess is simply the difference between the CO2 emissions generated by (the fuel used for) a real flight and the CO2 (feul) quantity calculated for that same flight in optimum conditions, ie. its OF.

2. The OF trajectory is a practical tool to investigate whether, where, and how much real trajectories deviate from their optimum conditions, ie. whether and why any "excess CO2" is generated.

Both these usages have been practically applied in some of the ALBATROSS demonstrations.

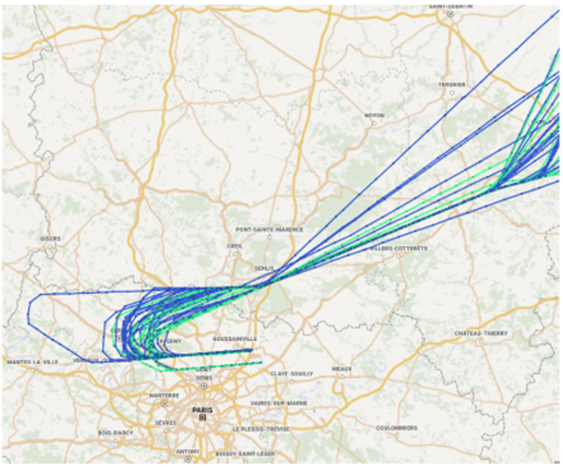
The illustrations below show actual examples from the ALBATROSS Gate-to-Gate exercise conducted on the LFPG-ESSA flights.

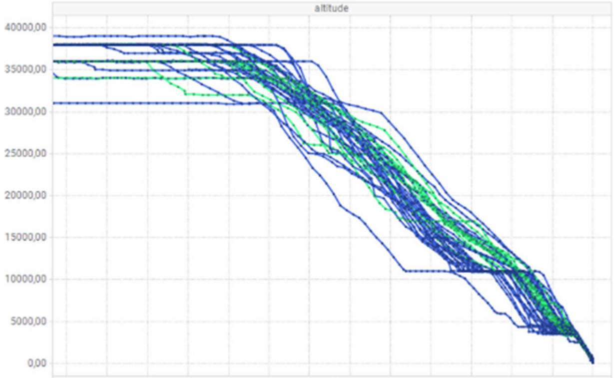
For the flight represented below it can be seen that climb is performed with fuel burn very close to the minimum necessary. Excess fuel burn takes place in cruise and also in descent.



The illustration below shows about 40 flights from the ALBATROSS LFPG-ESSA Gate-to-Gate exercise, zooming on the 3D "shape" of the arrival segments. OF flights have been calculated for each actual flight, and are visible in green color. The actual trajectories are visible in blue color.

(There are as many actual trajectories (in blue) as OF trajectories (in green). The variability over different OFs is less than variability of actual flights; therefore, the green traits tend to overlap much more than th blue traits and appear to be less.)





3. The OF trajectory is best calculated by the aircraft operator, who has the most accurate knowledge of the flight parameters. This totally unconstrained trajectory can be shared with ATC and serve as a reference of the optimal wished conditions. ATC could us it for decision making, when relaxation of certain conditions is allowed: propose alternatives close to that optimum, instead of deducting from partial knowledge of the parameters which proposals could interest the operator.

Initiatives such as FF-ICE and TBO would allow to make use of a trajectory of this kind.

6 Constraints counteracting OF

6.1 General

As airspace seems to be unlimited, one could imagine that aircraft would always travel without constraints along the most favourable route between two airports, taking into account meteorological conditions (for example, positive wind effects), following an optimised flight profile with unrestricted climb, fuel efficient airspeeds, optimum cruise levels, uninterrupted descent profiles, maximising aircraft capabilities and minimising Air Traffic Controller (ATC) intervention, thereby leading to the lowest fuel consumption possible. The flight mission would also take benefit in reducing taxiing time on ground together with minimum usage of auxiliary power to start the engines.

Unfortunately, this is generally not the case for many reasons; economical aspects, lack of infrastructure capacity, lack of aircraft equipment, the complexity of air traffic in certain en-route areas and especially in the terminal manoeuvring areas (TMAs) close to airports, and so on. Furthermore, safety is and must remain the top priority, both from an airline and flight crew perspective as much as from the ATM perspective. Safety must never be compromised even with all good intentions from an environmental impact point of view.

Not only are the factors not providing the most optimum trajectory (OF) for any given flight are very different they are very often linked together. The transversal impact of various constrains along the aircraft trajectory increases the complexity very quick and it may be difficult to find single and appropriate solution. This section will provide a summary of identified ATM constrains laying the foundation for further identification for possible solutions.

6.1.1 Non – optimal design (e.g., not yet full FRA or complex TMA procedures)

En-route airspace design is undertaken at the Network level, considering various rules and regulations in order to function as a block. In this way, air traffic flows containing more traffic may be prioritised in terms of optimisation against air traffic flows containing less traffic

In general, lower airspace is designed by national authorities and may be based on legacy traffic flows with the possibility to change aircraft routes being restricted by national regulatory processes or public demands such as noise dispersion. Over time, the development of lower airspace based on national requirements may have turned air traffic flows into a sub-optimised manner also given integration of arrival and departures from various airports leading to some traffic flows are prioritised against others.

The existence of a route network, not yet supporting the FRA implementation, doesn't allow AOs to fly in efficient way from origin to destination. Moreover, the implementation of FRA does not automatically imply the possibility to fly from entry point to exit point in the most efficient manner; there are still several restrictions in terms of RAD being applied in the FRA environment to "tune" the flows for a better management of the air traffic. This forces AOs to file non-optimal trajectories, i.e., flight plans.

6.1.2 CNS limits

If communications are restricted to HF without datalink, separation standards have to be much more restrictive in terms of lateral distance between aircraft and altitude separation. Subsequently, many aircraft flies at non-optimal flight levels, speeds, and routes. In addition, PBN navigation specification allows aircraft with certain equipage and training and to follow procedures which are optimised in terms of fuel consumption and noise but excludes aircraft without the required equipment and training. Without ground surveillance systems, for example, radar or ADS-B, separation standards have to be procedural and therefore aircraft are not able to fly at the most fuel-efficient flight levels, speeds or routes, as only limited air traffic flows can be handled.

6.1.3 ATC operations – Sequencing

At busy airports there are different strategies for separating aircraft and putting them into an arrival sequence. This may include vectoring, longitudinal holding (“tromboning”), or holding patterns. In this situation, flight crews do not longer have the required trajectory predictability (in terms of lateral track-miles to touchdown) and the descend profile may not be fully efficient. However, in some cases, based on local knowledge, usage of sophisticated on-board avionics and enhanced predictability, certain inefficiencies may be reduced.

6.1.4 Non-optimal route catalogues (AOs do not consider fully opportunities offered by the dynamic ATM)

ATM operations are currently quite dynamic, providing a continuous evolution of the airspace status. This dynamicity very often provides opportunities to get better routing offered to AOs. In principle, AOs should be able to capture these emerging opportunities by themselves. However, in reality, this is rarely the case. The services provided are aiming to fill the “gap” and trying to help AOs to file and fly more efficient trajectories. There are many different reasons:

- Lack of AO sophisticated system to capture the opportunities when available,
- Usage of route catalogues not always updated according to the ATM network evolution at strategic (example before) as well as pre-tactical and tactical levels,
- Flight dispatcher incapability to process the opportunities, even when provided for specific flights (RRP), due to lack of system/resources,
- The flight planning software may not provide, for example, the most optimal routing,
- Some flight planning companies do not have all the relevant waypoints in their software to optimise routings. For example, LIDO flight planning system does not link all FRA entry points with all FRA exit points hence the most optimal pair may not be an option to choose,
- Large FRA airspaces, lacking some kind of pseudo, intermediate waypoints may not provide the best option to optimise the route inside the FRA,
- AO internal fuel policies together with experienced dispatchers may in some cases be counterproductive. For example, dispatchers may base the flight plan on expected routing which may be longer and more fuel consuming than standard routing. Less experienced

dispatchers - planning the same flight - may therefore underestimated the fuel required and hence, over time, flight crews add discretionary fuel as they do not trust the flight plan fuel calculation. The case can also be reversed if flight crews add discretionary fuel based on flight plans already including an optimised routing, i.e., route deviations are already considered by the dispatcher and does not require additional fuel. In all cases, the more fuel the aircraft is carrying, the more fuel is used. Aircraft mass increases with added fuel and with increase in aircraft mass, more fuel is required to power the engines sufficiently to transport the aircraft from point A to point B.

6.1.5 Existing RAD restrictions preventing optimal trajectories

The RAD enables States, FABs and ANSPs to maximise capacity and reduce complexity by defining restrictions that prevent disruption to the organised system of major traffic flows through congested areas. It’s evident the implementation of RAD restrictions, whilst supporting capacity, can be detrimental for flight efficiency, penalising optimum trajectories areas with due regard to AO requirements. Restrictions imposing re-routings and or level capping prevent AOs to fly optimum trajectories.

6.1.6 Activities, mainly military, requiring segregation of airspace

Different activities of various airspace users, mainly military, require segregation of certain portions of airspace, whenever deemed unsafe for other non-participating aircraft. This is required for daily operations as well as special events (for example, large scale military exercises) regularly organised throughout the year. Whenever a portion of airspace is segregated, the opportunity to fly efficient trajectories are reduced, requiring extra NM flown and/or utilisation of non-optimal flight levels to circumnavigate the segregated areas, with direct, negative impact on CO2 emissions.

6.1.7 ATFM measures, like ATFM scenarios/STAM (mandatory re-routing or level capping)

Some parts of ATFM operations are measures normally agreed on at strategic level and applied at pre-tactical and tactical level whenever required to balance capacity versus demand. They have a direct impact on not facilitating flight efficiency, imposing re-routing or level capping constrains, thereby offsetting routings from the optimal trajectory.

6.1.8 LoAs between ATC centres

LoAs are designed to reduce the handover protocol between sectors and centres, enhancing safety and predictability. For example, all arrivals to airport X will be required to be at, or descending to, a certain flight level before being handed over to the next sector. In the event of an extremely busy sector this ensures that any safety events are minimised. However, in busy sectors and even in quieter sectors - due to the performance capability of certain aircraft - unless the aircraft is transferred in time for the receiving ATCO to issue a follow-on descent or climb clearance, this may result in small periods of inefficient level flight which consumes more fuel. In addition, LoAs are often conservative to allow for busy traffic periods or extensive vectoring. Furthermore, LoAs may be also used to strategically separate traffic flows and ensure that certain flows avoid busier airspace sectors.

6.1.9 Traffic delays

Slightly different are the considerations for the effect on OF generated by the application of delays to flights, aiming to decongest specific areas (or airport) where the demand exceeds the available capacity. In principle, flying “late departure” does not penalise the optimum trajectory. However, it can trigger reactions that will penalise the optimum trajectory. Excessive delay can “force” AOs to search for alternative routings (horizontal and vertical) – which are non-optimal - but offering less delay. This could be quite relevant in case of hub and spoke operations, where punctuality is a strong requirement for AO operations. Similarly, flight crew can increase aircraft speed – which is generally non-optimal in terms of fuel consumption - to re-gain the time lost based on imposed restrictions (“slot allocation”).

6.1.10Unpredictability of traffic evolution

Linked to the capacity constraints and the possible consequences against the opportunity of flying OF is the lack of predictability of the traffic demand, potentially producing negative domino effects. Again, there are numerous and different factors contributing to the lack of predictability; from external factors (e.g., weather) to factors directly linked to the ATM operations, such as tactical management of the traffic, as well as to the AUs “modus operandi”, for example filing flight plans not utilised in the execution phase.

The consequences are directly affecting the capacity levels declared by ANSPs, used to keep some manoeuvrability – “room” – for undeclared capacity to cope with unpredictable traffic evolution. Moreover, it could be detrimental for the planned utilisation of ATM solutions facilitating the execution of more efficient trajectories. Indeed, tactical modification of the trajectories can spoil the downstream utilisation of solutions (e.g., TOD) forcing the flights to execute less efficient trajectory (e.g., holding).

Unpredictability generating domino effects is also one of the inefficiencies linked to the airport operations, sometimes not directly linked to the responsibility of AOs or ATM operations (e.g., passengers arriving late at the gate). Layout of airports, long taxing routings, airport procedures, lack of coordinated airport/ATM operations are other factors generating inefficiencies in terms of fuel consumption. Another factor that potentially generate inefficiency is the lack of coordination between the processes for the assignment of airport slots and the definition of ATM capacity, producing unbalanced situation asking for the application of ATFM measures or inefficient ATM operations for the lights being airborne.

Not directly ATM related constraints

6.1.11Weather conditions

Weather conditions are not controllable but not completely unpredictable. Certainly, they have an effect on the trajectories, amplifying the domino effects whenever handled tactically. Indeed, the tactical management generate the unpredictability previously mentioned, amplifying the negative effects of the weather conditions.

6.1.12Industrial actions

Industrial actions have a strong impact in terms of exceeding fuel consumption, not only for the delays they generate - with all consequences stated above - but also longer re-routings chosen by the AOs to avoid areas subject to industrial actions.

6.1.13Route charges

Route charges can have a direct and negative impact on fuel consumption and subsequent CO2 emission. AOs are business oriented and therefore considers total costs for each flight. Route charges is one of the factors to consider calculating the total costs and - considering the differences between unit rates of the ANSPs - quite significant in some cases. Sometimes longer routing is filed to avoid areas with higher route charges with the total cost being lower, despite the additional fuel required to fly the less efficient route, resulting in overall negative effect in terms of CO2 emissions.

6.1.14Fuel Management

When the negotiated fuel price and the cost of fuel services at the departure airport are significantly lower than at the destination airport, some airlines policies instruct flight crew to carry more fuel than required for their safe flight in order to reduce or avoid refuelling at the destination airport for subsequent flight(s), and thereby minimising total cost. This is by the industry called “tankering”. EUROCONTROL estimated that in 2018 was likely to be used by 21% of ECAC flights, representing a net saving of 265M€ per year but 286,000 tonnes of additional fuel consumption (equivalent to 0.54% of the whole ECAC jet fuel used), or 901,000 tonnes of CO2 per year. Clearly, in the context of fuel conservation and emissions reduction, tankering should be avoided.

As stated above, carrying additional – or extra – fuel will also increase total fuel consumption for that specific flight. “The extra fuel consumption attributable to additional weight carried on board an aircraft is typically of the order of 2.5 to 4.5 per cent of the additional weight, per hour of flight, depending on the characteristics of the aircraft. For example, 500 kg of extra weight for a ten-hour flight could result in the additional consumption of 125 to 225 kg of fuel and an increase in CO2 emissions of 390 to 710 kg.”

6.1.15Balanced with other types of emissions

Another factor is the need to satisfy the requirements to reduce other type of emissions. One very good example is noise dispersion which is included in the environmental impact domain (a kind of emission). Noise is very relevant in terms of social impact, especially around airports that impose the adoption of solutions (arrival and departure procedures) not necessarily aiming to reduce CO2 emission (e.g., longer routings, non-optimal climbing rates and/or turning bank angles, utilisation of non-efficient runway configurations to disperse thee noise more conveniently for neighbouring communities).

7 Solutions to overcome constrains

7.1.1 General

This section will provide strategies to overcome constrains counteracting OF. The reason this methodology initially provides strategies rather than specific solutions is based on outcome from discussions within WP2 Core-Team together with lessons learnt from gate-to-gate trials performed in WP3. Being a demonstration project, the aim is to find tangible solutions enhancing environmental efficiency, possible to implement in daily operation. Candidate mitigations will be selected from mature operational solutions with demonstrated fuel/CO2 savings, such as: SESAR catalogue of Solutions, the SESAR Performance Assessment Report (PAGAR), the European ATM Master Plan or other operational solutions, already in operation or in an advanced stage of validation (e.g., local trajectory optimizations as proposed by EFB/pad applications for pilots, Dynamic RAD).

The key point will be to identify actual conditions allowing certain technology improvements or solutions available today, to be deployed and sustained in daily operations for a given airspace, while requiring an implementation effort accessible in the short term. These low hanging fruits will bring immediate benefit and complement the deeper and more complex ANSP system upgrades, new FMS technology, full airspace re-design etc. that is developed in parallel for the medium and long term.

The solid conclusion from gate-to-gate trials in conjunction with work done in WP2 is all airspace – whether its TMA, En-route etc. – have its own solutions when aiming to achieve quick-wins and early benefits.

Of course, the initial idea is based on, for example, a concept (e.g., RNP to ILS procedure) but the actual solution requires local adjustment to be suitable and beneficial in the short timeframe. It is difficult to find tangible and immediate results stemming from a more complex and generic solution (e.g., airline benefits using EPP). Also, the solutions deployed, depend very much on the chosen city pair conformation, making the extrapolation of this kind of approach very hard to be generalized.

In this respect, the understanding of the relevant actors' role in the current operations is essential. The annex A provides a broad description of this role during the process for the preparation and execution of AUs trajectories

7.1.2 Strategies

Given the reasoning above, the overall methodology strategy to overcome constrains is quite straightforward:

1. With basis in OF (defined in this document) identify any constrains counteracting the OF. This would mean *any* constrain, whether its ATM or not (for example, en-route charges). In ALBATROSS this is the difference between OF and Baseline Flight(s), BF.

   NOTE: How to make the comparison is described in WP4 documentation.

2. This comparison will create a list of constrains counteracting the OF. Depending on the level of scrutiny, these may be very local and specific constrains (e.g., local noise restrictions for

only some time of the day and only some days in a week) or more globally constrains (e.g., FRA not possible to utilise for certain segments of the flight).

3. The next step is to investigate *each and every* constrain to its core and try to answer the following questions:

    a. What does the constraint impact specifically? (E.g., descend profile, optimum departure runway etc.)

    b. How much does it impact? (E.g., only one specific flight, general traffic stream etc.)

    c. Why is this constraint present? (The root cause for having the constraint at all.)

    d. Is the constraint conditioned? (E.g., only time of day, specific wind conditions etc.)

    e. Is it possible to isolate the constraint to one specific KPI? (e.g., the constrain only have environmental impact)

    f. Is the constraint valid? (e.g., maybe the constraint is a leftover from previous airspace design).

4. Based on the outcome of the above stated questions, the list of constrains can be elaborated and more specific. Especially in terms of judging whether it is worth the effort trying to remove or limit the constraint, whether the constraint is possible to remove or limit at all and which constraints should be prioritized over the others.

5. With the more expanded list, the next step is to reach out to **all** stakeholders impacted or impacting the constraints. Depending on constraint, this could include airline representatives (dispatchers, pilots, back-office engineers), airport representatives (if within TMA), all adjacent ANSPs (from impacted sectors), Network Manager (if more globally, en-route oriented constrains) etc.

6. Within this group, start picking constrains *one by one* and agree on way forward for each and every one of them.

    Way forward is of course the key word as it implies the actual solution to overcome the constraint. This is the difficult part and could mean many things:

    a. Can the constraint be removed?

    b. If not possible to remove completely, can the constraint be conditioned? For example, only applicable in a certain timeframe, a certain time of day, only for specific airlines, aircraft etc.

    c. Are there other ways to limit the constraint? For example, long arrival and approach route is replaced with shorter RNP to xLS routing. Or RNP AR is introduced to increase runway throughput in parallel runway operations (less holding).

7. The outcome above will then initiate a feasibility study (if not previously performed). In short – is it worth the effort, investments etc. to move forward?

8. The next step – if the feasibility study is positive – is the following:

   a. Introduce solution
   b. Demonstrate solution
   c. Analyse (in terms of KPI positive effect or not)
   d. Implement (if not discarded above).
   e. Post-analyse

This strategy may seem obvious, but it is not. There is a general tendency to put all hopes on new, hi-tech system support solutions. This will of course solve a lot of problems on a fundamental and global level – a paradigm shift - but there is still a big gap between future ATM systems and today's operation. So, if any stakeholder is looking to find quick-wins and immediate benefits without waiting for the critical mass to invest in new technology, this is the way forward: Identifying all constrains and try to solve them one by one. Hard (and sometimes endless) work but as simple as that.

7.1.3 Collaboration

For the above provided strategy to be successful the key word is **collaboration.** This cannot be stressed enough. Without proper collaboration and management of the collaboration it is very difficult to succeed in trying to overcome a constraint. Of course, there are many levels of complexity identifying and overcoming constraints, but in general. Collaboration in this context means a group of people from all stakeholders having an impact/being impacted by the constraint working together with one, single target: to remove, minimise or at least limit a (or many) constraints.

The following list is tips on how to proceed in succeeding with the methodology strategy in terms of collaboration:

1. Build a relatively small group from all stakeholders. Try to find people with possibilities to impact their roster (very important involving operational people).

2. Involve people **directly involved** in the constraining environment. This is paramount and a showstopper if not possible. What this means is, for example, actual ATCOs working daily in the targeted sector, actual pilots flying in that area etc.

3. Having these people regularly around the table will have the following positive effects, in addition to the actual strategy:

   a. Information sharing and knowledge enhancement between the people/various groups. This always leads to positive effects in the daily operation (for example, an ATCO more clearly understands a shortcut may not always be the best choice).

   b. Fruitful discussion between specialised professionals always opens the door the new problems and possible ways to solve them. Which, in addition to maybe solving a problem not targeted from the beginning, it may find a solution not identified from the beginning.

4. **Run the strategy in style of a project**. Objectives, clear assignments, deadlines, final target etc. Dedicate a project coordinator/manager as focal point and keeping oversight.

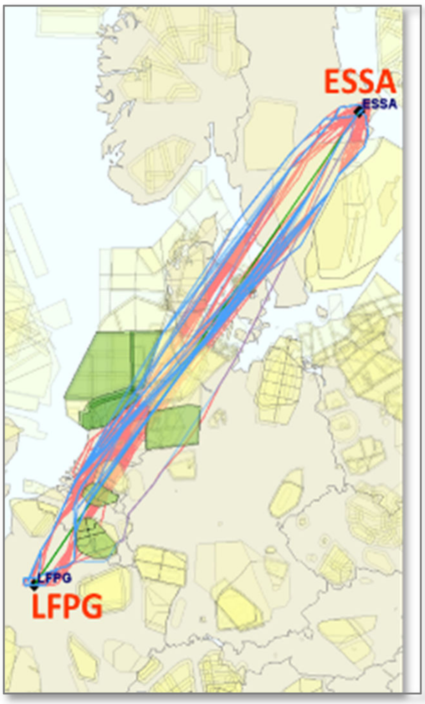
5. **Turn every stone.** There are so many good and simple solutions never been realised as tradition, old habits, reluctance etc. doesn't allow to make it happen. This is why the group must be looking for all solutions possible, even if they sound trivial from the beginning. Simple is very often the best choice forward.

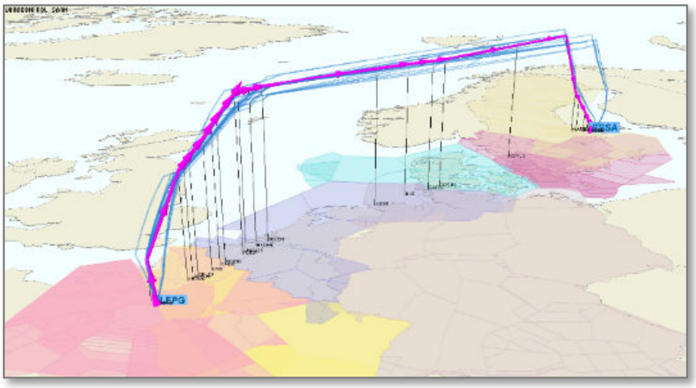
6. **G2G Approach**. To concretise the desirable spirit of cooperation between the different partners it seems appropriate a pragmatic approach to dela with specific use cases. The G2G approach have demonstrated the potential opportunities to set up a project round a concrete objective (optimise the routing between city pair), identify the relevant stakeholders to be involved, analyse the delta between possible OF and the baseline Flights, identify possible ATM constraints and put in place solutions to offer improvements whenever available (e.g. dynamic RAD). Experience demonstrated the complexity of the process and the need to a sufficient time to perform all the steps in preparation of the daily application of the solutions identify. The objective is not to optimise all flights with all possible improvements, but to ensure the operational sustainability of the process in the long terms, to offer a systematic availability of any kind of solution at any possible time. Not a revolution but a pragmatic approach to look at short term concrete improvements that not necessarily need sophisticated technical support. Due to the complexity and potential length of the process, it is evident the need to focus the attention on those more promising cases in terms of better improvements in terms of fuel saving and/or number of flights involved. In this respect, NM can play an active role in coordinating this approach, e.g. defining a strategic project, focusing on the identification of the most penalised city-pairs. In the longer terms more systematic approach could be considered when more sophisticated system supports (e.g. AI and ML capabilities) will be available.

7.1.4 Concrete Examples Illustrating the Methodology

Gate-to-Gate approach

As anticipated before, the aim was to prove the concept using selected city pairs (CPs). To facilitate the preparation and execution, the selected CPs were not necessarily the most promising in terms of substantial improvements but those were more Albatross partners were involved. The following is just an example of the selected CP that granted a good cooperation with all the major stakeholders: NM (mainly in the preparation phase), ANSPs (DSNA, MUAC, LFV), airports (Paris CDG, Stockholm Arlanda) and AOs (AF).





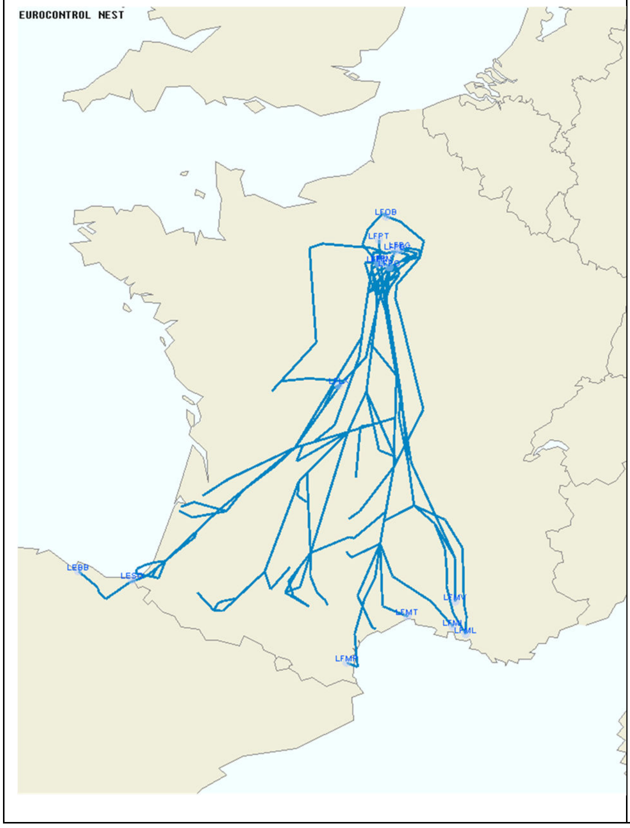
As depicted in the picture, the routing already offers today a good trajectory, quite close to the OF. Nevertheless, the cooperation among the different partners identified some improvements, even if small in some cases, that allow the AUs to optimize the trajectories whenever the improvements have been offered by the ANSPs (great contribution of MUAC). The process allowed to proposed improvements in the planning phase, allowing a more efficient FPL, but also tactically.

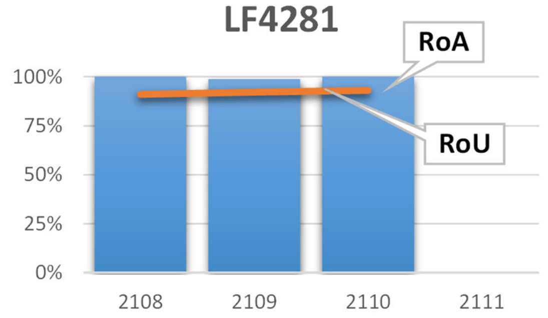
The demonstrations were relatively limited in time (three weeks in March and three weeks in November 2021), highlighting the need to further improvements of the process to standardise the methodologic approach (no ad hoc solution) and ensure an operational sustainability.

Dynamic RAD

The aim was to reduce the utilisation of permanent RAD restrictions and to introduce a process allowing a more dynamic management of restrictions according to traffic evolutions. Different trials have been run, proving the feasibility of the concept and demonstrating the effectiveness of the process. The following example provides concrete evidence of the opportunities to get more efficient trajectories, having all the partners involved.

Dynamic RAD restriction: LF4281
From PARIS_GROUP, LFOB/LX crossing LF to LFBBFIR, LFMP/MT/ML/MI/MV/MU, LEBB/SO via LFBBCTA FL capping: FL295 Applicability: 12-08-2021 until 03-11-2021 (84 days)





Eligible flights:	6288
Acceptor flights:	5797
Days RAD active:	1
Actual fuel saved:	388.8 t
Potential fuel savings:	421.8 t
Actual CO2 reduction:	1224.8 t
Potential CO2 reduction:	1328.7 t

RoA= 99.6%

RoU= 92.1%

The trial of 3 months proved the possibility to offer the relaxation of the RAD restriction (level capping) with high percentage of availability (Rate of Availability – RoA) and demonstrated the high interest of the AUs in using the opportunity of improving the efficiency of the trajectories with a high rate of utilisation (Rate of Utilisation – RoU) for FPL purposes.

The coordination with relevant stakeholders and the sharing of information are essential to ensure the effectiveness in applying the dynamic RAD concept. In the example, the initial coordination between DSNA and NM has permitted the selection of useful RAD restrictions to be proposed for the management through a dynamic process. The selected restrictions have been published on the NOP Portal to provide a general awareness for the AUs. The published information includes the description of the process used for the daily notification via EAUP (European Airspace Use Plan).

Every day, DSNA performed an assessment of the traffic demand and identified the opportunities to propose a relaxation of the selected RAD restrictions. The coordination process at national level was finalised with a daily AUP publication to notify NM the information about the proposed relaxation of the restrictions.

NM consolidated all the information with the daily publication of the European AUP (EAUP)

The information was available on the NOP Portal (B2C) and via B2B services. This allowed AOs/CFSPs to process the notified relaxation (mainly via B2B) to file the FPLs accordingly. Being the publication available at D-1, the lead time to “reach” the AUs community was sufficient to allow them to take into consideration the proposed relaxations.

In those cases were the information was not processed, the day of operation NM was able to revalidate the FPLs received and eventually suggest the improvement via the OPP tool (still a proposal to be accepted or not by the AOs).

The high percentage of acceptance and usage of the proposed relaxation demonstrated that the process worked and was able to deliver benefits as far as the proposed relaxation match with the interests of the AUs. A good lessons learned, to ensure in the future that the application of the concept not only requires a feasibility from the ANSPs but also full collaboration of the AUs to identify possible RAD restrictions of great interest to improve flight efficiency.

Green Descent in CDG

The aim of this exercise was to demonstrate the possibility to enable optimized descents in the Paris area, when possible in specific traffic conditions, by "relaxed" interfaces between control centers; less stringent constraints in delivering traffic are expected to enable: less or shorter level-offs, performed a higher flight levels; flights starting to descend (ToD) later than in current operation or closer to preferred ToD; flights able to better manage their energy in the vertical profile also in terms of speed

Completely eliminating level-offs is not possible. Besides the necessary deceleration level-offs, some altitude constraints are necessary (in particular in the structure of the Paris TMA airspace) to separate intersecting traffic flows (departures and arrivals of multiple airports) and to ensure the necessary interfaces between control centers (Paris-ACC and the Approach Controls).

However, when traffic density is not at its peak, Paris-ACC and CDG-Approach are able to coordinate in order to reduce the necessary vertical constraints on the descents. Based on these precedents, a wider and semi-permanent deployment of these "coordination procedures to allow for conditionally relaxed constraints" was studied as part of the ALBATROSS project (by DSNA in cooperation with Air France and other airlines).

Multiple instances of "raised altitudes at the IAFs" exercises took place:

1. On the BANOX and OKIPA IAFs, November 2020 until April 2021

2. On all 4 Paris IAFs April until June 2021

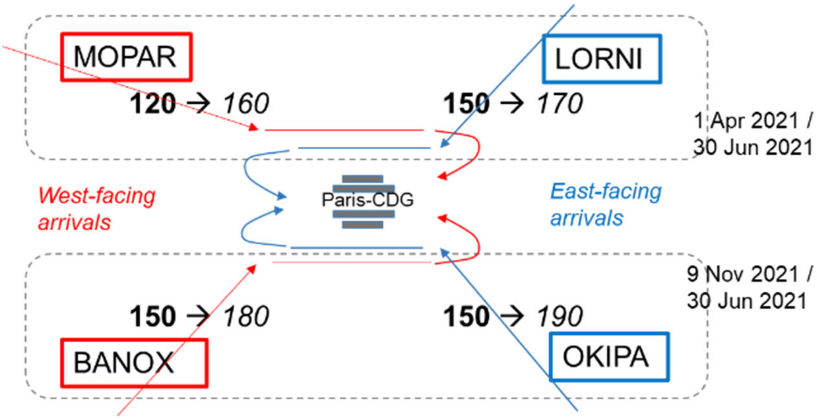
3. With an AIP-SUP publication February until July 2022

Two studies of "Further descent optimization from ToD" have also been performed: the improvements made possible at the intermediate altitudes of the TMA (interface between Paris-ACC and CDH Approach) were pushed further upstream, to the interface between the Upper Area Centers and the "extended TMA" (Brest and Bordeaux ACC to Paris ACC) :

4. CDO coordination Brest-ACC, Paris-ACC, CDG-APCH April 2021

5. Study of the PEPAX flow (coordination Bordeaux-ACC, Paris-ACC, CDG-APCH) Q2-Q4/2022

Although these two explorations resulted in a limited number of flight trials (at least during ALBATROSS – later implementation is being considered), they are excellent examples of the approach put forward by ALBATROSS : Examine in detail the constraints of a certain airspace portion; Analyze the reasons that make those constraints necessary; Evaluate whether under specific conditions (eg. certain hours in the day, or certain traffic levels or configurations) the constraints can be relaxed; Define the coordination procedures (ATC/ATC, ATC/Airlines) that must be followed in order to activate the "greener" airspace.

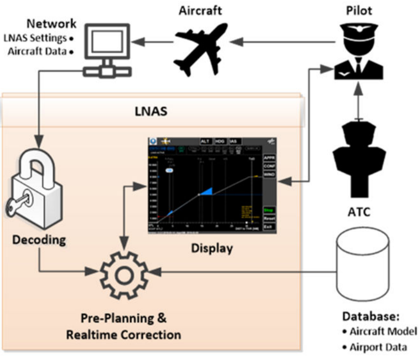


LNAS- CDA along closed-path PBN-to-ILS

The objective of this exercise was to demonstrate Continuous Descent Approaches (CDA) using the pilot assistance system LNAS (Low-Noise Augmentation System) applied to closed-path PBN-to-ILS procedures. Closed-path PBN procedures offer the great advantage of completely eliminating the uncertainty of the lateral path distance, the so-called distance-to-go (DTG), while enabling optimized energy management. For this purpose, Skyguide defined a temporary PBN-to-ILS procedure, called “ALBATROSS Sequence”. It allowed a PBN-to-ILS onto Zurich's runway 14 during off-peak hours.

DTG information for performing energy-optimized approaches was used for the profile computation in LNAS. The LNAS is a pilot assistance system developed by DLR helping pilots to optimize approaches in terms of fuel consumption and noise emissions by predicting both the optimum vertical flight path as well as the ideal speed schedule, location and timing for the flap configuration changes and landing gear extension. During the approach, recommendations are given by LNAS and executed by the pilots to obtain an energy-optimal profile at any given time.

In order to optimally integrate the ALBATROSS demo flights into the regular approach sequence, two speed constraints were defined. One is the initial TMA speed, which typically ranges between 220 kt and 250 kt. The other is the glideslope intercept speed, which was set at 170 kt for the demonstration flights. This corresponds to an un-accelerated speed on the glideslope in CONF 2 on an A320 at normal landing weights.



TMA optimization thanks to AI based tools

Within the scope of the exercise "TMA Optimization", an analysis of the TMA has been carried out by means of machine learning (artificial intelligence) and suitable algorithms, with the aim of identifying correlations and features, which lead to inefficient trajectories. The ALBATROSS project demonstrated a way, how impact factors, under which more efficient flight trajectories could be achieved, can be identified, by using machine learning methods in various traffic demand situations.

These methods considered not only local phenomena, such as load factor or weather conditions at the airport but each flight was evaluated with respect to the state of the entire air traffic system with a radius of 120NM around the airports of Frankfurt (EDDF), Düsseldorf (EDDL) and Cologne-Bonn (EDDK).

Overall, the ALBATROSS project demonstrated that machine learning methods can be applied to identify factors that can lead to more efficient flight trajectories in various traffic demand situations.

This can ultimately help optimize flights in the airport terminal area, improve the efficiency of airport operations, and enhance safety.

Appendix A Optimum Flight Detailed Description

A.1 FLIGHT vs. GROUND phase

Ground operations are intentionally excluded. The rationale is the following:

The constraints that affect Ground operations are of a very different nature than those that affect Flight. The most obvious difference is the aircraft on ground can turn its engines off.

Although some of the constraints on Ground operations can be classified as ATM measures (taxiway routings, specific runway configurations etc.), Ground operations are considered more related to airport operations (CDM processes such as gate allocation etc.) and therefore not fully aligned with the scope of this document, which is primarily about the flight.

Assessing Ground operations like ALBATROSS is doing for the Flight phase, i.e., by using the "ideal optimum" as a comparison, is out of the scope and off the expertise of this project.

That being said, improvements to reduce CO2 emissions during GROUND operations can certainly be identified, but should be considered as stand-alone Solutions (e.g., single-engine taxi, TAXIBOT, usage of renewable power supplies for ground equipment etc.) or referenced to via other initiatives and/or projects. These improvements will then be added cumulatively to the overall improvement of the Gate-to-Gate concept.

A.2 Aerodynamics / Speed

A.2.1 Cruise flight

In cruise flight, the thrust (or power) required to sustain a certain airspeed can be illustrated in figure 8 below:

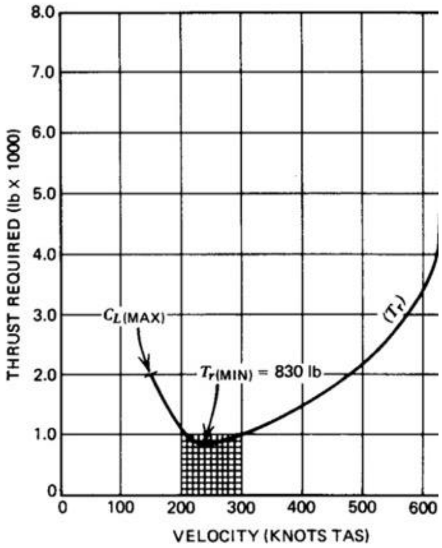


Figure 3: Thrust/Power vs. TAS

NOTE: The distinction between thrust and power refers to jet-engines (thrust) versus propeller-engines (power). The curves for these have a similar shape, and turbo-fans are somewhere in-between the two.

NOTE: The thrust required in order to sustain a certain airspeed means more precisely the thrust necessary to produce lift (over the wing) required to overcome drag of the aircraft.

For the reasoning on the minimum CO2 flight (OF), the quantity of interest is the minimum fuel required to produce necessary thrust or power to provide the most fuel optimum trajectory (either momentarily, the whole trajectory or anything in-between). The fuel required can be considered as proportional to that thrust or power.

Therefore, those curves are the basis for optimum performance reasoning.

The equations and curves governing cruise flight can be used to evaluate both range and endurance of an aircraft, both of which are linked to fuel flow:

Range is the **distance** that the aircraft can fly until it runs out of fuel

Endurance is the **time** it takes to run out of fuel.

For the same aircraft, the flight conditions that give the maximum range are different from the flight conditions that give maximum endurance.

ALBATROSS OF will be defined as the flight giving minimum fuel required to reach its destination at a given **distance**, i.e., maximum range, and the necessary **time** is not of interest (the aircraft can stay in the air forever as long as it corresponds to minimum fuel for that specific distance).

Maximum range – during cruise – corresponds to a given Indicated Airspeed (IAS) or Mach number (M) displayed on the aircraft speed scale, and this is the speed methodology uses as requirement to define OF, i.e., IAS/M for maximum range.

NOTE: Whether IAS or Mach is used depends on aircraft altitude. Mach is aircraft speed relative to speed of sound and as aircraft climbs, the relation to speed of sound becomes important as airline aircraft are not designed for supersonic flights. The change from IAS to Mach occurs at the so called “crossover” altitude which normally is between FL250-FL300, depending on aircraft type.

Furthermore, aircraft mass significantly changes maximum range where higher mass equals less range and vice versa. The rational is quite intuitive; the more weight (aircraft mass) you need to carry the more effort (engine thrust) you need to put in. To be able to provide more effort you need to be more energized (fuel). I.e., higher aircraft mass requires more thrust (end consequently higher fuel flow).

A.2.2 Cost Index (CI)

It is for this document necessary to briefly describe Cost Index (CI) as this parameter often is confusing and difficult to fully understand.

In short, CI is defined as the ratio of airline time-dependent operating costs over fuel costs. Whatever ration used by the airline (or specific flight, in some cases) this ratio is transformed into an Indicated Airspeed (IAS) on-board the aircraft, which the flight crew follows during the flight. As the ratio is timedepended, operating costs over fuel costs this means you need to fly faster to reduce your operating costs. Basically, the shorter you stay airborne, the less operating costs you have (for that flight).

However, flying faster means increased thrust and hence increased fuel flow and subsequently increased fuel consumption. This means a higher CI gives a higher IAS, thereby decreasing the operating cost but increases fuel consumption.

Now, for this approach, cost is irrelevant. The methodology only focuses on minimum fuel (for a flight from A to B). Furthermore, flight time in respect to timetable is also not relevant as the only flight time interesting for the methodology is the flight time giving the lowest fuel consumption. CI is therefore not relevant.

Nevertheless, CI can indirectly be used in the context of the most fuel optimum flight. If the cost of time is ignored (i.e., you can stay airborne "forever") then CI will equal maximum range and hence minimum fuel (this is achieved by using C = 0 on-board the aircraft). Consequently, if using CI = 0, this will be transformed to the most fuel optimum IAS (i.e., maximum range) to be used by the flight crew (with additional margins to lowest, possible speed for that specific aircraft including all variable parameters, e.g., aircraft mass).

In summary, CI = 0 can be used as an enabler to provide the most fuel-efficient IAS, but CI as such is not an indicator for most fuel-efficient flight (as it is focussing on costs).

A.2.3 Take-off and Landing

The explanation and discussion above apply to cruise flight only.

Takeoff and landing are very limited in optimizing from a fuel perspective. The reasons are several:

- For performance reasons (i.e., safety), takeoff and landing are conducted in headwind to greatest extent possible. The reason is headwind has a positive effect on aerodynamic lift hence lower groundspeed for liftoff/touchdown is needed and subsequently shorter runway required. I.e., further optimizing based on atmospheric conditions is very difficult as takeoff and landing in headwind is strongly driven by safety.
- For takeoff, one of the main contributors to fuel saving is lowest flap setting possible. This leads to less drag, better initial climb performance and therefore less time spent at low altitude overall (meaning less fuel usage). However, as takeoff is defined from liftoff to stabilized CAS at 35 ft above runway end, the actual winning of lower flap setting will take place in the departure phase rather than the takeoff phase.
- Landing is defined from 1000 ft to touchdown. The reason for the gate at 1000 ft is this is the commonly used gate by most airlines to be stabilized in landing configuration (streamlined to fit aviation community as a whole).

  Stabilization criterions are (normally):

    - Gear down
    - Landing flap extended
    - Within margins for lateral and vertical profile (for the given approach)
    - Final Approach Speed (+10 / - 5 kts margin).
    - Engines partially spooled up (to react faster in case of go-around)
    - Landing checklist (or equivalent) completed

Any divergence from these criteria's must (by most airlines) trigger an initiation of a go-around procedure. Therefore, additional fuel saving initiatives after this gate is in theory possible, but in reality, very difficult.

Given this reasoning, takeoff- and landing phases are not further prioritized in the context of the methodology.

Note: Takeoff and landing in tailwind is normally limited to maximum 10 knots of wind.

A.3 Vertical profile

A.3.1 Climb profile

In short, the overall rationale to define the most fuel-efficient vertical climb profile is to reach cruising altitude as early as possible (if not considering cruise climb where the trajectory does not have a specific initial cruise level-off). The reason for this is for the aircraft to reach thinner air as early as possible where fuel usage is the lowest (relative to the entire flight mission from A to B).

In aerodynamic theory there are two defined speeds to reach the cruising altitude:

Vx = Best angle of climb. Meaning reaching cruising altitude at the shortest **distance**.

Vy = Best rate of climb. Meaning reaching cruising altitude at the shortest **time.**

In the context of this document, Vy will be used as the speed defining the most fuel optimum climb as this will give least time to reach cruising altitude. This may be perceived as a bit contradictory as the OF cruise portion of the flight is focused on range (which is the longest distance and not time for a given amount of fuel). The reason is quite simple; climb phase is very fuel consuming because the thrust setting is at its highest and the most fuel-efficient climb is where cruise altitude is reach as quick (timewise) as possible, i.e., best altitude gained over time (rate of climb). Vx is used if the aircraft prioritises to clear obstacles, i.e., the best speed to gain altitude over distance no matter the time it will take.

However, Vy will vary during climb to cruising altitude. Basically, to maintain best rate of climb throughout the entire climb, the speed needs to be decreased continuously. As of today, aircraft FMS does not fully cater for this requirement. Climb speed is often more a fixed climb speed/Mach being a reasonable compromise between being fixed and providing proper overall performance. Choosing CI = 0 will provide the best economical climb speed (ECON Climb) with CI as the enabler however this will only be Vy for some part of the climb.

In addition, the reasoning of having the best vertical climb profile is based on using maximum thrust possible to be maintained during the entire climb. (This is in fact not the maximum thrust possible for the engines to achieve but the maximum thrust possible still giving reasonable margins to avoid excessive engine deterioration ion. In short: careful use of high thrust settings). Using highest possible thrust setting during climb profile is the commonly used way forward in defining various climb profiles. However, in a theoretical perspective, aiming to achieve the most fuel-efficient climb profile, other thrust settings may be used. Investigating these variants is not within the scope of this methodology as this will be much more exploratory research rather than demonstration.

A.3.2 Cruise altitude

The general rule for cruise altitude is the higher the better. Thinner air at higher altitudes calls for an overall lower fuel consumption in the cruise phase. Aircraft limit for the cruise altitude are many, but one of the most significant is aircraft mass (aircraft structural limit – outside pressure vs. cabin pressure – is another). The heavier the aircraft, the lower the maximum altitude. As the aircraft burns fuel along the cruise phase, its mass decreases and it can continue to climb to a higher altitude. Ultimately, if the maximum altitude will not be reached (i.e., the distance between origin and destination is short enough) the trajectory would look like a parable where the aircraft would continue to climb until it would need to start its descend; subsequently no cruise level-off at all (called "cruise climb" and was for example partly practised by Concorde aircraft during supersonic flights).

This is the easy explanation if not considering the effect of atmospheric conditions, especially wind effect in terms of head- or tailwind.

NOTE: If going into details, the higher the better altitude is not entirely correct. The optimum altitude is the altitude corresponding to best lift to drag ratio. This is the reason maximum altitude and optimum altitude is not the same. However, in the context of this document, higher is better (not considering wind effect) is sufficient as the common rule of aircraft climbing to higher altitudes.

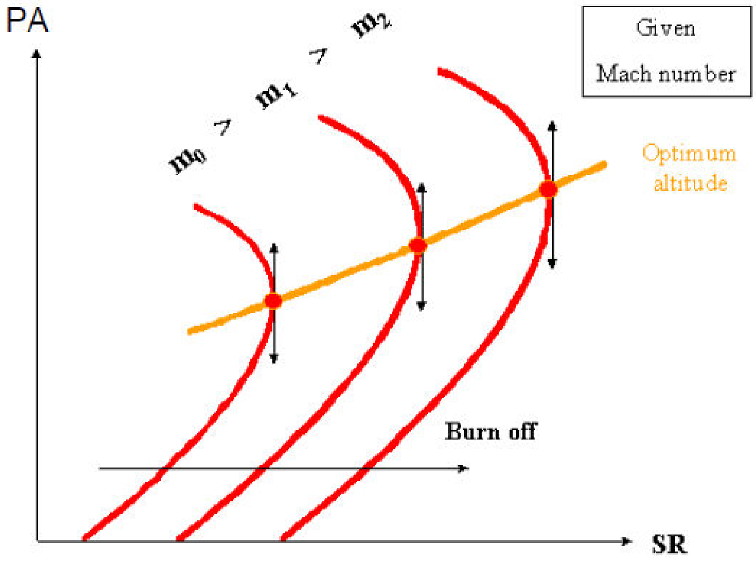
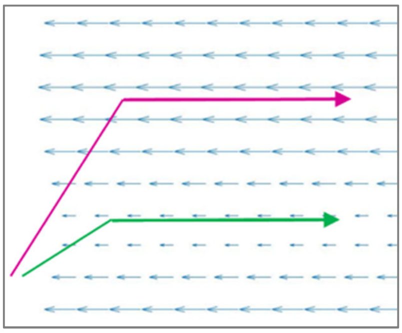


Figure 4: Optimum altitude

When considering the effect of head- or tailwind, the vertical profile of the cruise portion is getting a bit more complex, and some general rules can be highlighted:

1. It may be more fuel optimised to choose a lower altitude with more favourable winds (higher tailwind or less headwind) rather than climbing to the highest altitude as possible. This is a trade-off between the (additional) fuel required to fly at lower altitude (but with a shorter duration – air distance - due to positive wind effect) and the fuel required to climb to the highest altitude (thinner air and lower fuel consumption but lesser/no positive wind effect).

2. It may also be a combination of above-mentioned possibilities. A flight can for example start at the highest possible altitude and then descend along the route (before ToD) where the net effect of the wind is positive (or vice versa).



3. If combining the potential wind effect in the vertical plane with the potential wind effect in the lateral plane – i.e., 3D cube – the complexity of the overall trajectory increases dramatically. This would mean there are almost endless possibilities to combine different altitudes with different lateral paths and all the variants within this scope. Flight planning systems today do some kind of comparison of various routing depending on wind effect in both the vertical and lateral plane, but not exhaustive.
4. The more reliable and granular wind data, the more optimum the flight profile. This is of course valid for the entire flight missions, but as the cruise portion also may divert from trying to stay within as thin air as possible (see above) the reliability and granularity of wind data before deciding to make the trade-off becomes even more critical (as not to sub-optimise the flight instead).

Given the above-mentioned elaborations, it is once more very important to understand there is not one single OF possible to define. The *requirements* for an OF are possible to define (e.g., Vy speed during climb, idle thrust during descend, lowest possible flap setting for landing etc.) but the *actual* OF is valid only for one specific flight. And, if pushing this argument even further, OF is not valid for a specific flight, but for a specific instance of a flight. I.e., the actual conditions there and then (wind, temperature, aircraft mass etc.).

More on atmospheric conditions (i.e., wind effect) in section 4.2.6.

Note: Todays wind and weather forecasts used for flight planning are normally within 6 hours update interval. Although these forecasts are surprisingly accurate (maybe not at every specific point, but for the overall flight mission), there is still room for uncertainties. I.e., to come as close as possible to a real-life OF, the wind and weather data must be more reliable.

Note: Several studies have been done to find an optimum (vertical) profile considering wind effect, for example “Calculation of Fuel Optimal Vertical Profile” (click here for study). Further reading on this subject may interest some readers.

A.3.3 Descent profile

As for the climb profile, there is an overall rationale to conduct the most fuel-efficient descent (being part of OF):

The sum of potential and kinetic energy accumulated during climb and cruise phases must be dissipated without any excessive fuel consumption up to the point where the aircraft is stabilised at 1000 ft above field elevation. In summary, this means start descending at the exact point where the descend can be conducted with idle thrust, configured as late as possible but no later than being stabilised at 1000 ft. This also dictates a descend without any level-offs, constraining speed instructions or speed brakes.

There are some variants advocated on this description, for example, level-offs does not need to be penalising if thrust is not added (i.e., still idle thrust the entire descend). This is however not correct. To be able to reach 1000 ft and simultaneously being stabilised (i.e., in landing configuration with final approach speed spot on) there is only one optimum Top Of Descend-point possible. Any alterations from this specific point after reaching will sub-optimise the descend and the aircraft will not be at 1000 ft at the same time as all stabilised criteria are fulfilled.

A study made by DLR indicates potential fuel savings if initial and intermediated approach speed(s) are as high as possible (just below gear and flap extensions speeds) and glide slope angle around 3.4° (instead of nominal 3.0°). However, this implies a slightly later ToD (compared to optimum ToD) which then would constitute flying at cruise level a bit longer and subsequently more fuel usage overall (as the cruise portion is not conducted in idle thrust as the optimum descend would be). To be confirmed by DLR but the overall fuel consumption would still be less with a slightly later ToD (compared to nominal/optimum ToD).

NOTE: This study is not yet fully embraced by WP2 Team and should – at this point – only be seen as additional information requiring further analyse to be fully implemented in OF definition. Study reference will be provided in next version of this document, if useful.

A.4 Turning during departure and turning approach segments

For an ideal (shortest) 2D trajectory between A to B the runways would be aligned to the same runway heading. For example, take-off from airport A on a runway with heading 090° (designated as runway 09) and landing on airport B on a runway also with heading 090°. This also implies headwind must exist from the same direction on both airports (see section 4.2.3.3)

Of course, this ideal case very rarely exists (if ever) and OF must therefore also consider turning departure and arrivals in the definition.

In geometry, the term "Dubin's Path" refers to the shortest curve (path) that connects two points in a 2D plane, when the vehicle connecting the two points only can move forward. The overall conclusion is there are only three ways two make the connection:

1. Right turn (R)
2. Left turn (L)
3. Straight segment (S)

Dubin's Path further states: "An optimal path will always be at least one of the six types: RSR, RSL, LSR, LSL, RLR, LRL".

To summarize:

For OF considering turning departure and arrival there are six possible types/combinations of turns possible to make the shortest 2D trajectory (as stated above).

Figure 5: RSL connection according Dubin's Path

The intuitive logic for an OF is to use the tightest radius possible with turns as close to runway as possible, with the following considerations and limitations:

Take-Off and Departure

ICAO Doc. 8168 (PANS-OPS) states no turns are allowed before 400 ft above runway elevation. PANS-OPS also states minimum climb gradient after take-off must be minimum 3,3% (two engine operation). Given these conditions, the following applies:

400 ft / X = 0,033 -> X = 12.121 ft.

12.121 ft x 0.3048 = 3695 meter.

3695 m / 1852 = 2 NM.

Conclusion is therefore turns after take-off earliest 2 NM to be consistent with PANS-OPS regulations.

Arrival and Landing

Worldwide usage of stabilization criteria (although only recommended in regulations) at 1000 ft above runway elevation equals close to 3 NM. I.e., no turns after 3 NM before landing for OF definition.

NOTE: These limitations for OF definition are used to be fairly compliant with reality and not only have the theoretical view. However, if using available RNP AR technology, these limitations are somewhat conservative. There are not yet any set regulations for RNP AR departure, but for landing, a straight final approach segment may be less than 1 NM. However, this methodology will use the above limitations for OF definition to be compliant with the general modus operandi.

Radius of turn (both departure and arrival)

Again, one would think the most fuel-efficient way to turn from and to an airport would be to have the smallest radius of the turn as possible. Smallest in terms of aerodynamically limited (i.e., maximum bank angel, lowest permissible speed etc.). This is also the assumption for OF definition up to and including document Third Edition. However, there is ongoing work within WP2 team investigating whether it is possible to define the “perfect turn” in terms of fuel efficiency as it may not be a turn with the smallest radius. Result of this investigation will be provided in “Methodologic Approach towards green Flight” Final Edition.

A.5 Atmospheric conditions

General

One main challenge in defining the OF is how to consider atmospheric conditions and in particular the effect of wind on the lateral trajectory. Wind effect on the vertical trajectory is somewhat simpler to recognise (basically identifying differences in flight time). That said, if combining the effect of both lateral and vertical aspects together (3D), it can be very complex.

There are two (2) options of consideration for the lateral effect:

1. OF does **not** consider atmospheric conditions. This option would in many aspects simplify the definition of the trajectory, which then would be a simple great circle line between two points (origin and destination) and thereby provide a clear and recognisable reference for further comparison with live-trail flights.

2. OF **considers** atmospheric conditions which, in theory, will complicate the definition of the trajectory as all aspects of atmospheric conditions at any given point in space and time should be considered. Which, in the view of granularity, is very difficult to achieve at an appropriate and reasonable level given all the possible variants emerging.

The conclusion from WP2 Core-Team discussions identifies a need to be able to use atmospheric conditions whenever beneficial for optimising the trajectory. One simple and good example is the trajectory that is longer than great-circle distance because of offset, high-level positive wind effect which, for the entire flight mission, will have a positive net effect on the overall fuel consumption compared to a straight (great-circle) line between origin and destination.

The actual outcome of this reasoning is that the trajectory is defined as **Maximum Range / Minimum Fuel Track,** which implies that atmospheric conditions may be considered when beneficial for a specific case or cases (e.g., a specific city-pair).

This means the trajectory, in the view of defining OF, is not a set trajectory, specifically defined by geographical means (i.e., latitude, longitude and altitude) but variable depending on usage. Whether the user (e.g., WP4 will compare OF with other flight(s) to find possible improvements, the user may choose to use OF either as a great circle distance if the atmospheric conditions will not be considered in the comparison, or the user may choose to use a trajectory effected by atmospheric conditions if more relevant for the comparison in terms of minimum fuel consumption.

This reasoning is also valid for other dynamic parameters impacting the trajectory, for example aircraft mass.

Wind

From intuition and personal flying experience, it is understood flying is affected by the wind, either positive or negative (shorter or longer flying time). The explanation is somewhat different than, for example, the experience when riding a bicycle with wind in your back, but the overall conclusion is the same: wind from the back is much better than fighting against.

When flying, the wind effect can be so substantial that it may be more efficient to fly a route offset from the shortest ground distance from A to B (i.e., offset the great circle distance). What this means is the offset route (i.e., longer route) has a wind distribution giving such a favourable effect overall, the net effect of flying a longer route is positive. Furthermore, this is valid both laterally and vertically and is in all sense's dynamic. If the spital distribution of the wind is not uniform (both longitudinally and vertically), OF may need to relocate along the path (laterally, vertically, or both) to find the most optimum trajectory overall (more tailwind or less headwind).

NOTE: Efficiency or optimum in the airline sense is normally based on total cost, i.e., the most cost-efficient routing. This is not the scope of this methodology; however, the consequences of wind effect are the same both for cost efficiency and fuel efficiency.

Wind effect

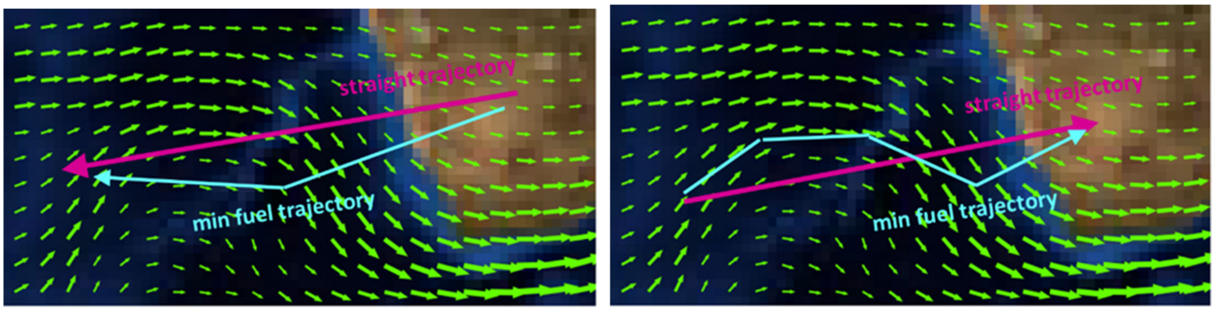
As mentioned in section 4.2.3.1, a flight achieves its longest range, and therefore the minimum fuel usage to go from origin to destination, by cruising at a certain optimum airspeed (true airspeed - TAS). The aerodynamic performance of the aircraft (how much thrust it needs, how much lift it experiences and so on) only depends on the aircraft speed relative to the surrounding air (i.e., TAS). In this context, wind is not relevant in terms of aerodynamics.

Ground speed (GS) however, is the speed taking wind into consideration. The motion of the aircraft relative to ground is the resultant (vector sum) of this motion through the air mass, and the motion of this air mass relative to the surface. This resultant is GS. In short, TAS +/- wind = GS. For example, you are flying through an airmass with TAS of 450 kts and tailwind of 50 kts, resulting in a GS of 500 kts (450 + 50).

The total time for a flight from origin to destination will depend on the speed relative to ground and is therefore depending on the wind component. Therefore, total fuel required for a flight will change with different wind components, although the fuel flow per time is the same (i.e., TAS is the same, but GS will vary).

For this reason, OF will be most fuel optimum performing its cruise flight in an air mass whose motion relative to ground (wind) is the most favorable. If the wind is not uniform over a large portion of the airspace, OF may need to relocate to where it experiences the most favorable wind component (strongest tailwind component or weakest headwind component).

Co-funded by the European Union



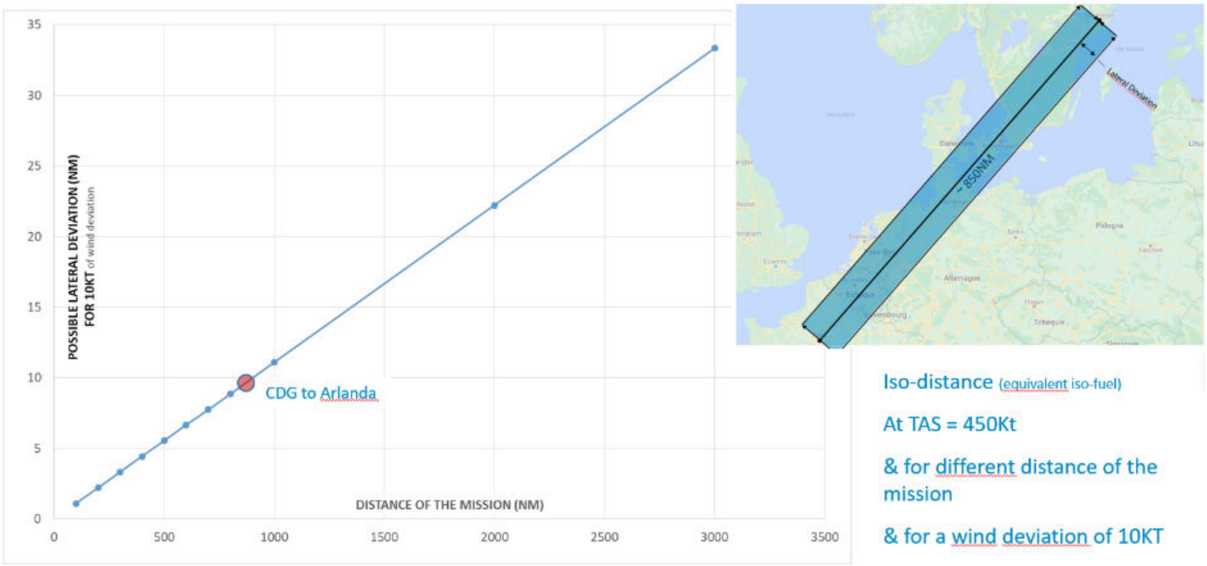
The fuel usage overall – fuel for additional distance plus (more positive) wind effect vs. straight distance plus (less positive) wind effect – will then determine the most optimum routing. In addition, as stated above, there is not only one variant and not only either in the vertical or lateral plane – but multiple combinations of these aspects that must be compared to achieve the optimum flight.

Various methods to perform this calculation are utilized; however, it is very difficult to know the instantaneous local wind very precisely, at every single point and in time and space. Flight planning software takes the wind information in consideration to some extent (tradeoff between distance and wind components in different areas and altitudes), but these tools are normally based on coarse-grained weather predictions and are therefore not full-covering and does not give the ultimate trajectory in the end.

NOTE: It is not so much the magnitude of the wind, that is of importance, but its spatial change. In short, how much stronger/weaker the wind is and how near/far to the shortest ground distance trajectory. That said, the stronger the wind in general, the greater spatial change can be found. This means magnitude does matter in terms of finding greater gradients.

Nevertheless, as a first order of magnitude, a wind difference of 5 kts leads to a variation of 1% of the fuel/CO2 usage for that particular section of the flight.

Concerning the impact of the wind on the lateral deviation, it will depend on the distance of the mission. The associated graphic can help to illustrate order of magnitude. For example, on the mission CDG to Arlanda, a lateral deviation until ~10NM can present an interest if there is a wind difference of 10kt compared to the great circle distance. The graphic illustrates that this possible lateral deviation increases with the distance for a same wind deviation of 10kt.



Iso-distance (equivalent iso-fuel)

At TAS = 450Kt

& for different distance of the mission

& for a wind deviation of 10KT

A.6 Other decarbonisation initiatives

It is clear that other decarbonisation initiatives that are not directly or indirectly related to ATM constraints and/or Solutions are also critical to improving European air traffic from an environmental sustainability perspective (e.g., Sustainable Aviation Fuels, SAF).

However, in this concept other decarbonisation initiatives are not part of OF definition, as these initiatives does not improve the trajectory as such. Indeed, these initiatives reduces CO2 emissions overall, but should be considered as an added value to what can be accomplished in optimising the 4D trajectory (horizontal, vertical, altitude and time), which is the main mission when defining the OF.

A.7 Optimum Flight Requirements

See appendix A for specified Optimum Flight Requirements.

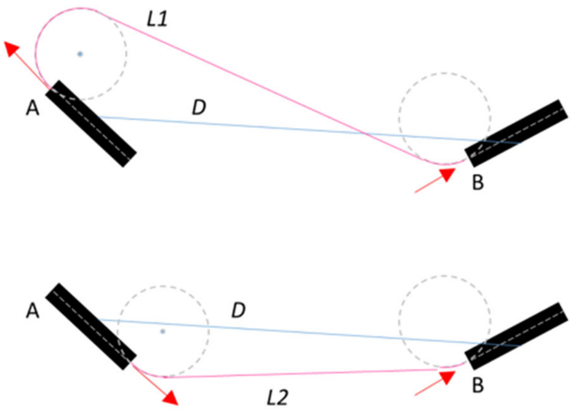
A.8 Approximations for a practically usable "Optimum Flight"

The characteristics of the OF described above are quite complex to calculate exactly. Furthermore, they are nearly impossible to achieve on a real flight. For these reasons, for a concept of OF that can be more useful in practice, some simplifications and approximations must be introduced. These are described in this section.

The magnitude of the error introduced by those approximations will be estimated.

Turns

Estimation of the error caused by ignoring the turns, i.e., approximating the flight path as straight from A to B: difference between lengths D (straight line) and L1, L2 (actual flight path).


L1
A
D
B
A
D
L2
B

Appendix B Optimum Flight Requirements Table

Flight Phase	Number OF Requirements		Constrains	Solutions
GROUND OPERATIONS	1	**Zero-fuel usage during GROUND operations** *Today's (and tomorrows) technology will - in theory - allow GROUND operations without any fuel used before take-off and after landing, except enging starting and warm-up / cool-down period.*	Technology not available Airport infrastructure Airport procedures Airline policies	
TAKE-OFF	2	**Low drag configuration (minimum flaps/slats)** *By choosing lowest flap/slat setting that meets regulatory take-off performance requirements, the aircraft will be operated with as low drag as possible. It generates better climb performance, and the aircraft spends less time at low altitude.*	Noise for population	Optimization based on a trade between CO2 / fuel versus noise.
DEPARTURE	4	**Low thrust reduction/acceleration altitude** *Reduce take-off thrust to climb thrust as early as possible and start retracting flaps/slats to have an aerodynamically clean aircraft as quickly as possible.* *Note: ICAO NAPD1 should be avoided.*	Noise for population	Optimization based on a trade between CO2 / fuel versus noise.
CLIMB	5	**Continuous Climb Operations (CCO)** *The fuel economy is improved with higher altitude, thus level flight at non optimum altitude should be avoided.*		
	7	**Climb with fuel economic speed (close to best-rate-of-climb (Vy))** *By choosing Cost Index (CI) = 0, fuel is minimised for climb and cruise to a common place in space.*	- Speed constraint : Speed limit - Be at a variable CAS, impact on Human factor (pilot and ATC).	_ If variable speed, ADS-C / APP will help the ATC to capture the aircraft behaviour. - If we stay with the current procedure: use CI=0.
	8	**Routing towards destination as early as possible** *To fly shortest possible route from Departure Airport to Destination Airport to minimize fuel usage/maximise Specific Range*	Non optimum design in TMAs Noise for population	PBN - RNP1
CRUISE	9	**Cruise at optimum altitude *and speed* to maximize Specific Range (SR)** *Change altitude with lowered mass*	ATC speed control	Miminmize ATC speed control
	9.1	**Cruise at optimum altitude *and speed* to maximize Specific Range (SR)** *Change altitude with lowered mass*	RAD restriction for level capping.	Dynamic RAD
	9.1	**Cruise at optimum altitude *and speed* to maximize Specific Range (SR)** *Change altitude with lowered mass*	Turbulence / danger area due to weather	Optimization at minimum fuel but with respect to safety
	9.1	**Cruise at optimum altitude *and speed* to maximize Specific Range (SR)** *Change altitude with lowered mass*	Contrails / Nox / Others environmental parameters	Optimization based on a criteria which consider the global climate impact and not only CO2.
	10	**Cruise Climb** *Change altitude over time in small segments to optimize the cruise altitude.*		
DESCENT	11	**DCT routing** *Fly along a route that will take you towards the destination in an as direct manner as possible.*	Arrival holding; RAD restriction imposing rerouting; activation of areas	Minimize holdings; dynamic RAD; advanced AFUA CDM
	12	**Leave cruise at optimum ToD**		
	13	**Shortest, predictable (closed) route from ToD to Final Approach Point (FAP)** *To enable a short and optimum descent trajectory*		
	14	**Continuous Descent Operations (CDO)** *Corresponding to low power/drag configuration of the aircraft until the FAP to minimize fuel from a given point in the en-route phase until the FAP, representing a speed optimizing the aerodynamic efficiency of the aircraft.*		
	14.1	**Continuous Descent Operations (CDO)** *Corresponding to low power/drag configuration of the aircraft until the FAP to minimize fuel from a given point in the en-route phase until the FAP, representing a speed optimizing the aerodynamic efficiency of the aircraft.*	250 kts below FL100	Remove 250 kts FL100 if more CO2 efficient
ARRIVAL	15	**Short and efficient IAPs** *Taking advantage of e.g. novel ICAO PBN navigation specifications*	Noise for population	
APPROACH	16	**Decelerated approach** *Managing aircraft energy in an optimized manner.*	Noise for population	
LANDING	18	**Variable Flight Path Angles in the Final Approach Segment** *Using optimum FlightPath Angle in the Final Approach segment.*	Noise for population	

Table 3: Optimum Flight Requirements

Appendix C Aircraft Flight Mechanics

The equations of motion

The forces of flight, lift, drag, intake momentum drag, weight and gross thrust, denoted by L, D, D_M, W and F_G are typically illustrated below:

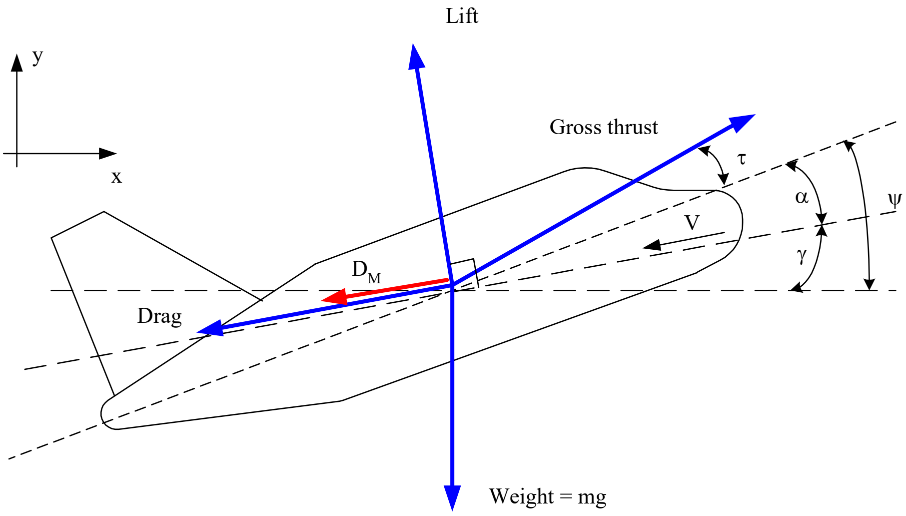


Figure 6: Forces of flight.

The velocity V is the true airspeed (TAS) and parallel to the direction of flight. The angle of attack α is the angle between the longitudinal datum or body axis and the flight trajectory.

The air path angle is denoted by γ and represents the angle between the horizon and the flight path, in level flight $\gamma = 0$. The aircraft pitch attitude is denoted by ψ. The aerodynamic forces on anybody are due to only two basic sources: Pressure distribution over the body surface and the shear stress distribution over the body surface, generating a resulting force. Lift is defined as the component of that resulting force perpendicular to V, and drag is the component of the resulting force acting on the body parallel to V.

The aerodynamic equations of lift and drag are a function of the dynamic pressure, two dimensionless coefficients and a reference area. The reference area S is commonly defined as in XX. The area is considered to extend without interruption through the fuselage. The dynamic pressure is denoted by q and C_L is the dimensionless coefficient of lift and C_D is the coefficient of drag.

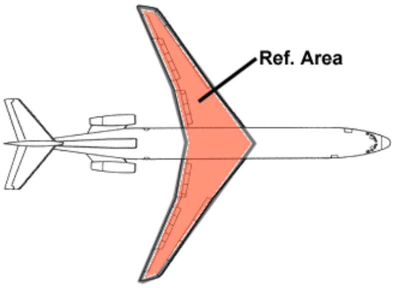


Figure 7: Definition of the reference area, S.

A distinction is made between net thrust F_N and gross thrust F_G. The net thrust plus the intake momentum drag also known as ram drag equal's gross thrust. τ is the angle between the projection of engine gross thrust vector and the aircraft longitudinal datum. The mass fuel flow is denoted Q.

The dynamic pressure is a function of the density (ρ) and velocity squared. In general, for high-speed aerodynamics is the dynamic pressure expressed in the non-dimensional speed Mach (M), which is the ration of velocity to the local speed of sound. The reason for this is a pure engineering purpose and that the speed indicator in the cockpit is associated with large errors in compressible flow. This means that all relevant equations can be expressed in many different ways.

Below, these equations are expressed in their basic forms in SI units. Note that it is common for engineers within the aerospace industry to work with SI units, although a lot of data are expressed in nautical units, for instance speed, which is commonly expressed in knots (nautical miles/hour), range in nautical miles, altitude in feet etc. The conversion is easily made with different factors. The numbers presented in this document are expressed in the most common way used within the aviation industry.

The following equations are valid:

$$L = q\ S\ C_L\ [N]$$

$$D = q\ S\ C_D\ [N]$$

$$M = \frac{V}{a} = \frac{V}{\sqrt{\Theta}\, a_{SL}}$$

$$q = \frac{1}{2}\rho V^2\ \left[\frac{N}{m^2}\right]$$

$$F_N = F_G - D_M\ [N]$$

Most methods regarding performance calculations treat the aircraft as a point mass and so ignore all considerations of rotational motion and airframe flexibility.

The following assumptions are made: If the effects of thrust asymmetry, sideslip and buoyancy are ignored and the aircraft is assumed to be flying over a flat, non-rotating Earth in still air conditions, the equations of motion may be expressed as follows[11, 12]:

Along the air path (*V* direction),

$$m\frac{dV}{dt} = F_G\cos(\alpha+\tau) - D_M - D - mg\sin\gamma$$

Normal to the air path and in the vertical plane,

$$mV\frac{d\gamma}{dt} = L + F_G\sin(\alpha+\tau) - mg\cos\gamma$$

The instantaneous mass of the aircraft is related to the fuel flow by

$$\frac{dm}{dt} = -Q$$

The equation along the air path is of interest, and the following assumption is generally valid since the angles are small:

$$m\frac{dV}{dt} = F_G\cos(\alpha+\tau) - D_M - D - mg\sin\gamma \approx F_N - D - mg\sin\gamma$$

Of particular interest is steady level flight, i.e., $\frac{dV}{dt} = 0$ and γ = 0, generating the well-known statement:

$$F_N = D$$

In a similar manner can the equation normal to the air path be used and generate the following statement in steady level flight:

$$L = W = mg$$

Range

The range *R* of the aircraft is one of the fundamental parameters affecting the aircraft. Per definition, *R* is defined as the total distance traversed for a certain amount of fuel. A related quantity is endurance, which is defined as the total time that an aircraft stays in the air for one certain amount of fuel. The ratio of range over time gives velocity. *Q* is the ratio of decreased mass over time, i.e., the fuel flow neglecting things such as water drained overboard. Specific Fuel Consumption (*SFC*) is defined as the mass of fuel consumed per unit net thrust per unit time, i.e., the ratio of fuel flow to net thrust. By using some algebra, the range equation can be obtained.

$$\frac{dR}{dt} = V \qquad Q = \frac{-dm}{dt} \qquad SFC = \frac{Q}{F_N} \quad \Rightarrow$$

$$dt = \frac{dR}{V} = \frac{-dm}{Q} = \frac{-dm}{SFC\, F_N} \quad \Leftrightarrow \quad dR = \frac{-V\, dm}{SFC\, F_N} = \frac{-V\, dW}{g\, SFC\, F_N}$$

$$dR = \frac{-V\, W\, dW}{g\, SFC\, F_N\, W} = \left\{ L = W \;\; \& \;\; F_N = D \right\} = \frac{-1}{g\, SFC} \frac{V\, L}{D} \frac{dW}{W}$$

$$R = \int_{W_{START}}^{W_{END}} \frac{-1}{g\, SFC} \frac{V\, L}{D} \frac{dW}{W} = \int_{W_{START}}^{W_{END}} \frac{-a}{g\, SFC} \frac{M\, L}{D} \frac{dW}{W} = -\int_{W_{START}}^{W_{END}} \frac{a_{SL}\sqrt{\Theta}}{g\, SFC} \frac{M\, L}{D} \frac{dW}{W}$$

$$R = \frac{a_{SL}}{g} \int_{W_{END}}^{W_{START}} \frac{\sqrt{\Theta}}{SFC} \frac{M\, L}{D} \frac{dW}{W}$$

In general, it can be stated that the flight conditions for max range is obtained by carrying a lot of fuel, having a small *SFC*, flying at a relatively high altitude at the correct Mach number.

Specific Range

The most general method of considering an aircraft's range performance is in terms of Specific Range (*SR*) also known as fuel mileage, i.e., the distance travelled per unit of fuel used. *SR* is commonly expressed in nautical miles/metric ton of fuel. *SR* is an instantaneous property of the aircraft-engine combination and is usually presented as a function of aircraft mass, speed, altitude, and ambient temperature. By examining the equation for *SR* and assuming that $L = W$ and $F_N = D$ the following equation applies:

$$SR = -\frac{dR}{dm} = -\frac{V\, dt}{dm} = \frac{V}{Q} = \frac{M\, a}{SFC\, F_N} = \frac{M\sqrt{\Theta}\, a_{SL}}{SFC\, F_N} = \frac{a_{SL}}{\frac{SFC}{\sqrt{\Theta}}\, W} M \frac{L}{D}$$

Three major sources affecting the *SR* are observed, an engine term through the *SFC*, the weight of the aircraft (*W*) and an aerodynamic term, consisting of $M\frac{L}{D}$.

The *SFC* and the *W* are located in the denominator, i.e., they should be kept as low as possible to maximize *SR*. $M\frac{L}{D}$ should be maximized, which is different from the endurance equation where $\frac{L}{D}$ should be optimized.

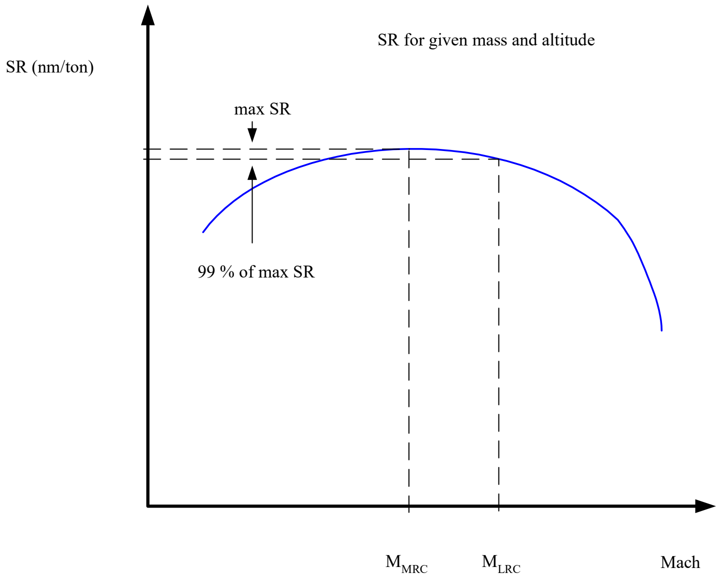


Figure 8: SR for given mass and altitude.

A typical *SR* graph is shown in XX. For a given mass and altitude, one particular Mach number corresponds to maximum *SR*, denoted by M_{MRC}. Traditionally long-range cruise has been of interest for operators, denoted as M_{LRC} defined by 99 % of max *SR* and $M_{LRC} > M_{MRC}$.

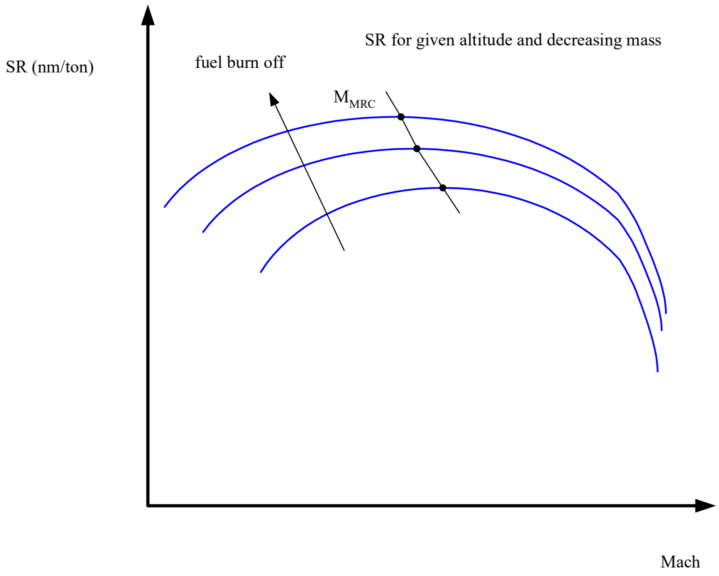


Figure 9: SR for given altitude and decreasing mass.

During cruise, the aircraft mass is decreasing due to the fuel burn. At the same time is the *SR* increasing due to the lower weight, but M_{MRC} is decreasing for a given altitude as shown in XX.

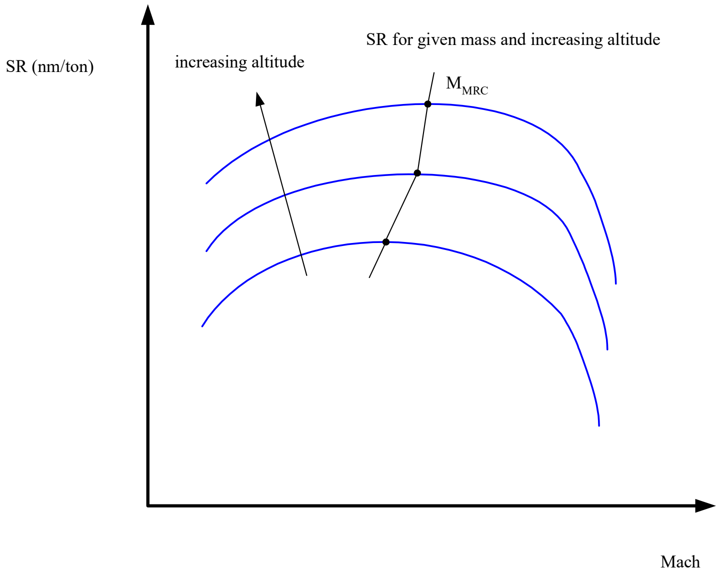


Figure 10: SR as a function of increasing altitude at a given mass.

In general, is the *SR* increasing with altitude and M_{MRC} is also increasing due to decreasing ambient pressure and temperature as shown in XX.

An easy way for the flight crews to check the *SR* in flight is to determine $\frac{V}{Q}=\frac{TAS}{fuel\ flow}$

Example:

TAS = 450 knots (nm/h)

Fuel flow = 2·1500 kg/h

$$SR=\frac{450\ \frac{nm}{h}}{3\ \frac{ton}{h}}=150\ \frac{nm}{ton}$$

Cost Index

In the end of the 1980s and beginning of 1990s with the introduction of the Flight Management System (FMS), the aircraft manufacturers gave the operators a possibility to arrange the trajectory of the flight mission with regard to time costs and fuel cost. They introduced the Cost Index (*CI*). The *CI* is defined as the ratio of time costs [€/min] (fuel excluded) to fuel costs [€/kg] and consequently is the CI expressed in kg/min.

$$CI=\frac{Time\ cost}{Fuel\ cost}=\left[\frac{kg}{\min}\right]$$

The *CI* is used by the on-board FMS to calculate minimum cost speeds for climb, cruise, and descent, known as Economy Speed/Mach or commonly abbreviated Econ Speed/Mach.

The rationale for using the CI is to allow each operator to calculate the most economical speed for their specific cost structure. It can be adjusted for changes in economic variables and considers more variables than traditional speed schedules, such as a fixed Mach number speed schedule. The price of fuel has usually been very easy to determine, but an issue for many airlines has been to properly determine a correct time cost for their specific operation. A number of varying ideas about what the CI is and its proper determination of time related costs in the execution phase have circulated among aircraft operators.

The *CI* concept can be illustrated as in XX below, where the Econ Mach number (M_{ECON}) is associated with the lowest total cost and differs from the speed linked to minimum fuel cost.

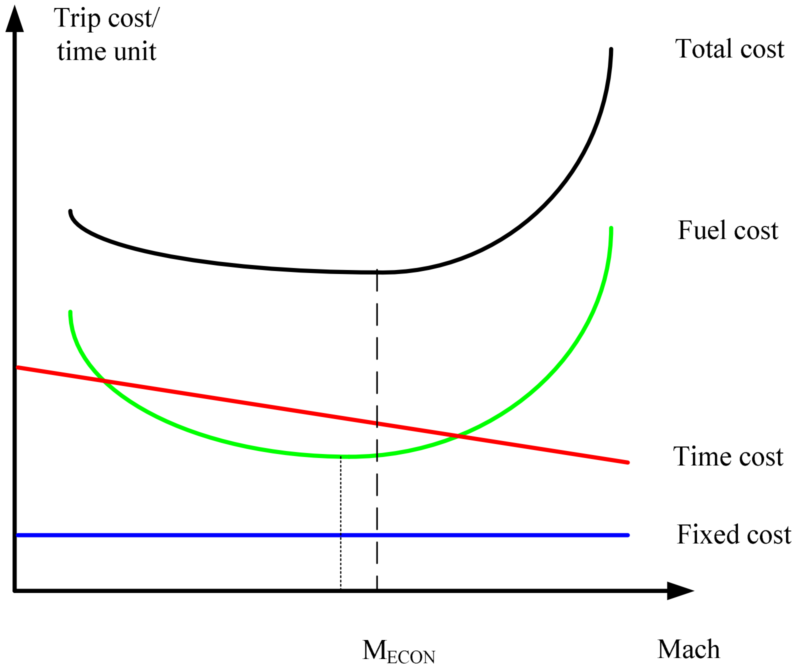


Figure 11: The relationship between CI and the minimum total cost.

There is a close relationship between the *CI* and the SR of an aircraft.

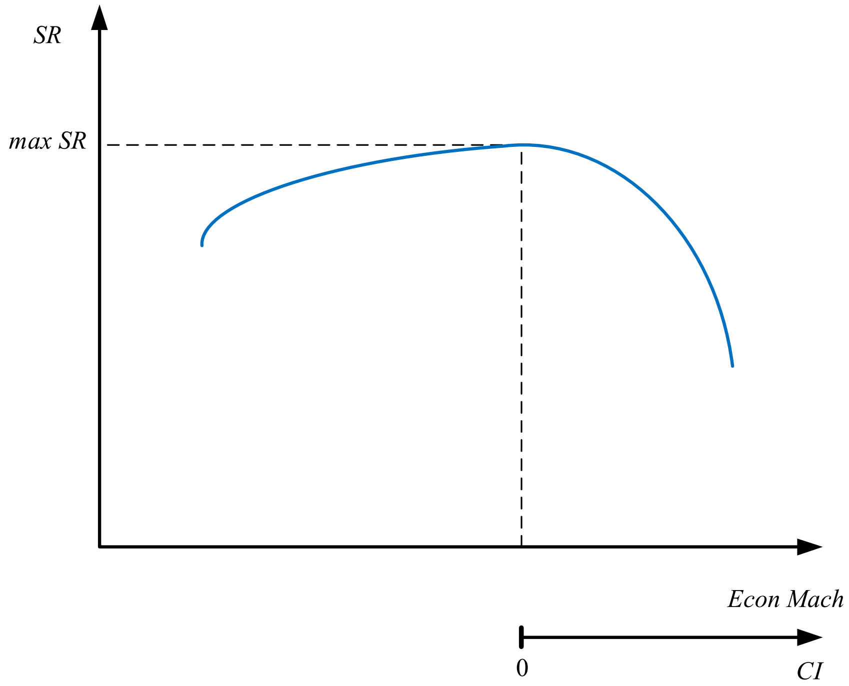


Figure 12: Relationship between SR and CI for a given mass and altitude.

For the en-route phase, the relationship between aircraft mass, altitude, SR and *CI*, which is illustrated in the relationship between *CI* and SR:

$$CI = -\left(\frac{a_{SL}\sqrt{\Theta}M^2}{(SR)^2}\right)\frac{d(SR)}{dM}$$

CI = 0 corresponds to a scenario where the time costs are infinitely small, and the FMS will guide the aircraft along the given trajectory with a speed corresponding to maximum *SR*. All other scenarios will move away from the maximum *SR* scenario allowing the aircraft to fly faster, at the price of increased fuel usage. Since the majority of all airline operation is associated with time costs, *CI* will be greater than 0.

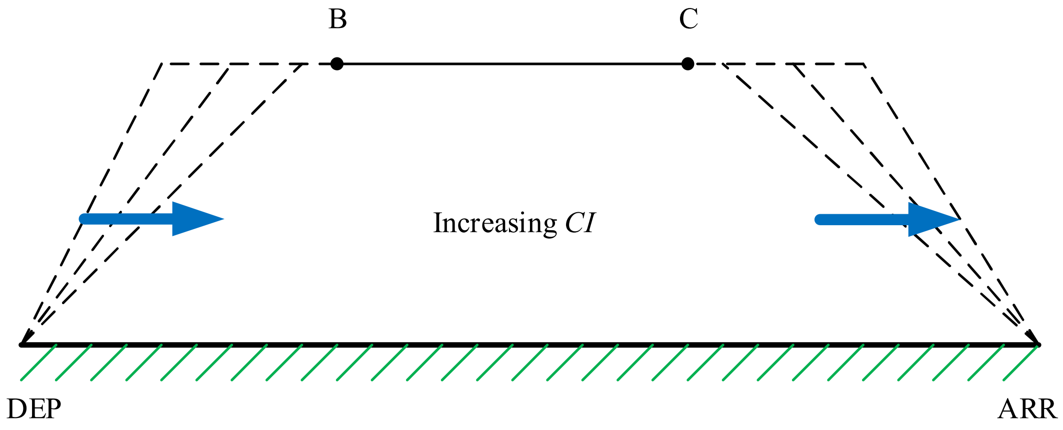


Figure 13: A typical flight with different CI.