D4.1: ENVIRONMENTAL-FRIENDLY AIRSPACE STRUCTURING AND TRAFFIC SEQUENCING

SECURITY: PUBLIC

Lead beneficiary: Michael Finke (DLR)

Contractual Due Date: M14 → M16

Actual Submission Date:
30/04/2021 (M16)

Grant Agreement number:	875154
Project acronym:	GREAT
Project title:	GREENER AIR TRAFFIC OPERATIONS
Funding scheme:	RIA/H2020
Start date of the project:	January 1st, 2020
Duration:	42 months
Project coordinator (organisation):	Michael Finke (DLR)
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This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 875154 GreAT.

DOCUMENT INFORMATION

DOCUMENT NAME	D4.1 Environmental-friendly airspace structuring and traffic sequencing
VERSION	V1.00 (final version)
VERSION DATE	30/04/2021
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SECURITY	Public

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TASK LEADER	-	-	-
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DOCUMENT HISTORY AND LIST OF AUTHORS

VERSION	DATE	MODIFICATION	NAME (ORGANISATION)
V0.01	15/01/2021	First draft	Marco Temme (DLR)
V0.02	26/02/2021	Draft	DLR, HC
V0.03	09/03/2021	Draft	DLR, HC, Pildo Labs
V0.04	22/04/2021	Draft	CARERI, HC, Pildo Labs, DLR
V0.05	27/04/2021	Review and improvements	CARERI, HC, Pildo Labs, DLR
V1.00	30/04/2021	Final version for submission	DLR

DISTRIBUTION LIST

FULL NAME OR GROUP	ORGANISATION
GreAT Consortium EU	DLR, L'Up, HC, CIRA, Pildo Labs, UPM, KLM
GreAT Consortium China	CAAC ATMB, CARERI, CAUC, CETCA, NRIEE, NUAA
Project Officer	European Commission / INEA
Other	

EXECUTIVE SUMMARY

Addressing environmental challenges, especially global warming, is more than ever a must for the community. This matter is becoming an increasing priority at regional and global level. Europe has made commitments to reduce the aviation's environment footprint; hence, it is contributing to climate change, increasing noise, affecting local air quality and consequently affecting the health and quality of life of European citizens. Due to Covid-19, the air traffic is drastically reduced and it is expected that it will need five to ten years to recover to 2019 numbers. This offers the chance to rebuild it greener than before. The air traffic in Europe was growing until 2019 and is expected to continue increasing significantly in the future again in order to cope with the growing demand for mobility and connectivity. A long-term effect on the environment from aviation sector, mainly caused by aircraft noise and exhaust gases (especially CO_2, nitrogen oxides NO_x and methane), make it a clear target for mitigation efforts. The future growth of aviation shall go hand in hand with environment sustainability policies. Therefore, studies and research are being conducted in Europe exploring possible optimization of the aircraft technologies as well as Air Traffic Management operations. Given the close interdependency between flight routing and environment impact, optimization in flight trajectory design and ATC operations are an appropriate means to reduce the emissions in short- and medium-term periods.

The international project "Greener Air Traffic Operations" (GreAT) has been launched in line with this perspective. This project will be conducted in cooperation between Chinese and European partners.

Within this concept document on hand, the foundation is created for developing and advancing greener ATM procedures and techniques in the project. This is done by performing a detailed description of new ATM principles for airspaces and airports in Europe and China, considering the requirements for ATM collected and evaluated in the GreAT main work package 2 document "Current TBO Concepts and Derivation of the Green Air Traffic Management Concepts".

A new airspace design is described with a slightly extended scheduling horizon for arrival manager and late merging points on the final for the organization and guidance of inbound traffic, sub-divided for different airport topologies. The necessary and desirable controller support system enhancements for arrival, departure and surface management systems are presented for implementing the green late merging principles. Next to the extended horizon for the early considering of approach air traffic to enable individual trajectory based operations, the T-Bar and the Point Merge airspace structure designs and approach procedures are described with its operational implementation. In addition, T-Bar controller and pilot supporting functionalities of MergeStrip for controller assistance systems to guide approaching aircraft crews are part of this document. The final section addresses the special challenges of closely spaced airports whose arrival and departure routes interact. These constellations, known as metroplex areas, represent a special situation for controller planning and support systems, since the requirements of neighboring airports must be taken into account in their own sequence planning.

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GLOSSARY

Acronym	Signification
$\Delta L_{A,max}$	Difference between maximum noise levels
A-CDM	Airport Collaborative Decision Making
A-FMS	Advanced Flight Management System
ADCO	AMAN-DMAN-Coordinator
ADS-B	Automatic Dependent Surveillance Broadcast
AFI	Arrival Free Interval
AI	Artificial Intelligence
AIM	Aeronautical Information Management
ALDT	Actual Landing Time
AMAN	Arrival Manager
AMSL	Above mean sea level
ANSP	Air Navigation Service Provider
AO	Aircraft Operator
AOBT	Actual off-block time (AOBT
AOC	Airline Operation Center
ATC	Air Traffic Control
ATCO	Air Traffic Controller
ATFCM	Air Traffic Flow and Capacity Management
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
ATS	Air Traffic Service
CADEO	Controller Assistance for Departure Optimization
CCO	Continuous Climb Operation
CDA	Continuous Descent Approach
CDM	Collaborative Decision Making
CDO	Continuous Descent Operation
CFMU	Central Flow Management Unit

CTO	Calculated Time Over
CTR	Controlled Traffic Region
DMAN	Departure Manager
DME	Distance Measuring Equipment
DNM	Directorate Network Management
DOMP	Direct-only Merge Point
DTG	Distance-To-Go
eFPL	extended Flight Plan
EIBT	Estimated In-block Time
ELUT	Estimated Line-up Time
EOBT	Estimated Off-block Time
EOC	Essential Operational Changes
ENGM	Oslo Gardermoen Airport
ETA	Estimated Time of Arrival
E-TMA	Extended Terminal Maneuvering Area
EUROCAE	European Organisation for Civil Aviation Equipment
FDR	Flight Data Recorder
FIR	Flight Information Region
FMS	Flight Management System
FRA	Free-route Airspace
FUA	Flexible Use of Airspace
HMI	Human Machine Interface
IAF	Initial Approach Fix
IAP	Instrument Approach Procedure
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
kg	Kilogram
KPA	Key Performance Area
KPI	Key Performance Indicator
LDACS	L-band Datalink/Digital Aeronautical Communication System

LKPR	Václav Havel Prague Airport
LMP	Late Merging Point
MATIAS	Hungarian Automated and Integrated Air Traffic Control System
MET	Meteorology
MTMA	Military Terminal Maneuvering Area
MWP	Main Work Package
MUC	Munich Airport
NOP	Network Operations Plan
OPD	Optimized Profile Descent
OTA	Oceanic Tailored Arrival
P-RNAV	Precision Area Navigation
PBN	Performance Based Navigation
PCP	Pilot Common Project
PMS	Point Merge System
RAD	Route Availability Document
RBT	Reference Business Trajectory
RLUT	Earliest Line-up Time
RNAV	Area Navigation
RNP	Required Navigation Performance
ROT	Runway Occupancy Time
RPAS	Remotely Piloted Aircraft Systems
RPM	Revolutions Per Minute
RTC	Remote Tower Center
RTO	Remote Tower Operations
RWY	Runway
SFC	Specific Fuel Consumption
SGMAN	Stand and Gate Manager
SID	Standard Instrumental Departure Route
SLDT	Scheduled Landing Time
SMAN	Surface Manager

SOIA	Simultaneous Offset Instrument Approach
SPO	Single Pilot Operations
STAR	Standard Arrival Route
STOT	Scheduled Take-off Time
SWIM	System Wide Information Management
TA	Tailored Arrival
TBO	Trajectory-based Operations
ToD	Top of Descent
TMA	Terminal Maneuvering Area
TMAN	Turn-around Manager
TRA	Temporary Reserved Areas
TOBT	Target Off-block Time
TRACC	Taxi Routes for Aircraft: Creation and Controlling
TSAT	Target Start-up Approval Times
TTOT	Target Take-Off Times
UAS	Unmanned Aircraft System
VGMT	Variable Ground Movement Time
VMC	Visual Meteorological Conditions
VTT	Variable Taxi Time
XMAN	Cross Border Arrival Manager
XMAN	Abbreviation for the group of AMAN, DMAN, SMAN, TMAN, SGMAN

1. INTRODUCTION

Climate change and global warming is one of today's most serious global challenges that will constitute a significant danger for future generations [Matthews 2017]. This is even amplified by the fact that the climate change is a relatively slow process, which is caused by the accumulation of greenhouse gases over years and decades [Rahmstorf 2007]. When thinking only for the next couple of years in advance, the changes are hardly measurable; this is why economic interests have always been prioritized in the past. The further emission of greenhouse gases by daily traffic, energy production with coal or an outdated technology used in a factory was seen as acceptable, as it provides seemingly only a relatively small contribution to worldwide climate change. In addition, trying to save emissions here would not noticeably change the situation within the near future.

In the last few years, this attitude started to change, as the consequences of the climate change are more and more recognizable to the public. In the same way, also the awareness increases that every emission of greenhouse gases – no matter how small it is – accumulates over the years and decades and makes a difference. The Intergovernmental Panel on Climate Change (IPCC) considers carbon dioxide (CO_2) as the principal greenhouse gas [IPCC 2014]. Aviation represents approximately 2% to 3% of the total annual global CO_2 emissions from human activities and, in addition to CO_2, has impacts on climate from its non-CO_2 emissions (e.g. NO_X, particles) [McCollum 2010]. Uncertainties still exists in the assessment of the impact of the aviation emissions on the environment especially effects associated with non-CO_2. Nonetheless, non-CO_2 impacts cannot be ignored as they potentially represent approximately 60% of total climate impacts that are important in the shorter term[1]. Regarding the Radiative Force (RF) of all aircraft emissions, studies estimate the aviation impact to be within the range 2% to 8%. The wide range of the impact estimations results from the complicated calculations of the altitude depending of all involved emissions [Jungbluth 2018]. The CO_2 and non-CO_2 emissions from aviation are increasing continuously. Nevertheless, CO_2 emissions are becoming of high priority provided its long-term effect. A more precise assessment of the environment impact caused by aviation sector will be performed within GreAT Work Package 7 "Evaluation of Environmental Impact". As a conclusion, it is also worth thinking about how even small gas emissions can be reduced or avoided. Although aviation only contributes to global CO_2 emissions with a low percentage, emissions savings that can be achieved there – even if they are small – are important.

In the further context of this document, the word "controller" is used synonymously with "air traffic controller"(ATCO).

1.1. PURPOSE OF THE DOCUMENT

The purpose of this document is to describe and derive greener ATM ideas and concepts for further developments, which are the basis for the MWP4 (short-haul) developing procedures and for validation activities of Work Package 6. These procedures and improvements will lead to an advanced ATM in specific use cases (e.g. TMA of a medium-size airport), capable of handling the same or even a higher amount of traffic with less fuel consumption and greenhouse gas emissions.

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[1] https://www.easa.europa.eu/eaer/climate-change/aviation-environmental-impacts

1.2. SCOPE

This document will present new ATM practices for supporting environmentally friendly flying in Europe and in China. This serves the developing of support systems for the realization of the greener ATM concepts, described in the GreAT document D2.1 “Current TBO Concepts and Derivation of the Green Air Traffic Management Concepts”. Further, existing developments, achievements and intentions regarding greener ATM in all participating countries are considered, as well as requirements on ATM concepts defined by ICAO. As current research activities and future roadmaps are very much pointing at realizing trajectory-based operations (TBO), this document is also focused on TBO, being the way to go in order to transform the Air Traffic Management System.

Based on this, flight-centered concepts and procedures of fuel-efficient ways of conducting flights during approach and departure phase are described. The approach procedures follow the Late-Merging principle, allowing appropriate technical equipped arriving aircraft to fly along separated routes individual FMS-optimized trajectories with their own speed and altitude profiles as long as possible. The merging of the approaching traffic is implemented only a few miles before touchdown. Into this approach-centered airspace and procedure design, departure routes are integrated allowing Continuous Climb Operations (CCO) with a minimum amount of constraints. For the operational implementation of these procedures, this document describes new controller supporting functionalities and visualizations for Arrival, Departure and Surface Manager.

1.3. INTENDED READERSHIP

This section describes the intended audience for this document. In general, readers of this document can be:

1) Readers internal to the project, using this document as input for their own activities.
2) Readers of GreAT sister projects (ACACIA, CLIMOP, ALTERNATE), using to follow latest developments and approaches, and to drive scientific exchange between the sister projects. This is for aligning the activities of all four projects and identifying synergy effects. Finally, this document can also serve as reference for scientific publications.
3) Readers from the GreAT Advisory board, in order to provide input and to follow the developments from a stakeholder point of view.
4) Readers involved in current and future projects dealing with reducing the impact of aviation on climate change and other environmental parameters, especially to build upon the approaches described in this document; and to align other developments (e.g. modifications to aircraft propulsion and airframe) with it.
5) Readers from air navigation service providers or other stakeholders not involved in the project but effected from its developments (especially airports, airlines or ATC equipment providers).
6) Standardization bodies and regulating authorities and organizations like ICAO, EASA, EUROCONTROL or CAAC.
7) All other interested members of aviation community.

1.4. STRUCTURE OF THE DOCUMENT

This document contains the following sections:

Chapter 1 Introduction – describes the purpose and scope of the document, the intended audience and the document structure.

Chapter 2 Analysis of Existing Airspace Designs and Procedures – summarizes airspace design and approach procedures to organize inbound traffic in the TMA and the vicinity of airports.

Chapter 3 Extended Horizon and Late Merging – outlines the new airspace design with the extended planning horizon for arrival manager and the positions and constraints of late merging points for different airport topologies.

Chapter 4 New Controller Assistance Functions for Late Merging – describes necessary and desirable controller support system enhancements an arrival, departure and surface management systems.

Chapter 5 The T-Bar Airspace Structure and Approach Procedures – outlines the new T-Bar airspace design and the operational MergeStrip implementation.

Chapter 6 Controller and Pilot Supporting Functionalities Enabling a Greener Use of T-Bar Based Procedures – describes necessary and desirable controller support system enhancements and arrival management systems to guide approaching aircraft crews.

Chapter 7 Point Merge Based Airspace Modelling and Flight Procedure Design - describes basic mechanisms of the Point Merge approach system technology usually used in conjunction with Continuous Descent Operation to improve trajectory predictability and fuel efficiency.

Chapter 8 Integration of Metroplex Areas – describes the concept in traffic sequencing for metroplex areas, where the competition of airspace resources among airports, runways and space for arrivals and departures arise.

Chapter 9 Summary – brief summary of the document content.

Chapter 10 References – contains the references.

2. ANALYSIS OF EXISTING AIRSPACE DESIGNS AND PROCEDURES

The Terminal Maneuvering Area (TMA) as the airspace around an airport is the region, where arrival and departure flows converge. Designed to support the organization of traffic in a safe manner by controllers, it may be a source of significant flight inefficiencies, particularly in dense and complex TMAs [EUROCONTROL 2021]. This is especially true for metroplex situations, where airspaces serving more than one large airport and traffic flows have to be strategically separated to ensure the highest possible level of safety.

The ideal approach procedure keeps aircraft high, at low thrust, and in a clean aerodynamic configuration for as long as possible [Reynolds 2005]. In this way, noise impacts on the ground are minimized and fuel burn savings are maximized. Although approximately 80% of the remaining inefficiencies of a flight occur within a 40 NM radius of an airport [Molloy 2015], it is particularly difficult in the TMA to meet the specifications of an ideal approach.

As a result, Air Traffic Control (ATC) has to make trade-offs between environmental benefits, the technical and aerodynamic realities of the way aircraft must be flown by flight crew, and the need for operational flexibility for a safe and efficient handling of traffic.

According to the air traffic, further constraints must be considered. First, there are other aircraft around. Some have the same destination airport, some are departures, and some aircraft are only crossing the airspace. All airspace users have to be coordinated and it is obvious, that everybody has to make compromises regarding routes, speeds, and altitudes. Usually, aircraft arrives from all directions to an airport, where they must be merged into several streams based on the number of runways. Theoretical, the latest waypoint for merging is the runway threshold. For obvious reasons, it is not possible to merge the arriving traffic only at the threshold.

The progressive merging of arrival flows into a runway sequence is often performed in current day operations with open loop vectoring when path stretching or shortening is required [EUROCONTROL 2010]. In case of high traffic, air traffic controllers typically issue a large number of tactical heading, speed, and altitude instructions. The average number of clearances of a route system is an indicator for the complexity of an airspace and therefore is used for its complexity calculation [Sridhar 1998]. This method is highly flexible, enabling the controller to synchronize the aircraft behavior through speed and altitude advisories. However, it results in high workload both for flight crews and controllers, and in an intensive use of the radiotelephony. Indeed, it generally requires numerous actions to deviate aircraft from their most direct route for path stretching – and later put them back towards a waypoint (e.g. the Initial Approach Fix IAF) or the center line for integration in the arrival stream.

Today, in a number of busy European TMAs, Arrival Management tools have been deployed to support controllers in planning and building of arrival sequences. These are important, because some of the busiest airports are determined to use old airspace structures and procedures, which were defined in former days with much less air traffic, but are not suitable for high traffic situations common today. Additionally, the runway systems of some of the biggest airports like London Heathrow and Paris Charles de Gaulle are running most of the time at their absolute maximum of the theoretical traffic capacity. This can only be achieved through perfect coordination between the structuring of the available airspace, excellent training of air traffic controllers and sophisticated controller support systems tailored to the airport.

Due to uncertainties on aircraft trajectories (for example in the case of short haul flights), and sometimes airspace boundaries issues, these support tools are offering at best an operational horizon in the range of a little more than 30 minutes before touchdown.

However, in some of the busiest TMAs like London, Paris or Frankfurt, the use of an AMAN has proven useful to support the sequence optimization and implementation, including traffic pre-sequencing through coordination between ACC and Approach [EUROCONTROL 2010]. Nevertheless, some airports like Heathrow in London and Schiphol in Amsterdam have successfully tested Extended AMAN (XMAN) functionalities with a planning horizon of more than 90 minutes (500 NM radius around the airport) [Besnard 2019].

During the last twenty years, the DLR Institute of Flight Guidance in Braunschweig has developed arrival management systems for different kinds of scientific applications on various international airports. The latest version of DLRs previously developed arrival manager tools "COMPAS" [Voelckers 1990] and "4D-Planner" [Gerling 2002] is the 4-dimensional Cooperative Arrival Manager (4D-CARMA). Both previous versions are results of research projects in close cooperation with the Deutsche Flugsicherung GmbH (DFS). Considering different constraints like weight classes, runway separation criteria, or runway allocation, 4D-CARMA uses radar data and additional information like flight plans of all arriving aircraft for sequencing and trajectory calculation. The conflict free 4d-trajectories are generated from the current aircraft position to the threshold of the assigned runway and generates advisories for controller support to enable pilots to follow timely precise the planned trajectories. In coordination with other air traffic controller support tools like Departure Manager (DMAN) or Surface Manager (SMAN), this works through the Terminal Maneuvering Area (TMA), upstream sectors, and the airport runway- and taxi-system. At the same time, 4D-CARMA monitors the actual traffic development and adapts the scheduling to all deviating trends.

Having modern AMAN available, new arrival procedures considering aspects like aircraft noise emission and fuel consumption can be implemented at airports and Area Control Centers (ACC) [Temme 2004]. It is particular interesting if modern AMAN systems are connected via data link with Advanced Flight Management Systems (A-FMS) to coordinate the traffic timely precise in a semiautomatic mode. In this way, for all arriving aircraft individual optimized approach procedures will be possible [Kuenz 2009]. Even the integration of time based and distance-based approach guidance will be possible through new airspace design and the use of XMAN [Oberheid 2008].

In this context, A-FMS or 4D-FMS means flight management systems to plan and calculate a full four-dimensional trajectory and the ability, to fly this trajectory out temporally with a deviation fewer than four seconds at every significant waypoint. This should work even in highly variable winds or fragmented wind forecasts. Three-dimensional FMS means in this context to have the ability to calculate a complete four-dimensional trajectory on a route with fix (real or virtual) FMS-points, but no added FMS-functionality to compensate deviation in time during flight because of wind uncertainties.

When constructing new airspaces for a specific airport, there are a whole bunch of constraints to consider. Runway topology, obstacle freedom, populated areas, adjacent airports, restricted military zones, or main wind directions are important for new routes and altitudes. So, if one parameter like flight distances is optimized, the downgrade of other parameters like noise emission around dense populated areas have to be considered. If the AMAN has some specific functionalities available, parameters can be optimized in dependence of traffic context or daytime. Ideally, the airspace supports the ATCO management systems and the management systems support the airspace.

Summarized, the development of new airspaces to support optimized approach procedures requires modern AMAN functionalities to exploit all benefits. Therefore, there exist some challenges of airspace design. In principle, flight management equipment of today's aircraft allows fuel saving and noise reducing continuous descent approaches (CDA). Without controller and pilot support and in conventional airspaces with narrowed approach routes, continuous descent operations have a noticeable capacity reducing effect on high traffic airports [Erkelens 1999]. For the effective and conflict free use of CDAs, arrival traffic has to be guided "time-based" instead of "distance-based" [Coppenbarger 2007]. Modern trajectory-based arrival management systems can support approach controllers in arrival sequencing and time-based guidance especially if the scheduling starts very early like

XMAN can do [Korn 2005]. But today's heterogeneous flight management system equipage of civil aircraft (A-FMS, standard 3D-FMS, and no FMS) needs an integrative concept to use the maximum advantage of the respective technical equipment [Sinapius 2015]. During all phases of approach, this requires full support for controllers and pilots [Uebbing 2011]. To prove the effectiveness of noise reducing and the reduction of fuel consumption, arrival procedures along routes have to be measured continuously and reported to arrival support systems.

In the next subchapters, today common airspace route organizations are described. Starting with direct approaches for low traffic volumes, it continues with Fan and Trombone routings for airports with medium and heavy traffic volumes. More complex structures like DME-Arcs and the Point Merge System are then presented. As special airspace solutions the holding patterns of London Heathrow and the parallel approach of San Francisco Airport are shortly introduced. All described airspace design elements will be brought more or less in the new Early Full Clearance Approach (EFCA) concept of the GreAT project.

2.1. DIRECT APPROACH

Direct approach routes are the common airspace structure for low and medium frequented airports (Figure 2-1). For example, Braunschweig/Wolfsburg Airport (EDVE) with around 12.000 IFR movements[2] per year [DFS 2015] has one east-west aligned runway with two direct transitions from the north and south to the final [DFS 2004]. However, there are some bigger airports like Los Angeles International (KLAX) or Halle/Leipzig (EDDP) which use only a direct approach airspace structure during low traffic at night times[3].

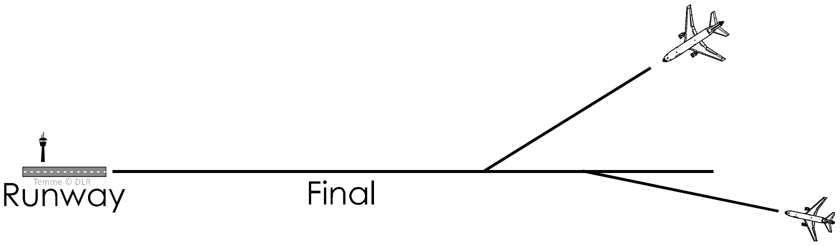

Figure 2-1: Schematic diagram of direct approach routes to the final.

The benefits of direct routes as the standard approach procedures at an airport are the simple design and the easy adaption on the traffic situation. However, the direct approach structures are unsuitable in medium and high traffic situation, because the implementation of an efficient aircraft staggering for the final is almost impossible.

2.2. FAN APPROACH

For medium- and high-frequented airports or airports with a parallel runway system exist arrival routes starting in a metering fix and fanned out to virtual points on the final. Overflying the metering fix, the controller clears a new heading in the direction of the centerline. Sometimes, several aircraft from different directions arrives at the same time at the entry fix separated by flight levels. If the aircraft have insufficient separations for the final, because they are too much in a short time, the first aircraft gets the shortest most direct route to final. The second one gets a heading resulting in a little longer route and the third one a further heading with a correspondent longer flight distance to the

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[2] IFR and VFR together at Braunschweig/Wolfsburg Airport: Around 30.000 movements per year.

[3] During daytime, EDDP uses Point Merge arrival procedures.

threshold. In this way, all aircraft gets a clearance for a slightly different intercept position (and sometimes altitude) on the final. The challenge for the controller is to be able to clear different speeds to the aircraft, because depending on the angle at which an aircraft hits the extended centerline, the remaining flight distance to the threshold is lengthened or shortened. As an additional guidance instrument, controllers have the possibility of varying the time when they clear the transition from the base onto the centerline resulting in a different angle of final intersection. This allows little corrections on separations to preceding aircraft.

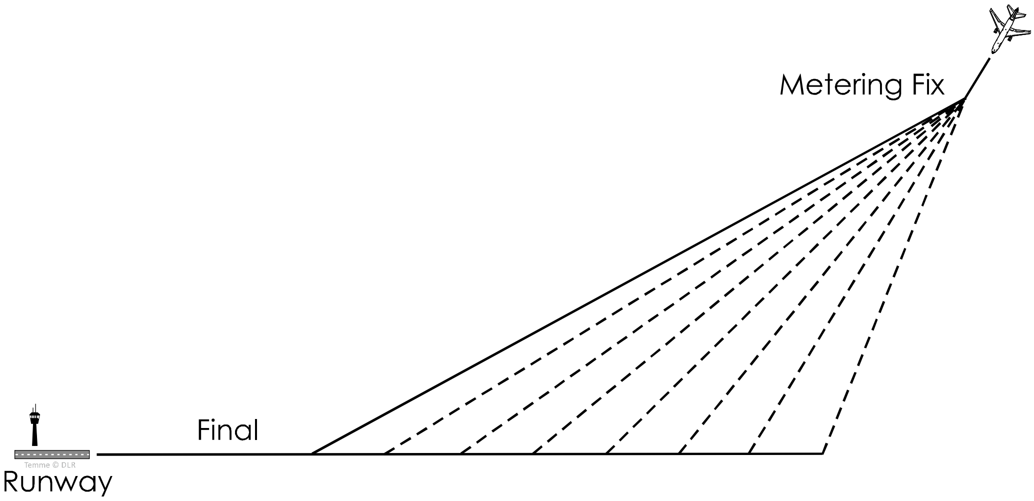

Figure 2-2: Schematic diagram of Fan airspace structure.

As an example, Paris Charles de Gaulle International Airport (LFPG) uses this kind of inbound organization (Figure 2-3). For example, starting at the north-eastern metering fix LORNI, controllers give heading and altitude advisories to the final.

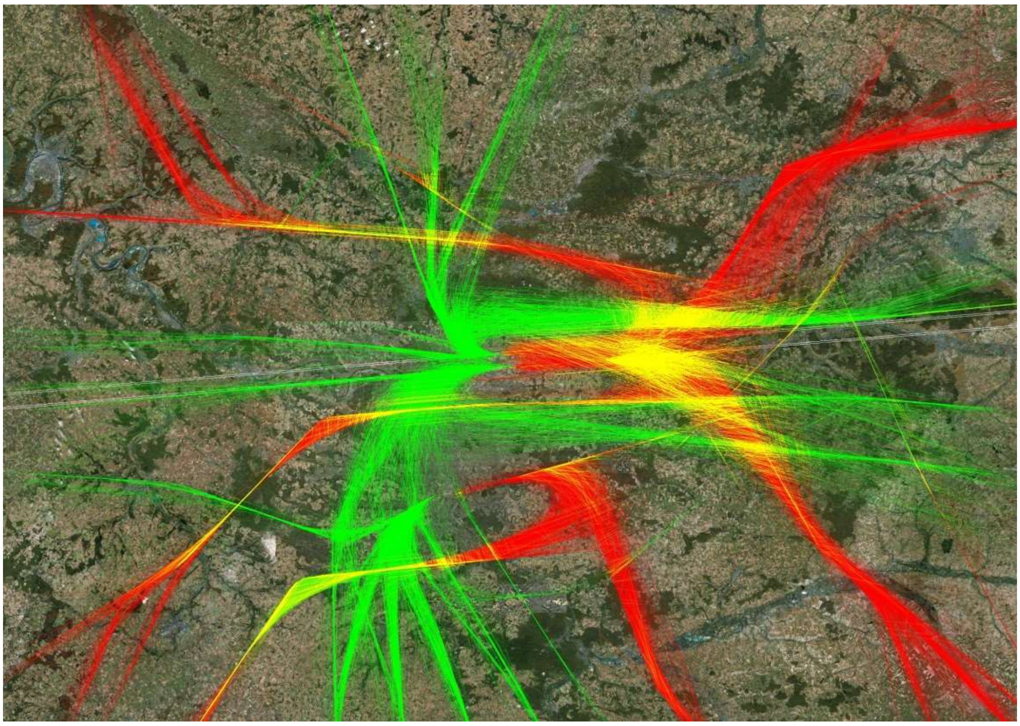

Figure 2-3: Flight trails of CDG airport in Paris. The red lines are flight tracks of inbounds and the green ones of outbounds. The Fan approaches are coming from the north-east and south-east directions (data from flightradar24.com).

The altitude clearances depend on the position where the aircraft intercept the final: The shorter the distance between intercept and threshold on the final, the lower is the cleared altitude. Usually cleared altitudes are levels of 2000 ft, 3000 ft, 4000 ft and 5000 ft.

2.3. TROMBONE APPROACH

Using downwind, base leg and final for the approach procedure, this airspace structure is called Trombone. The specific feature of the Trombone is the simple way to fit the target times and wake vortex separations when aircraft arrive from more than one direction onto the final. This Trombone airspace structure for Transitions is a very common procedure for airports with heavy traffic and therefor introduced on many airports around the world.

Like a zip fastener, the aircraft are sorted from both sides on the final at the end of the inbound stream or into a gap if available (Figure 2-4). If a downwind aircraft reaches its ideal position to meet the final, the "feeder" controller advises a turn to base and, if possible, clears the aircraft for ILS on the final.

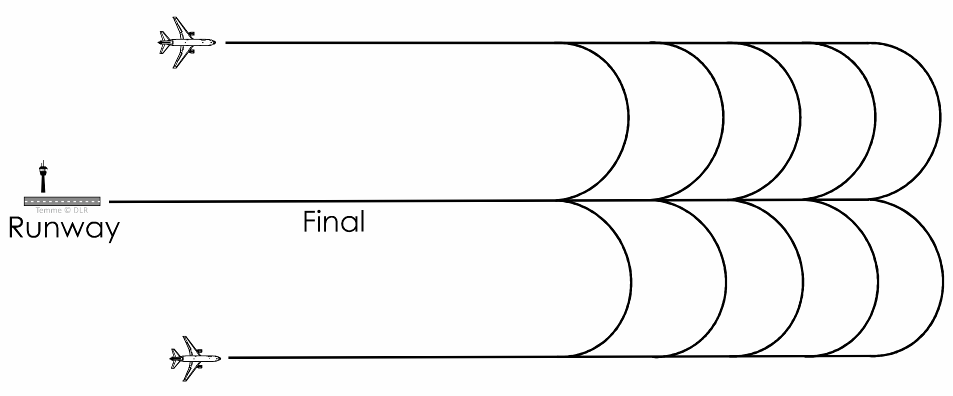

Figure 2-4: Schematic diagram of a Trombone path stretching area with north and south downwind, base legs, and final.

There are some variations of this airspace structure in use. For example, at Munich International Airport (EDDM) the controllers operate with an open Trombone. This means the aircraft have to stay on downwind until they get the turn to base clearance. At Frankfurt Airport (EDDF) for example, the Trombones have a closed structure: This means, if the flight crew gets no turn advisory, they fly as far as to the end of the Trombone like defined in the AIP and then turn on the base leg and further to the centerline. Especially in loss of communication situations on the downwind, an open or closed Trombone structure makes a little difference in the course of actions. In Frankfurt, the further steps in this non-nominal condition are defined by the airspace structure, in Munich it is defined in the procedures [DFS 2016].

Another difference between Trombone path stretching areas lies in FMS-waypoints on the final and the centerline. At some airports, there are virtual FMS-waypoints on the centerline and the final available. Therefore, controllers can give clearances for waypoints on the centerline when the aircraft is still on downwind and far away from its intended turn to base starting point. Controllers may but not need to use these defined waypoints to keep the flexibility in traffic guidance.

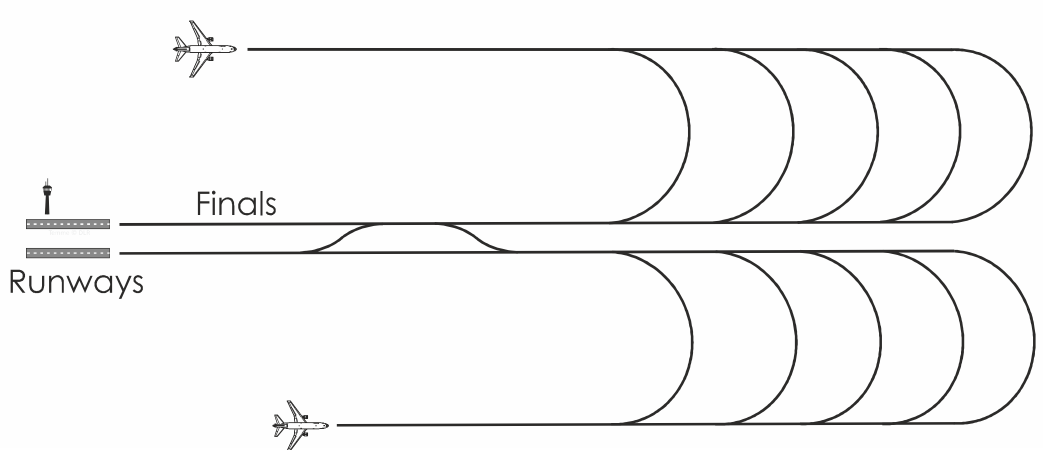

Figure 2-5: Trombone airspace structure for a dependent or independent parallel runway system with the possibility of switch-overs between the centerlines.

Some bigger airports with a dependent or independent parallel runway system implemented a double trombone system with two separated downwinds for each runway. In the example in Figure 2-5, aircraft from the north would typically guided to the north trombone to the more northern runway and aircraft coming from the south to the southern one. In the case of an unbalanced amount of traffic from one direction, controllers have the possibility to compensate capacity limitations by giving individual aircraft a clearance to swing over on the final of the parallel runway. However, this maneuver may imply a safety restriction and is therefore not very often used. A better and more safe solution for a traffic balancing is to guide aircraft spaciously around the trombone patterns to the adjacent final and runway.

If the distance between the runways is wide enough, they can be operated completely independently. For example, this is the case at Munich and Los Angeles airports. If the parallel runway system is located to narrow to each other, the runways have to be operated like a single final and runway. This is the case at the middle and southern runways in Frankfurt/Main and all runways at San Francisco International. In these cases, the controller responsible for the final approach and the double trombone system has to feed the finals in a zipper style with aircraft from the north and south alternately.

2.4. DME-ARC APPROACH

DME Arcs represent a worldwide used but not very common approach airspace structure. A DME (Distance Measuring Equipment) for air traffic navigation is a transponder-based radio navigation technology that measures the slant range distances by timing the propagation delay of VHF or UHF radio signals. DME Arcs are in use for example in Delhi/India (VIDP), Santa Fe/New Mexico (KSAF), Baltimore/Maryland (KBWI) and Clermont Ferrand/France (LFLC). Aircraft use DMEs to determine their distance from the land-based transponder by sending and receiving pulse pairs, which are of fixed duration and separation. A low-power DME can be collocated with an ILS glide slope antenna where it provides a distance to threshold function.

Some airports provide DME range measurement to lead aircraft overflying defined Initial Approach Fixes (IAF) on a ring around the airport and to guide them on final approach (Figure 2-6). On the DME arc approach, pilots are guided onto a circle flying on a ring structure around an airport until reaching the final approach path. There, controllers clear a turn to final. During flight on the arc, aircraft have to stay in level or descend slightly between cleared waypoints.

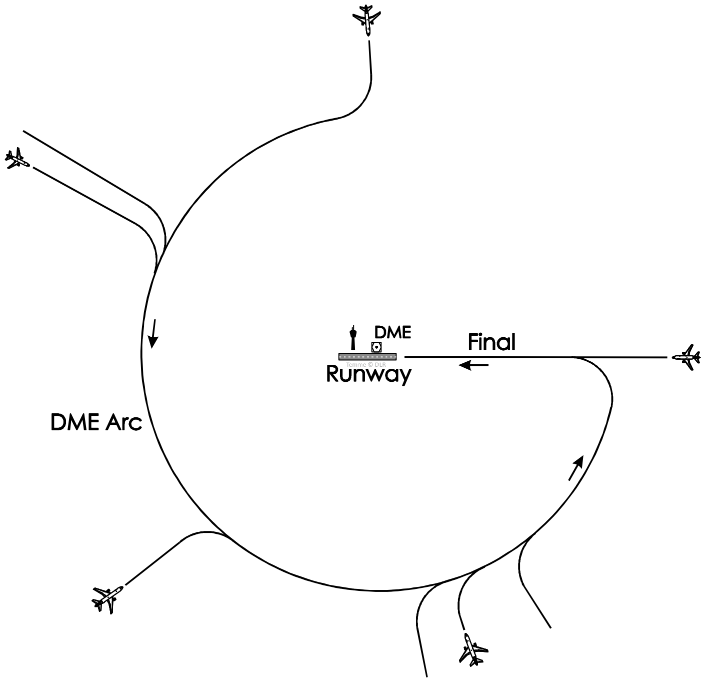

Figure 2-6: Schematic diagram of DME Arc airspace structure. At some airports, the DME Arc route structure is used like a roundabout.

On the arc, pilots may have the possibility to fly a continuous circle or partition the curved flight into smaller straight flights segments covering 20° or 30° of the circles. On airports, which are using DME Arcs to guide aircraft directly to the final, aircraft noise may be an issue, because usually glide scope intercepts are at flight levels between 2500 ft and 3500 ft. Another disadvantage of the DME Arc approach is the long distance to fly in cases, when aircraft converge the final from the averted side of the final approach path, so they have to fly nearly the complete ring structure without reducing the distance to the airport.

2.5. POINT MERGE APPROACH

The Point Merge System (PMS) is the latest development of the approach procedure airspace structures, which are now in operations. Elaborated by the EUROCONTROL, Point Merge bases partly on the principle of DME Arcs. The main differences to the older method are the number of the arcs and the fix waypoints on the sequencing legs [EUROCONTROL 2010].

A PMS should be defined as an RNAV STAR, transition, or initial approach procedure and can be described by the following characteristics: A single merge point per threshold is used for inbound traffic integration. Pre-defined sequencing legs, designed equidistant from the merge point and defined through FMS-waypoints, are dedicated to path stretching or shortening for each inbound flow. These legs are separated vertically and laterally by design (Figure 2-7).

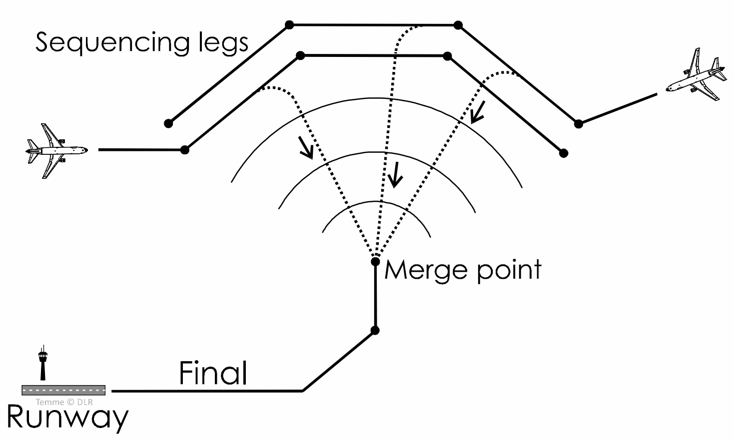

Figure 2-7: Schematic diagram of Point Merge route structure.

The distance to the merge point shall remain the same all along the sequencing legs. This is achieved with arcs centered on the merge point and FMS waypoints defining these legs. All FMS waypoints are located at the same distance from the related merge point. As a result, the arcs are not circular arcs. Instead of circles, they are segmented, forming iso-distance quasi-arcs centered on the merge point. The resulting envelope of possible paths towards the merge point is contained in a more "triangle-shaped" area. The PMS is a closed path stretching area which means, that the pilots, after flying through the complete arc without a turn to merge point clearance, heading interdependently of further controller advises to the center of the arc system.

Considering a simple configuration with two inbound flows from west and east, Figure 2-7 above provides a schematic example of a Point Merge system with two sequencing legs that are parallel and have a lateral distance of 2 NM. The flight tracks are in opposite directions and vertically separated with usually a minimum of 1000 ft.

EUROCONTROL has mentioned that there are actually some other possible PMS design options [EUROCONTROL 2010]. For example, double PMS, where one PMS feeds the arc of a second PMS. Another solution, to feed a parallel runway system, is the Multi-layer Point Merge System, a 90° rotating of the arcs [Liang 2018]. In this case, additional crossing points in the funnel area caused by the alternately approached runways from the same arc must be considered. However, the single merge point and the iso-distances with the equidistance property of sequencing legs to the merge point are the key features and invariant aspects of the entire approach procedures.

The benefits of Point Merge operations are the creating of space between the aircraft through path stretching without ATC intervention, by leaving aircraft fly along the sequencing leg, and a conclusive "direct-to" clearance to the merge point. This is advised when the appropriate wake vortex spacing is reached with the preceding aircraft in the sequence, which is already flying from the arcs to the point merge waypoint. After leaving the legs, the spacing is maintained through speed control. Unlike other procedures, the aircraft remaining in the PMS at high altitudes as long as possible and thereby reduce the aircraft noise impact on the ground. Furthermore, is has been shown, that PMS reduces the amount of radio contacts between ground and air during approach phase.

On the other hand, there are some disadvantages, which prevent the introduction of the Point Merge method at all bigger airports. For instance, the PMS is a static spacing system that needs a large airspace and is flight time consuming in low traffic periods. PMS can handle only two approach streams for each runway and through the size of the airspace structure, aircraft need extra fuel for the long approach distances. For the Point Merge System, P-RNAV is necessary, but provides only limited Continuous Descent Operations. Another disadvantage is the slightly reduced airspace capacity compared to the Standard Terminal Arrival Routes (STAR) on parallel runway systems [DFS 2017; Heumos 2017].

For this reason, the airport Halle/Leipzig in Germany quitted the PMS procedures and come back to the STARs in Spring 2020.

The PMS is set for example in Oslo-Gardermoen (ENGM), Stavanger (ENZV) and Dublin (EIDW). A special variant of PMS was introduced at London City airport (EGLC) in 2016 [EUROCONTROL 2020]. To reduce the aircraft noise exposure of downtown London, the arcs were rotated 90° and positioned above the River Themse estuary in the east of the airport. In this way, the approach funnel passes directly into the centerline and final via the merge point.

2.6. STACKING PATTERNS

Heathrow is one of the busiest airports in the world, located in the very cramped airspace around London. Most aircraft coming to land at Heathrow are guided into holding stacks, which were established in the 1960s [Reynolds 2005]. Each stack acts as a waiting room, allowing the air traffic controllers to gather aircraft for landing efficiently (Figure 2-8). There are four stacks located around Heathrow called Bovingdon (in the north-west), Lambourne (north-east), Biggin (south-east), and Ockham (south-west) (Figure 2-9).

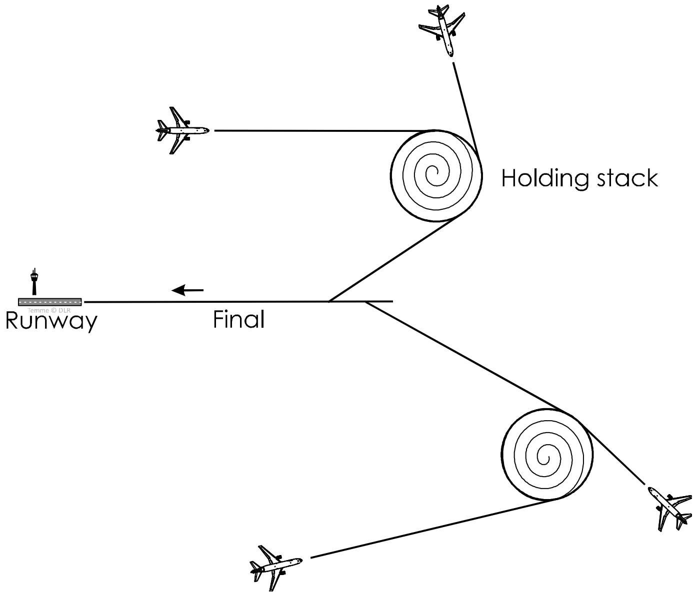

Figure 2-8: Schematic diagram of the holding stacks at London Heathrow. (In reality, the shapes of the stacks are not spirally. This illustration is only used for better appreciation.)

With clearances from controllers, the aircraft enter the stacks and then circle and descend at the same time. The lower limit of the stacks is set to FL80 and therefore at the boarder of aircraft noise influence on the ground. Once the planes leave the holding stacks, air traffic controllers direct them to the centerline and the final approach. The controllers sequence the planes from all four stacks into a single stream of traffic and guide them onto one of Heathrow’s two parallel runways.

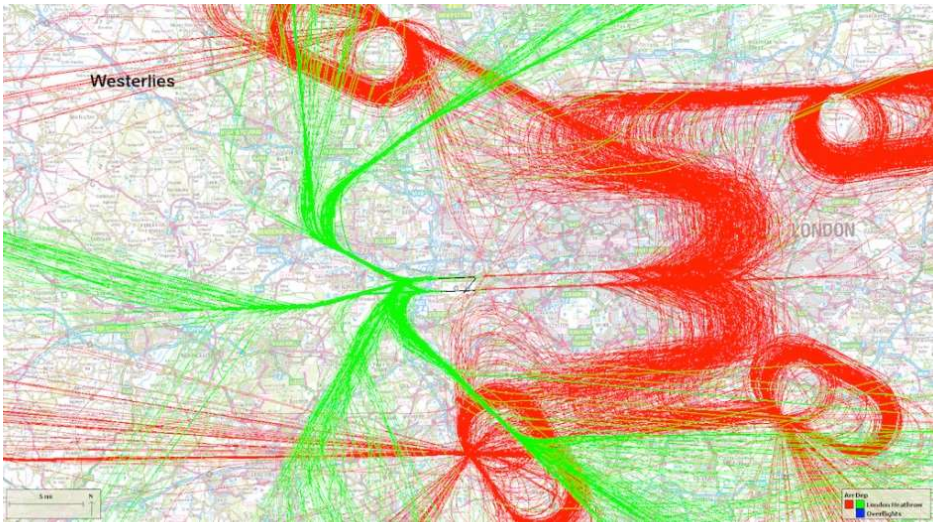

Figure 2-9: The four arrival stacks are located over navigation beacons with the names (counter clockwise) Bovingdon, Lambourne, Biggin, and Ockham. Red lines are arrival tracks, the green ones are departure tracks of typical day of westerly arrivals and departures [Heathrow 2014].

There are defined routes for aircraft moving from the holding stacks to the final approach, but ATCOs use the airspace between the stacks and the finals as trombone path stretching areas for fine adjustment the inbound wake vortex separations (Figure 2-9). Factors such as geographic positions of the stacks, how busy they are, weather conditions, or the position of other aircraft on route, affect how aircraft are sequenced by air traffic controllers to leave the stack and make their way to the final approach [Springall 2007]. Usually, all four holding stacks are active at the same time.

The advantage of this worldwide unique system is the slight airspace volume needed fpr the inbounds even in high traffic situations at Heathrow. On the other hand, at less busy times, arriving aircraft have to use the stacks anyway, as there is not enough airspace between the surrounding London airports. Due to relating flight altitude restrictions, they cannot reduce the flight height beforehand.

2.7. SAN FRANCISCO PARALLEL APPROACH

Looking at San Francisco International Airport (KSFO) in California/USA, the characteristic runway layout is the first that caught the eye and the most noticeable of the 895 registered airports of California. Established in 1940, the double parallel runway system looks like a slightly rotated hash symbol. The distance between the parallel runways are a little more than 200 Meters. This layout brings some challenges for the air traffic control, especially during high traffic peaks. Usually, arrivals and departures assigned on different runways, so that controllers have to look very carefully on the runway crossings. The second challenge is the little space between 28L and 28R (10R and 10L). With a distance of around 228 Meters from center line to center line, the runways are much too narrow for independent use.

The reason for dependent approaches at 28L and 28R is the danger of wake vortices. During the last years, some estimates were done how big the risk of wake turbulences are under different weather conditions [Burnham 2002]. However, usually the studies consider parallel runway layouts, which are only a few meters under the mandatory 1000 ft spacing. For San Francisco, ATC developed the Simultaneous Offset Instrument Approach (SOIA) being considered for runways 28L and 28R. The airport adopts this method, which does not require avionics or surveillance technology beyond the current state of the art [Hammer 2000]. SOIA derives the benefit from the effect, that in the beginning phase (the first few seconds after detaching from the wings) wake vortex turbulences have an extension only some meters larger than the span of the inducing aircraft [Holzaepfel 2012]. In this way, a safe zone without turbulences exists beside an aircraft (Figure 2-10). Using this small area next to an aircraft for a second parallel approach, it enables ATC to nearly double the theoretical arrival capacity of the runway system.

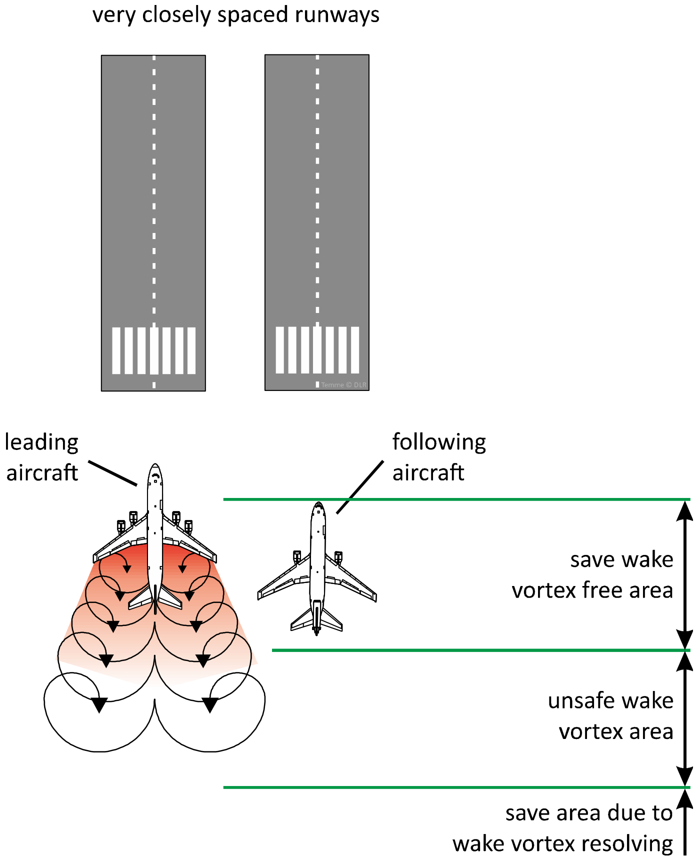

Figure 2-10: Schematic diagram of the safe wake-vortex-free area between two parallel flying aircraft.

To increase the airport capacity, San Francisco airport decided to establish the parallel approach procedure for the landing direction 28, where two aircraft of different sizes approach directly next to each other. In the operational practice, this procedure starts with the aircraft scheduled for runway 28L[4]. For a straight-in approach, it is guided on the final around 25 NM before threshold (Figure 2-11).

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[4] In later years, the concept was extended to start with an aircraft cleared for runway 28R. In this case, the procedure works in the same way, only mirror-inverted.

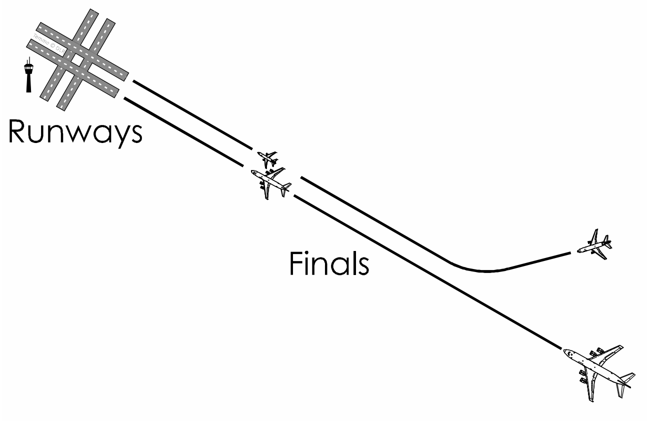

Figure 2-11: Schematic diagram of the runway layout and the parallel approach on 28L and 28R.

At the same time, a second and usually smaller aircraft is guided from the north on a western heading. On its track, it would cross the final of 28L around 9 NM before threshold. Now, the task of air traffic control is to lead the smaller aircraft coming from the side to the final of 28R directly next to the first aircraft that is already on the final of 28L. The challenge of this maneuver is to guide both aircraft in this way that they will have the same groundspeed and arrive both at the meeting point at the time. After approximation at the meeting point, the second aircraft from the east makes a little right turn to pursue the final down to the threshold. During final approach, the aircraft have to stay in the correct position relative to one another. To stay in the safe area next to each other, they have to reduce the speed and the altitude with the same rate.

Before the maneuver, some pilots inform their passengers, that a second aircraft will approach from the right and will make a little turn just before collision to approach directly adjacent to their own plane down onto the runways.

2.8. SUMMARY

When designing airways and complex airspace structures, familiar and best practices should always be used whenever possible. This is especially true for the approach into and around the TMA, which is one of the most challenging phases of a flight due to the reduction of altitude and speed while merging different traffic flows. The GreAT concept is to give pilots as much freedom as possible during the approach so that they can use the onboard Flight Management System (FMS) to calculate and fly an optimal approach profile in terms of time, distance, fuel consumption and aircraft noise emissions. At the same time, approach controllers face the challenge of coordinating aircraft with their individual profiles in terms of time and space so that the airport is operated safely and efficiently. This requires that at least a minimum of waypoints, routes and constraints be specified.

Ideally, all aircraft are given clearances for individual approach routes so that, by design, no conflicts can occur. However, on final at the latest, all approaches must be merged, regardless of whether they were routed over structures such as fans and trombones or were routed directly onto the final. Direct approaches require more precise timing and spacing than structures with an integrated Path Stretching Area (PSA), because there is less space for corrective actions when deviating from the ideal route.

Until it will be possible for all aircraft to perform direct approaches with the required precision, traditional PSA airspace structures as described in the previous sections must be integrated and used in the TMA in addition to direct routes. Care must be taken to ensure that these can be combined with the direct approaches without conflict on the one hand, and interact conflict-free with the departure routes on the other.

3. EXTENDED HORIZON AND LATE MERGING

This chapter outlines a new airspace design with the extended planning horizon for arrival manager and the positions, constraints and usage of late merging points for different airport topologies.

The capacity limits of major airports are already largely exhausted. With the exception of the year 2020, global air traffic has continued to grow in recent years. Despite economic fluctuations, a steady increase is predicted for the future [EUROCONTROL 2019]. Not only the extension of capacity limits is a major challenge, but also the demand for more environmentally friendly and cost-effective flight control procedures is becoming more and more urgent, since the environmental awareness of the population has also increased.

In the GreAT Project airspace concept, the approaching flight traffic is operational divided into two groups: The conventional arrivals, and flights implementing Early Full Clearance Approaches (EFCA) deploying individual optimized continuous descent operations (CDO). The concept assumes that appropriate equipped aircraft which can hold negotiated target times at waypoints with accuracy of ±6 seconds are permitted to use individual approach routes and individual optimized procedures like continuous descent approach (CDA) and to perform a conflict free direct approach from transitions to a Late Merging Point (LMP) and threshold [Kuenz 2009].

The first key factor to facilitate fuel and CO_2 optimized approach procedures is an airspace route system around and within a TMA, which allows long distance independent approach procedures and coherent clearances starting at the top of descent and ending on the final. The second key factor on the way to the GreAT flexible and time-based aircraft guidance concept is to provide support to controllers and pilots via tactical assistance systems, which have to provide much more sophisticated support functionalities than today [Ohneiser 2015].

The Early Full Clearance Approach bases on the concept elements Extended TMA as a horizon and planning area of an AMAN, direct approaches in the TMA until final, a differentiation regarding the technical equipage of the aircraft, negotiated target times for significant waypoints, Aircraft Separation Points, where the inbound streams are separated in directs with negotiated target times and conventional guided approaches, and the Late Merging Point, where both streams are merged for the last miles on the final before touchdown.

3.1. SEPARATED APPROACH ROUTES AND TAILORED ARRIVALS

In the recent years, concepts of separate approach routes for differently equipped aircraft to reduce fuel consumption, CO_2 emissions and aircraft noise were developed.

In 2004, an approach called "Tailored Arrival" (TA) in Australia and the USA, or "Advanced Arrival" in Europe, was intended to significantly mitigate these situations, especially in the immediate vicinity of airports. The goals of implementing tailored arrivals are to improve the use of airspace and airports, to improve economic efficiency through shorter flight times and the associated lower fuel consumption, which also results in fewer exhaust gases, and to reduce aircraft noise [Evans 2005]. The noise reduction is to be achieved additionally by a consistent application of Continuous Descent Approaches (CDA) [Coppenbarger 2007], which are to be carried out in this way even in complex and tight traffic situations without loss of capacity. However, recent studies at Zurich Airport show that CDAs, at least for some types of aircraft, are more likely to cause aircraft noise displacement than to achieve any real noise reduction in the vicinity of an airport (Figure 3-1) [Zellmann 2018].

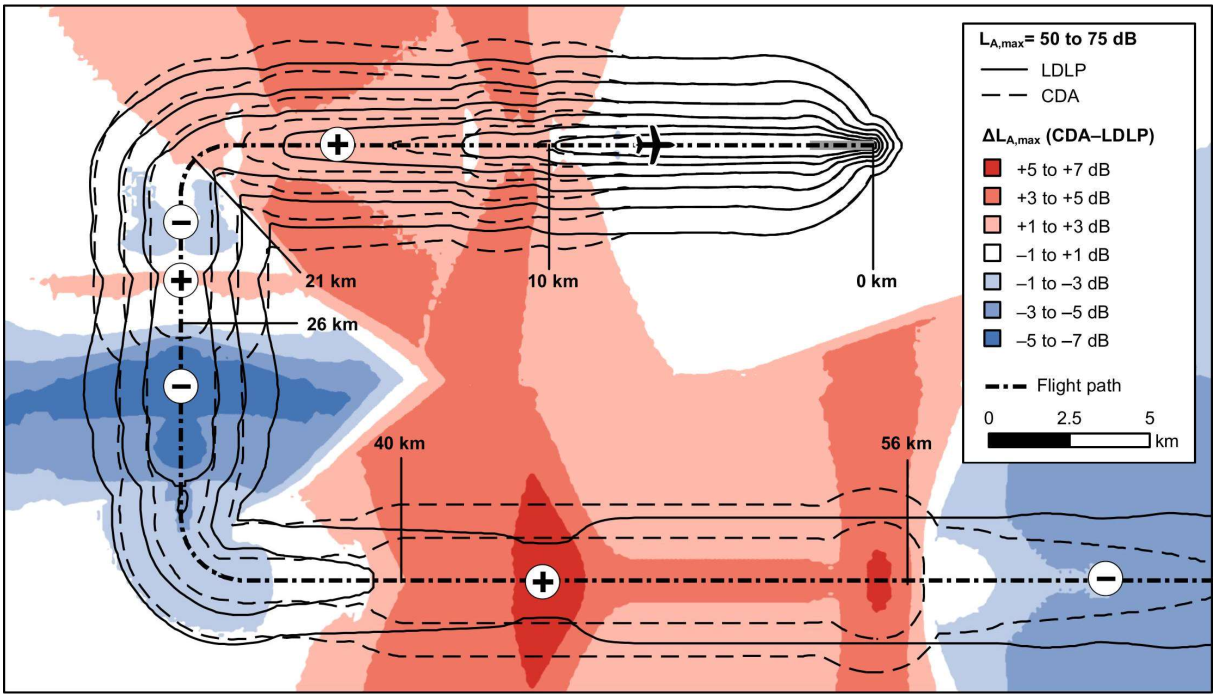

Figure 3-1: Example of a CDA and LDLP approach procedure comparison of an Airbus A320 with CFM56-5B engines. The noise map depicts the differences $\Delta L_{A,max}$ between maximum noise levels of a CDA and a LDLP approach [Zellmann 2018].

By eliminating level segments compared to a standard or low drag - low power approach (LDLP), kerosene can be saved, which is otherwise consumed by the stepwise descent combined with the temporary thrust increases in the last 30 minutes of the approach phase [Evans 2005]. In addition, Tailored Arrivals are also expected to reduce the workload of controllers and pilots while increasing or at least maintaining the safety level.

With the Tailored Arrival, aircraft are to be guided to one or more points (metering fix, merging points and threshold) with precise timing and accuracy. In combination with a CDA, starting at the cruising altitude of flight level 350 or higher, a trajectory negotiated between the cockpit and ground control is started well before reaching the Top of Descent (TOD). However, this can only be achieved through improved coordination between the cockpit and ground, which in a very simple form is already mastered by many aircraft today [Mead 2007], but has yet to be developed for a complete implementation of TAs.

In Australia, a consortium of Air Traffic Alliance (EADS, Airbus, Thales), Boeing, Airservices Australia and the airline Quantas Airways joined forces to conduct joint Tailored Arrival flight trials in Sydney and Melbourne in 2004 [Fischer 2005]. The special feature of these trials, which involved several Airbus 330s and Boeing 747-400s from Quantas on different routes, was the exclusive use of existing technical equipment for data link communications. The Future Air Navigation System (FANS) 1/A data link network, which was already available and in use by airlines in the Pacific region, was selected as the bidirectional communication medium [Fischer 2005]. Furthermore, the approaches were performed according to the local standard procedures and without any additional training of the crews. Via the data link connection, aircraft were cleared for continuous descent of the CDA as early as 140 NM before the threshold. During Phase, the consortium conducted a total of 70 approaches in this manner. With a forecast period of 40 minutes, the highest temporal accuracy for the arrival or the overflight at a significant point was two seconds; the other deviations were always less than 30 seconds. Since the aircraft do not always hit the times exactly, so-called temporal windows were used for each section so that the target time plus/minus a few seconds does not immediately lead to conflicts. In addition, these windows were necessary in order to maintain separations between the individual approach sections and to be able to consider the different performance data of the aircraft. The radiotelephony effort decreased to almost zero for these approaches, so that the workload of the responsible approach controllers could be significantly reduced.

According to the consortium, these tests, as well as simulations, showed that jet fuel consumption could be reduced by 180 and 350 liters per flight (this corresponds to 570 till 1100 kg CO_2 approximately), which could add up to a cost savings of around $100,000 per year.

The same consortium of Air Traffic Alliance, Boeing, Airservices Australia and Quantas also tested automated approaches to San Francisco Airport in California in a second phase [Mead 2007]. This time, the trials, called "Oceanic Tailored Arrivals" (OTA), involved only Boeing 747, 757, 767 and 777 aircraft. A total of 35 OTAs were conducted in 2006 and 2007, all arriving in the early morning hours to avoid disruption during the busiest times of the day. Data Link communications used the FAA's newly deployed ATOP/Ocean-21 systems at the Oakland Air Route Traffic Control Center [Coppenbarger 2007]. As in Australia, clearances for the CDA were given well in advance of TOD for the entire approach to the runway threshold. The clearances also contained information on the approach procedure, transition and the planned runway, in this case 28R. It contained the flight altitudes and speeds to be maintained. In addition, there were special speed clearances in order to be able to perform fine tuning for the times at the TOD and at the threshold. A special issue here was how the pilots configured thrust by using the FMS to maintain trajectory under various wind conditions. Estimates from the tests and computer simulations of the possible kerosene savings potential showed, depending on the aircraft type and the level flight saved compared to a standard approach, up to 1300 liters (B747, level flight 40 NM, corresponding to a flight time of 297 s) per approach, which correspond to more than 4.4 tons of CO_2.

Two other examples are the Future Air Ground Integration (FAGI) project and the Flexible Flight Guidance to Reduce Environmental Impacts (flexiGuide) project, which had the separating of aircraft on pre-cleared routes to fly individual optimized approach profiles as goal [Kuenz 2010, Sinapius 2015].

Based on concrete airports and current traffic scenarios, the GreAT project concept is to show, that the new airspace and procedure design provided sufficient solutions to meet many requirements for sustainable flying. In the previous airspace structures analysis, rigid boundary conditions for approaching and departing air traffic were initially requested, but in reality, these conditions require considerably more flexibility as a reaction to current traffic and meteorological conditions. These include an airspace structure that can change dynamically within limits, making it possible for approach controllers to guide aircraft with low traffic loads and less technologically advanced aircraft manually or semi-automatically on preferred and shortened routes, as well as to bypass airspaces flexibly that are closed for short periods [Rataj 2017].

For the design and implementation of such a flexible and adaptable GreAT airspace structure, an extension of the Terminal Maneuvering Area (TMA) can be a solution, with regard to both optimized route and procedure design. A spatially extension of the TMA allows earlier access of the planning systems on aircraft with its individual approach profile in the current air traffic. When adapting the approach airspace structure (Standard Arrival Routes, STAR), the integration of 4D-FMS and 3D-FMS equipped and non-equipped aircraft as well as departures and possibly overflights have to be always considered.

One of the main aims of the GreAT project is the design and implementation of more individual and flexible approach procedures to reduce environment impacts through fuel consumption and Carbone dioxide emission reduction. In the past, different approaches for the reduction of fuel consumption, aircraft noise, and air pollution were developed and initiated at different international airports [Morrell 2000, Girvin 2009, Zellmann 2018].

Through a combination of modern 4d flight management systems, data link connections, optimized approach routes and procedures, and a broad sequence planning and trajectory negotiation support for arrival and departure controller, these technologies may enable continuous descent operations on busy airports even at peak traffic hours. The GreAT concept expands the conventional Standard Instrumental Arrival Routes (STAR) and transitions by a Late Merging Point (LMP) on each final. The distance should be around five to six miles before threshold, and therefore roughly positioned on the half way between Final Approach Fix (FAF) and runway threshold. Military restricted areas, severe weather zones, individual approach routes, and many more constraints have to be considered when aircraft merge at final joint airspace points.

3.2. DATA LINK FOR TRAJECTORY NEGOTIATION

The greatest technical challenge when implementing individual and flexible approach procedures like the EFCA remains a fast, secure and reliable data interface between airborne and ground systems. There have already been initial attempts to implement this with different procedures for tailored arrivals. Specifically, the following positive effects are to be achieved by trajectory-based planning and coupling of an arrival management system (AMAN) on the ground with flight management systems (FMS) on board via data link [Czerlitzki 2005, Temme 2005]:

- Especially under Instrument Flight Rules (IFR) conditions, a better use of the available runway capacity shall be achieved by a more precise and tighter staggering.
- The average length of stay of aircraft in the TMA with holdings is to be reduced.
- Consideration of user-preferred trajectories on approach to the destination airport, allowing better utilization of aircraft capabilities in terms of ecological, economical and low-noise approach procedures.
- Support for planning and guidance, as well as for radiotelephony through the use of the data link, is intended to reduce the workload of approach controllers.
- Automation of mechanical activities on the ground (push-back, fueling, loading and unloading of baggage, etc.).

In the GreAT project airspace, the data link is to be used for the automatic trajectory negotiation between an aircraft and arrival planner. However, to keep the system lean and error-prone, trajectory negotiation is reduced to pure target time coordination for by AMAN preselected approach routes. One possible system is the L-band Datalink/Digital Aeronautical Communication System (LDACS), which provides a large bandwidth [Schnell 2014]. As a basic requirement for the use of the Early Full Clearance Approach procedure, Required Navigation Performance (RNP) equipment is also needed, since the corresponding procedures are always flown with autopilot. In contrast, with Aerial Navigation (RNAV) manual steering is also possible. If it is not possible at all to establish data link communication between board and ground, target time agreement can also be made between the pilot and the controllers via voice and radio due to the lean project approach. However, in this case, the percentage of aircraft that can fly an EFCA is significantly reduced and the controller workload will consequently increase.

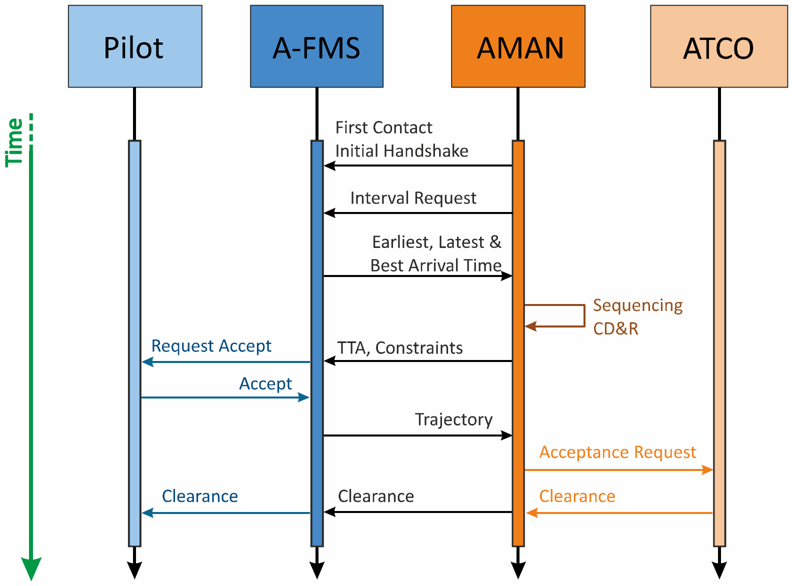

Figure 3-2: The three GreAT communication channels between pilots, controllers, flight management systems and arrival managers. After the AMAN contacts the A-FMS and negotiating the route and the target times, the pilot and controller is involved to accept the negotiation result and issue the clearances (simplified representation without feedback and renegotiation loops).

In the GreAT project the use of three bi-directional communication channels[5] between pilots, controllers, flight management systems and arrival managers are suggested (Figure 3-2). After the AMAN gets its first radar contact with an approaching aircraft, it contacts the Advanced FMS with an initial handshake. With an arrival interval request for an AMAN proposed STAR, the AMAN starts the trajectory negotiation. To execute an EFCA, the A-FMS has to send a possible earliest, latest and optimal arrival time for the Direct-only Merge Point (DOMP), LMP and the threshold. After collecting the time windows of the equipped aircraft, the AMAN uses these times, the until then negotiated target times of the other an EFCA conducting approach and the target times of the standard approaches calculated on its own to build arrival sequences for all runways. The target times and possibly resulting constraints for the newly arrived EFCA aircraft are then send back as a request to the A-FMS where the crew has to accept the route and the assigned times. Know, the A-FMS calculates an optimized trajectory and send the times for significant waypoints to the AMAN for monitoring. At a minimum, these waypoints cover the DOMP and the LMP on its route with the beforehand negotiated target times. The AMAN displays an acceptance request to the controller. This is granted by the controller by giving the clearance from actual aircraft position until the final approach and the hand-over to the tower controller.

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[5] At the time of writing, neither a sufficiently secure nor a sufficiently bandwidth-equipped digital connection between on-board and ground systems exists. Therefore, during project validation, internal simulation subsystems are used that can mimic the existence of such a connection. However, for an immediate implementation of the GreAT airspace concept, trajectory negotiation could also be performed via voice radio between controllers and pilots. Controllers and pilots would then have to enter the results of the negotiation (routes and target times) into their respective systems on board and on the ground. However, detailed monitoring of the flight progress is then only possible to a very limited extent on the ground.

3.3. THE EXTENDED TERMINAL MANEUVERING AREA

The GreAT airspace design represents an extension of the tailored arrivals concept as well as the flexiGuide and FAGI project’s airspace and route structures. However, in some details, it has modifications that resulted from the former project’s evaluations and the work with an international team of air traffic controllers. In addition, the GreAT structure will be extended by some elements like direct departure routes, flexible direct approach routes and multiple Late Merging Points (LMP in Chapter 3.1).

The Extended Terminal Maneuvering Area (E-TMA) is now an area with a radius of 125 NM around the considered airport. The E-TMA does not represent a sector in the proper meaning of the word, but reflects the planning horizon for an Extended Arrival Manager (XMAN). The wide radius was chosen because large aircraft of the weight classes Heavy and Super Heavy (e.g. Boeing B747, Airbus A340-600 and A380) require more than 100 NM approach distance from cruising altitude to landing. In order to provide a sufficiently long approach path for individual aircraft Optimized Profile Descents (OPD) such as the Continuous Descent Approach (CDA) before the aircraft has overflown its Top of Descent (TOD), the AMAN visibility horizon was enlarged accordingly. However, this may also increase the coordination effort of two airports located close to each other, which both use a GreAT airspace structure.

Compared to today's airspaces, the GreAT airspace structure contains the three additional types of waypoints Aircraft Separation Point, Direct-only Merge Point and Late Merging Point. The Aircraft Separation Points (ASP) describe significant points located on the TMA boundary similar to today's metering fixes and must be overflown by all inbounds. However, at the ASP, approach flows are additionally separated by aircraft equipment level and cleared routes. At Direct-only Merge Points (DOMP), all Early Full Clearance Approach (EFCA) aircraft of a given compass direction are clustered before these approaches are merged with conventional approaches at the Late Merging Point (LMP) for the final approach.

3.3.1. AIRCRAFT’S 3D-FMS AND 4D-FMS EQUIPAGE

All common used Flight Management Systems (FMS) can calculate optimized descent procedures bases on the actual aircraft position in relation to the destination airport, the weight and the surrounding meteorological conditions. They are all capable of flying the calculated routes on RNAV 2 to 10 standards. But only the newer ones complying the RNAV 1 standards are capable to fly aircraft precisely on track and time with a maximum deviation of a few seconds at the threshold, independently of the possible change in meteorological conditions.

In the GreAT airspace concept, the difference in the approach procedure cleared for an aircraft is primarily owned to the technical functionality of the onboard FMS. In this concept, approaching air traffic is sorted into two categories, which are distinguished by their level of technical equipment. On the one hand, the aircraft equipped with common FMS, autopilots and no or only simple data link such as CPDLC. These are referred to in the concept as 3D-FMS or non-equipped aircraft. They are able to perform a flight along a calculated trajectory but without the ability to meet a target time with less of twenty seconds reliability, since they cannot sufficiently compensate changing wind conditions with an influence on their own airspeed. Additionally, the limited bandwidth of the data link does not allow a target time negotiation between FMS and AMAN. On the other hand, there are the aircraft equipped with an Advanced FMS or 4D-FMS and a broadband data link. These are referred to as 4D-FMS equipped aircraft and have the ability to perform an Early Full Clearance Approach on a defined route with negotiated target times. With a 4D-FMS, aircraft have the capability to fly along a predefined 4d-trajectory and meet the target times at all points of the way with a divergence less than plus-minus six seconds. Deviations in route, altitude and speed due to changing wind conditions are automatically compensated by the 4D-FMS, even if this may mean a divergence from the optimal approach profile.

3.3.2. AIRCRAFT SEPERATION POINTS

The GreAT airspace waives the STARs and uses Free-route Airspace (FRA). When crossing from an outside sector the border of the Extended TMA, the two aircraft categories are distributed on direct routes leading to Aircraft Separation Points (ASP) (Figure 3-3, green and orange lines representing trajectories).

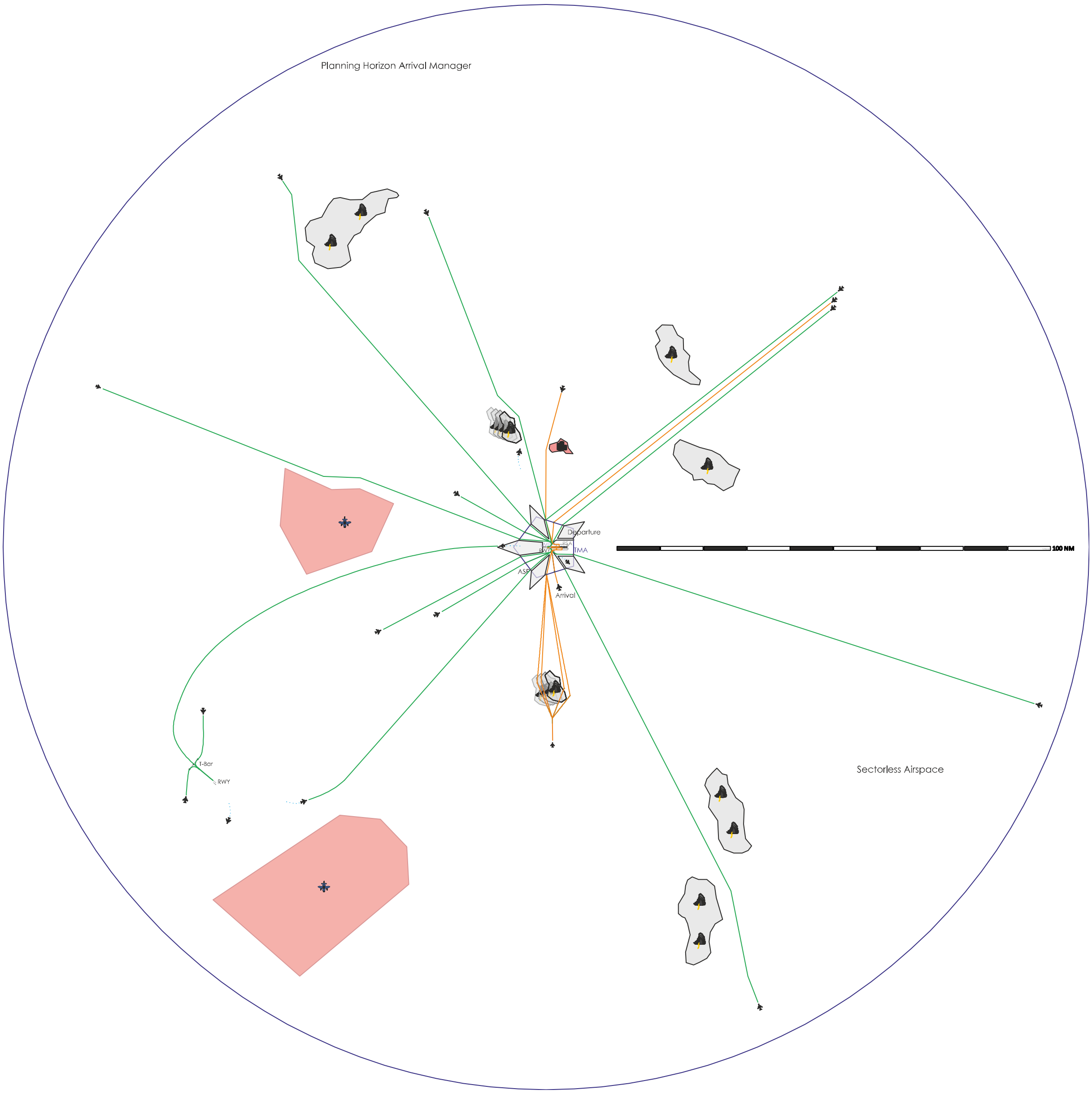


Figure 3-3: The GreAT Extended Terminal Maneuvering Area (E-TMA) for Early Full Clearance Approach (EFCA) scheduling. The considered airport is located in the middle of the circle and an associated airport is displayed in the south-west. Green lines symbolized direct approaches implementing Early Full Clearance Approaches (EFCA) with negotiated target times and orange line represents conventional approaches guided manually by controllers and using path stretching areas like downwind. The grey fields represent adverse weather areas and the red ones military restricted areas. The distance between the airports is not in scale.

Until the ASPs, all aircraft use the same direct routes until they reach the TMA. No entry fixes or other strict defined waypoints exist on the Extended TMA boarder, which have to be fly over. The aircraft can follow the direct great circle route until the ASPs. This TMA is symmetrical structured as a pentagon with an operational mode dependent orientation. The ASPs are all located on the TMA's border and depend of the current landing direction. One edge of the pentagon directs in the current departure direction of the main runway every time, the pentagon border side of the approaches points to no edge (Figure 3-4).

At the Aircraft Separation Points, the inbound streams are separated in dependency of the equipage: The 4D-FMS equipped aircraft follow a direct route to the Direct-only Merge Points (DOMP), located on the right and left side of the finals (green lines in Figure 3-3 and Figure 3-4). This DOMPs have the task to serve as stream collection points only for the Early Full Clearance Approach (EFCA) flights from one compass direction. The non-equipped or 3D-FMS aircraft are guided from the AOPs onto the downwind manually by the controllers (orange lines in Figure 3-3 and Figure 3-4). To separate the streams of equipped and non-equipped aircraft in the area between ASPs and finals, the downwind intercept altitude is 8000 ft. In this way, the directs submerge the standard approaches at the possible crossing points. If there are more than one aircraft heading to the same ASP, the wake vortex separation will be established with the traffic distribution to nearby ASPs before entering the TMA. In case too much aircraft arriving at one ASP at the same time, additional speed and level clearances have to be advised. This can be done by the controller with the help of an AMAN.

The ASPs are positioned around the airport with a distance of around 20 NM to the runways and have nearly the same functionality like TMA Entry Fixes today. The difference to traditional Entry Fixes is that at this point the aircraft with differing FMS equipage are split in direct approaches and downwind transitions on Trombone patterns. An AMAN may be fitted with an additional dynamic timeline for each ASP, where controllers can read the planned sequence, altitudes and time-to-loose as well as time-to-gain information for the last miles until touchdown.

3.3.3. SEQUENCING AND TARGET TIME NEGOTIATING WITH AMAN SUPPORT

One of the AMAN's tasks during EFCA is to coordinate the separated aircraft in the free-route areas and the TMA. If necessary, the concept can take severe weather and prohibited areas into account, but the AMAN functionalities have to support this. At the TMA borders are two to three Entry Fixes which are used as ASPs for traffic separation per main flight direction located (Figure 3-4). Due to the chosen distances between the waypoints to each other, the Entry Fixes are evenly distributed more or less on a circle around the destination airport. In this way, the TMA-structure prefers no main route direction, instead of this the flight distances on the transitions are nearly equal for all direct approaches.

When an arriving aircraft reaches the Extended TMA border and therewith the planning horizon of the Extended AMAN, the controller support system AMAN contacts the A-FMS of the equipped aircraft and asks for earliest and latest possible target times at threshold on a proposed direct route defined by real and FMS-waypoints. The A-FMS has then to calculate its optimal approach trajectories for the proposed waypoints, considering the specific constraints for every point regarding speeds and altitudes and send them back to the AMAN. The AMAN uses the FMS-calculated earliest estimated target time at the runway and the time window to sequence the inbounds and schedule the aircraft into the stream. The earliest and latest target times of the non-equipped aircraft are calculated by the AMAN itself. Then all aircraft are sorted by their earliest possible landing time. If two aircraft undercut the wake vortex separation, the following one is pushed back in time until the mandatory separation is reached.

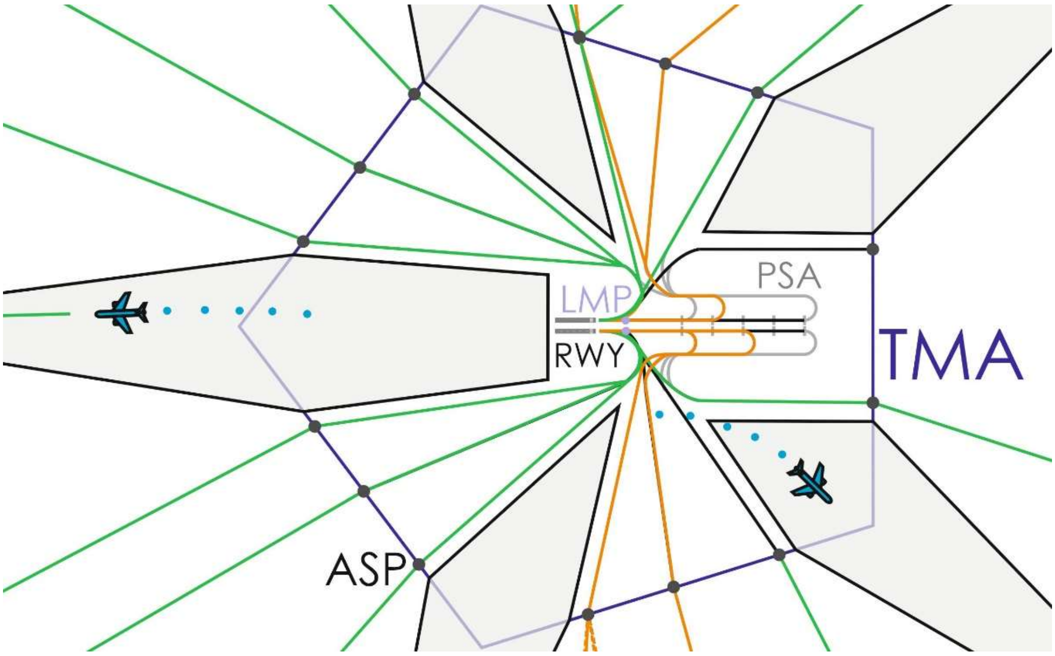


Figure 3-4: Schematic diagram of the GreAT airspace TMA for a parallel runway system with two Late Merging Points (LMP) and a trombone shaped Path Stretching Area (PSA). The Direct-only Merge Points (DOMP) are not plotted in this illustration. After passing the ASP, aircraft are separated depending on their technical equipage. A-FMS equipped aircraft with negotiated target times are cleared on the green routes directly onto the final and with regular FMS equipped aircraft are integrated by controllers manually on the orange routes to the final sequence using the PSA.

After positioning all aircraft in the sequence and assigning the touchdown time, the negotiated target time is sent back to the aircraft and marked in the AMAN inbound sequence as non-modifiable target time – independently of the further traffic progress. Subsequently, the aircraft with the negotiated STAR and target time can get all clearances up to the final to conduct the EFCA. On final approach, the pilot contacts the tower controller for the landing clearance. Thus, the crew gets the possibility to fly a great circle route almost onto the final and simultaneously to choose an optimized procedure descent profile to reduce fuel consumption and CO_2-emissions as well as noise generation. The only task for the controller is to monitor the EFCA with automatic support by the AMAN.

In order to keep the intersection area of the direct approaches and the conventional approaches to the right and left of Final free and clear for controllers, sufficient vertical separation between aircraft must always be maintained there. This is achieved by guiding the conventional approaches at 8000 feet onto the counter-approach and thus onto the Trombone. However, this relatively high altitude means that the Trombone must be extended to give aircraft sufficient opportunity to reduce altitude and airspeed before landing (Figure 3-5).

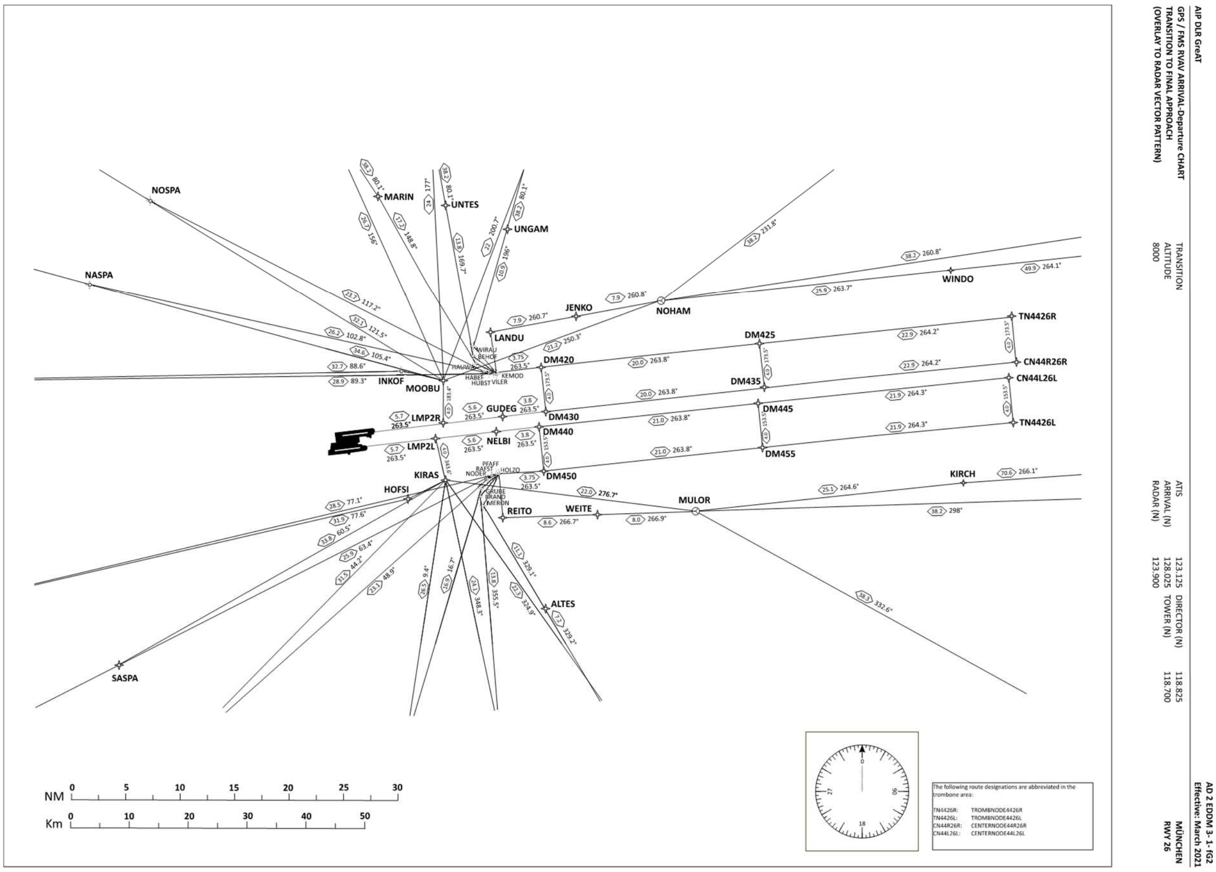


Figure 3-5: GreAT aerodrome chart with all STARs (standard approaches) and EFCAs for the runways 26R and 26L. It is clear that the trombone area is very long to give the aircraft enough way to drop the 8000 ft altitude before touchdown.

3.3.4. THE EARLY FULL CLEARANCE APPROACH GUIDANCE CONCEPT

The non-Advanced FMS equipped aircraft (Section 3.3.1) are guided like the equipped ones on direct routes from the E-TMA border through the free flight areas until the ASP. In contrast to the 4D-FMS aircraft, the standard arrivals have to fly from there a trombone path stretching area along downwind, base leg, and final (Figure 3-6). The AMAN supports the controllers by calculating target times and 4d-trajectories for each non-equipped aircraft in a way, that the standard and the EFCA inbounds can merge at the Direct-only Merge Point and the Late Merging Point without separation violations.

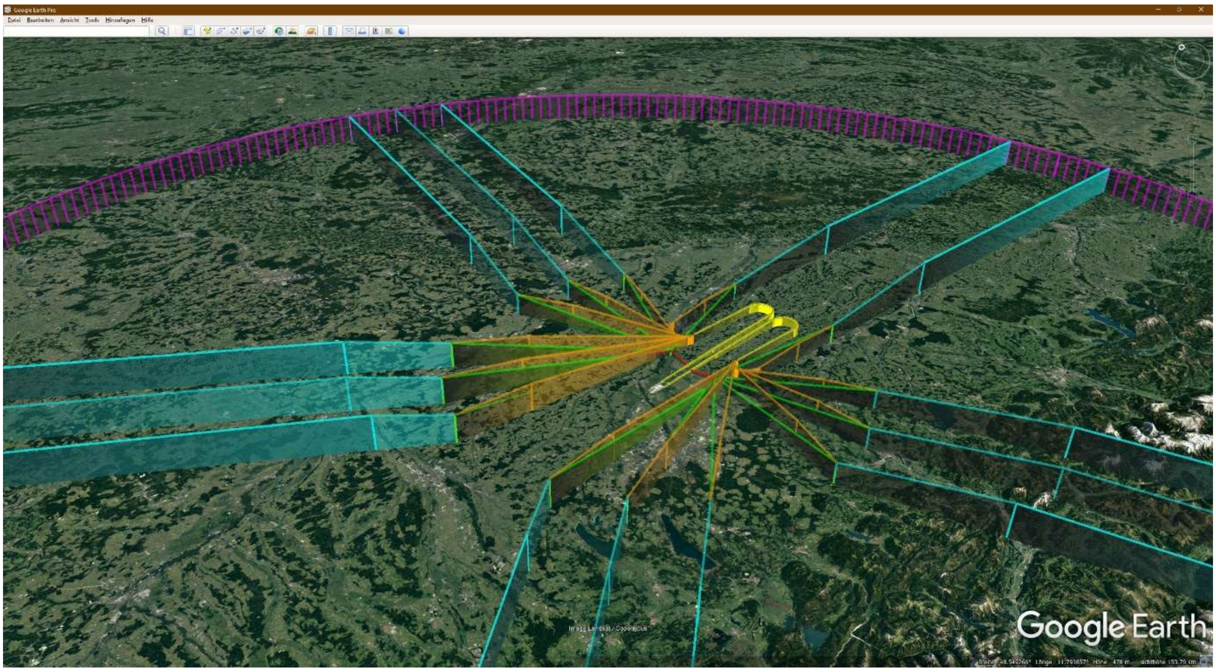


Figure 3-6: The GreAT approach routes transferred to the Munich airspace. The magenta circle symbolized the viewing and calculation horizon of the Extended AMAN with a radius of 125 Nautical Miles. This radius can be easily variegated. The turquoise lines are no routes, but present the shortest connections between the extended planning horizon and the ASP waypoints at the boarder of the TMA. The green lines mark the direct routes starting at the ASPs and ending at the LMPs. The yellow arcs are the downwind and trombone area for the standard approaches. The Direct-only Merge Points (DOMP) are the merging points of the green lines with the red lines on both sides of the yellow final. The red lines connect the DOMPs with the LMPs and therefore are part of the direct approach routes [visualized with Google Earth Pro].

To implement the new airspace structure, controllers need new dedicated support functions. The challenge here is that the controller must know how to guide the standard approaches so that the approach remains conflict-free with each other and with the directs. Unlike conventional distance-based approach guidance, the controller must now guide based on time. This is necessary because the AMAN has negotiated a time window for the EFCA overflight. The controller must now guide the manually controlled aircraft so that they do not reach the LMP at the already negotiated and thus fixed target times for the EFCA inbounds. In the case of EFCA approaches, controllers now only have a monitoring function due to the comprehensive clearances before TOD.

For this purpose, the AMAN generates guidance instructions out of the 4d-trajectories, which cover speed reductions, descents and direction instructions. These can be displayed verbally via advisories or graphically on the radar screen. The visual display aids on the radar screen can be methods like ghosting (Section 4.1.3.2), TargetWindows (Section 4.1.3.3) and trawl-net (Section 4.1.3.4) to lead them on a time-based basis and to avoid conflicts at the LMP with equipped aircraft [Oberheid 2009; Ohneiser 2015]. It is important to note that the controller does not necessarily have to follow the AMAN suggestions, but still retains all freedom to guide the aircraft through the airspace. However, he should always be informed whether and by how much the respective aircraft is currently deviating from its ideal trajectory and therefore from the envisaged target times at merge point. At the same time, the AMAN should recognize at an early stage whether a controller is deliberately deviating from the AMAN proposal and react adaptively to this by recalculating target times and a corresponding trajectory.

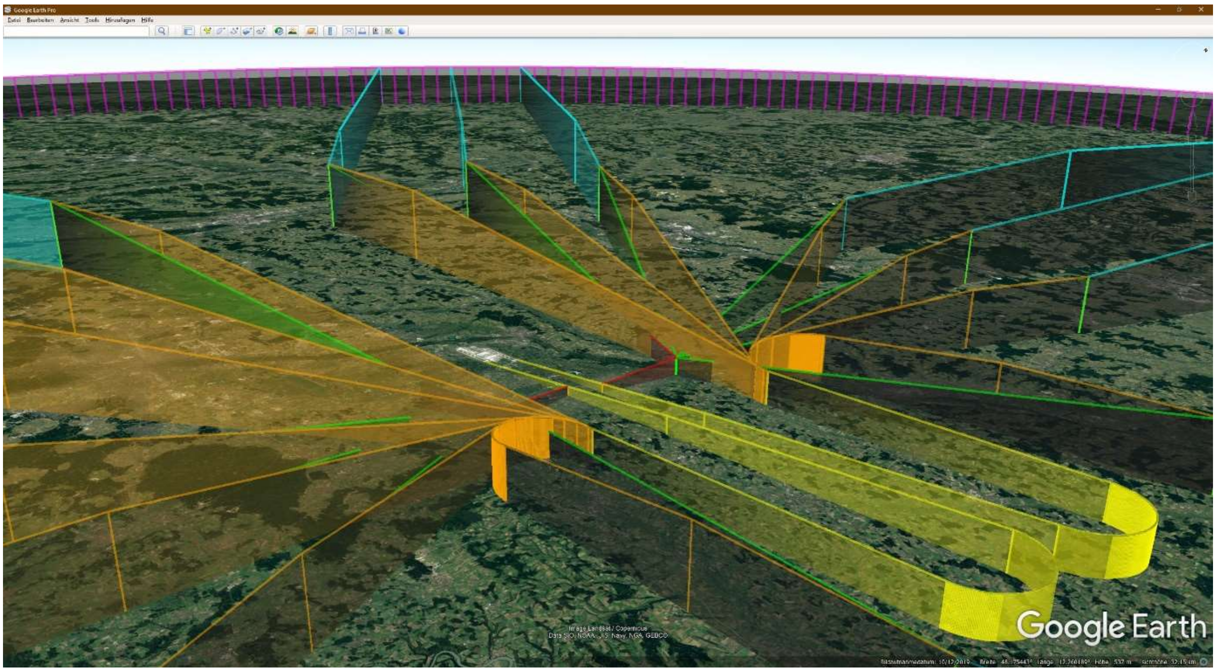


Figure 3-7: In this more detailed illustration, the areas with the crossing inbound routes of the direct-only (green and red lines lines) and the standard arrivals (orange lines) are better discernable. The magenta circle at the horizon symbolized the viewing and calculation boundary of the Extended AMAN. The turquoise lines present the shortest links between the extended planning horizon and the ASP waypoints. The yellow arcs are the downwind and trombone area for the standard approaches and the extended centerline with final. [visualized with Google Earth Pro].

In the case of go-arounds, aircraft have to follow the respective runway departure routes until the next crossings with the STARs guiding to the downwind areas. The go-around aircraft have then to be integrated into the arrival stream of the conventional guided aircraft independently of negotiated target times and technical equipment.

3.4. DEPARTURES

A particular challenge in implementing the GreAT airspace structure and flight routing is the integration of departure routes. These should meet several specific criteria to ensure both smooth interaction between approaches and departures, be equally efficient or better so that the advantages gained by optimized approaches are not nullified by them, and of course meet all the prescribed safety criteria. When looking at the airspace, especially in the immediate vicinity of the LMPs, it quickly becomes apparent that the airspace optimized for two independent approach flows has more crossing points and thus more potential conflict points than previous route structures (Section 2). In addition, the departure routes must now also be integrated, because a wide-area fly-around of the aforementioned area would lead to a significant lengthening of the departure routes and thus on the one hand to higher kerosene consumption, which is always associated with higher CO_2 emissions, and on the other hand to longer flight distances and times, which would probably not be accepted by the airlines.

A major afford of research has been done in the area of departure optimization in recent years, and even more has been achieved [Böhme 2005, Rathinam 2009, Simons 2012]. Continuous Climb Operations (CCO) and all variants thereof today represent a very good widely accepted compromise between fuel consumption, engine load and noise generation [Rosenow 2016], so that the GreAT concept can concentrate on pure and thus conflict-free routing within the airspace.

Under normal circumstances, departures always have with 6° to 9° larger angles of climb than approaches with 1° to 5° descent angle [Turgut 2018, Itoh 2019]. Thus, departing aircraft always gain altitude faster than comparable aircraft lose altitude on the same route. If the routes of approaching and departing flights intersect at a distance between a few and about 80 miles from the airport, the departing flights will almost always be above the approaching flights. In this way, safe separation can be established and monitored by controllers without further intervention. The challenge are crossings, where the altitudes of the outbounds and inbounds in the same range due to considerable different flight distances from and to the airport (Figure 3-8).

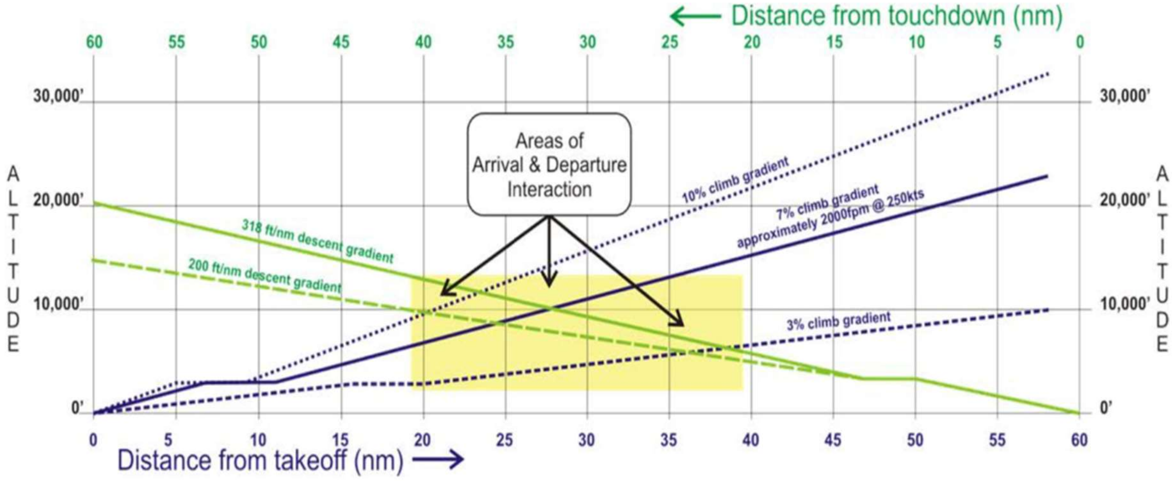


Figure 3-8: Dependencies of the flown and still to fly distances of inbound and outbound traffic causes separation violations [ICAO 2013].

Due to the pentagonal shape of the GreAT TMA, departures following the extended runway can be easily integrated into the arrival structure. A challenge, however, is posed by departures that have to continue their flight at directions transversely to or even against the direction of takeoff. After a 90° or 180° turn around two to five miles behind the runway, they move directly into the area between ASPs and DOMPs, where EFCAs are also on approach to the LMP. The EFCA are moving along optimized approach profiles, so any belated controller intervention to establish safe separations would result in a significant loss of efficiency and target time violations at the LMP.

However, based on the distance already traveled by the departures compared to the remaining distance traveled by the approaches, the departures can be safely routed over the approaches. However, monitoring these intersections remains a challenge for the controllers in charge, as aircraft will be moving toward each other almost continuously in this area. This could be controlled and monitored with the help of an automatic surveillance system, but so far only systems such as STCA and MTCD exist, which today are part of the general air traffic control technology at the controller's workstation [Brooker 2005].

Despite everything, the intersections near the airport between departures and standard approaches pose a challenge. Conventionally guided approaches are guided onto the downwind at an altitude of 8,000 feet in the GreAT airspace structure, and thus flying relatively close to the airport at a significantly higher altitude than direct approaches. This is partly due to the fact that standard approaches must first fly over the downwind, on which they first move back away from the airport and reduce their altitude. On the other hand, the high intercept altitude ensures that the directs and the standard approaches do not get in each other's way. As a result, departures can cross the directs without any problems even in the vicinity of the airport, but to cross the standard routes they must have covered a significantly longer distance after takeoff. An additionally challenge results, if the departures perform CCOs. In this case, the risk of separation violations between arrivals and departures rise significantly [Pérez-Castán 2019a] and have to be supported by a planning and monitoring tool [Pérez-Castán 2019b].

In summary, initial design proposals and their evaluation have shown that departure route integration into the airspace might be a big challenge as long as the conventional and direct approaches are operated in parallel. Whereas the integration of departure routes and only the EFCA routes depends on the compass direction of the SID.

Basically, it is important that the starting aircraft can first gain altitude. One way to do this is to let it fly straight for several miles after takeoff. Then it makes a left or right turn depending on the relative position of the destination airport. This should not be followed by a kind of zigzag flight to cross all approach routes at a 90-degree angle if possible [Hilb & Utrobicic 2020]. This makes it easier for controller tos monitor the separations to the inbounds. In Figure 3-9, a SID for departures to the north-west of the Munich airport are constructed and presented in the airspace of the airport.

Figure 3-9: Proposal to integrate a departure route for north-western outbounds (green line). This is of course only a general route guidance, as all departures have to be merged into the existing upper airspace routes [DFS 2020, extended].

To minimize the potential for conflicts, a sufficient vertical separation is necessary between the flights. For this reason, it seems reasonable to allow the departures to climb as quickly as possible. Figure 3-10 shows an example of an altitude profile, from which it can be seen that altitude is built up during the first miles with aircraft type-dependent maximum climb power. The climb profile was calculated for an Airbus A320 with parameters from EUROCONTROL's Base of Aircraft Data (BADA) [Nuic 2015].

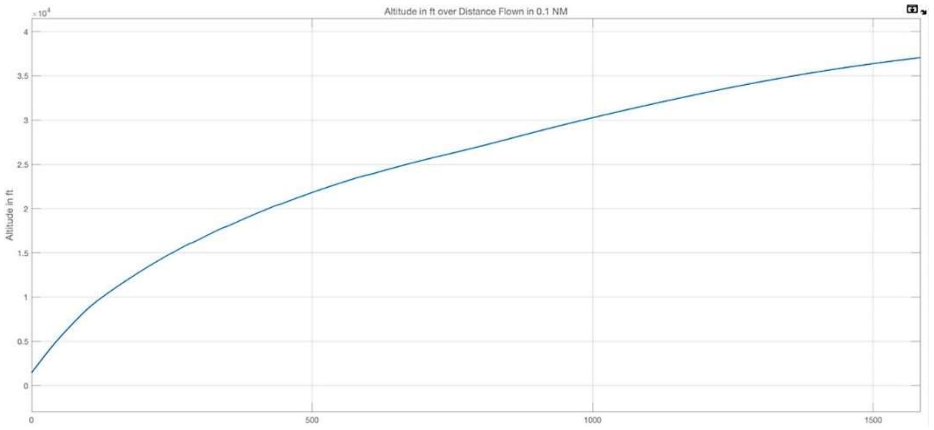


Figure 3-10: Example for an altitude profile of an Airbus A320 departure on the SID of Figure 3-9 starting at Munich airport (EDDM) [Hilb & Utrobicic 2020].

To calculate the altitude that can be reached as a function of the distance traveled, the common estimate was used that the climb performance of an aircraft decreases by about 10% during the turns (Figure 3-11).

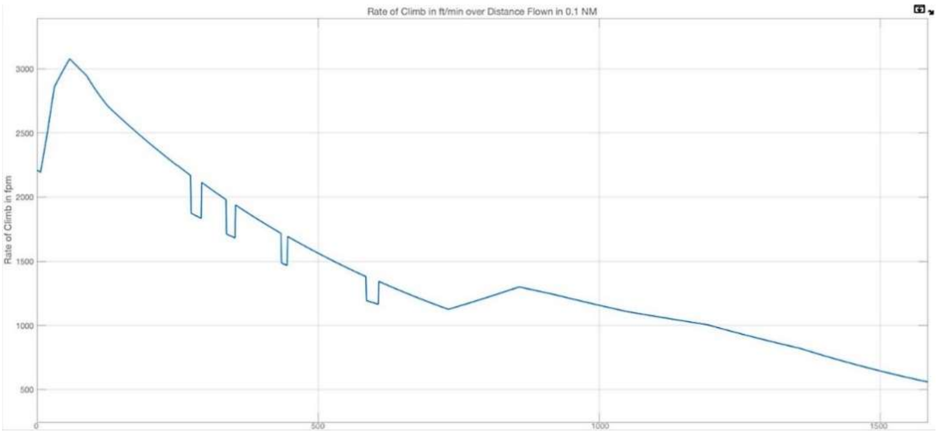


Figure 3-11: Example for a rate of departure's climb profile to the north-west of the airport. The inlets result from the average 10% reduced climb rate during turn maneuvers [Hilb & Utrobicic 2020].

In Figure 3-12, the north-western departure route is visualized in blue with Google Earth Pro. At the first intersection between arrivals and departures, the average altitude difference between SID and STAR account for 2200 meters or around 7200 ft. Due to the course, the next crossings show altitude differences between 2000 and 2200 meters. This was accomplished by the departing aircraft first following a 25 nautical mile straight line flight to the west before making a short turn in the opposite direction for approximately 22 miles. In this way, altitude can be gained quickly and without endangering the approaching traffic.

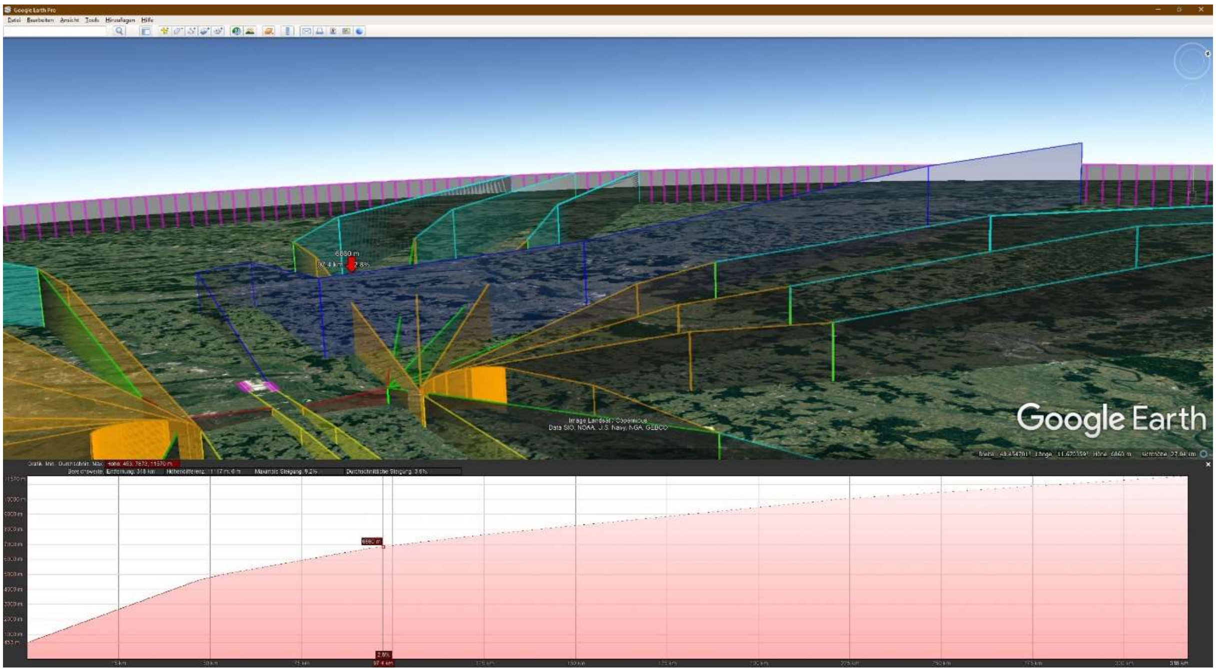


Figure 3-12: Departure route to the north-west starting on the 26R of the Munich airport (MUC) in blue. The average altitude difference of SID and STAR at the red arrow are 2200 m or around 7200 ft. The altitude profile shows an average CCO departure of an Airbus A320 [visualized with Google Earth Pro].

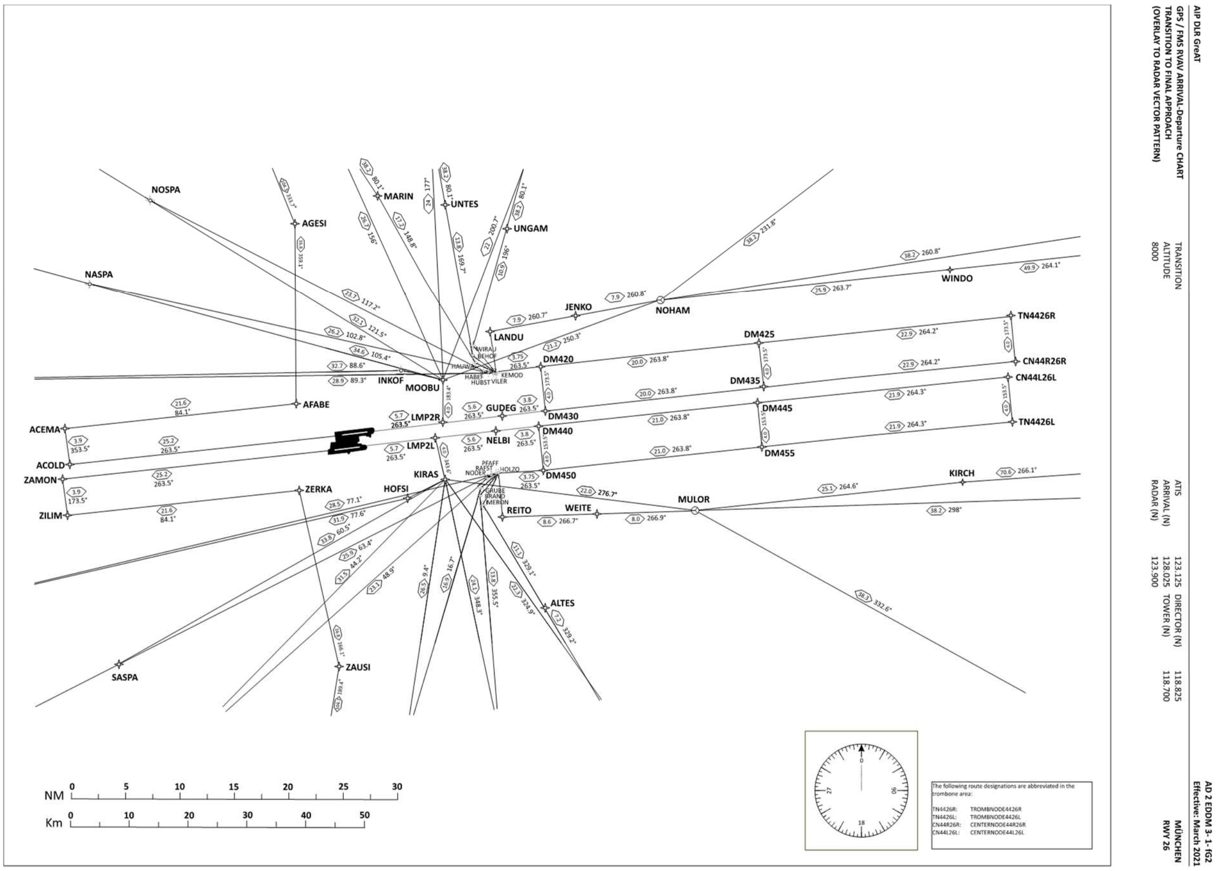


Figure 3-13: GreAT aerodrome chart with all STARs for the runways 26R and 26L and the SIDs heading north-west and south-west.

Through the continuous climb operations, this distance is sufficient to head then northern and crossing the STARs. If it turns out that the targeted separation of at least 2000 meters is more than enough, the first straight flight immediately after takeoff could be shortened. In this way, the total flight path of an aircraft taking off from MUC would also be reduced somewhat.

Figure 3-13 shows an airspace map inspired by the airport charts of the Aeronautical Information Publications (AIP) with the STARs for standard and direct approaches and the SIDs for aircraft departing to the north-west and south-west.

For integrating departures to the north-east or south-east, can be used partly the same waypoints in the west of the airport. But instead of flying directly north at the airport, the route now swings north-east (Figure 3-14).

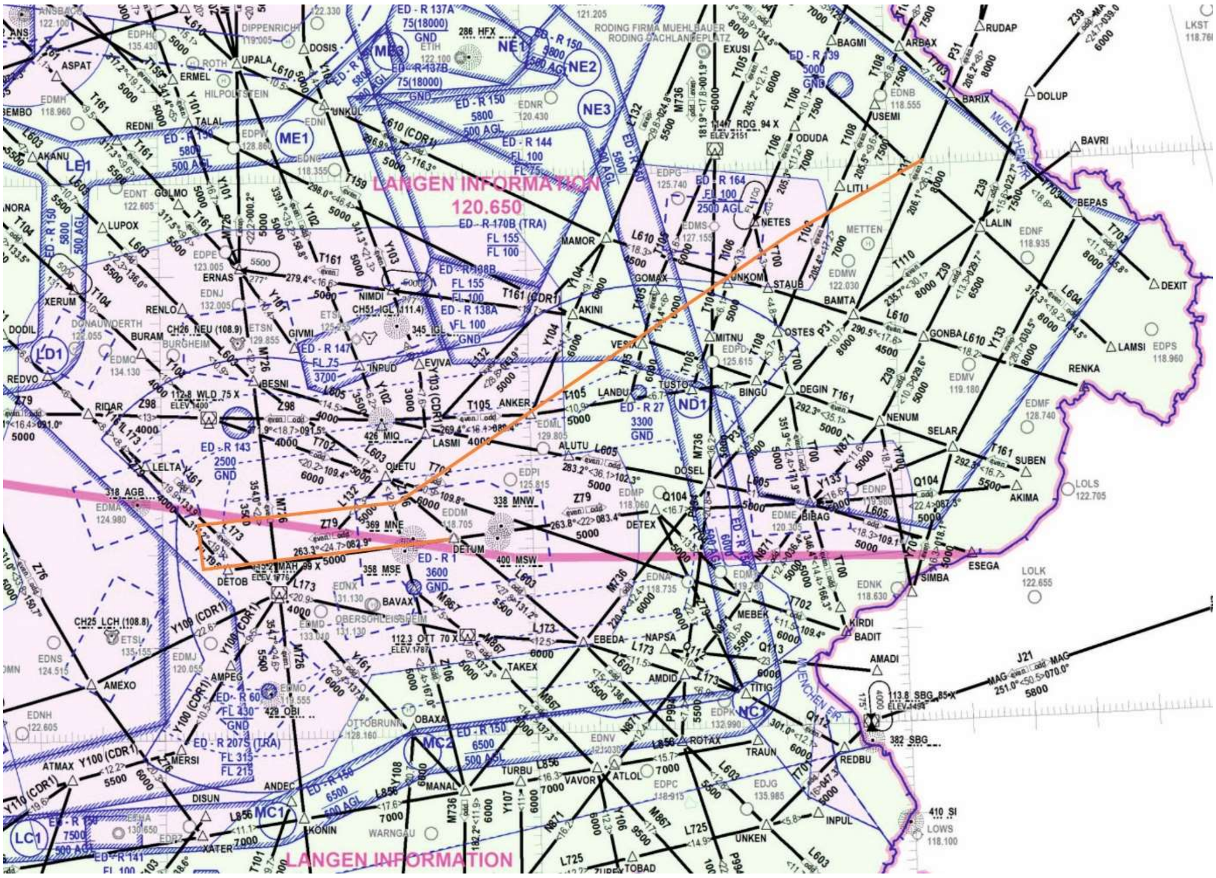


Figure 3-14: Proposal to integrate a departure route for a north-eastern outbounds (orange line). This is of course only a general route guidance, as all departures have to be merged into the existing upper airspace routes [DFS 2020, extended].

As with westbound departures, eastbound departures must be routed over the STARs. However, instead of crossing the STARs in the north-west, the STARs in the north-east of the airport are crossed here. Due to the longer distance traveled by then, this SID can be routed slightly more to the north and thus closer to the northern ASPs, thus avoiding longer loops and detours in this way. The average altitude separation between arrivals and departures is thus also here, as in the north-west, more than 2000 meters (Figure 3-15).

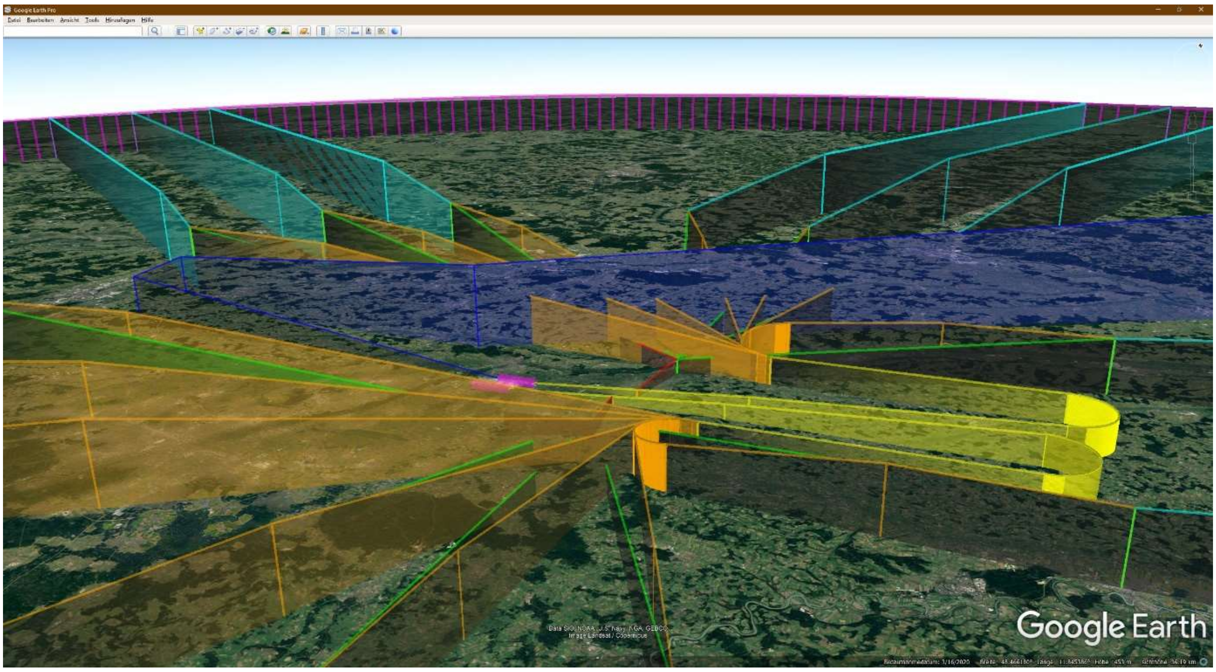
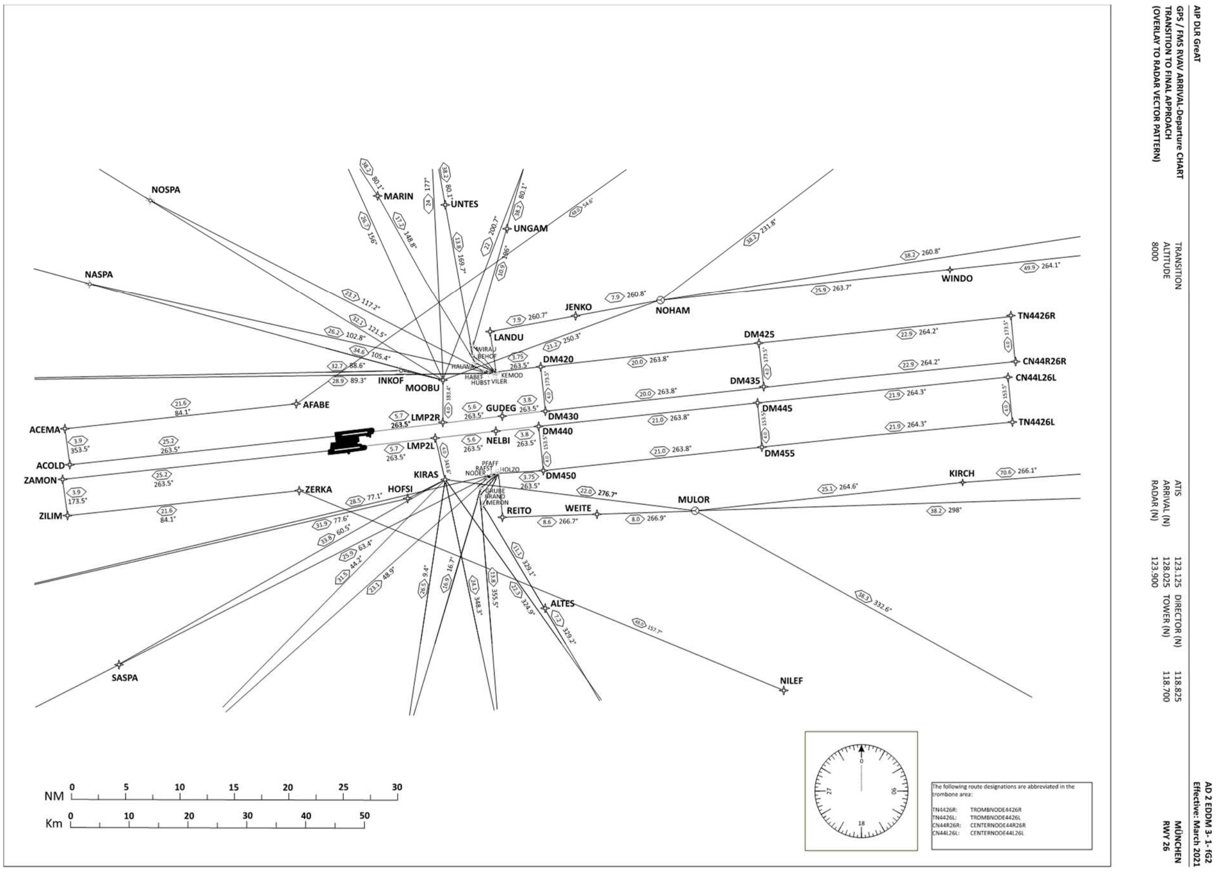


Figure 3-15: Departure route to the north-east starting on the 26R of the Munich airport (MUC) in blue [visualized with Google Earth Pro]

Figure 3-16 shows an airspace map inspired by the airport charts of the Aeronautical Information Publications (AIP) with the STARs for standard and direct approaches and the SIDs for aircraft departing to the north-west and south-west.



The following route designations are abbreviated in the trombone area:

TN4426R: TROMBNODE4426R
TN4426L: TROMBNODE4426L
CN44R26R: CENTERNODE44R26R
CN44L26L: CENTERNODE44L26L

Figure 3-16: GreAT aerodrome chart with all STARs for the runways 26R and 26L and the SIDs heading north-east and south-east.

Despite the complex approach structure, which makes a difference between technically better and ordinary equipped aircraft in the approach procedures and allows some crews to perform arrivals without regular clearances by controllers, it is possible to integrate departure routes that meet today's standards [Hilb & Utrobicic 2020]. This ensures that optimization of approach procedures does not occur at the expense and efficiency of departures.

4. NEW CONTROLLER ASSISTANCE FUNCTIONALITIES FOR LATE MERGING

This section describes necessary and desirable controller support system enhancements an arrival, departure and surface management systems.

4.1. AMAN

Arrival Manager (AMAN) have the task of supporting air traffic controller in guiding approaching air traffic in the vicinity of one or multiple airports. These systems are pure suggestion systems and have a planning horizon of round about one hour. They ease the air traffic controller's tasks by taking over the particularly difficult planning and optimization of approach sequences, while considering all given constraints. This technical support in approach planning can have a clearly positive influence on the effectiveness of the air traffic controllers work, since approaching aircraft are integrated at an early stage and the required distances on the final are precisely considered, while at the same time throughput is slightly increased and approach trajectories are more direct and thus shorter.

The first arrival managers already developed the systematic base for air traffic controller support and this has not changed in principle. According to this the tasks of an AMAN can be divided into different levels:

- **Sequence Planning** – Optimal landing sequence based on airspace structure, current air traffic situation and performance criteria for all aircraft in the airspace
- **Trajectory Calculation** – Optimal 4d-route for every individual aircraft to fulfil the planned sequence
- **Advisory Generation** – Calculation of required instructions from air traffic controller to pilot to follow the calculated trajectory
- **Conformance Monitoring** – Tracking if aircraft is following the planned trajectory

In order to support late merging the assistant functionalities of an AMAN have to be adapted and new assistant functionalities need to be provided. The following subsections partially describe the already existing functionalities, but mainly focus on support functionalities and improvements required for late merging.

4.1.1. TRAJECTORY CALCULATION

The basis of the trajectory calculation are flight performance data and a waypoint list with local constraints regarding speed and altitude limits. This trajectory must then be subjected to two screenings. Firstly, it is tested whether the trajectory for the aircraft is feasible. This includes, for example, checking radii of curves with respect to the approach speed planned there. Another test criterion is conflicts with other aircraft. It has therefore to be checked whether the new trajectory is conflict-free with other approaches and, if known, departures. If both conditions are met, the estimated landing time can be calculated from the new trajectory.

For trajectory calculation, the AMAN 4D-CARMA uses the following basic equation [Helmke 2011b]:

$$X_{i+1} = X_i + T \cdot \frac{\delta X_i}{\delta t}$$

where X_i and X_{i+1} are the state vectors of an aircraft at the times i and $i+1$. T is the integration step size, which is usually set to one second. Correspondingly, $\frac{\delta X_i}{\delta t}$ is the change rate of the state vector of the considered aircraft.

During straight-ahead flight at constant altitude, the step size T is increased to ten seconds in the reverse calculation until at least one of the parameters – speed, height or direction – changes. During curve flight trajectory calculation, the step width T can also be increased, because the calculation of the circle segment of the curved flight path is known.

Several functions are available in 4D-CARMA for calculating sink and reduction rates [Helmke 2011b]. The very simple functions are based on fixed reduction rates with 1 knot per second and constant sink rates of 6,0958 m/s (equivalent to 1,200 feet per minute). These rates are independent of aircraft type, current speed and altitude. They are not realistic and are only used for fast testing of algorithms.

In the more complex and thus more realistic functions, the sink rates depend on the type of aircraft and the current state of the flight. For each type of aircraft, the corresponding Base of Aircraft Data (BADA) is determined [Nuic 2015]. Therefore, the rates depend also on the current altitude and speed of the aircraft. Thus, if the calibrated air speed (CAS) is reduced at the same time, the sink rate is reduced by almost 50% compared to a sink rate with a constant CAS to indicated air speed (IAS) ratio.

However, there is also the possibility to use correction parameters for the BADA data resulting from simulations and flight tests and to include them in the corresponding trajectory calculation functions.

When using increase or decrease rates for example, a few characteristics have to be considered. Rates are negative when the trajectory is calculated forward and correspondingly positive as soon as a reverse calculation is carried out. Starting from a planned target time, the trajectory is calculated backwards starting from the threshold into the air. The forward calculation always starts at the current position of the aircraft. It takes place for at least 25 seconds from the actual time because it is assumed that no AMAN-advised flight state changes are possible during this short period of time due to the operations of pilot or controller. It is assumed that the aircraft continues to fly as before and thus neither sinks, nor reduces, nor changes the direction of flight in this short period.

However, if advisories that are already displayed to the controller are known, it is assumed that these clearances are also given and executed at the scheduled time. Until all advisories already displayed to the controller have at least been started, the procedure of the forward calculation is always continued.

The reverse calculation is normally used from the Final Approach Fix (FAF) in the direction of the current aircraft position to the endpoint of the forward calculation. As input it receives the waypoint list until where the forward calculation has been performed, with all points after the FAF being removed.

If the decrease or reduction rate was zero in the last time step of the calculation and a decrease or reduction phase now begins, it starts abruptly from one state vector to the next. For example, the decrease rate can rise from zero feet per minute to 1.800 feet per minute. However, this effect is somewhat reduced, since $\frac{\delta X_i}{\delta t}$ is always calculated from the mean value of the current and the preceding rate. Thus, in this case, an intermediate step of 900 feet/minute is used. If the target value in the reverse case is achieved, the rate drops directly to zero. However, the algorithms ensure that the target value never falls below the value of the connected forward calculation and is never exceeded in the reverse calculation. This does not happen even if the target value is already achieved in a fraction of the integration step size. To obtain softer transitions between the individual phases, the second and higher derivatives of the decreasing and reduction rates would have used. However, particularly at the end of a flight phase, these are very difficult to implement.

When calculating the coordinates, it is assumed that the current position and the current track (flight direction) are known in state vector X_i. Furthermore, the 2d-route of the aircraft through a list of predetermined waypoints P_1, P_2, … P_N is described with constraints. These constraints are maximum and minimum values for the flight levels and CAS speeds to be maintained. The waypoint P_0 corresponds here to the current aircraft position and the waypoint P_N to the runway threshold.

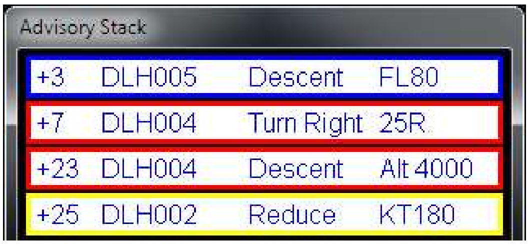
If the position of the aircraft now approaches the next waypoint P_i on the route by less than a predetermined distance L of 2 NM, a track change to the next point P_{i+1} with a constant radius is started. Of course, this applies only if the flight to the next waypoint is connected with a significant change of the direction. Directional changes with more than 0.5 degrees are considered as a significant route change in the AMAN. An alternative to the constant distance of two nautical miles would be to determine this distance from the required angular change, the ground speed and the maximum roll angle. Another possibility would be to determine the distance at the beginning of a curve approximately in advance from the angular change at this point.

In both cases – the forward and the reverse calculation – an attempt is made to place an arc of a circle from the current position onto the following segment, so that further at the end of the arc with track in the direction of the following way point or the segment can be flown. If this is not possible, a direction change of a maximum of three degrees per second takes place per integration step until the new track runs directly to the next waypoint. At the end, the track is always flown to the next waypoint, but it can happen that the track then deviates somewhat from the segment between the last waypoint and the next waypoint. This deviation in most phases of approach is uncritical, however this phenomenon is undesirable on the final approach.

4.1.2. ADVISORY GENERATION

Advisories are instructions and clearances that allow a controller to guide an aircraft along a planned route and trajectory. Arrival planning and support systems generate 4d-routes for each aircraft approaching, calculated internally as a 4d-trajectory. In this trajectory, the 3d-position and the time are usually encoded [Visser 1994]. In addition, speeds or headings can be stored there, which can be calculated within certain limits directly from the trajectory at a correspondingly high time resolution of the plan data. Some trajectory calculation algorithms can also calculate other parameters such as flaps and slats or gear positions based on the individual aircraft type [Stump 2003].

The task of the controller is then to guide an aircraft through corresponding clearances in such a way that it follows both spatially and temporally its planned trajectory and is integrated into the local inbound traffic sequence. The advisories are generated from the trajectory. For this, the trajectory is traversed point by point to search for changes in one or more relevant flight parameters. If, for example, the planned flight altitude is reduced in the trajectory data, a descend instruction is displayed in a corresponding temporal advance. The new target flight level is provided by searching of the height at which the next planned level segment is inserted. The same is done with speed and heading instructions. A special feature is a turn advisory from downwind onto the final. In this case, it will be checked in the trajectory whether the heading change starts on the downwind and ends accordingly on the final approach direction. If this is the case, no heading advisory is generated, but a turn instruction is displayed directly onto the final of the planned runway. This is a simplification compared to the general operational method, since aircraft on the downwind usually receive two separate instructions: First a heading to leave the downwind and shortly after that a clearance to allow interception with the ILS on the final approach is given. Figure 4-1 shows an example on how this support functionality can be presented to an air traffic controller. The "Advisory Stack" in the figure shows, which instructions are required in the near to comply with the plan made by the AMAN. Besides detailed information on the instruction itself (callsign, type of command, related value) the stack provides time information on the optimal moment in time when the advisory should be instructed.



Advisory Stack

+3	DLH005	Descent	FL80
+7	DLH004	Turn Right	25R
+23	DLH004	Descent	Alt 4000
+25	DLH002	Reduce	KT180

Figure 4-1: Example for a possible visual output of advisory generation as support to an air traffic controller

Trials and briefings at the DLR air traffic validation center with active and retired air traffic controllers have shown in the last years that advisories should be presented on the screen around 30 seconds before the maneuver have be started to be perfectly implemented. This is enough time for the controller to recognize the new advisory, contact the crew and to receive the confirmation of the clearance. A countdown in front of the related advisory indicates the controller, when to start the implementing of the advisory to follow the 4d-trajectory perfectly (Figure 4-1). In the second column, the callsign of the aircraft is displayed. The third column contains the maneuver the aircraft have to execute next. For the implementation of the GreAT airspace, the following clearances are necessary:

1. Descent: Instruction to reduce the flight altitude.
2. Reduce: Instruction to reduce the flight speed.
3. Turn left: Instruction to execute a left turn to turn onto the final.
4. Turn right: Instruction to execute a right turn to turn onto the final.

In the fourth column of an AMAN advisory, a target value is displayed. In the case of a descent, the advisory shows the target altitude of the maneuver and therefore the next cleared flight level and the reduce-advisory shows the next cleared flight speed as ground speed. The turn-advisories assign the cleared runway.

Theoretically, it would also be possible to display the AMAN-planned trajectory as a route in the radar display for each aircraft. In addition, the altitude and speed profile could also be displayed so that the pilot could check at any time whether the AMAN planning is plausible and safe in the traffic context (Figure 4-2).

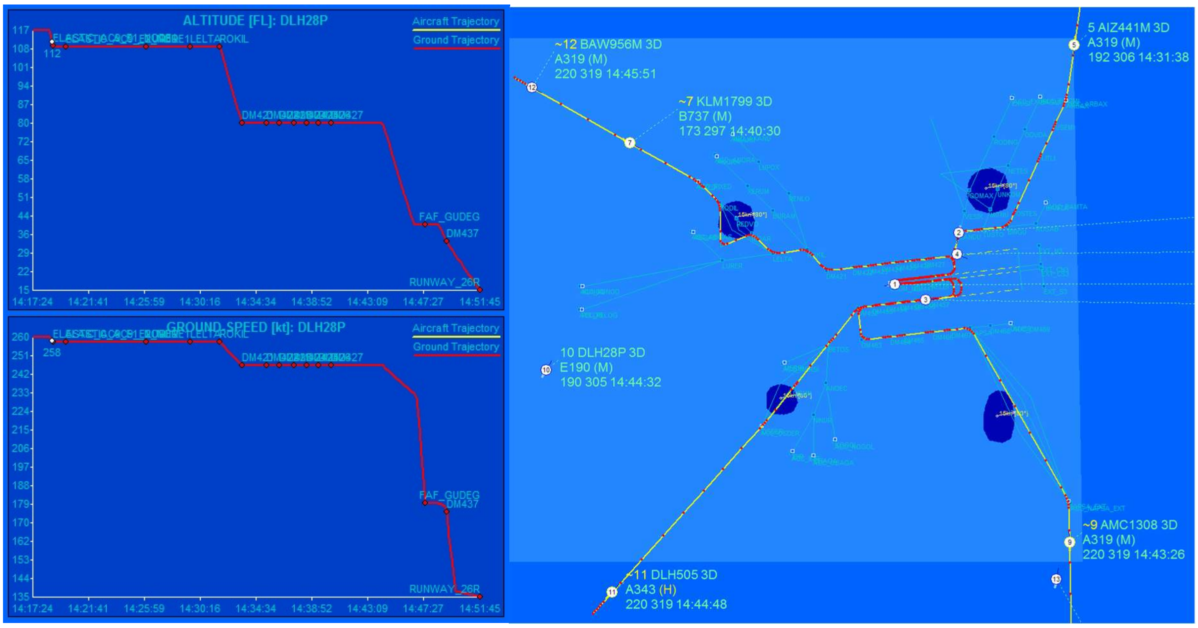


Figure 4-2: Screenshots of a radar display for AMAN development with prototypical illustrations of planned flight routes and altitude- and speed profiles. On the one hand, the danger of cluttering exists (yellow lines make the numbers difficult to read), on the other hand, the re-planning to avoid extreme weather is immediately visible.

This is especially true if aircraft have to deviate from their STARs due to traffic or special meteorological conditions. Typically, however, controllers do not want to see planned trajectories to avoid cluttering effects on the display.

4.1.3. VISUAL CONTROLLER SUPPORT FUNCTIONS

The direct display of planned flight routes in the radar display of controllers is controversial, and guidance instructions have the disadvantage that they can only be shown at the edge of traffic situation displays. For this reason, solutions are being sought to show guidance aids and instructions directly and immediately in the context of the display. To this end, graphical elements have been developed in the past to provide guidance to controllers when guiding aircraft to make safe and precisely timed maneuvers to allow an aircraft to follow an AMAN-planned trajectory with sufficient accuracy. These graphical guidance visualizations will be adapted in the GreAT project to the requirements of the new airspace structure and the Early Full Clearances Approaches procedures.

The following examples of simulator implementations for a comparison between different air traffic controller display techniques showed the advantages and disadvantages of all systems in a direct comparison under uniform conditions.

4.1.3.1 CENTERLINE SEPARATION VISUALISATION TOOL

An essential task of an approach controller is to set and monitor the separation between the aircraft on the centerline and the final. They do this perfectly due to extensive training and years of practice. In addition, distance markers (scale) are available on a modern radar display, which in a mile subdivision allow a quite fast and reliable estimation of the distances between the aircraft. For a much more finely graduated distance display, the Centerline Separation Visualization Tool was developed. This is a separate window in which, for each centerline and final, the aircraft that are currently on final approach to one of the runways are represented by defined symbols with call signs. In addition, the current distances between the aircraft are displayed in nautical miles with two decimal places (Figure 4-3). In this way, the alphanumeric display enables the controller not only to monitor the current distances, but also to immediately detect any changes in their tendency and to intervene with guidance in the event of imminent separation violations.

Figure 4-3: The Centerline Separation Visualization Tool. The symbols mark the position of aircraft (triangle), ghosts (square) and TargetWindows (semicircle). The label colors represent the aircraft weight class (yellow: medium; green: heavy) and the white numbers between the labels indicate the current separation between them.

In addition to actual aircraft, labels for Ghosts (Subchapter 4.1.3.2) and TargetWindows (Subchapter 4.1.3.3) can also be displayed with this tool, allowing approach controllers to estimate how large the separation will be after turning over Base or LMP and before reaching the final.

4.1.3.2 THE AIRCRAFT LABEL-PROJECTION TECHNIQUE GHOSTING

“Ghosting” is the method of projecting an aircraft's label on a radar display on a different route in order to make it easier for the air traffic controller to merge two routes at one waypoint [Mundra 1989]. Separation between ghost and real aircraft on different routes then shows the actual relative temporal spacing between those objects as if both aircraft would be on the same route. This was originally done for two arrival streams on converging runways simulating a dependent parallel approach [Smith 2005]. In principle, two different methods can be used to calculate ghost label positions: Time-based and distance-based ghosting. While distance-based ghosting can be used without problems for regular arrival routes, where two approach streams are merged on which the aircraft move with the same standardized approach procedure and speed [Becher 2004], the merging of approach streams with different approach procedures and speeds poses new challenges. These can be partially solved if a time-based "segmented ghosting" with dynamic approach speeds is used for the ghost label's position calculation [Oberheid 2009].

One of the tasks of approach controllers in the GreAT airspace is the merging of aircraft with different speed profiles at a merging point onto a common route. A particular challenge for controllers is that they do not know the speed profile of the EFCA aircraft. This is the case, when controllers have to merge Early Full Clearance Approaches (EFCA) and manually guided standard approaches at the Late Merging Point (LMP) on the final. In this project, it is assumed that EFCA conducting aircraft are equipped with an Advanced Flight Management System (A-FMS) and choose usually a Continuous Decent Approach (CDA) as optimized approach procedure. A Low-Drag-Low-Power (LDLP) speed profile is assumed for the standard approaches.

To do the merging in a conventional manner, controllers first bring all aircraft to the same speed and altitude to facilitate the merge. The instrument used to monitor all movements is the radar display, which shows the 2D position of the aircraft as well as additional information about them. If the controller brings together aircraft from different directions in such a way that they are closely staggered according to the wake turbulence separation regulations, under certain conditions he can be relieved of some of the work by projecting the aircraft of one route onto the other route on the radar display. This is a procedure that has become known in the past as "ghosting" [Beers 2005], but in recent years has also been referred to as Converging Runway Display Aid (CRDA) under patent rights [Burnett 2006]. This projection can help a controller estimate the spacing of aircraft before they are actually behind each other on the same route. In Boston, a variant was also tested in which the routes of two aircraft only intersect on the intersecting runways [Simmons 2000]. In the Future Air Ground Integration project (FAGI) of the DLR, this form of ghosting was further developed, since here aircraft with significantly different speed profiles had to be merged and therefor projected on one route [Temme 2010]. One of the main conditions, however, was that the real and the projected labels of the aircraft had to be clearly distinguished from each other in order to prevent confusion by the controller.

Guiding an Early Full Clearance Approach, approach controllers are faced at the Late Merging Point (LMP) around six miles from the threshold with the challenge of having to merge aircraft on different STARs and Transitions at different speeds with precise timing. However, aircraft equipped with an Advanced FMS (A-FMS) are not guided directly by the controllers, but have been negotiated a mandatory target time for the LMP by the AMAN. The task of the approach controller is now to time the remaining conventionally equipped aircraft guided by radar vectoring into the A-FMS aircraft stream. The ghosting idea is to show the feeder what the current approach flow would look like if all approaching aircraft in the TMA with a remaining flight path shorter than the length of the final were to move along the centerline. Ghosting works very well in principle, but only if all aircraft on the different routes have approximately the same speed and also change this speed at the points with the same distance to the merging point with the same rates. Ghosting does not give any direct help in this kind of label projection whether an aircraft is currently moving too fast or too slow in relation to its planned target time.

4.1.3.2.1 DISTANCE-BASED GHOSTING

Using distance-based ghosting, the label of an aircraft is projected onto the route according to its remaining flight distance to a merging point. In the GreAT airspace structure, the result would be a ghost label on the final that must travel the same distance to the threshold (or LMP) as the associated real direct approach aircraft on its actual route. For example, if an aircraft is 30 NM north of the LMP and has to travel 36 NM to the threshold due to a turn and the distance from the LMP to the threshold, its label is additionally mapped to the centerline with a distance of 36 NM to the threshold. It moves on the final towards the runway with exactly the same speed as it approaches the LMP from the north.

The final approach controller guides the conventionally guided aircraft directly in front of or behind the projected aircraft and be certain that he has now staggered them correctly. However, the A-FMS equipped aircraft conducting a Continuous Descent Approach (CDA) changes speed at a different rate than a conventionally guided aircraft due to the procedure design. As a result, the two aircraft may become too close at the LMP or create an unacceptably large gap. On the other hand, it is possible that a real and a projected label overlap at the beginning of the final, although they show a correct stagger at the LMP or will show a correct separation in unaffected flight, because one of the aircraft is still moving at a significantly higher speed. An advantage of distance-based ghosting is, however, that the position and speed of the ghost label is correctly reproduced. A possible way out of the comparability dilemma may be offered by time-based ghosting.

4.1.3.2.2 TIME-BASED GHOSTING

In GreAT project, the time-based planning and staggering of aircraft on final is carried out with the support of an Arrival Manager. Because of this and because of the difficulties mentioned in the previous subchapter, it seems obvious to calculate the projection of an aircraft label not distance-based but time-based. In this case, an aircraft that is not yet on final is projected onto the centerline based only on its remaining flight time to the LMP and the typical approach procedure design of the aircraft guided manually onto the final by a controller.

For example, if an aircraft equipped with an Advanced FMS conducting a CDA is on an approach to the LMP from the north, its remaining flight time is determined from the difference between the current time and the planned landing time. The position on final can then be calculated by looking at the spatial distance from the LMP using the current speed versus the remaining flight time. Now, however, the aircraft will continue to reduce its speed as the approach progresses with the effect that it will actually travel a smaller distance in the remaining flight time. In order to obtain a somewhat more realistic airspeed for calculating the projected ghost-label position, there is the possibility of calculating an average airspeed from the current and the projected landing speed (transmitted via Data Link by the CDA-performing aircraft) and using this as a basis for time-based ghosting [Mundra 2001].

Compared to ghosting based only on the current aircraft speed, time-based ghosting then shows a different position on the final. However, another effect occurs with time-based ghosting using the mean airspeed: The airspeed is initially underestimated when using the mean airspeed, so that the projected aircraft initially moves too slowly on the final towards the threshold. Towards the end of the approach, just before the ghost and the real label converge on the final of the radar display, the speed of the label will relatively accelerate and exceed the real speed of the aircraft, since the label is now moving at a higher speed than the real speed.

Also, dynamically adjusting the airspeed of the aircraft being projected does not do much for the controller in terms of movement behavior, because it only reduces the current deviation between ghost and actual position to the extent that the actual airspeed is underestimated and the ghost label moves too slowly along the final. The further away the aircraft is from the LMP, the greater the error in the position estimation.

As a further possibility, a constant speed can be assumed for the ghost label, which ideally corresponds exactly to the speed that the conventionally guided aircraft fly on the same route section. With time-based ghosting, if the positions of all projected labels are calculated based on the same speed of, say, 220 kn, controllers can guide their manually guided aircraft between the ghosts at the appropriate wake vortex spacing and then be assured that the spacing, once guided, will be maintained along the final, at least as long as they guide their aircraft at exactly the same speed of 220 kn. However, for the route segment around the LMP, the approach controller should plan for an additional buffer between the differently equipped aircraft, as this is where the discrepancies between actual, assumed, and guided speeds of the EFCA conducting and conventionally guided aircraft will be in full effect: The ghost labels become real labels at the LMP and then move abruptly at the real speed on the screen instead of the assumed speed. The position determination is based on the target time at the LMP, and since this does not change when passing the LMP, there is at least no jump in the ghost label position. The conventionally guided aircraft, on the other hand, will usually already have a much lower approach speed in the area ahead of the LMP than that which they had further out on final and which was recommended by the assumed speeds for the ghost labels. The distances previously shown on the radar display could then shrink within a very short period of time which could eventually lead to a separation underrun.

Assuming that the speed profiles of CDA and standard approaches do not differ greatly over the last few miles between the LMP and the runway threshold, since the landing speed is aircraft type specific and not dependent on the approach procedure, a combined speed profile can also be used to calculate the ghost label positions under certain circumstances, resulting in a "two-segment ghosting" procedure. In this case, the ghost label positions on the final are calculated using a combination of a velocity reduction phase and a constant velocity phase. These are based on speeds of aircraft conventionally guided a LDLP approach procedure in the same segment, so that once separated, the spacing between aircraft is broadly maintained during the approach.

However, a prerequisite for the operational capability of this procedure is that controllers, when guiding aircraft on the final, adhere to the airspeeds assumed for the conducting EFCA conducting aircraft and that, beforehand, these assumed speeds are selected in an appropriately skillful and realistic manner. This applies until a few minutes before reaching the LMP. Thus, this assumed constant speed should correspond to the approach speed reached by an aircraft in the intercept area and in the first section of the final - and thus on the last level flight segment. The speed reduction profile from a CDA approach differs only slightly from that of a standard approach in the final segment before the threshold, since both aircraft ultimately touch down at nearly the same speed. From the LMP onwards, the position of aircraft and associated ghost coincide, so that the ghost display can be switched off from the LMP onwards[6].

To allow a more precise ghost label projection, which reduces the moving speed difference between manually guided aircraft and EFCA conducting ones on the last miles before the LMP, the Three-Segment Ghosting was developed, which compared to the Two-Segment variant contains another phase with constant speed. The Three-Segment method now maps the typical approach of an LDLP much more precisely. The additional phase of flight at a relatively low speed also reduces the distance of a ghost from the LMP at any point during the approach. This causes ghost labels to be drawn closer to the LMP at a given time, but they approach it slightly slower overall and thus fail to catch up with the true aircraft labels on the radar display (Figure 4-4).

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[6] In reality, it turns out that the ghost label can be switched off as early as 30 seconds before reaching the LMP, since controllers there no longer have any problems estimating the spatial distances between the standard and CDA approaches.

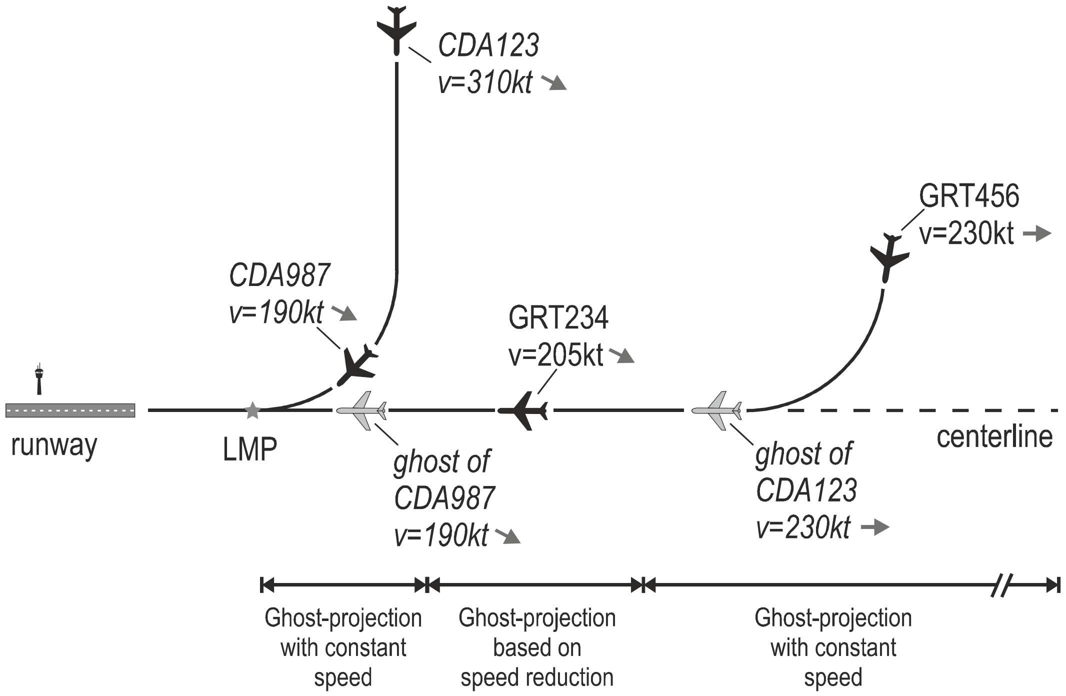


Figure 4-4: The working principle of 3-Segment Ghosting. GRT234 and GRT456 are regularly guided aircraft, CDA123 and CDA987 are aircraft conducting an Early Full Clearance Approach (EFCA). The two CDAs are "ghosted" onto the final and centerline by adjusting their position calculation at the typical approach procedure of the manually guided aircraft.

First simulations show that the introduction of a constant speed phase of 50 seconds at the typical LMP overflight speed, the estimated distance from the Ghost to the LMP at the time 200 seconds before reaching the merging point is reduced by nearly 1.5 nautical miles. A visible gap between a conventional aircraft flying ahead and a following Ghost due to AMAN planning is thus slightly smaller than with the 2-segment variant, and a gap to the following aircraft is correspondingly larger. Also, the maintenance of the set separation between conventional and EFCA conducting aircraft is increased in this way during the approach to the final.

In the Great project, the three-segment ghosting algorithm will be implemented in the DLR Arrival Manager 4D-CARMA and tested for visual support of approach controllers during sequencing and staggering on the final.

4.1.3.3 THE TURN- AND SEQUENCING SUPPORT FUNCTION TARGETWINDOW

Another optical supporting function for approach controllers is an indicator target circle on a route to visualize an aimed position for the merging of two arrival streams. This system also may consider several turns of an aircraft [Shepley 2009, Atkins 2009]. Another approach is using "slot marker" circles to show the aircraft's expected position along its trajectory if it were conforming to the schedule [Parke 2015, Al Gingihy 2013]. Similar target position indicators may also be used for certain waypoints in upper airspace, for wake vortexes [Burnett 2009], or in lower airspace for aircraft on several arrival routes, which are mapped onto one centerline [Oberheid 2009, Uebbing 2011].

A TargetWindow on the controller's radar display is a marked interval on the centerline where it is safe for individually guided aircraft to be fed into the planned or established arrival stream by the controller [Ohneiser 2012]. Target positions in this window indicate the best positions after a turn-to-base maneuver. When aircraft are flying on downwind, they will get a turn-to-base command to perform the base and final leg by feeder controller

[Ohneiser 2015]. It does not matter whether an aircraft is turned in from downwind or guided to final by a direct or a fan approach. The decisive factor is that the aircraft moves as precisely as possible within the TargetWindow when reaching the its last phase of approach.

For one thing, the task of the controller is to clear the turn not too early to avoid wake vortex separation violations. On the other hand, the clearance has to be given early enough, so that the aircraft is not too far behind its predecessor and loosing capacity and effectiveness of the airport after the turning flight. A special challenge in this context is the wind, as its influence on the airspeed can change extremely during the 180°-turn.

In the TargetWindows concept, target positions for turning aircraft are indicated by a dotted semicircle on the final with the open side facing the for this position by the AMAN scheduled aircraft (Figure 4-5). The surrounding TargetWindow symbolizes a safe area around this optimal target position even if the aircraft does not hit its planned position exactly. Furthermore, there is a buffer of half a mile, shown by a tapering of the TargetWindow at both ends. This helps ensuring that controllers do not violate separation minima from predecessors and successors.

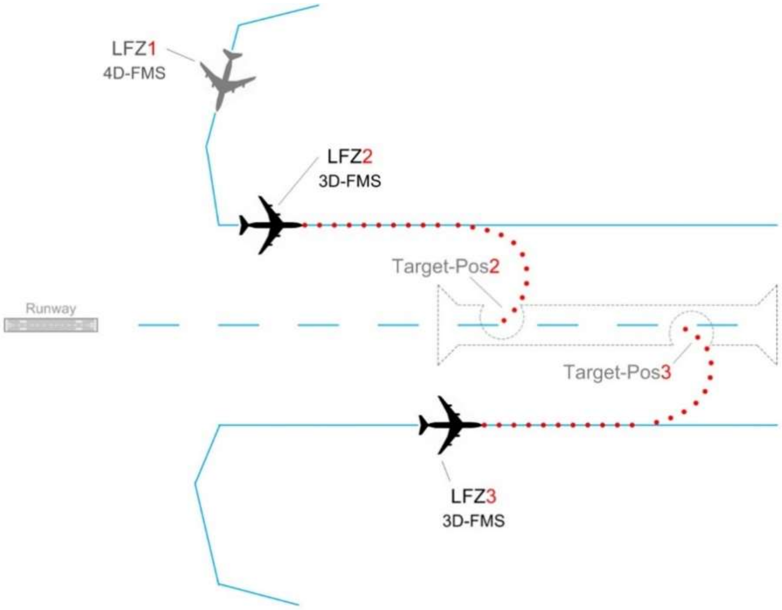


Figure 4-5: Schematic illustration of the TargetWindow concept displayed on a controller's radar display. The dashed lined area moves with the time in the direction to the runways. The controller's task is to turn the aircraft at the right time, as they fit in the open areas in the TargetWindow to meet their scheduled landing time perfectly. Additionally, controller have the possibility to easy read if an aircraft is to fast or to slow and if these deviations will have any impact on the wake vortex safety distances.

With the passage of the time, the TargetWindows moves in the direction to the runway. The controller is shown the current sequence planning of the AMAN, which thus symbolizes not only the sequence, but also their planned distances from each other. From this point of view, the TargetWindow also represents a "ghost", since it projects the position of the corresponding aircraft from another route onto the centerline depending on the distance still to be flown until touchdown, at least as long as the aircraft is moving along its planned trajectory. Unlike a ghost, however, a TargetWindow does not change its movement on the final because it represents the ideal position after the corresponding aircraft has turned on base and final. The controller can therefore use the TargetWindow as an indicator of whether the aircraft will be too early or too late at the LMP and thus at the threshold. If the aircraft label is in the forward area of the TargetWindow gap, it is slightly too fast and should be slowed down by the controller to avoid a possible conflict with the aircraft ahead. If, on the other hand, it is in the rear area of the TargetWindow gap or even completely behind it, then the controller could wait a little longer with the next reduce command in order not to let the separation to the preceding aircraft become unnecessarily large and thus lose part of the theoretical runway capacity. At the same time, the controller must ensure that the distance to the following aircraft remains sufficiently large to avoid a separation violation.

Nevertheless, the controller retains both the responsibility for the approach guidance and all freedom to follow the AMAN suggestions or to establish his own sequence. The TargetWindow reacts just as adaptively to traffic changes as the entire Arrival Manager.

For the introduction of RECAT I, a new categorization of the mandatory wake vortex separations in to six instead the today in most countries used four categories, EUROCONTROL introduced the LORD display aid for approach controllers [Cappellazzo 2018]. With two additional triangular symbols for each inbound moving on the final, it follows the principle of DLR’s TargetWindow (Figure 4-6).

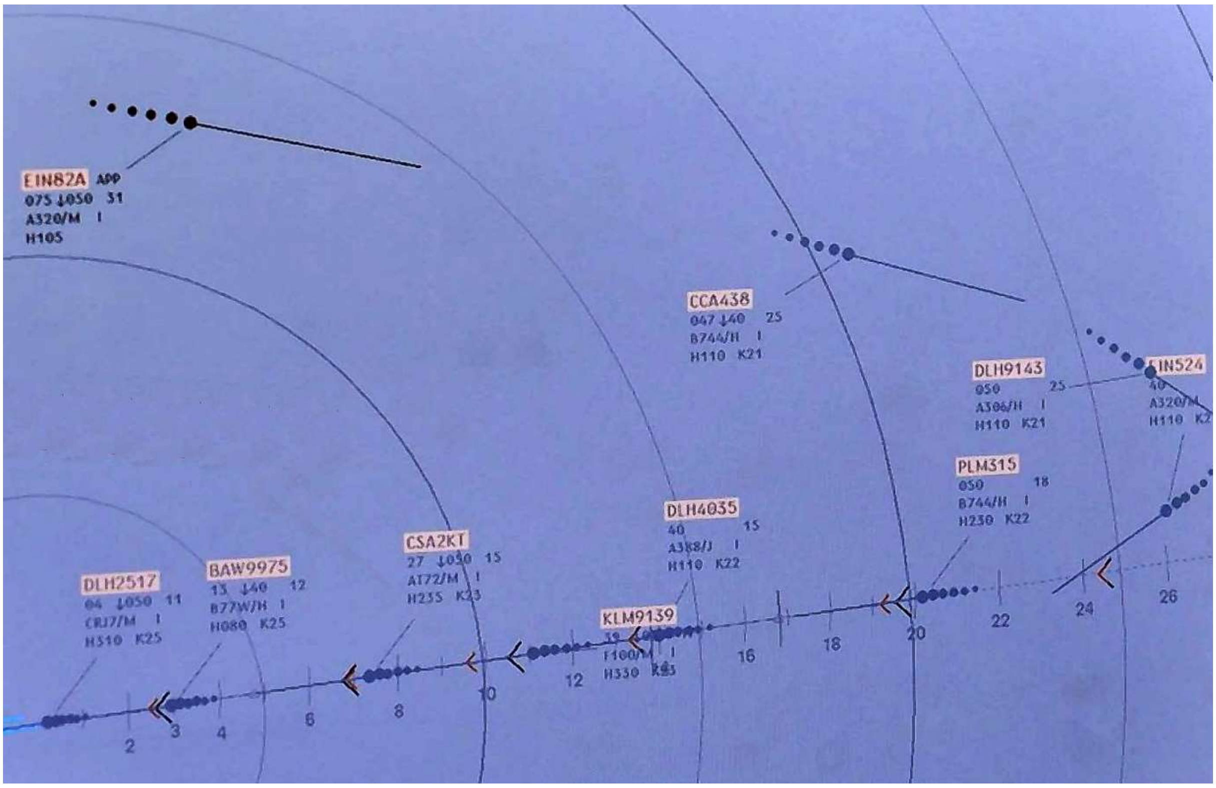


Figure 4-6: LORD display with the black Initial Target Distance (ITD) (black tringles) indicator and the red Final Target Distance (FTD) indicator (red triangles) [Treve 2015].

The smaller red triangular (Final Target Distance FTD) displays the final separation to the preceding aircraft and therefore also the minimum possible separation during the closest approximation. This separation is usually obtained when the first aircraft of the aircraft pair is touching down. The bigger black triangular (Initial Target Distance ITD) indicates the actual best position of an aircraft behind its predecessor considering the current speeds of both aircraft and their assumed speed reduction action on the final. This is the position into the controller should guide the succeeding aircraft with turn-to-final clearance.

Another solution for a visual controller support directly on the radar screen introduced NATS at Heathrow Airport. Facing a segregated runway mode during daytime due to Government policy and a night curfew, the airport tried to find solutions for reducing capacity shortages. They identified the headwinds, which cause in sum up to 3.000 hours ATFM delay per year. The problem arises around 55-65 days a year with peaks at 95 days per annum when the headwind component surpasses 20 knots [Shand 2016]. Usually, the time-based wake vortex separations at Heathrow are 135 sec between Super Heavy and Heavy, 90 sec. between Heavy and Heavy and 113 sec. between Heavy and Medium sized aircraft. With a headwind component of 35 knots, the time-based separation climbs up to

160 sec, 107 sec and 133 sec respectively with constant distance-based separations. This means a capacity loss of 15% to 20%. The reason is, that in stronger headwinds, the aircraft's ground speed is slower and it takes longer for them on the final to cover the distance resulting in a reduced landing rate.

After a safety case based on LIDAR wake vortex measurements by NATS from 150,000 movements supported by SESAR and EUROCONTROL, Heathrow developed an HMI extension for the controller radar display with a Dynamic Separation Indicator (DSI) based on Trajectory Based Separation (TBS) rules and actual real time wind data derived from Mode S downlinked aircraft parameters. If onboard wind data are not available, LIDAR measurements are also usable.

4.1.3.4 TRAWL-NET CONTROLLER SUPPORT FUNCTION

With a transition to a time-based flight guidance approach in the Great airspace, timely precise flight guidance of aircraft will become more important than today. Amongst others, air traffic controllers will have to integrate several arrival streams of aircraft with different equipage at the Late Merging Point (LMP) in the final around six nautical miles before threshold. On the arrival stream on the final there are conventional equipped aircraft which are common today. From other directions, more and more aircraft will have advanced four-dimensional flight management system (A-FMS) available onboard and use the LMP for an Early Full Clearance Approach (EFCA). To stagger conventional aircraft against equipped ones which have negotiated overflight times at significant waypoints, time critical maneuvers exist in some phases of the approach routes and procedures. For the manually guided aircraft is this particularly applicable to downwind, centerline, and final. One example is the aircraft's turn from downwind onto the centerline where each second delay in the first direction is doubled in the other one on the centerline.

During the last years, the trawl-net technology supporting air traffic controllers in giving timely precise turn-to-base commands to pilots was developed at the DLR [Ohneiser 2015]. The trawl-net technology provides for every aircraft in the vicinity of the downwind a line of optimal turn points displayed on the radar display. Thus, the mechanism also works for aircraft flying parallel to the downwind and complement controller assistance systems like AMAN advisories or visual aircraft spacing tools.

Modern Arrival Manager have the ability to schedule all arriving aircraft to an airport and support air traffic controllers with time-to-loose and time-to-gain information at selected waypoint. In dependence of the airspace structure, an avoidable delay exists in the last phase of a flight waiting for a base turn from downwind to final ending up on the centerline (Chapter 0). In this structure, every delay on the downwind is doubled on the centerline when flying on the trombone pattern.

Advisories may help controllers to match the right time for turning on final, but this guidance aid is usually positioned at one edge of the radar display and thus out of the action window in typical support systems [Gerdes 2012 & Helmke 2009]. Additionally, controllers often refuse advisory technology, because they only have to read the AMAN suggestions and tend on this way to lose their situational awareness and in a long-term consequence their aircraft guidance skills. Using a second by second countdown at the aircraft label on the human machine interface (HMI) showing the perfect time for turning from the AMAN point of view could be better. But this turner suggests only the best time of starting the turn maneuver and gives no additional information about the possible start window to meet safety and efficiency targets. Thus, an advanced technology to help controllers turning aircraft timely onto the centerline is needed like the trawl-net technology, which is a graphical HMI enhancement to support ATCOs in guiding arriving aircraft more safely and precisely in a time-based working environment.

In the last years, various concepts were developed delivering calculations of relating virtual aircraft positions on alternative display positions respective merging routes. For the implementation, ghosting functionalities (Chapter 4.1.3.2) and TargetWindows (Chapter

4.1.3.3) shall be the base. The real aircraft label and the projected aircraft targets on a centerline have certain distances to their predecessors and visualize the real and the theoretic position in the arrival flow on the extended final. Finding the ideal position and the best time for the turn-to-base command is a challenge for arrival manager and air traffic controller when aircraft do not fly precisely on transitions (downwind).

The trawl-net displays graphically the earliest position and time when a downwind aircraft can start the turn-to-base regarding wake vortex separations independently of the side of the final where the aircraft actually moves. A trajectory-based countdown to the concrete start time for a turn can be derived from the turn start point of the AMAN-calculated 4d-trajectory. The first solution for this task was the extension of the advisory stack with additional clearance functionalities [Helmke 2011a]. Guiding commands with this countdown time are displayed in a specific advisory window anywhere on the screen, but in the past trials with air traffic controllers showed only minor acceptance for support features which are working on the edge of their visual field. This is due, among other things, to the fact that advisories need to be scanned once with an active gaze from the controller. However, it is the case that the advised guiding advisories demand a cognitive transfer between time and flight distance by the controller and as a consequence, the turn-to-base support should be displayed direct at the corresponding aircraft label. For this reason, the best turn position always stays in the area of the controller's HMI attention. The small trawl-net line on the HMI for the advised start of a turn-to-base is directly in the area of controller action and attention. This is predominant to other implementations of the same support functionality.

Showing a countdown time until turn-to-base starting time as part of the aircraft label on the radar screen is closer to the place of action. However, the challenge of the cognitive transfer from time digits to distances remains. When aircraft or controllers do not follow the AMAN 4d-trajectory with a certain accuracy, the algorithms for optimizing arrival sequences and time plans deliver new routes and target times after a few updated radar data. Little deviations from the plan assumed in the last calculation cycle may lead to completely new countdown times and the countdown next to the aircraft label would show "irregular jumping" digits.

To get rid of these disadvantages, the trawl-net line can be easily and for the controller traceable adapted to the current computation output. Every aircraft on the centerline with a supposed target position for its successor can drag a trawl-net indicating the earliest safe turning points and therefore times for each area on downwind.

For the reason of more than one downwind a trawl-net could only be plotted at a downwind with a current corresponding arrival flight. Contrariwise the controller has the chance to see the earliest possible turn point on both sides of the centerline to adapt the traffic sequence individually. Two trawl-nets are reasonable, because a trawl-net is valid for aircraft flying directly on the transition or in its vicinity. In the case of two parallel runways with two centerlines and only one downwind near each of them, only the trawl-nets pointing to the side of the to the final related downwind are computed.

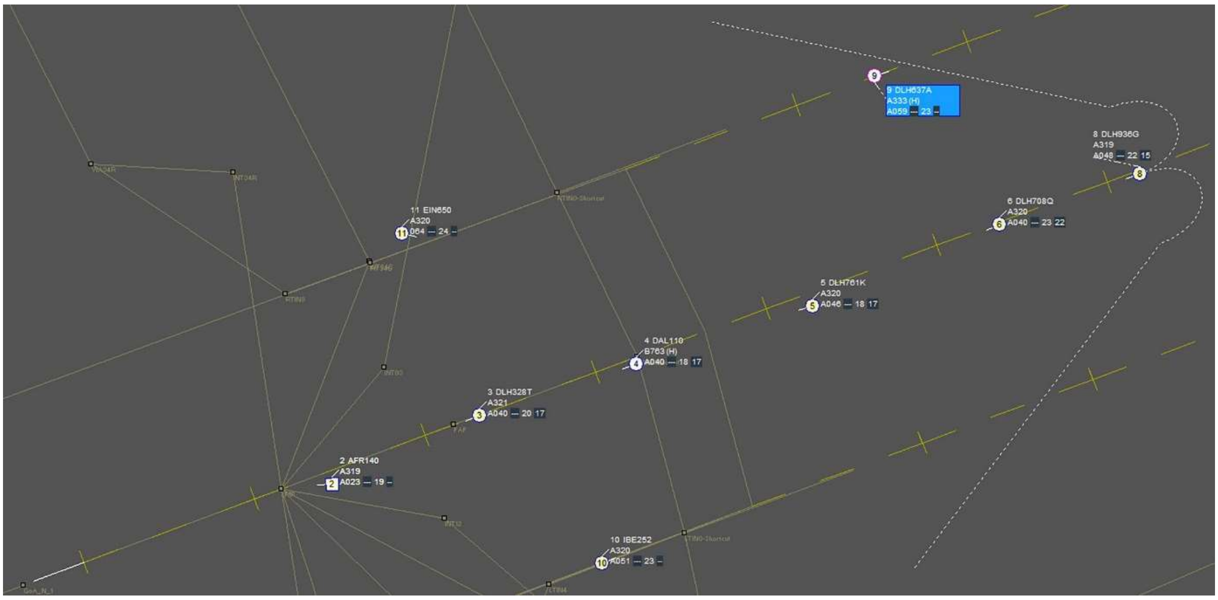


Figure 4-7: Double trawl-net displayed as dotted lines attached to the aircraft DLH936G with sequence number 8 on the final. In the moment, when aircraft DLH637A above the centerline with the sequence number 9 crossing the trawl-net line, the turn-to-base maneuver will result in a safe separation between number 8 and 9 on the final approach. Screenshot of a simulation scenario.

The trawl-net behind an object on the centerline represents an additional graphical information in the radar display and may cover other important information or distract from important traffic developments. For this reason, the trawl-net should disappear if one of the following conditions come to effect [Ohneiser 2015]:

1. The succeeding aircraft is already on the centerline
2. The preceding aircraft is too close to the runway
3. The preceding aircraft is too far away from the base area between downwind and centerline

As with a real aircraft label, it is also possible to plot a trawl-net behind a Ghost (Chapter 4.1.3.2) on the centerline. But in low traffic situations, controller should be able to switch off the trawl-net function. The calculation of the Trawl-Net lines is described in detail in [Ohneiser 2015].

In Figure 4-8, a possible simultaneous displaying of the visual controller support functions Ghosting, Trawl-net and TargetWindow is presented to assist controllers by the implementation of the Early Full Clearance Approach Operations.

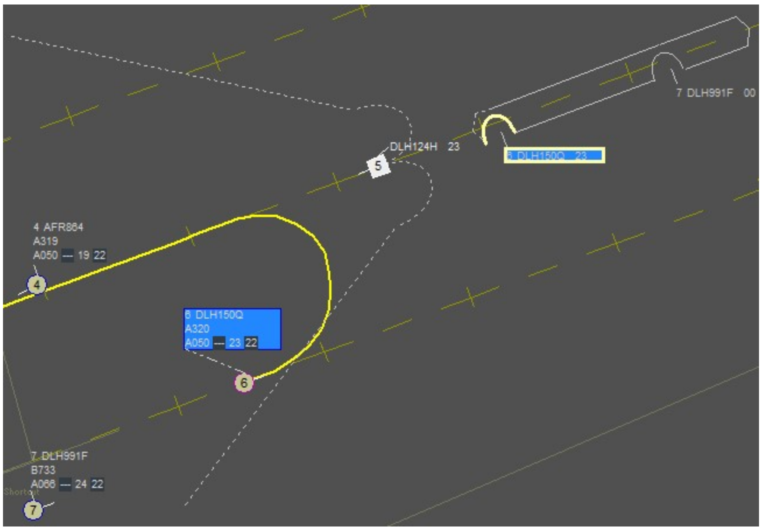


Figure 4-8: The combined controller display support functions Ghosting, Trawl-net and TargetWindow. The Ghost of the aircraft DLH124H is the white square with the number 5, the TargetWindow of aircraft DLH150Q with its yellow trajectory is the small yellow semicircle in the upper right, and the Trawl-net drawn for DLH150Q are the white dashed lines connected with its predecessor ghost-label from DLH124H.

4.2. DMAN

The departure manager (DMAN) is a tactical planning tool supporting the departure scheduling by apron, ground and tower controller. Today, departure planning systems are most commonly products of commercial software houses rather than research institutions prototypes. They aim to provide consistent optimized planning of the airport’s outbound traffic. Over the years, DLR developed a prototype of a DMAN called “Controller Assistance for Departure Optimization” (CADEO). It optimizes the take-off sequences at runway threshold with selectable pre-defined different optimization settings. This means at first step the optimization of the Target Take-Off Times (TTOT) and then the reverse calculation going backward to estimate the other required times for instance at stands so that the envisaged TTOT will be met. This prototype is seen as the most adequate to the GreAT project needs and goals as it enables to reduce (or even eliminate) the waiting time at the runway threshold by avoiding having a queue of aircraft waiting there. This optimization strategy might have an impact on the overall capacity as well as the runway throughput but it acts on favor of the environment by reducing the amount of unnecessary fuel burn due to reduced runway waiting times. For example, waiting at the runway, an Airbus A320 burns in engine idle mode with typically 4% thrust around 23 kg kerosene per minute, a Boeing B747 nearly 60 kg [Zhang 2019]. These are the equivalents to more than 72 kg and 186 kg CO_2 per minute.

In addition to the sequence planning, CADEO supports air traffic controllers to achieve this sequence without additional workload. It provides advisories and suggests control actions needed to implement the proposed sequence. Figure 2-9Figure 4-9: below summarizes and shows the departure manager processes described above. Using multiple received or configurable inputs, CADEO computes the TTOT for the departure flights, then uses it to deduce the optimized departure sequence and at the last step generates the related advisories to the air traffic controller. The details of each of these steps is provided in the following chapters.

It worth also noting that CADEO considers the separations at the runways and the SIDs, but it does not include conflict detection and prevention during ground movements. This could be only ensured when the DMAN is coupled with an SMAN.

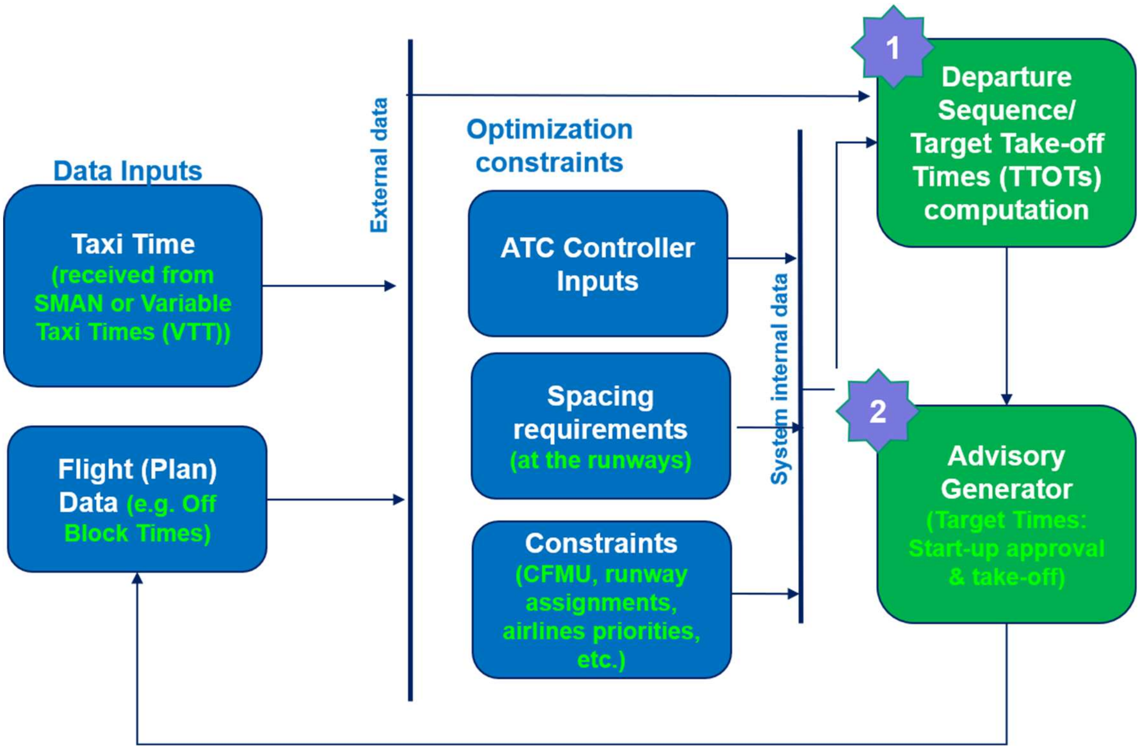


Figure 4-9: CADEO processes are displayed in green and numerated 1 and 2. CADEO processes the data coming from the external systems or sources and considers the optimization constraints locally defined as well as the ATC controller inputs.

To sum up, CADEO is a decision support tool for the management of the departure traffic aiming to fulfill the following objectives [Schaper 2008]:

1. Throughput enhancement
2. Slot compliance improvement
3. Taxi-out delay reduction
4. Stability of plans

To map it with SESAR, the first objective could be matched to "capacity KPA". The 2nd and 3rd objectives are more related to the "operational efficiency KPA". The 3rd objective has no match with the set of KPAs defined within the framework of SESAR, but it is important to make the proposed sequence viable and to avoid unnecessary increase of ATCO workload. It is also obvious that those objectives may act against each other's. Therefore, weighing each of these goals against the others will help emphasizing the optimization strategy and goals which best meet the project requirements. Different optimization settings are pre-defined in CADEO, which could be selected so that to change and adapt the targeted optimization objectives.

It is also important to note that "Environment KPA" is not listed within the objectives of CADEO because the objective related to fuel consumption reduction is independent from the optimization settings, as the CADEO concept itself is based on this idea. In fact, CADEO uses the optimized take-off sequences to derive off-block sequences. This means that the departures are recommended to stand with engines off at their parking position and they start taxiing exactly when it is expected that they arrive at the runway "just-in-time" to depart. CADEO is then primary targeting an environment-friendly flight sequence and provide a set of parameters to configure and optimize the other KPAs when needed. Hence, it is considered that the CADEO could be employed for the GreAT project without any further enhancements or improvements.

4.2.1. TARGET TAKE-OFF TIMES COMPUTATION

The CADEO has a configurable planning horizon. For example, it takes departures 20minute before TOBT, otherwise EOBT into the optimization. For departing flights, the departure manager receives flight plan data as inputs, containing Estimated Off-block Time (EOBT), Target Off-block Time (TOBT), information about given clearances and their timestamp, stand, runway and SID. Based on this data, CADEO computes Target Take-off Times (TTOT) for each departure using configured times (times for startup and push, variable or real taxi time plus line-up time) and then it derives the Target Start-up Approval Times (TSAT) for each departure from the TTOTs. When not connected to a SMAN, the Variable Taxi Times (VTT) defined within the European Airport Collaborative Decision Making (A-CDM) [EUROCONTROL 2012b] is used instead of the real computed taxi time. As intermediate step and in case of no SMAN available, aircraft position data updates might be used by CADEO to update the earliest possible take-off time through updates of the remaining taxi times. That brings benefit to the departure runway sequence planning [Schaper 2008].

The calculation algorithm of CADEO considers several constraints [Böhme 2005], among others:

- Planned arrival sequences for mixed mode operations
- Wake turbulence categories
- Planned runway and SID
- CFMU-slots
- Controller inputs for individual sequences or runway assignments
- Runway closure

Although the optimized sequence is calculated automatically, the air traffic controller can change the sequence. CADEO accepts sequence constraints like either freezing the sequence (then only TTOTs may change but the sequence keeps the same) or setting a defined sequence position for a departure (set #1, #2, etc.), which will update the TTOT calculation, the derived TSATs and other advisories. It has to be noted, that sequence constraints might not only influence the departures with the sequence constraints, but also all other departures with their TTOTs, TSATs and advisories. Both kinds of sequence constraints can also be repealed again.

4.2.2. ADVISORY GENERATION

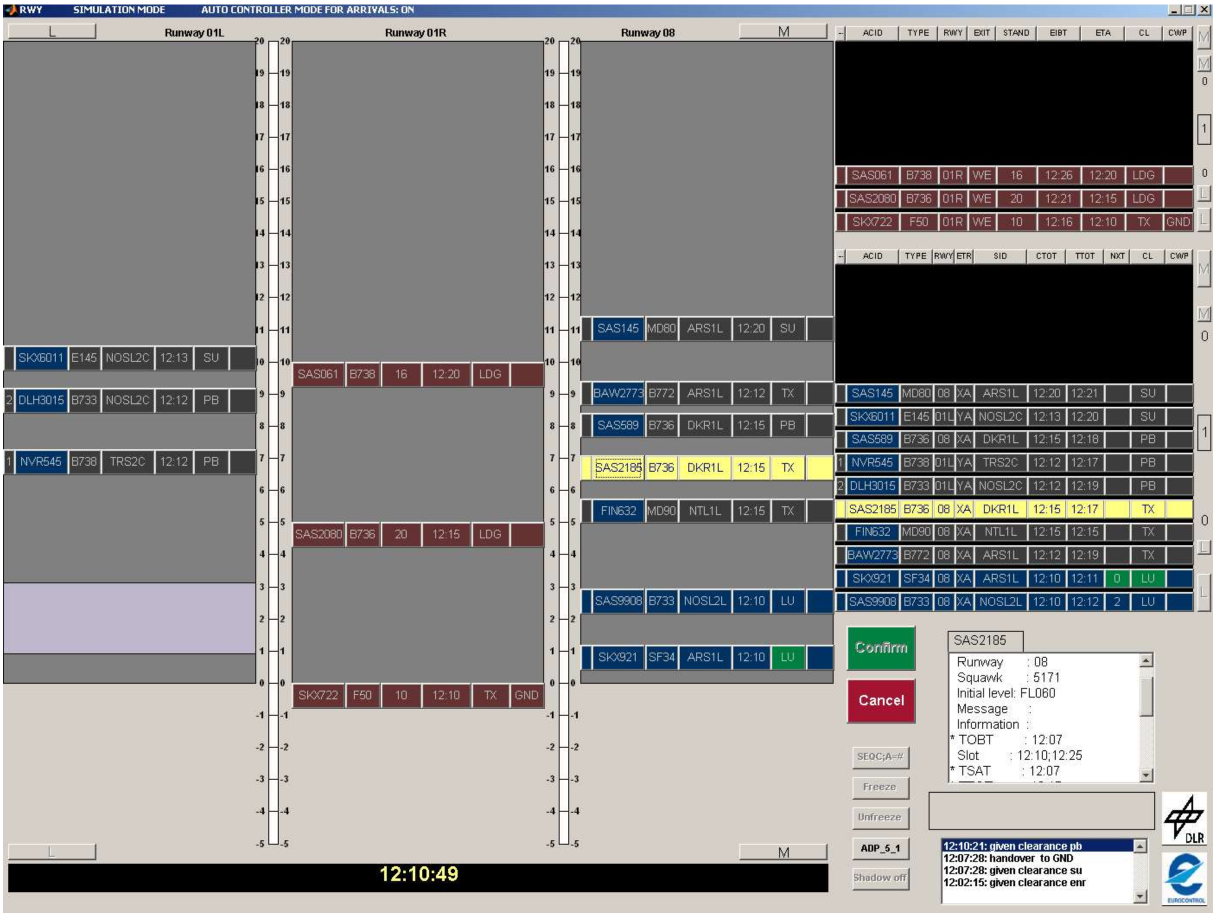
Based on the proposed take-off times and sequence, CADEO generates advices for the air traffic controller involved to meet the different target times computed. The ATC controller shall issue the required instructions to the departing aircraft, if possible. If the sequence could not be established as planned, the CADEO will reschedule and align with the behavior and wishes of controllers. The CADEO will monitor if clearances for departing flights are given as planned and will update the sequence based on received clearances and actual times of actions.

Flight data updates (e.g. ETA and TOBT) are also considered by the DMAN and lead to dynamic adaptations of the suggested sequence.

4.2.3. VISUAL CONTROLLER SUPPORT FUNCTIONS

CADEO can be integrated with any Human Machine Interfaces (HMI) being able to show TTOTs and Recommended Time Until Next Clearance” (i.e. a CADEO advisory). Nevertheless, for test purposes, CADEO itself has three kinds of HMIs for three kinds of air traffic controller working positions: Clearance delivery, apron/ground and tower/runway. The tower controller HMI is shown in Figure 4-10:. It displays timelines for each configured runway as well as the “Flight Table”. In each timeline, the sequence and the timing of the departure flights are shown in blue and arrivals in brown. Each flight is additionally presented with a flight strip in a bay.

Flight strips convey information not only by their textual information but also by their appearance (color coding). It is possible as well to interact with the flight strip to adjust specific fields in the strip (for instance the clearance issue, etc.).



-	ACID	TYPE	RWY	EXIT	STAND	EIBT	ETA	CL	CWP
	SAS061	B738	01R	WE	16	12:26	12:20	LDG	
	SAS2080	B736	01R	WE	20	12:21	12:15	LDG	
	SKX722	F50	01R	WE	10	12:16	12:10	TX	GND

-	ACID	TYPE	RWY	ETR	SID	CTOT	TTOT	NXT	CL	CWP
	SAS145	MD80	08	XA	ARS1L	12:20	12:21		SU	
	SKX6011	E145	01L	YA	NOSL2C	12:13	12:20		SU	
	SAS589	B736	08	XA	DKR1L	12:15	12:18		PB	
1	NVR545	B738	01L	YA	TRS2C	12:12	12:17		PB	
2	DLH3015	B733	01L	YA	NOSL2C	12:12	12:19		PB	
	SAS2185	B736	08	XA	DKR1L	12:15	12:17		TX	
	FIN632	MD90	08	XA	NTL1L	12:15	12:15		TX	
	BAW2773	B772	08	XA	ARS1L	12:12	12:19		TX	
	SKX921	SF34	08	XA	ARS1L	12:10	12:11	0	LU	
	SAS9908	B733	08	XA	NOSL2L	12:10	12:12	2	LU	

SAS2185
Runway : 08
Squawk : 5171
Initial level: FL060
Message :
Information :
* TOBT : 12:07
Slot : 12:10;12:25
* TSAT : 12:07

12:10:21: given clearance pb
12:07:28: handover to GND
12:07:28: given clearance su
12:02:15: given clearance enr

Figure 4-10: The CADEO display configured for a three runways system. Blue labels show departures and brown the arrivals. The purple color on RWY 01L displays the time the runway is closed. The yellow flight strip is selected and its details are shown at the right bottom of the screenshot.

4.2.4. INTERFACES WITH OTHER PLANNING TOOLS

To optimize departure sequences regarding further criteria, an automated exchange of information between different planning managers may also be conducted. The departure manager could be then interconnected for instance with:

- Airline Operation Centers (AOC): this link may enable to influence off-block times of their aircraft by assigning priorities. If take-off times are postponed, aircraft can be kept at the gate longer, so that they do not have to wait with running engines on taxiways or runway holding points and pollute the environment with exhaust gases and engine noise. This is considered by CADEO through the use of TOBTs.
- AMAN: this is made through collaborative sequence optimization by the DLR AMAN-DMAN-Coordinator (ADCO in Chapter 4.5)
- SMAN: this is made through the DMAN-SMAN interface for the reception of the real computed taxi time (Chapter 4.4).

4.3. SMAN

AMAN and DMAN are planning tools that assist ATC controllers in sequencing arrival and departure flights in an optimized way. To achieve these optimized takeoff times and sequences under consideration of the actual traffic situation on apron and taxiways, another tool called Surface Manager (SMAN) was introduced. SMANs could support air traffic controllers in creating optimized conflict-free taxi trajectories as well as with conflict detection and resolution. For the time being, SMANs exist mainly as research prototypes and are not often implemented in real operational environment despite the clear need for such useful tool to improve the efficiency of incoming and outgoing air traffic. Certainly, it is extremely important to compute the most efficient and optimized flight sequence in order to match as much as possible the greenest trajectories but it is equally important to monitor and guide the aircraft along these optimized sequences, otherwise the environmental benefit could be significantly reduced when unexpected stops, diversions, accelerations and decelerations during taxi are required. As analyzed within WP2.1 and summarized in GreAT deliverable D2.1, the main causes of unnecessary fuel burn on the ground could be for instance [Finke 2021]:

- Inaccurate prediction of the taxi trajectory before leaving the gate which implies the need for additional braking maneuvers or several stops until take-off
- Inaccurate execution of the 4d ground trajectories[7]
- Inaccurate estimation of the taxi time which is used by the planning tools AMAN and DMAN

An SMAN could help to solve these issues as it will enable to:

- Compute 4d ground trajectories[8]
- Optimize 4d ground trajectories
- Assist the controller/pilot to accurately execute the 4d ground trajectories through advisory generation
- Monitor the 4d ground trajectories and adapt them when needed

More broadly, the primary SMAN goal is to organize and optimize the taxiing movements of aircraft around the runways, taxiways and apron areas alongside defined parameters and constraints such as taxi distances or times. It supports the control of the taxiing traffic through planning of 4d ground trajectories and advisories to execute them. It could feature speed control as new element of surface management and could extend the concept of time-based trajectories to the ground. It can also feed the other planning tools with more accurate information about taxi times and route.

In the past years, DLR has developed research SMAN prototypes and used them to realize a trajectory-based ground movement management. One of these prototypes is called Taxi Routing for Aircraft: Creation and Controlling (TRACC). It was deployed to enable precise time-based taxiing on aprons and taxiways. The ground trajectory represents a section of a SESAR 4d-business trajectory and can be implemented, controlled and monitored by controllers with the help of an SMAN. The following chapters focuses on describing the TRACC features as an example of an SMAN prototype that might bring environmental benefits. In some cases, additional possible alternatives to TRACC are also presented.

The TRACC algorithm computes optimized taxi trajectories based on a set of external data which includes flight plans, airfield geographical data and aircraft performance data. The

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[7] Obviously, the position of ground moving air traffic can be described through the two dimensions in space and one in time. Nevertheless, in recent years it has become customary to speak of four dimensions in order to emphasize that time is considered in the calculation.

[8] The "ground trajectory" computed by TRACC covers the aircraft trajectory from push back inclusive until takeoff.

scheduling and trajectory generation of TRACC bases on three main principles [Gerdes 2012]:

- Cost-by-cause-principle: If an aircraft deviates from its assigned trajectory, the trajectory is re-planned only for this aircraft.
- Equality and reliability principle: A recalculated trajectory should deviate as little as possible from typical operational procedures.
- Stability principle: Changes to calculated trajectories should occur as rarely as possible. Speed changes or stopping instructions should be preferred to route changes.

During the evaluation by controllers, the novel concept for moving flight traffic planning and conflict avoidance on the movement areas using 4d ground trajectories was extensive and successful tested and assessed [Schaper 2013].

4.3.1. CONFLICT-FREE TRAJECTORIES

The SMAN TRACC aims to compute a conflict free ground trajectory and assist controllers and pilots to execute it as planned. The time-based trajectory is one of the most important criteria in evaluating if the taxi movements will be free of conflicts. To use optimized taxi procedures efficiently, the detection of conflicts prior execution of the trajectory is of particular importance, because every deviation through acceleration or deceleration pushes up the fuel consumption and thus the CO_2 emissions. During the taxi procedure, a conflict is considered to be the shortfall of the minimum distance between aircraft, where the minimum distance to be considered depends on the aircraft types. The conflict detection are triggered when any deviation of trajectory is detected or requested.

For instance, after a flight plan has been submitted, TRACC assigns a "TRACC standard" taxiway to this flight, which corresponds to the usual taxiways at the airport. After that, the Estimated In-block Time (EIBT) and the Variable Ground Movement Time (VGMT) for arrivals and ELUT, TSAT and VGMT for departures are updated. At a fixed time before the activation of a flight, the flight is optimized considering all other already planned flights.

In case of a departure, a check is made before optimization whether the push-back leads to a conflict with an already planned aircraft (Figure 4-11). If so, the push-back timing is adjusted. Subsequently, it is checked whether the TSAT has been planned in such a way that the TLUT can be reached on time. If this is not the case, the TSAT is adjusted accordingly. There are two possibilities for the optimization itself:

1. Time planning: Only speeds are changed and waiting times are introduced if necessary.
2. Route planning: The rolling route is also changed, in addition to rolling speeds and waiting times.

Route planning is only performed if it was not possible in the first step to construct a conflict-free route that also complies with the time specifications by the CADEO. After a trajectory has been constructed, an "Earliest Line-up Time" (RLUT) is determined for the CADEO, in which the earliest possible TSAT is determined in a first approach and the intended speeds of the taxi route are multiplied by a factor. If the resulting trajectory shows conflicts, the time optimization is performed again and optimized according to the earliest possible arrival time.

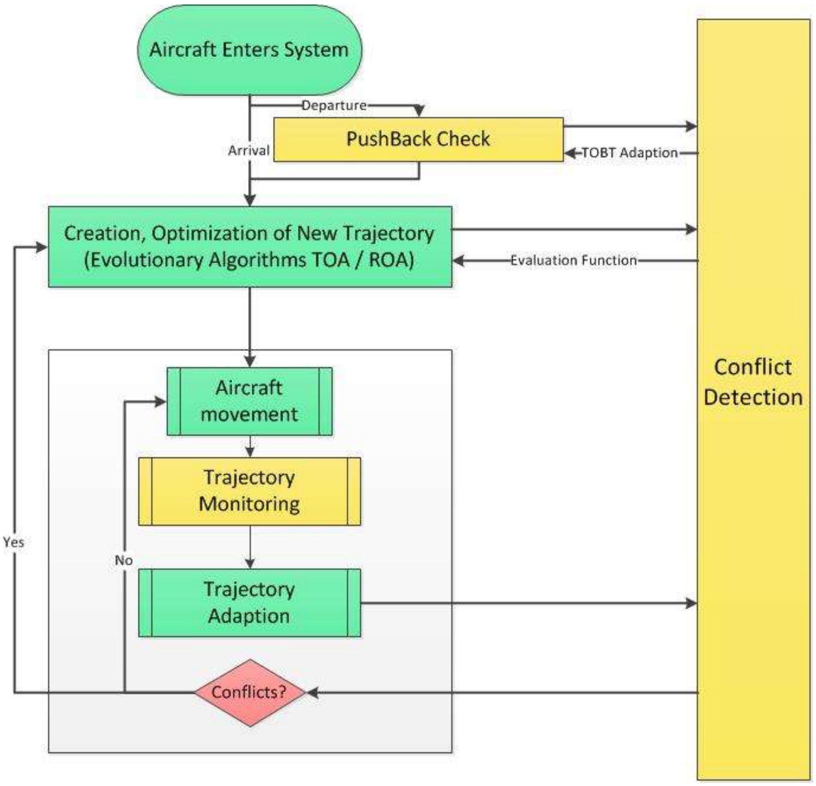


Figure 4-12: The TRACC process including the computation of conflict free trajectories, trajectory monitoring and adaptation. Depending on the detected conflicts, many iterations might be necessary [Gerdes 2013].

4.3.2. TAXI TIME COMPUTATION

Calculating precise taxi times for all individual aircraft considering the complete apron traffic enables a DMAN to give timely precise clearances for pushback and taxi request to avoid standby times at gates, runway crossings and runway heads.

The total taxi time of an aircraft consists of the taxi time and the waiting time. In this document, the push-back time is treated as a part of the taxi time, as the aircraft is in a moving phase with a waiting time for towing rod removal showing a small temporal dispersion. The taxi time depends on the taxi distance and the taxi speed. The taxi distance is a function of the stand or gate, the assigned runway, the chosen taxi route and possibly de-icing advices. The taxi speed depends on the route, the aircraft type and the meteorological and traffic conditions on the airport. The summarized waiting time for an aircraft is a function of the meteorological and traffic conditions, the runway queue and the number of runway crossings (Figure 4-13).

As a starting point for the taxi routes, an SMAN could plan standard routes used typically by the local tower controllers. For the route and time calculation, the runway- and taxi system of an airport could to be transferred into a mathematical graph. For example, in DLR’s TRACC system, evolutional algorithms are developed and implemented for the best-way calculation regarding the defined optimization criteria. In this way, the computed trajectory might not be the optimal solution every time, but the computational time is reduced from a few minutes down to some seconds.

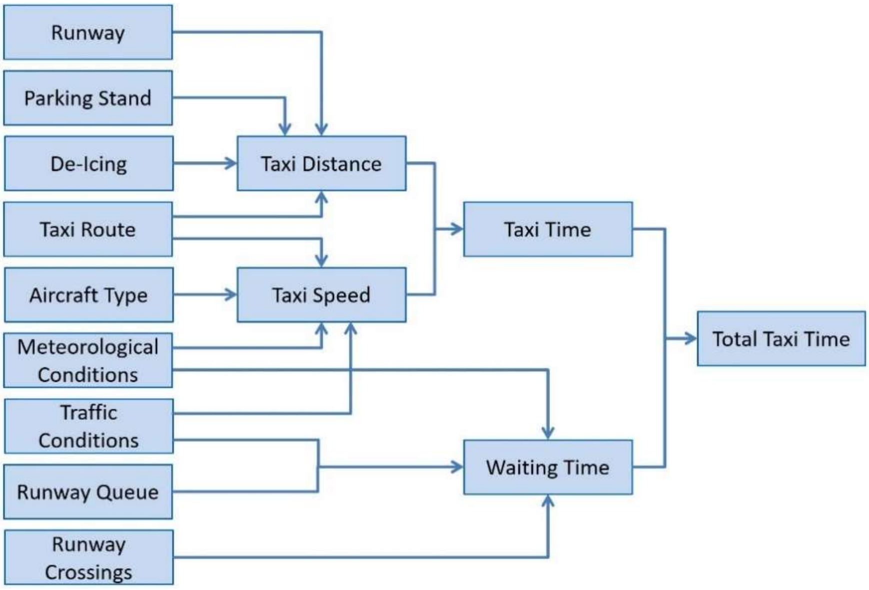


Figure 4-13: Dependencies of airport factors and total taxi time calculation [extended after Sparenberg 2016].

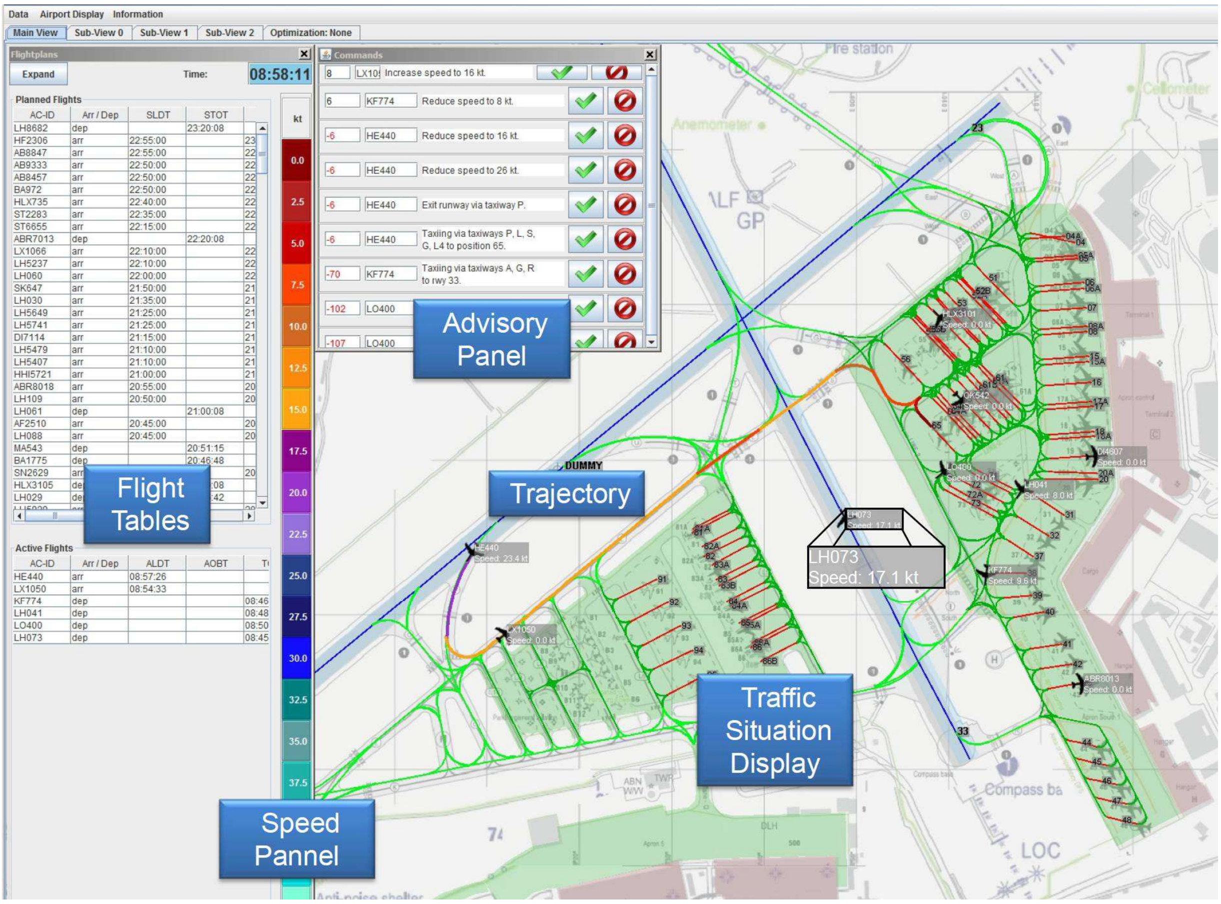
In GreAT, the main focus is the reduction of the environmental impact during all flight phases, including the taxi phase, while limiting the impact on the runway throughput and the overall aerodrome capacity as minimum as possible. The SMAN to be used should be able to estimate the aircraft individual fuel consumption during the taxi-phase and generate fuel- and CO_2-optimized taxi-routes and procedures, including taxi speeds on different areas of the apron.

4.3.3. VISUAL CONTROLLER SUPPORT FUNCTIONS (EXAMPLE: TRACC)

Figure 4-14:Figure 3-13 shows the TRACC display as an example of an SMAN Human Machine Interface (HMI). The TRACC display is mainly divided in several areas providing different kind of information:

- Flight tables
- Advisory panel
- Traffic situation display
- Speed panel

The way these panels are displayed is configurable and could be customized by the ATC controller depending on its role or preferences.



Planned Flights

AC-ID	Arr / Dep	SLDT	STOT	
LH8682	dep		23:20:08	
HF2306	arr	22:55:00		23
AB8847	arr	22:55:00		22
AB9333	arr	22:50:00		22
AB8457	arr	22:50:00		22
BA972	arr	22:50:00		22
HLX735	arr	22:40:00		22
ST2283	arr	22:35:00		22
ST6655	arr	22:15:00		22
ABR7013	dep		22:20:08	
LX1066	arr	22:10:00		22
LH5237	arr	22:10:00		22
LH060	arr	22:00:00		22
SK647	arr	21:50:00		21
LH030	arr	21:35:00		21
LH5649	arr	21:25:00		21
LH5741	arr	21:25:00		21
DI7114	arr	21:15:00		21
LH5479	arr	21:10:00		21
LH5407	arr	21:10:00		21
HHI5721	arr	21:00:00		21
ABR8018	arr	20:55:00		20
LH109	arr	20:50:00		20
LH061	dep		21:00:08	
AF2510	arr	20:45:00		20
LH088	arr	20:45:00		20
MA543	dep		20:51:15	
BA1775	dep		20:46:48	
SN2629	arr			20
HLX3105	de		:08	
LH029	de		:42	

Active Flights

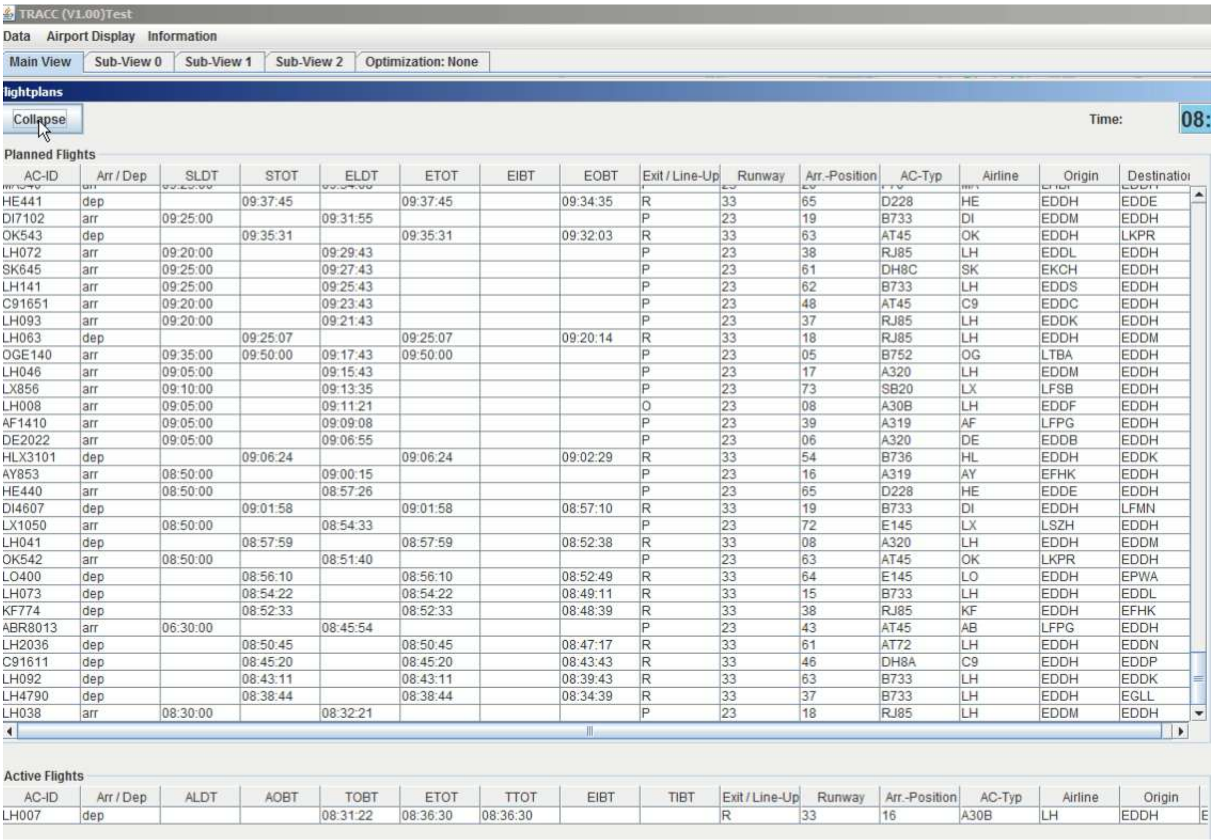
AC-ID	Arr / Dep	ALDT	AOBT	T
HE440	arr	08:57:26		
LX1050	arr	08:54:33		
KF774	dep			08:46
LH041	dep			08:48
LO400	dep			08:50
LH073	dep			08:45

8	LX10	Increase speed to 16 kt.	✓	⊘
6	KF774	Reduce speed to 8 kt.	✓	⊘
-6	HE440	Reduce speed to 16 kt.	✓	⊘
-6	HE440	Reduce speed to 26 kt.	✓	⊘
-6	HE440	Exit runway via taxiway P.	✓	⊘
-6	HE440	Taxiing via taxiways P, L, S, G, L4 to position 65.	✓	⊘
-70	KF774	Taxiing via taxiways A, G, R to rwy 33.	✓	⊘
-102	LO400		✓	⊘
-107	LO400		✓	⊘

Figure 4-14: The TRACC display: It is a traffic situation display with additional panels for advisories, speed, the flight tables and trajectories.

4.3.3.1 FLIGHT TABLES

The Flight Table is divided into two sub-tables. All expected flights are listed in the upper table, while only the flights that are already active are displayed in the lower table. The plan table is sorted so that the earliest flights are at the bottom, while the reverse is the case with the active table. This should make it possible to get an overview of the traffic situation by looking at the transition between the two tables. A color coding for arrival and departure is also configurable to ease their differentiation, for instance here departures are highlighted in yellow and arrivals in green. The tables summarize the relevant information related to each flight for instance Scheduled Landing Time (SLDT), Scheduled Take-off Time (STOT), Actual Landing Time (ALDT) and Actual off-block time (AOBT). The Flight Tables could be displayed in extend (Figure 4-15) or reduced format (Figure 4-14).



Planned Flights

AC-ID	Arr / Dep	SLDT	STOT	ELDT	ETOT	EIBT	EOBT	Exit / Line-Up	Runway	Arr.-Position	AC-Typ	Airline	Origin	Destinatio
HE441	dep		09:37:45		09:37:45		09:34:35	R	33	65	D228	HE	EDDH	EDDE
DI7102	arr	09:25:00		09:31:55				P	23	19	B733	DI	EDDM	EDDH
OK543	dep		09:35:31		09:35:31		09:32:03	R	33	63	AT45	OK	EDDH	LKPR
LH072	arr	09:20:00		09:29:43				P	23	38	RJ85	LH	EDDL	EDDH
SK645	arr	09:25:00		09:27:43				P	23	61	DH8C	SK	EKCH	EDDH
LH141	arr	09:25:00		09:25:43				P	23	62	B733	LH	EDDS	EDDH
C91651	arr	09:20:00		09:23:43				P	23	48	AT45	C9	EDDC	EDDH
LH093	arr	09:20:00		09:21:43				P	23	37	RJ85	LH	EDDK	EDDH
LH063	dep		09:25:07		09:25:07		09:20:14	R	33	18	RJ85	LH	EDDH	EDDM
OGE140	arr	09:35:00	09:50:00	09:17:43	09:50:00			P	23	05	B752	OG	LTBA	EDDH
LH046	arr	09:05:00		09:15:43				P	23	17	A320	LH	EDDM	EDDH
LX856	arr	09:10:00		09:13:35				P	23	73	SB20	LX	LFSB	EDDH
LH008	arr	09:05:00		09:11:21				O	23	08	A30B	LH	EDDF	EDDH
AF1410	arr	09:05:00		09:09:08				P	23	39	A319	AF	LFPG	EDDH
DE2022	arr	09:05:00		09:06:55				P	23	06	A320	DE	EDDB	EDDH
HLX3101	dep		09:06:24		09:06:24		09:02:29	R	33	54	B736	HL	EDDH	EDDK
AY853	arr	08:50:00		09:00:15				P	23	16	A319	AY	EFHK	EDDH
HE440	arr	08:50:00		08:57:26				P	23	65	D228	HE	EDDE	EDDH
DI4607	dep		09:01:58		09:01:58		08:57:10	R	33	19	B733	DI	EDDH	LFMN
LX1050	arr	08:50:00		08:54:33				P	23	72	E145	LX	LSZH	EDDH
LH041	dep		08:57:59		08:57:59		08:52:38	R	33	08	A320	LH	EDDH	EDDM
OK542	arr	08:50:00		08:51:40				P	23	63	AT45	OK	LKPR	EDDH
LO400	dep		08:56:10		08:56:10		08:52:49	R	33	64	E145	LO	EDDH	EPWA
LH073	dep		08:54:22		08:54:22		08:49:11	R	33	15	B733	LH	EDDH	EDDL
KF774	dep		08:52:33		08:52:33		08:48:39	R	33	38	RJ85	KF	EDDH	EFHK
ABR8013	arr	06:30:00		08:45:54				P	23	43	AT45	AB	LFPG	EDDH
LH2036	dep		08:50:45		08:50:45		08:47:17	R	33	61	AT72	LH	EDDH	EDDN
C91611	dep		08:45:20		08:45:20		08:43:43	R	33	46	DH8A	C9	EDDH	EDDP
LH092	dep		08:43:11		08:43:11		08:39:43	R	33	63	B733	LH	EDDH	EDDK
LH4790	dep		08:38:44		08:38:44		08:34:39	R	33	37	B733	LH	EDDH	EGLL
LH038	arr	08:30:00		08:32:21				P	23	18	RJ85	LH	EDDM	EDDH

Active Flights

AC-ID	Arr / Dep	ALDT	AOBT	TOBT	ETOT	TTOT	EIBT	TIBT	Exit / Line-Up	Runway	Arr.-Position	AC-Typ	Airline	Origin	
LH007	dep			08:31:22	08:36:30	08:36:30			R	33	16	A30B	LH	EDDH	E

Figure 4-15: TRACC Display - Flight Table (extended format).

4.3.3.2 ADVISORY PANEL

Like an AMAN or a DMAN, the TRACC generates advisories for the controllers for transmission to the cockpit crew from the 4d-trajectory data. The controller can interact with the TRACC via buttons on his traffic situation display and other associated information windows. One of these windows is the Advisory Panel or Controller Panel, which displays all pending commands for all active aircraft (Figure 4-16). For each aircraft, TRACC shows on the electronic flight strip the callsign, the suggested clearances and/or instructions as well as the time left to issue this clearance. Usually, several consecutive instructions are suggested for a flight, but only the first one is activated (Figure 4 16) the others remain grayed until the previous one is executed. This panel provides also the possibility to enter whether a clearance was actually given or whether the SMAN's suggestion was ignored by the controller. The inputs are considered in the next planning cycle. For best timing, TRACC uses a countdown scaled in seconds to indicate when a command should ideally be implemented, so that the tower controller can instruct the crews accordingly. This panel gathers the list of clearances to assist the ATC controller in the monitoring and planning of aerodrome traffic on aprons and taxiways between stands and runways. The list of suggested instructions is sorted in a timely manner.

13	LH038	Exit runway via taxiway P.
13	LH038	Taxiing via taxiways P, L, S, G, L2 to position 18.
13	LH038	Reduce speed to 50 kt.
19	LH038	Reduce speed to 30 kt.
27	LH007	Taxiing via taxiways A, L2, A, G, R to rwy 33.
74	LH038	Reduce speed to 20 kt.
87	LH007	Increase speed to 18 kt.

Figure 4-16: TRACC Display - possible configuration of Advisory Panel. Each row represents a suggested clearance. The controller can validate or discard the clearance using the two available buttons. For each clearance, the remaining time, callsign and a description of the instruction are provided, only one clearance per aircraft is active at the same time. The other ones are grayed and therefore inactive.

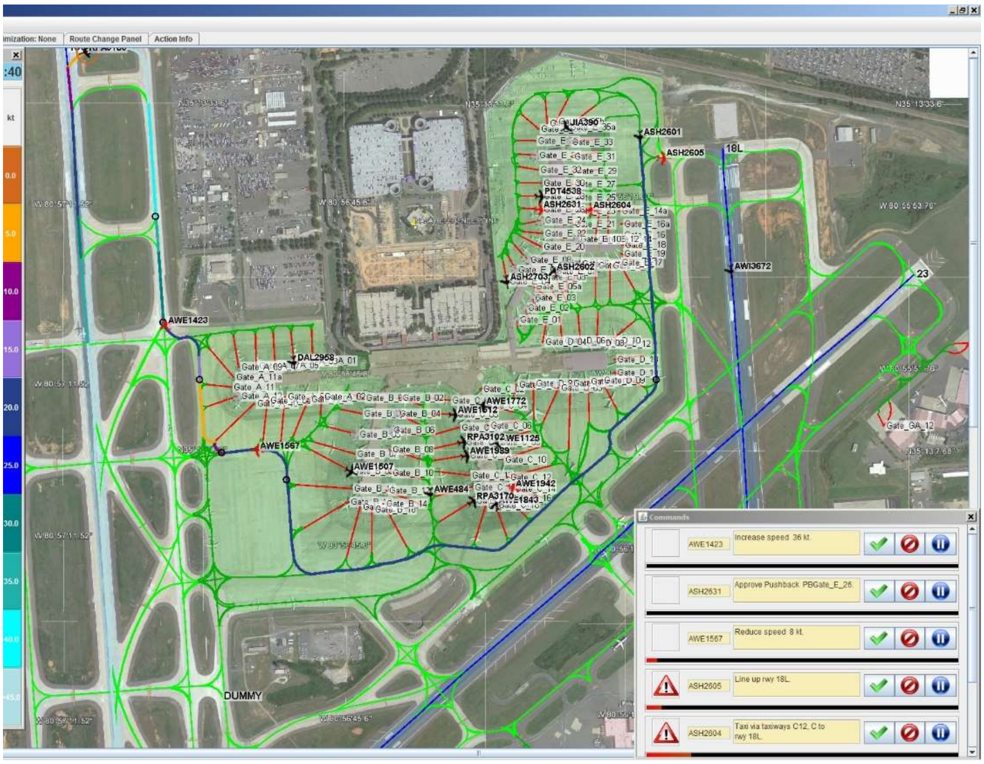
Different design configurations are possible for this panel (see Figure 4-16**Erreur ! Source du renvoi introuvable.** and Figure 4-17). In addition, the list of the suggested instructions will be relevant to the ATC Controller role assigned to this workstation and further freely configurable information could be also made available.

ASH2631	Approve Pushback PBGate_E_26.
ASH2601	Increase speed 15 kt.
AWI3672	Taxi via taxiways C12, C to rwy 18L.
AWI3672	Increase speed 22 kt.
RPA3183	Increase speed 30 kt.

Figure 4-17: TRACC Display - possible configuration of Advisory Panel. Each row represents a suggested clearance. The controller can validate, discard or pause a clearance using the three available buttons. For each clearance, a timer, the callsign and a description of the instruction are provided. Only one clearance per aircraft is active at the same time. The other ones are grayed. The most urgent instruction to be issued is highlighted through an alert symbol.

4.3.3.3 TRAFFIC SITUATION DISPLAY

TRACCs traffic situation display shows the airport air traffic situation through the presentation of the identification, position and tracking of aircraft within the maneuvering area. With one main view and three auxiliary views, several airport views are available for controllers, which are configurable regarding the visible section of the airport and the information to be displayed. Already planned or active aircraft are displayed in black, others in gray. For all planned flights the callsigns are displayed, which can be extended with additional information by clicking on the callsign. A click on an aircraft shows the colorcoded planned taxi route, if applicable, and the corresponding aircraft in the table. The taxi route of a selected flight could be also displayed using the different colors as per speed value. The Speed Panel defines the color coding used for identifying the speed per route segment. The Route Change Panel can be used to change routes for aircraft that are not yet active. The push-back can also be set via this panel.



	AWE1423	Increase speed 36 kt.	✓ ⊘ ⏸
	ASH2631	Approve Pushback PBGate_E_26.	✓ ⊘ ⏸
	AWE1567	Reduce speed 8 kt.	✓ ⊘ ⏸
⚠	ASH2605	Line up rwy 18L.	✓ ⊘ ⏸
⚠	ASH2604	Taxi via taxiways C12, C to rwy 18L.	✓ ⊘ ⏸

Figure 4-18: TRACC's Traffic situation display with advisory panel and the overview of trajectory colors assigned to taxi speeds at the left border.

The controllers have several possibilities to adapt the route generation and the runway assignment to their wishes via some input panels. Via the "Change Route" panel the route, the push-back direction and the runway can be changed (Figure 4-18).

4.3.3.4 SPEED PANEL

A speed control must be used to implement the planned taxi trajectory at the airport accurately to the second. Therefore, it was necessary to make some assumption about technical standards of the future like the cockpit's ability to comply with exact speed advisories which are used by TRACC for controlling the aircraft in accordance to their calculated trajectory. Currently, it is very difficult for pilots to follow speed advisories which are more complex than "increase speeds" or "slow down" because the accompanied head down time will increase considerably. This was shown within real time simulation trials testing the ability of pilots to follow speed or time advisories [Foyle 2011] with and without a special support tool integrated into the flight deck. Hence exact commands like "increase speed 15 knots" are unusual, but with upcoming technologies like electric taxi, the usage of taxi bots (e.g. ZETO project at University of Darmstadt in Germany) or an additional support tool it would be possible for pilots to keep up with a prescribed taxi speed. In Figure 4-18 the color bar on the left shows the speed-dependent color coding for routes that have already been planned.

4.3.4. CONFORMANCE MONITORING

As reality does not usually stick to plans, a conformance monitoring function is needed. The function shall monitor the conformance of each flight to its planned trajectory and inform the ATCO in case of non-conformance. Depending on the implementation of an SMAN, this could also trigger a re-planning of trajectories automatically to solve the non-conformance or even a conflict.

The necessary taxi commands and speed instructions are derived from the finished ground trajectory and displayed chronologically to the controller in the advisory panel. The controller then has the option to accept the command and pass it on to the pilot, cancel it or reject it. If the command is accepted and cleared to the pilot, the TRACC also activates the command internally and continues to run normally.

In the event a command is rejected, the reaction of the program depends very much on the command itself and on the resulting consequences such as the arising of conflicts. For example:

- If a push-back or a taxi clearance is cancelled at a roll-through position, 60 seconds are added to the TSAT and a push-back is checked to see if conflicts now occur during the push-back operation. In any case, the roll route is re-optimized. If it comes in conflict with taxi clearance of an inbound or a currently pushing outbound, first a waiting time is added for the waypoint to which the command is assigned. If there is an additional waiting time, it is also checked whether this causes conflicts with other aircraft, which then have to be assigned a new route. In any case, the taxi route of the current aircraft is then re-optimized.
- If only a speed change is rejected, a check is made to see whether continuing at the current speed until the next planned change will lead to conflicts. If this is the case, the aircraft is re-optimized, if not, only the planned route is adapted to the change. The same procedure is followed for rejected holding commands.
- In the case of rejected line-up commands, the waiting time at the line-up position is increased by 60 seconds and a check is made to see whether this leads to conflicts with other aircraft already planned. If a crossing clearance is denied, 30 seconds are added and the route is re-optimized.
- In the case that the TRACC for approaches also proposes a taxiway that was then rejected, the next possible taxiway is simply taken as the new taxiway and the route is re-optimized.

If there is no input or other reaction from controller’s side, TRACC reacts in a similar way as for a rejected command. This applies in particular to the postponement of a push-back or a delay of the taxi clearance. The main difference is that a subsequent re-optimization only occurs if the adjusted roll route leads to a conflict. If a speed instruction is delayed, the planned speed change is moved to the next waypoint. The same procedure is used for a holding instruction.

To sum-up, TRACC constantly compares the planned position with the actual position of every taxiing aircraft. If there are deviations, TRACC tries to adjust the planned route accordingly. If this leads to a loss of conflict freedom (or non-compliance with CADEO specifications), a re-optimization is initiated. It performs the resulting necessary actions and re-optimizes if necessary. The re-planning of trajectories follows the above-mentioned principles of less changes than possible and especially less route changes as possible.

4.4. DMAN-SMAN COORDINATION

During several test, a considerable reduction in fuel consumption when holding departures at parking positions was proven [Simaiakis 2014]. Concerning reductions in fuel burn and emissions, a reduction of 24% per departure was calculated when reducing the total taxi time in the airport movement area [Griffin 2012]. The overall delay was not reduced by this method, but shifted to other points of the airfield (spots/gates) [Gupta 2012]. With these former results in mind, it seems necessary to combine tools for surface and departure management for a better use of departure runways and the taxiway system itself. Thereby, it should be ensured that the number of aircraft on the taxiway system will not come close to a saturation value for this system because this will increase the taxi delay without benefitting the departure runways with a high number of available departures [Simaiakis 2014]. This will be supported by coupling a DMAN, which create an optimized departure sequence, with an SMAN, responsible for calculating appropriate gate release times and optimized taxi trajectories with respect to planned take-off times. In this chapter, the focus is on the example of coupling TRACC and CADEO as prototypes for SMAN and DMAN controller support systems.

The so-called earliest possible take-off time serves as lower boundary constraint for a DMAN's optimization, the quality of the result increases with better quality input [Malik 2010]. Additionally, one of CADEO's aims is to reduce the queuing and engine running time. This overlaps perfectly as task for a surface management system. SMAN like TRACC take the task to calculate und update the earliest possible take-off time, assign an appropriate pushback time and generate a taxi trajectory which delivers the departure on time at the runway regarding the TTOT for maintaining the planned departure sequence and keeping the queues short. This will support CADEO greatly as well as ATCOs and pilots in meeting these prescribed target times.

To achieve this, data has to be exchanged between CADEO and TRACC. The most important ones are earliest takeoff times and target times at the runway. As a surface manager shall not plan for any runway use, the runway holding point (i.e., the point where the line-up clearances are given) was chosen for CADEO-TRACCs coordination as described in [Schaper 2013]. This is reflected in the definitions of "Target Line-up Time" (TLUT) corresponding to the TTOT and "Earliest Line-Up Time" (RLUT, defined by DLR) corresponding to the earliest possible time for the take-off.

The earlier the RLUT is, the bigger the possibility to improve TTOT (for a specific flight). On the other hand, the departure shall not necessarily reach the runway holding point at RLUT to avoid queuing (in case the RLUT is much earlier than TLUT). So SMAN has to come up with a trajectory trying to fit (less or equal) to TLUT as best as possible. The time, TRACC plans to deliver the departure at the runway holding point, was defined as "Estimated Line-up Time" (ELUT) and should be close to TLUT [Schaper 2013].

For the coupling of CADEO and TRACC, some modifications of the tools are necessary. For CADEO, they have been quite simple: Use of the RLUT calculated by TRACC instead of VTT. For TRACC, several enhancements were required as preparation for the coupling with a runway sequence optimizer because of the necessary calculation of an appropriate TSAT for each departure.

4.5. AMAN-DMAN-SMAN-COORDINATION

One key issue on the way to a flexible and time-based aircraft guidance concept is the support of controller and pilots with tactical assistance systems, which have to provide much more sophisticated support functionalities than today [Ohneiser 2015]. New and innovative air traffic controller support functions have to be integrated into Arrival, Departure and Surface Manager whereas most of them embody optical support elements for time-based flight guidance to give aircraft the facility to meet reliably the negotiated target times in the air and on the ground. For example, the experience of the former DLR-project "Future Air Ground Integration" (FAGI) showed the importance of timely precise turn-to-base implementation and navigation. When flying on a downwind of a trombone approach pattern, every delay starting the turn on the downwind is doubled on the centerline and reduces or lengthens the disposable spacing between arriving aircraft.

Reducing the spacing may leads to separation violation, where as an unnecessary lengthen of the separation leads to a loss in airport and airspace capacity as well as efficiency.

For the optimal use of available airspace and airport capacity, the planning and management systems should use partly automated air-ground target-time and trajectory negotiation and have to integrate the negotiation results into the aircraft arrival and departure scheduling. This applies in particular to the runway as a resource, which is claimed exclusively by both the Arrival Manager for landings and the Departure Manager for take-offs. Due to the close planning link between Departure and Surface Manager, the coordination of take-offs and landings also has a decisive influence on the conflict-free planning and use of taxiways. Through the advanced supporting tools, controllers should get planning and visual support for guiding conventional air traffic during approach and taxiing. The thesis is that arrival gap tailoring is capable to increase the departure throughput while preserving landing capacity.

Therefore, the purpose of an AMAN-DMAN-coordination is the AMAN-supported arrivals coordination with the DMAN-supported departures on the same or more than one dependent runways. In this case, however, the dependence on two runways do not only concerning the flying phase but also may exist on the ground, for example, when aircraft must cross a runway to reach another one. The scope of the coordination includes mainly the information exchange, but also the planning algorithms (Figure 4-19).

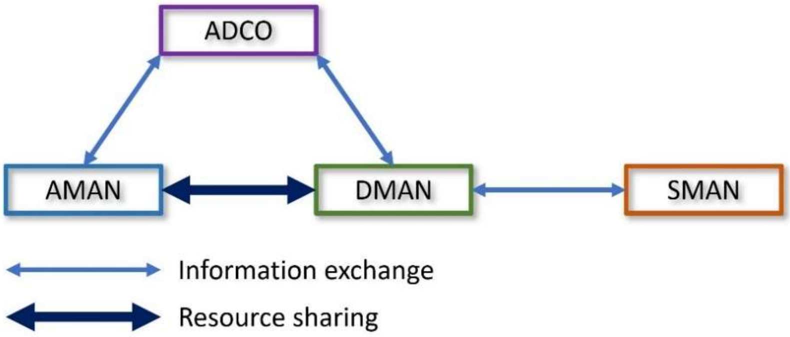


Figure 4-19: The ADCO AMAN-DMAN-SMAN information sharing.

The approach for the coordination support systems covers functionalities for the negotiation of target times, the coordination of the systems' requirements and the integration of the controller supporting tools. For the automatic coordination support, there are four support level defined [Böhme 2006]:

1. Level: No tool support
2. Level: AMAN & DMAN in master-slave configuration
3. Level: Coordinated AMAN & DMAN
4. Level: Integrated planning of runway operations

These objectives may be achieved by introduction of departure intervals on the runways during which no landing takes place (Arrival Free Intervals: AFI). The size of the departure intervals should not have the size that gaps between arrivals or between a departure and a subsequent arrival, cannot be used for departures. Departure intervals should be created in particular for urgent departures where, for example, a CFMU slot violation lie ahead [Christoffels 2006].

4.5.1. THE ADCO WORKING PRINCIPLE

For the deployment of a coordination system, an AMAN and DMAN with required minimum functionality have to be available. The minimum requirements of an AMAN include the optimum planning of landing operations, the consideration of blocked intervals (Arrival Free Interval: AFI), the planning has to be based on 4d-trajectories and the AMAN has to cover the area of the complete TMA at a minimum. The requirements for the DMAN are the optimum planning of take-offs regarding take-off time and take-off sequence and the consideration of arrivals. The main aim of the AMAN-DMAN-coordination is the aspiring of the runway throughput maximization (besides other objectives). Meet this goal, plan operations have to be finished as early as possible.

For an efficient use of a coordination system at an airport, mixed mode operations have to be allowed at one runway at a minimum, the arrival and departure flow rate vary in time due to daily arrival and departure peaks, and there is (or might be) an inconsistent density of the arrival stream. The last point is essential because if a runway is one hundred percent occupied by approaches, no departures can be integrated into the inbound flow even under the best conditions.

The coordination process can be divided into two objectives. The first one is the improvement of the runway utilization, and the second one is the design of gaps for urgent departures to meet their CFMU slots[9] [Christoffels 2009]. Objective 1 can be achieved by the reduction of the unused intervals regarding numbers and length and by tailoring of the arrival gaps for an integral number of take-off operations. However, it must be noted that landings can be delayed only and take-offs might be possible earlier by changing the departure sequence if possible. The second objective is the design of gaps for urgent departures to meet their CFMU slots (Figure 4-20). Additional constraints are the coordination should not change the operational procedures and it should be possible without major adaptions of existing systems [Christoffels 2006]. Therefore, the AMAN-DMAN-Coordinator (ADCO) will be introduced as an additional coordination layer with bi-directional communication channels to the AMAN and the DMAN (Figure 4-19).

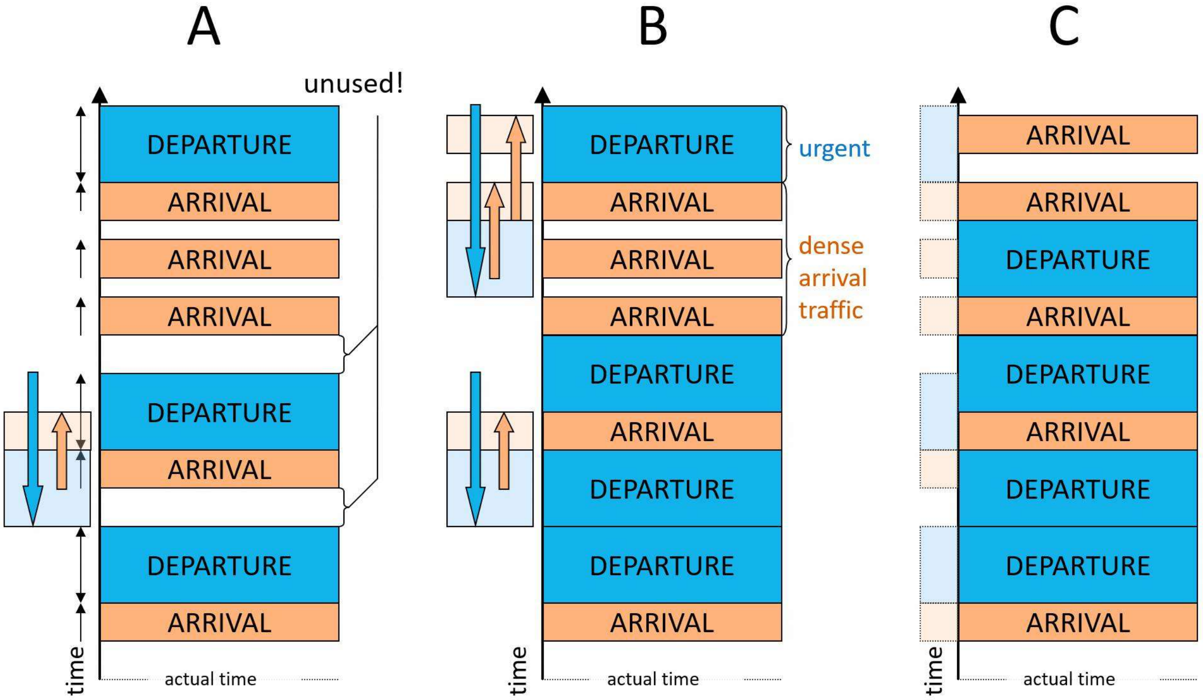


Figure 4-20: Example rescheduling of arrivals and departures of an ADCO. Stage A shows a typical first come first serve arrival-departure sequence. After identifying possible spaces between the flights, the ADCO shifts departures in two directions and arrivals only to the future (stage B). In stage C, the coordinated inbound-outbound sequence shows a nearly optimal use of the available runway capacity [modified after Böhme 2006].

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[9] The centralized air traffic flow management DNM (Directorate Network Management, formerly CFMU or Central Flow Management Unit) of EUROCONTROL in Brussels imposes airways slots for every fly-through sector of a flight.

The arrival gap tailoring has to be implemented in such a way that there is an improved runway utilization for departures, but the inbound flow must not be decreased, at least over a longer period, and the approach controller workload should not increase substantially.

The coordination works in following steps [Böhme 2007]. First, AMAN and DMAN deliver their actual planned sequences to the ADCO. The ADCO reserves departure intervals and sends these to the AMAN. The AMAN keeps the signaled departure intervals free from arrivals (Arrival Free Interval) and sends the updated sequence to the ADCO. Then, the ADCO transfers the updated arrival sequence to the DMAN (this has to be done as AMAN and DMAN does not have any direct connection). The DMAN has then the freedom to make use of the newly integrated gaps and sends the updated departure sequence back to the ADCO. Following this logic, an arrival free interval is a period, where no landing will occur, bit this gap is not assigned to a particular departure and does not necessarily imply any departure operation during this time.

4.5.2. THE ADCO ALGORITHM PRINCIPLE

The ADCO planning principle bases on an algorithm of recurring determination of the next candidate (time slot) for AFIs after a landing and after already established AFIs resulting from the previous cycle. The sequence and AFI availability situation is characterized with the help of features using linguistic meanings. To that belonging arrival stream and departure stream features. The arrival features cover the expected control effort, the arrival demand in comparison to a given flow and the controllability, basing for example on horizontal arrival path length or on latest (suitable) arrival times and density. The departure stream features inter alia availability, urgency and current or predicted demand.

The algorithm determines the properties, which means the measurement of the validities of statements. These statements are vague diagnoses like "arrival density is high" or "urgent departure will probably gain from AFI" (Figure 4-21).

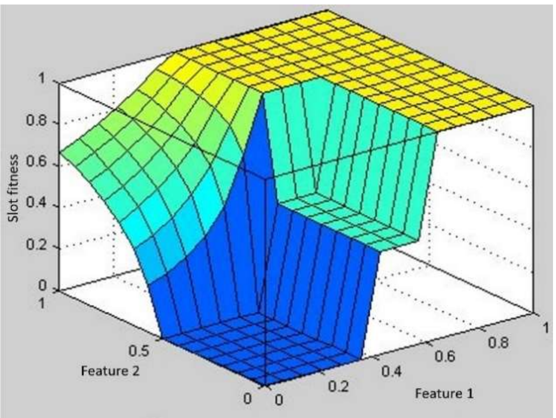

Figure 4-21: With the features a multi-dimensional solution space is calculated [Böhme 2006].

The used Fuzzy-system inferences from these claims on basis of "expert" rules, for example [Böhme 2006]:

- IF arrival density IS NOT high AND departure urgency IS medium
  OR
- IF controllability IS high AND departure availability IS high

- THEN AFI fitness is high

In this way, the fuzzy inference determines a fitness value for all rules and compares the fitness values with threshold parameters defined in the algorithms (Figure 4-22).

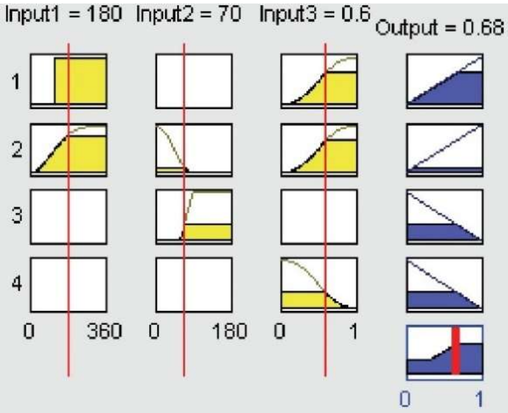

Figure 4-22: Three attributes used in a set of four rules are shown in this extract of the Fuzzy inference system. [Source: Böhme 2007].

The fast calculation possibility of the fitness values allows a dynamic adaptation of AFIs in real time. This enables sliding AFIs with sliding arrival times or to stick on arrivals or preceding AFIs. It is also possible to change the AFI size when a departure is within an established sequence. Maybe an additional feature could be the deleting of AFIs when departure cannot meet the slot.

4.5.3. SUMMARY

In summary, the ADCO support system concept bases on “experts’ rules” from air traffic controllers. The support system coordinates and influences the arrival management only if it is necessary or opportune. Its strength lies in the possibility, to incorporate a set of different and even contradictive objectives by considering both the inbound and outbound traffic situation on one or more runways. It is expected to be robust, because it cares for interval sizes as a second level functionality. This all works alone through narrow interfaces at AMAN and DMAN, through which information must be exchanged that is available in the classic support systems anyway.

The support system is considered to be sufficient to cope with the traffic demand of the next decade as long as the capacity limit of the considered runway system has not yet been reached. Furthermore, it is possible, to integrate interconnected systems like SMAN and data link and use their additional provided information, but the basic functionality can be performed without ancillary tools. The ADCO provides an easy to handle transition from precedent phase with more or less separate working AMAN and DMAN systems in a Master-Slave Mode and also the third level with a coordination of the controller assistance systems.

5. THE T-BAR AIRSPACE STRUCTURE AND APPROACH PROCEDURES

This section outlines the T-Bar airspace design and its operational implementation. In the frame of the GreAT project, the objective is to review and analyze the airspace structure for the medium-size airport to what extent it meets the requirements of the environment friendly flight guidance. In this chapter, first, the current state-of-the-art at a medium-size airport in Europe is presented, describing the most important GreAT project relevant changes of the last decade in chronological order that characterize the TMA even today. Then, this state is compared against GreAT concept elements identified under MWP2 [Finke 2021], and finally a justification is provided for the developments of the new functionalities of MergeStrip which is the system to be developed under this GreAT project.

5.1. ANALYSIS OF AIRSPACE DESIGN AND PROCEDURES AT A MEDIUM-SIZE AIRPORT IN EUROPE

Budapest TMA modernization is based on three main pillars:

1. Redesign of airspace structure of the TMA;
2. An optimized arrival procedure; and
3. An ATCO decision support system (MergeStrip) that fine-tunes the mentioned concept elements and the main ATM system, MATIAS, and enhances the effectiveness of T-Bar procedure.

Although Budapest TMA’s airspace structure safely handled the ever-increasing traffic during the mid-2010s, it could not always provide the opportunity of efficient arriving flight paths. On May 26th 2016, as a result of SESAR BUD 2.0 project, new instrument-based approach procedures were introduced at Liszt Ferenc Budapest International Airport (LHBP) TMA based on RNAV T-Bar procedure construction.

There were several reasons behind this step. First, HungaroControl wanted to make full use of Performance Based Navigation (PBN). Second, it was intended to provide more predictable arrival path, thus enabling more stabilized approaches, and to enable CDO. Finally, there was also a growing opposition from inhabitants, therefore noise emission had to be reduced.

The T-Bar procedure was chosen, as it is a solution that can be best applied at medium sized airports. This concept enables CDA from any direction (if supported by airspace), and if STAR ends at the Initial Approach Fix (IAF) of T-Bar instrument approach procedure – forming a closed STAR – CDO can be planned from Top of Descent (ToD). It can also be used with Point Merge STARs. In Figure 5-1, an example of T-Bar concept can be seen, as implemented at Liszt Ferenc Budapest International Airport.

The RNAV T-Bar procedures were designed according to ICAO’s Procedures for Air Navigation Services, Section 2., Chapter 3 [ICAO 2006]. This design methodology provides the opportunity of performing CDOs from any direction to a given runway even without the actual use of a STAR.

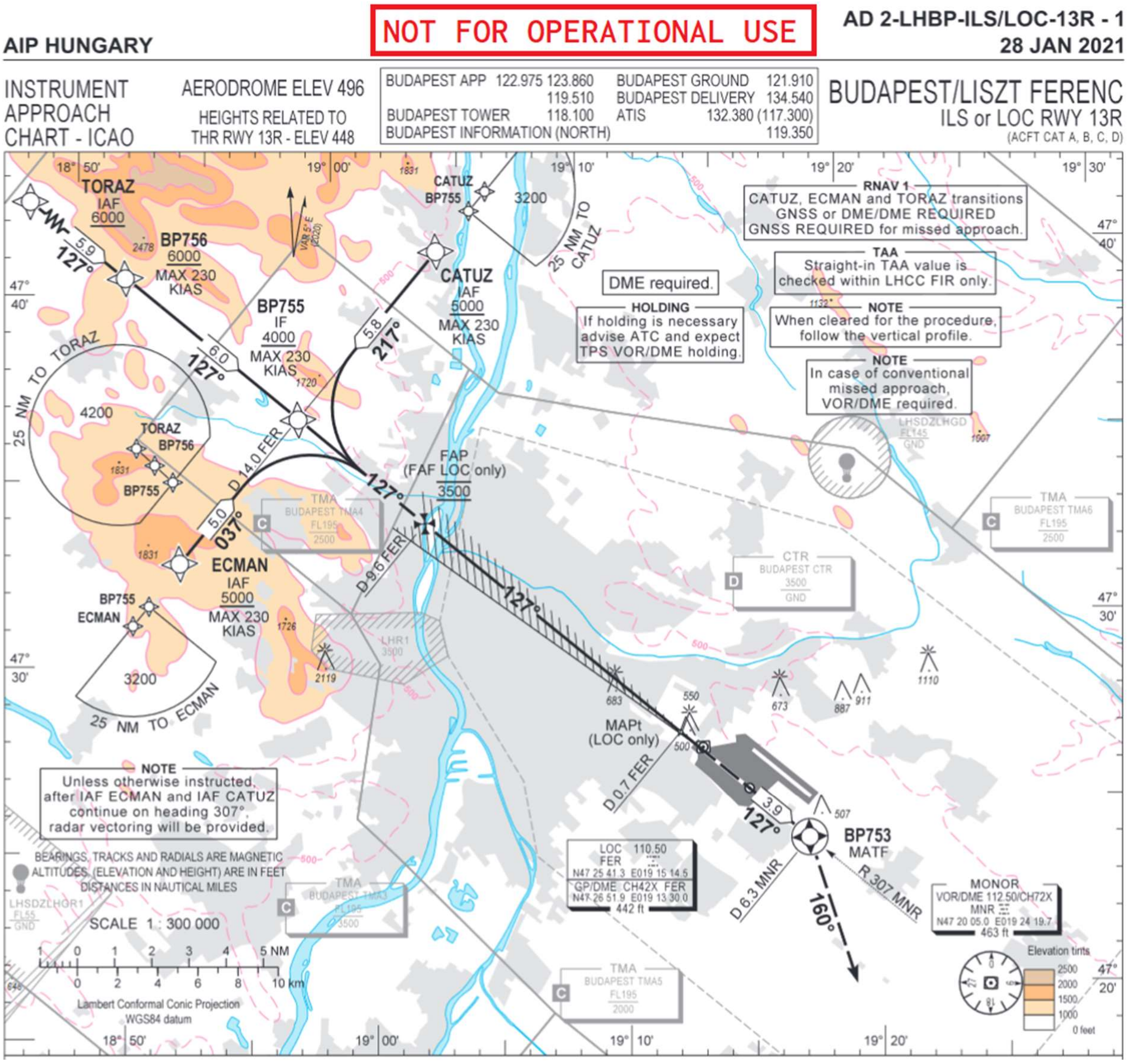

Figure 5-1: LHBP T-Bar based Instrument Approach Chart (not for navigation purposes).

During everyday operations, arriving aircraft receive ‘direct to’ instructions to the nearest appropriate T-Bar procedure’s IAF, which then represents a closed path up to the landing threshold, so the actual flightpath is known prior to entering the TMA. This concept enables Flight Management Systems (FMS) the calculation of optimal decent profiles from ToD point.

Under the T-Bar approach, the deviation of paths actually flown by aircraft is less than prior to its introduction, and aircraft may turn onto the final in predefined paths. Most airlines operating aircraft to Budapest are familiar with this procedure as there are similar procedures in use at several European airports, e.g. Prague in Czech Republic (LKPR) or Oslo-Gardermoen in Norway (ENGM). These existing procedures have been considered as examples when designing LHBP T-Bar. Another benefit of this procedure is that aircraft crew receive more precise information for optimal descent that may result in less level flights at low altitudes, which also translates into less fuel consumption and less noise disturbance [Micallef 2012].

Figure 5-2: T-Bar based Instrument Approach –Aircraft flight path as deducted from real radar data.

Finally, by analyzing historical traffic pattern, it can be seen that about 80% of the arrival traffic entering into Budapest FIR may fly directly to the closest Initial Approach Fix of the T-Bar based instrument approach procedure. This also makes flight planning more predictable, and allows considerable savings in fuel consumption, and consequently, less emission of CO_2, methane and other greenhouse gases.

The above-mentioned T-Bar introduction was not twinned with any airspace structure modification. During the late 2010s, the TMA airspace structure became the hindrance of being able to efficiently handle the 8-10% annual traffic growth and to serve other airspace users' needs (e.g. smaller aircraft, Drop Zone, Unmanned Aerial Vehicles (UAV)). The legacy airspace structure would not be able to provide CDO opportunities to the latest generation of aircraft types gliding in at a lower angle. Clearly, a major change in the airspace structure was needed. These factors were the main drivers of a complete redesign of TMA and CTR airspaces, and included the demands of neighboring military and general aviation airspaces.

In the framework of the complete redesign of TMA airspace of Budapest Liszt Ferenc International Airport in 2019, these T-Bar procedures and associated arrival routes (STAR) were revised. The observed average descent profile of the arriving aircraft (4% slope) were theoretically extended to any direction from the Initial Approach Fix of the T-Bar based procedure and were then connected to each other at intervals of 1000 feet. The resulting curve shapes were connected to form an ellipsoid providing an ideal airspace shape for optimum CDO possibilities (Figure 5-2). The final airspace structure was then optimized in accordance with the airspace user's need and was constrained due to national boundaries (Figure 5-3).

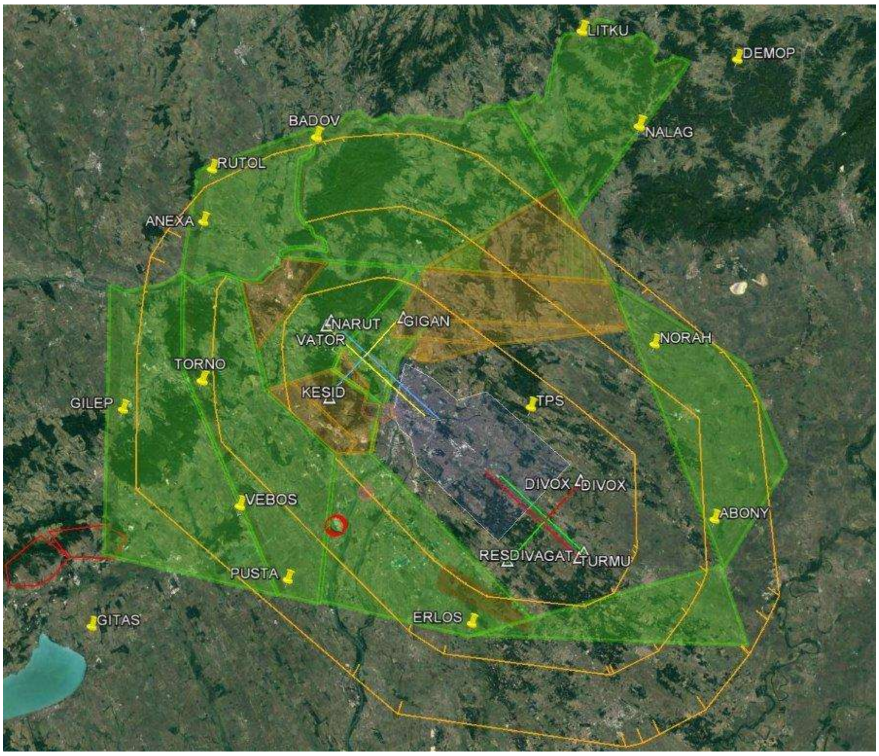

Figure 5-3: Conceptual view of previous Budapest TMA with the ellipsoid altitude intervals shown. Green and uncoloured in the middle are various TMA sectors, orange active glider areas within the TMA, yellow lines are altitude intervals with 6000, 8000 and 10000 feet respectively).

The SID and STAR route structure was redesigned as well to limit the number of conflicting crossing points and to enable optimal crossings where natural separation would exist between arriving and departure flights (e.g. departure traffic is already much higher than arriving or vice versa). As can be seen in Figure 5-3, the CDO in the southern part of the TMA was not possible as the optimal descent point from 10,000 feet was located outside of its perimeter.

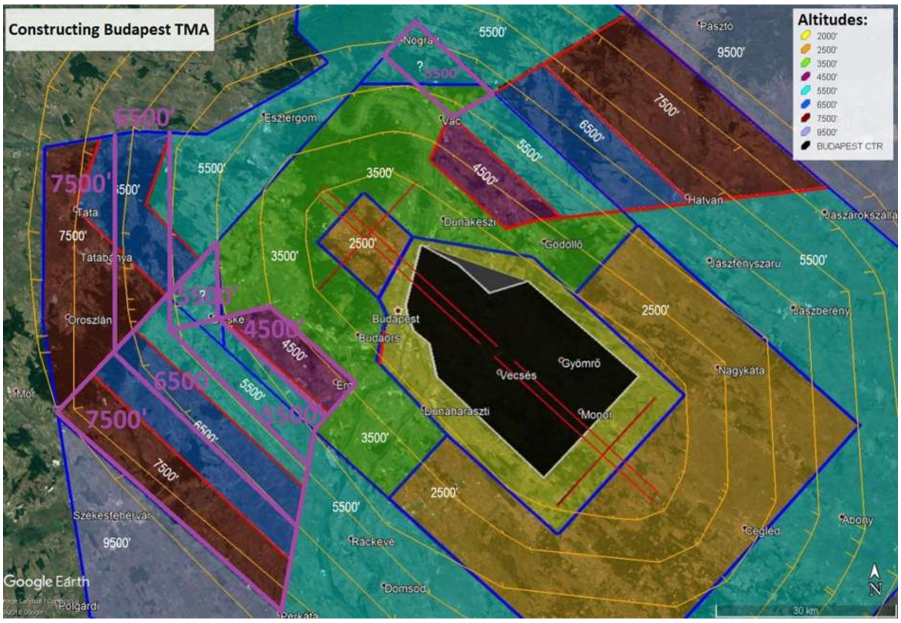

Figure 5-4: New TMA structure for Budapest airport.

On the January 30th, 2020, the whole Budapest TMA changed so that the new airspace structure could fully support CDA operations coupled with the use of T-Bar based

Instrument Approach Procedures (IAP). The new TMA airspace structure (Figure 5-5) increases ATC capacity through reduced ATCO workload as the symmetrical airspace is less complex than before, requiring less descend clearance instructions. It also reduces the pilot's workload through optimized descent profiles by providing more predictable and user-friendly trajectories which imply, in the most cases, less fuel consumption and greenhouse gas emission.

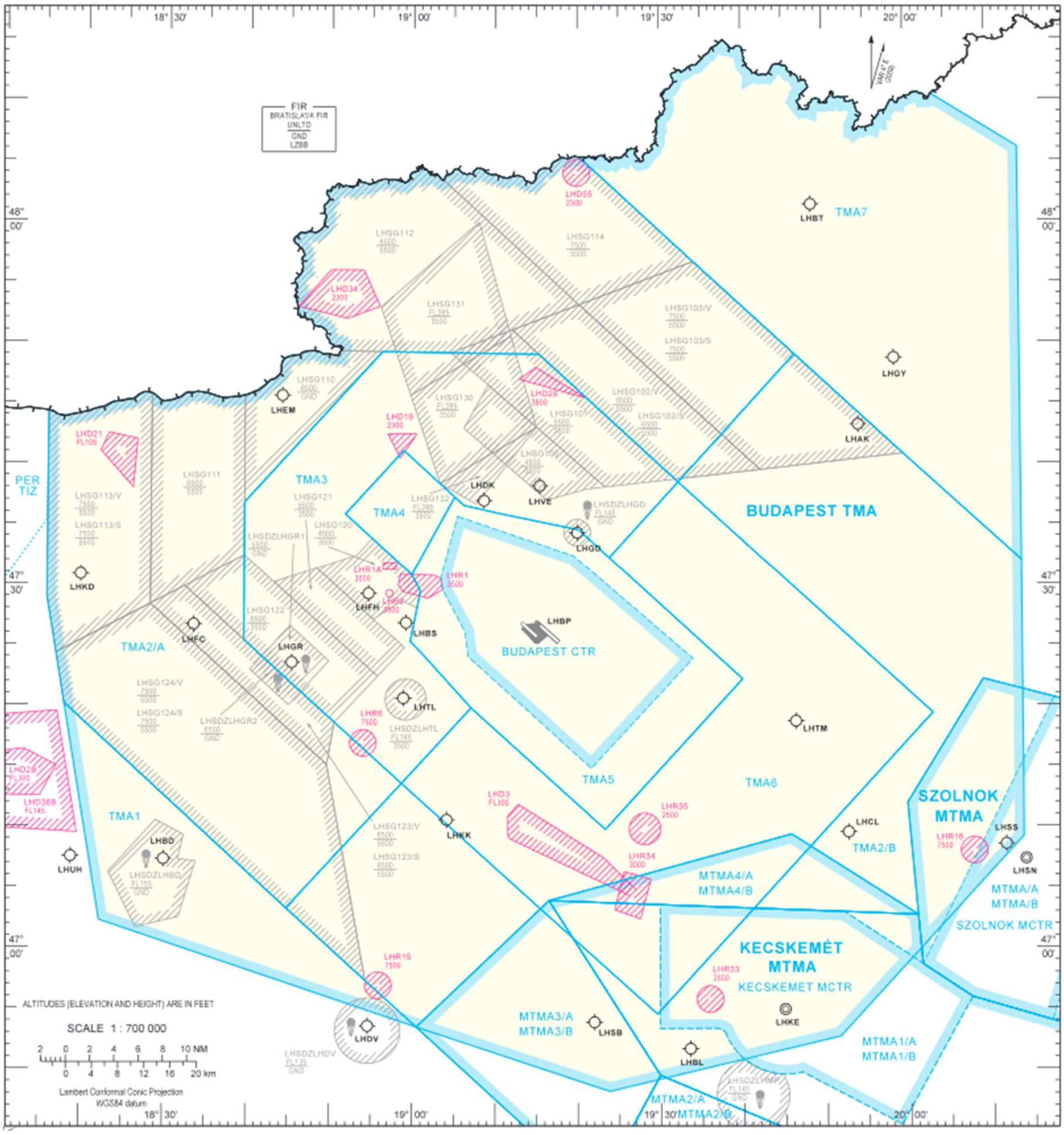

Figure 5-6: Final airspace structure of Budapest TMA.

In terms of numbers, it can be stated that the new TMA's ATS route structure has become 15% shorter, thus it allows a saving of an average of 100 kg jet-fuel per aircraft. As long as potential additional noise emissions are concerned, the new TMA's ATS route structure design took into consideration residential noise impact so no major route change was done below the area of 7000 feet AMSL. Based on EUROCONTROL estimation[10], it is expected that the new TMA will successfully be able to safely and efficiently handle the increasing traffic volume for the next 10 to 20 years.

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[10] EUROCONTROL estimation by 2050: https://ext.eurocontrol.int/airport_corner_public/LHBP

5.2. COMPARISON OF STATE-OF-THE-ART AT A MEDIUM SIZE AIRPORT IN EUROPE AGAINST GREAT CONCEPT ELEMENTS

The current TMA structure and T-Bar approach already apply a number of GreAT concept elements as enlisted in D2.1, Chapter 4.4.5 "TMA Operations" [Finke 2021]. However, it is expected from MergeStrip to further enhance the efficiency of the framework provided by the new TMA structure and T-Bar approach procedure, and to provide greener operations. Therefore, in this subchapter, each GreAT concept element from D2.1 is deeply analyzed and compared to the current state-of-the-art described in the previous chapter.

Free route in TMA: On strategic level, until the entry point, all arriving aircraft have to obey the RAD restrictions, but on tactical level, direct routing to the T-Bar instrument approach is the daily practice. Overflying traffic may follow FRA. The new TMA airspace structure enables the full use of FUA concept as well with two neighboring military air bases and their adjoining MTMA's and TRA structure as well as with temporary glider areas and parachuting areas surrounding Budapest CTR.

Continuous descent operations: Thanks to the new TMA structure, together with the new STAR's and IAP's, Continuous Descent Operations are enabled from any direction, as already discussed and illustrated in Figure 5-4.

Latency tolerant delay absorption: The new MergeStrip functionalities will enable a more reliable sequencing process as early as possible avoiding traffic concentration and sequencing on the downwind leg. In case of unavoidable vectoring, pilots will be informed about the remaining track miles to be flown. This may result in a slightly less efficient operation but we have to keep in mind that safety comes first.

Infinitely variable and low emission delay absorption: The use of holding pattern for sequencing is not applied. However, their use is necessary in abnormal situations such as severe weather conditions (e.g. thunderstorms, snowstorms) or runway closures (e.g. snow removal, bird strike). To enable more fuel-efficient holdings, the published holding patterns were constructed to accommodate aircraft up to FL340.

Late-merging-principle for arrivals: MergeStrip can be regarded as our way of application of Late-Merging Principle without the use of 4d-trajectory requirements from the arriving aircraft.

Continuous climb operations: CCOs has been applied since 2016 and the new TMA further improved its usability. As a result, altitude constraints of the SIDs have been abolished. Also, they were designed to fit into FRA and FUA seamlessly.

Early spreading of departures is also applied taking into consideration the noise constraints. Direct routing is provided either above 4000 feet or 7000 feet, depending on runway in use (i.e. whether the aircraft is above Budapest or not).

Highest freedom of movement with shortest airspace borders: During the redesign of Budapest TMA airspace, this principle was taken into consideration as far as possible. For the two runway directions, two circular airspace borders were developed and connected to each other, which resulted in an oval-shape airspace structure. However, operational advantages were acquired by connecting some smaller adjacent airspace portions (Figure 5-4).

Avoidance of speed control: Speed control for arriving aircraft is initiated as early as possible from the top of descent enabling clean configurations and reduction under minimum clean speed is only used during the final approach phase.

Flexible final approach legs: For certain aircraft types, visual approach is available at Budapest providing as short approach as possible. In VMC conditions, aircraft categories

A-C can make use of a short RNP approach for the most frequently used runway, 31R, also providing fuel efficient and environment friendly approach.

5.3. MERGESTRIP DEVELOPMENT IDEAS

As described in Chapter 5.2, HungaroControl has already implemented several GreAT concept elements. At medium sized airports where the use of Point Merge procedures may be too constraining and the implementation of an AMAN would be too costly, the use of T-Bar based IAPs, coupled with the use of MergeStrip, has been identified as an optimal solution.

MergeStrip is a software that enables the visualization of all arriving aircraft on a timeline related to the Intermediate Fix of the instrument procedure, thus efficiently helping the sequencing of all arriving traffic. With the new developments, more precise estimated times of arrivals and better conflict resolution advisories are expected, which results in less level flights and less use of vectoring or holdings, all of which are considered the worst-case scenario from fuel consumption's perspective, and thus CO_2 emission point of view. Therefore, an advanced and further developed MergeStrip could support the following GreAT concept elements: Free Route in TMA and Continuous Descent Operations.

As far as Free Route in TMA is concerned, this concept has been applied in Budapest TMA since 2015. As the Hungarian FIR is a 24/7 practically unrestricted FRA, the above-mentioned redesign of TMA in 2019-2020 could not have been done otherwise than taking this GreAT concept element into consideration or even as a fundamental basis. Also, aircraft may leave ACC and enter Budapest TMA in a more predictable way, therefore the new development has an indirect positive impact on ACC as well.

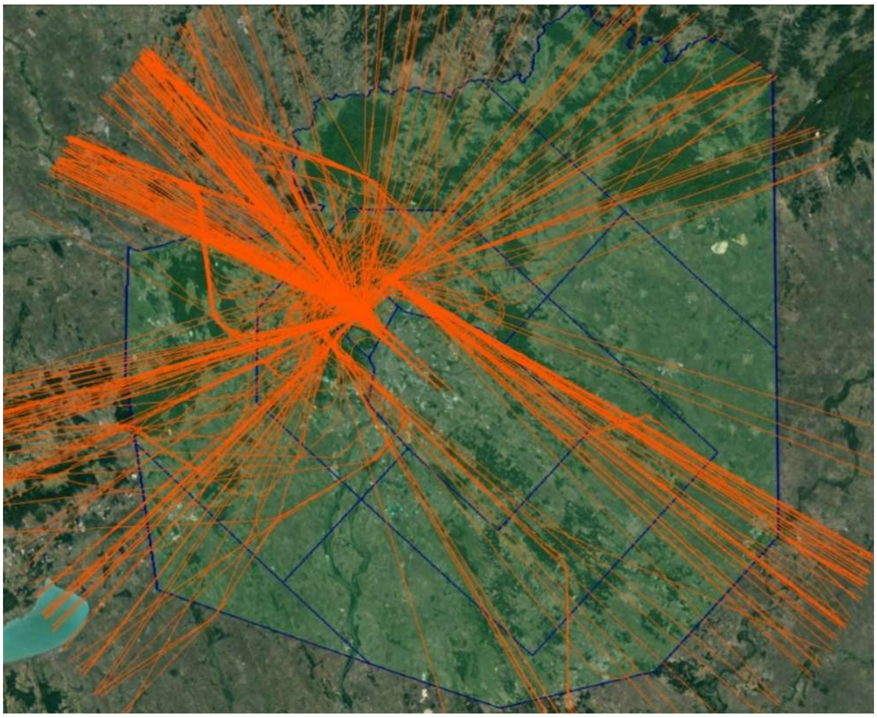


Figure 5-7: T-Bar based Instrument Approach – Aircraft flight pathes as deducted from real radar data. In this case, the approaches were executed from the northwest.

The development of MergeStrip facilitates Continuous Descent Operations by helping air traffic controllers to sequence arriving traffic more efficiently. With more precise estimated times of arrivals, separation minima can be guaranteed during the whole descent phase with high reliability and predictability. As mentioned before, the new TMA structure was designed to make an optimal use of CDOs, the new developments would supplement these two pillars (i.e. airspace design and procedures) from an improved execution on tactical level.

Before COVID-19, approximately 80% of arrivals to LHBP were using T-Bar (as can be seen on Figure 5-2. and Figure 5-6.), however with GreAT developments, it is expected that more traffic can use this path.

6. CONTROLLER AND PILOT SUPPORTING FUNCTIONALITIES ENABLING A GREENER USE OF T-BAR BASED PROCEDURES

The development of decision support tools for tower and approach air traffic services were undertaken by several American and European research programs. These developments aimed to increase the accuracy of both airport activities/operations and air traffic services, and were put into operation in the early 1980’s. Probably the most notable ones are the following: COMPAS (developed by DLR), 4D-Planner (successor of COMPAS), Controller-Managed Spacing (CMS, NASA), or „Automated Integration of Arrival/Departure Schedules” (MITRE) [Madácsi 2016].

6.1. MERGESTRIP AS AN APPROACH CONTROLLER SUPPORT SYSTEM AT A MEDIUM SIZE AIRPORT IN EUROPE

The MergeStrip system, that is to be further developed in the frame of the GreAT project, is an approach controller decision making and planning support tool, based on a concept with specific features like MergeStrip:

- enables spacing planning on any route (even using vectoring);
- requires neither additional airspace nor airspace restructuring;
- is able to plan the traffic arriving from different directions;
- enables the application of changing spacing values;
- enables CDA as the necessary distance to be flown is known at the Top of Descent;
- has a low implementation cost;
- can be introduced easily, and requires only a short ATCO training.

6.1.1. BRIEF INTRODUCTION OF MERGESTRIP

The most notable feature of MergeStrip is the allocation of arriving aircraft to a time-line, while considering their distance from the nearest IAF or IF and their ground speed. These pieces of information may help controllers to plan the arriving sequence more efficiently and makes their workflow more predictable.

The system also has a profile window visualizing the theoretical glide slope extended well beyond the actual glide slope horizon, and positions each arriving aircraft above or below the theoretical glide slope according to their actual altitude. This feature enables ATC to quickly determine if an aircraft is at the optimal profile or not, and can also help in determining which aircraft is more likely to cope with speed reduction in order to make the right sequence while remaining on the closed flight path.

The third feature of the system is the threshold spacing tool, which is used during the last 25 NM of the arrival path, and shows according to actual ground speeds what the spacing will be between two aircraft by the time the leader aircraft reaches the landing threshold.

6.1.2. DETAILED CONCEPT OF THIS IMPROVEMENT

Under the umbrella of this project, there are 3 new functionalities that are intended to be developed, which are briefly described below.

- **AI-based threshold separation tool** ("THR SepTool") for improving the calculation of the Estimated Time of Arrival (ETA). New techniques based on data analysis will improve the accuracy of the ETA estimation, allowing ATCOs to precisely sequence the arrivals at a very early stage and as a consequence enhancing the use of full CDOs (starting as close as possible to the Top of Descent). The Threshold separation tool is part of the system currently, and it provides estimated spacing values at the threshold based on instantaneous (actual) airspeed. With the currently used avionics, MergeStrip can calculate arrival intervals to the threshold. However, the current version does not consider the aircraft speed reduction (i.e. on the late phase of the final), therefore this functionality should be refined. The basis of this improved ETA calculation could be the application of more realistic speed profiles, which takes into consideration the aircraft type and AO practice, therefore it can provide much more accurate estimations. It is true that for some aircraft, the speed data is received, but in many cases MergeStrip has to calculate speed based on the time difference between two position coordinates. The three main parameters expected from improved ETA calculation are I) current (ground) speed II) ETA to the reference point and III) later on ETA to the threshold with more realistic speed profile.
- **"What-if" functionality**. This feature will allow ATCOs to analyze the consequences of any potential action before executing it (e.g. applying speed control or changing target waypoint). The impact on the overall scenario in terms of fuel consumption and CO_2 emissions will be one of the main outputs of the "what-if" analysis. In this way, ATCOs will be able to make their final decisions considering not only the operational consequences but also the environmental impact. This functionality is a brand new one under MergeStrip. This functionality supports decision making as it helps to find the best solution by the analysis of different options (could be another target waypoint or speed change). Maybe instead of IF, the reference point could be set to the T-Bar point and spacing between arriving aircraft could be set for the TD ATCO.
- "**AI-based sequencing and speed control advisory**" (conflict resolution recommendation): By making use of data analysis techniques, MergeStrip will recommend ATCOs more optimal solutions based on the application of speed control or target waypoint change at an early stage of the descent, allowing to maintain the runway throughput while avoiding non-optimal tactical interventions of ATCOs at the final part of the descent.

6.1.3. REQUIREMENTS TO IMPLEMENT THIS IMPROVEMENT

The requirements to implement this improvement concern technology, HF and safety as well as environment.

6.1.3.1 TECHNOLOGY REQUIREMENTS

MergeStrip is currently a web application that can be installed to any Linux or Windows server and can be accessed from any computer having a web browser. Therefore, there is no need for major infrastructural investment or adjustment for its proper use.

One of MergeStrip's input sources is the PildoBox, a device developed by PildoLabs that integrates an ADS-B/Mode-S receiver. For development and validation purposes, MergeStrip can also work with "dummy" positioning data (generated by an internal simulator) and it will be also compatible with data generated by MATIAS-BEST simulator, property of HungaroControl.

6.1.3.2 HF AND SAFETY REQUIREMENTS, ASPECTS

User requirement workshops were held with the participation of ATCOs as end users, technology experts and software developers from enabler side. The aim of these discussions was to involve human factor and safety experts so that they can understand both the ATCOs' need and the technology aspects, and can make recommendations in the early phase of development. This coordinated manner and common understanding is expected to save time and other resources. The most notable statements can summarized as follows:

- The common point of the new functionalities from human factor point of view is that ATCOs I) must find interaction with the tool and its functionalities easy, and II) these functionalities must gain ATCOs' trust. These issues will be dealt with special emphasis during the planned design sessions.
- Due to their characteristics, each new functionality has to live up to different HF and safety success criteria. E.g. improved ETA calculation should improve the ATCO's situational awareness, support their more efficient task performance, whereas the "What-if" functionality is rather expected to decrease the cognitive workload.
- Abnormal situations (e.g. emergency, adverse weather) and/or degraded mode operations are to be validated during the 2nd iteration.
- AI and machine learning should be handled with utmost attention. There is no widely accepted official protocol yet, the standardization process is ongoing, and will come from EUROCAE in the next few years.

6.1.3.3 ENVIRONMENT

The environmental impacts of an ATM development have to be analyzed as precisely as possible. However, under GreAT project, this key performance area is in special focus.

PildoLabs' DailyFuel is a cloud-based service used to monitor aircraft descent operations efficiency and to estimate fuel consumption at TMA level without depending on FDR data. The tool is complementary to MergeStrip, intending to quantify its benefits in terms of fuel consumption savings. Fuel estimation algorithms are fed only with ADS-B/Mode-S data and have been validated against FDR data (for Airbus A320 model), with -3.82% of mean fuel estimation error per descent.

Under the frame of the GreAT project, DailyFuel will be adapted to make it compatible to new data input sources (e.g. MATIAS-BEST simulator).

6.2. FLIGHT CREW SUPPORT FEATURES

Besides supporting ATCO work, MergeStrip provides some information to pilots as well, that can be useful during arrival phase and landing.

- MergeStrip calculates the Distance-To-Go (DTG), a distance that aircraft have to cover until touchdown. Pilots can be informed about the remaining track miles helping the crew selecting clean configurations as long as possible thus enhancing greener operations (as mentioned under latency tolerant delay absorption in Chapter 5.2).
- MergeStrip visualizes a theoretical 3° glide slope, where the profile of the arriving aircraft can be traced. If an aircraft deviates from this theoretical glide slope, the crew can be asked to confirm whether they are ready for the approach or not. If not, some additional vectoring results in a considerably lower workload increase both on ATCO's and on pilot's side and has smaller impact on environment than a possible missed approach. The proper use of this function, in certain cases, might result in increased flight safety.

The application of MergeStrip as an air traffic management concept carries significant benefits for both pilots and ATCOs.

7. POINT MERGE BASED AIRSPACE MODELLING AND FLIGHT PROCEDURE DESIGN FOR FUEL EFFICIENCY

There are many factors influencing the fuel efficiency, such as technology, operations, fuel price, average seat class of aircraft type, average flight distance, passenger load factor and load factor level. Fuel cost is the largest single cost of airlines [Huang 2019]. The increase in fuel prices may prompt airlines to pay more attention to fuel efficiency improvement and reduce fuel costs. The aircraft seat level is proportional to the maximum take-off weight, and the larger the seat level, the more available load tends. When the passenger load factor and load factor are in the same level, the fuel consumption per ton-kilometer is relatively lower. Because the fuel consumption of the aircraft mainly occurs in the take-off, landing and taxiing stage, the fuel efficiency of the cruise stage is higher, so long-distance routes are often more conducive to the improvement of aircraft fuel efficiency [Dube 2021]. Passenger load factor and load factor level reflect the industry's utilization of aircraft available seats and available load, and directly affect the fuel efficiency level of unit effective output.

7.1. FUEL EFFICIENCY

This chapter describes basic mechanisms making an aircraft flying with maximum fuel efficiency in an ideal atmosphere.

7.1.1. DEFINITION OF FUEL EFFICIENCY

Fuel efficiency refers to the energy contained in the fuel used to produce a specific thrust or horsepower divided by the total potential energy contained in this fuel. The evaluation index is the number of passenger kilometers that can be produced per gallon of fuel or per kilogram of fuel, expressed in RPK/gal or RPK/kg.

7.1.2. TECHNICAL AND OPERATIONAL INFLUENCE FACTORS OF FUEL EFFICIENCY

From a performance and technical point of view, there are mainly two aspects of fuel efficiency influence: The technology and the operations. The technical factors include Specific Fuel Consumption (SFC), lift-to-drag ratio, structural weight, etc. The operational factors include distance, fuel load, work load, reserve fuel, etc. Fuel consumption rate and lift-to-drag ratio increase by 1% can reduce fuel consumption by 1%. When structural weight is reduced by 1%, fuel consumption is reduced by about 0.7%-0.75%. Reserve fuel and structural weight have almost the same influence on fuel consumption, the reduction of reserve fuel in fuel consumption will also lead to a reduction in fuel consumption. A 1% increase in load is equivalent to a 1% increase in load factor, which will result in a 0.8% reduction in fuel consumption per passenger kilometer.

7.1.3. WAYS TO IMPROVE FUEL EFFICIENCY

For the fuel efficiency improvements, some procedures and approaches are investigated in the last years. In the GreAT project, flight plan, procedure and fleet planning optimization are important. Additionally, fuel-saving system formulation and concept establishment of fuel saving could make a corresponding contribution.

7.1.3.1 FLIGHT PLAN OPTIMIZATION

Flight plan optimization is based on a comparative analysis of the flight plan made in the past and the actual operation results, summing up experience, and formulating a more scientific, reasonable and economic flight plan. The optimized flight plan can increase the commercial load of the flight, improve the fuel efficiency, and reduce the fuel consumption of the flight, which has very important practical significance for improving the operation management level of the airline and controlling the operating cost (especially the fuel cost).

7.1.3.2 FLIGHT PROCEDURES OPTIMIZATION

The optimization of flight procedures is economical. In essence, it refers to the aircraft using flight procedures to reduce fuel consumption, shortening flight time and flight distance. It is required that the flight procedures should meet the requirement that the aircraft consume less fuel and shorter time during flight. Optimization of flight procedures aimed at reducing the cost of flight fuel consumption can be considered by redesigning the waypoint layout to optimize the approach and departure routes, reducing fuel consumption and exhaust emissions, or optimize aircraft approach procedures. Continuous Descent Operations (CDO) can also reduce fuel consumption, noise and exhaust emissions.

7.1.3.3 FLEET PLANNING OPTIMIZATION

Fleet planning refers to the systematic and dynamic arrangement of the structure and quantity of the fleet during the planning period based on the results of air transportation market research and certain principles and methods. Fleet planning requirements can not only meet passenger and cargo demand, but also obtain the best economic benefits, and adapt the fleet to the route structure and flight configuration. Fleet planning plays a very important role in the operation and management of airlines. The use of fleet planning methods based on maximizing fuel efficiency can have higher fuel efficiency and lower fuel costs than other fleet planning methods.

7.1.3.4 FUEL-SAVING SYSTEM FORMULATION

The airline fuel-saving operation should abolish the previous "egalitarianism" distribution policies [Luo 2009], and innovate to establish a unified and efficient fuel-saving management system, and formulate fuel-saving policies with clear rewards and penalties. Combining the actual situation of each functional department, the airline should also compile an operable fuel-saving operation workflow, and implement a unified and efficient fuel-saving operation management.

7.1.3.5 CONCEPT ESTABLISHMENT OF FUEL SAVING

Airlines should change the traditional and isolated fuel-saving concept of the past [Luo 2009], establish the company's overall fuel-saving operation concept, and strengthen the sense of ownership and responsibility of employees. At the same time, it is necessary to publicize the importance of fuel-saving work through multiple channels and various aspects, cultivate each employee's fuel-saving awareness, and let fuel-saving awareness guide fuel-saving actions. The airline should make it an indispensable part of the company's corporate culture, and all employees can truly participate.

7.2. SUPPORTING PROCEDURES AND SYSTEMS

Point Merge System (PMS) technology is usually used in conjunction with Continuous Descent Approach (CDA) or Continuous Descent Operation (CDO) [Wang 2012]. The point merge approach improves the predictability of the trajectory and lays a good foundation for the implementation of CDO. CDO refers to the process in which the pilot or autopilot manages the configuration of the aircraft (flaps, brakes, landing gear, throttle) when arriving at the airport at a continuous angle with using the minimum thrust. When approaching the airport, it can use higher power and maintain a more continuous cruise altitude, which can reduce fuel consumption and reduce noise impact. It is not only conducive to saving energy and protecting the environment, but also to save costs. The advantages of using Point Merge System technology in conjunction with CDO are mainly reflected in [Dai 2012]:

1. Improve safe approach operations and safety through the standardized application of stable approach procedures;
2. Improve pilots' posture awareness and reduce pilots' operational load;
3. Reduce the probability that the flight altitude is lower than the obstacle clearance altitude during the final approach segment.

7.2.1. CDA MODEL BASED ON POINT MERGE

A CDA model, based on point merge, optimizes the continuous descent approach operation mode, which means planning the optimal point merge on the continuous approach route in the terminal area. As a result, the controller can plan the approach flight through the judgment of the distance information between aircraft, and make the traffic flow from different directions complete the continuous descent approach flight process. The number of calls between controller and pilot can be reduced. And the approach process of the aircraft can be controlled more effectively through the distance information designed by the program, which ensures the flight safety in the airport terminal area.

The operation steps of the CDA program based on point merge:

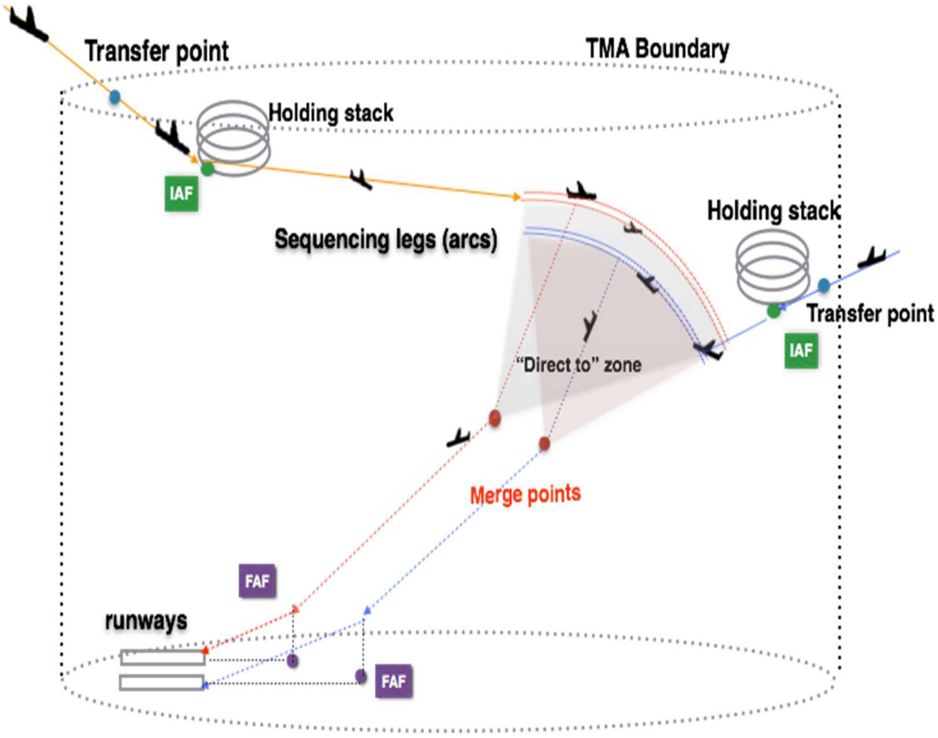
1. Aircraft approaching from different directions fly along their respective sequencing edges autonomously, and the controller will issue a direct flight to point merge instruction to the aircraft located on the sequencing edge at an appropriate time (when the distance from the previous aircraft reaches the required separation);
2. After leaving the TOD (Top of Descend) point of the sequencing side, the aircraft maintains the distance limit between adjacent aircraft by adjusting speed, and adopts the flight mode of continuous descent approach to the arrival points merge along the possible path, so as to complete the approach process along the planned unified route.

7.2.2. MULTI-LAYER POINT MERGE SYSTEM

The potential advantages of Multi-Layer Point Merge (ML-PM) system operating in a dense terminal area by simulating the arrival flow cases under three different operating modes are: baseline, Traditional Points Merge system and Multi-Layer Points Merge system (ML-PM). The results show that the ML-PM system can generate reasonable arrival sequence and conflict-free trajectory, which has good performance in flight time, fuel consumption and CO_2 emission [Liang 2018]. The ML-PM system allows for more flexible shift of sequential position and continuous descent. It also can handle higher density of arrival flow and eventually guarantee flight safety [Liang 2016b].

In order to test the performance of ML-PM system, two comparative experiments were carried out on runway redistribution for the Beijing International Airport (BCIA). The results show that: 1) it can produce a conflict-free trajectory; 2) it can shorten the average delay time, average landing time interval and runway reallocation time. Specifically, the average delay time is shortened by 36.36% [Liang 2016a]. And the average take-off and landing time interval are shortened by 1.35% and 1.36%. However, due to runway reallocation, the average flight time, flight distance, fuel consumption and CO_2 emissions are increased by 13.49%, 1.11%, 13.49% and 13.49%, respectively [Liang 2016a]. Thus, the capability of the ML-PM system to dynamically control the arrival flow aircraft to reach the parallel runway is demonstrated.

Based on the basic Points Merge system, a sample of ML-PM system which can operate independently on two parallel runways is developed. As shown in the figure, aircraft from different directions arrive at the sequencing leg remaining in lateral separation mode. Horizontally, the inner and outer sequencing leg have a common center of the circle. Vertically, according to the type of wake flow, the sequencing legs' different flight levels can provide different separation standards for subsequent aircraft. A heavy aircraft will be assigned to a higher level, while a medium using a middle one and lights using a lower one. And all three tiers have the same projection horizontally. After entering the sorting edges, aircraft will fly at a constant and predefined speed. When there is no conflict or when the weather is clear, aircraft will execute the "Direct to" command and turn to the merge point, performing a continuous descent during the merge. Aerial separation between aircraft is automatically maintained through conflict detection and resolution algorithms. Due to weather, drones, military control, etc., the landing runway of arrival flow aircraft can be easily changed, thus this ML-PM system is more convenient and smarter.



7-1. ML-PM system for parallel runway operations. One challenge in organization the traffic in this interlaced system is the conflict detection and resolution in the merging zone [Liang 2016a].

8. INTEGRATION OF METROPLEX AREAS

For metroplex areas, the competitions of airspace resource among airports, runways, as well as between arrivals and departures, are very significant. Meanwhile, different traffic sequencing solutions may directly impact the allocation of airspace for airports in metroplex areas. From both technical level and operational level, the integration of metroplex areas is a sophisticated and difficult issue. However, collaboration is a key concept in traffic sequencing for metroplex areas.

8.1. ORGANIZATION

For management of departure flights in metroplex areas, the Collaborative Decision Making (CDM) systems and operational mechanism have been built up in the local Air Traffic Management Bureaus (ATMB) of CAAC. This promotes the information sharing capabilities and common situational awareness, and improves the efficiency of departure sequencing. CDM system integrates the information of airspace resource, airport resource and flight status, and generates the accurate and reasonable departure queue, including the off-block time and take-off time for each flight (Figure 8-1). With the application of CDM system, the taxi time on ground and waiting time after hatch closed are shortened evidently.

The CDM system is not independent running, it requires accessing the real-time operational time of flight from the participant units. To achieve the traffic sequencing before departure and generate the Calculated Off Block Time (COBT) and Calculated Take Off Time (CTOT), CDM system receives the operational capacity data from ATC. For the problem that multi traffic flows merged into a busy route, CDM system will receive the entry time given by the route sequencing tools.

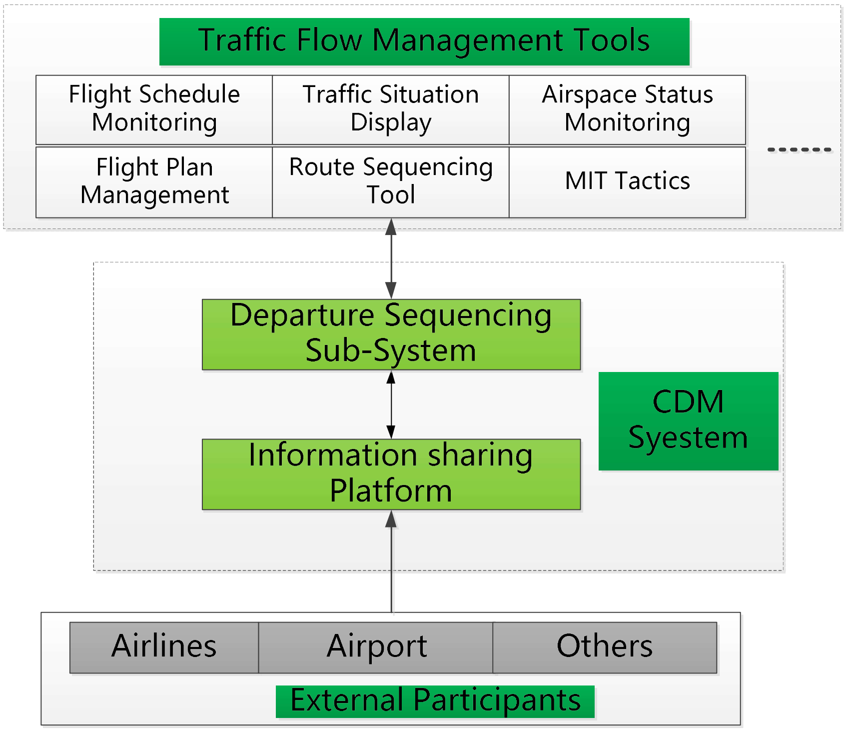


Figure 8-1: The architecture of CDM system and its relationship with other systems.

Traffic sequencing in CDM system is based on the intersections of routes. According to the constraints and conflicts on intersections, the departure slots are assigned to flights at different airports (Figure 8-2). Specifically, the matched CTOT and time slots on intersections are selected based on the sequencing rules, such as "First Come First Serve".

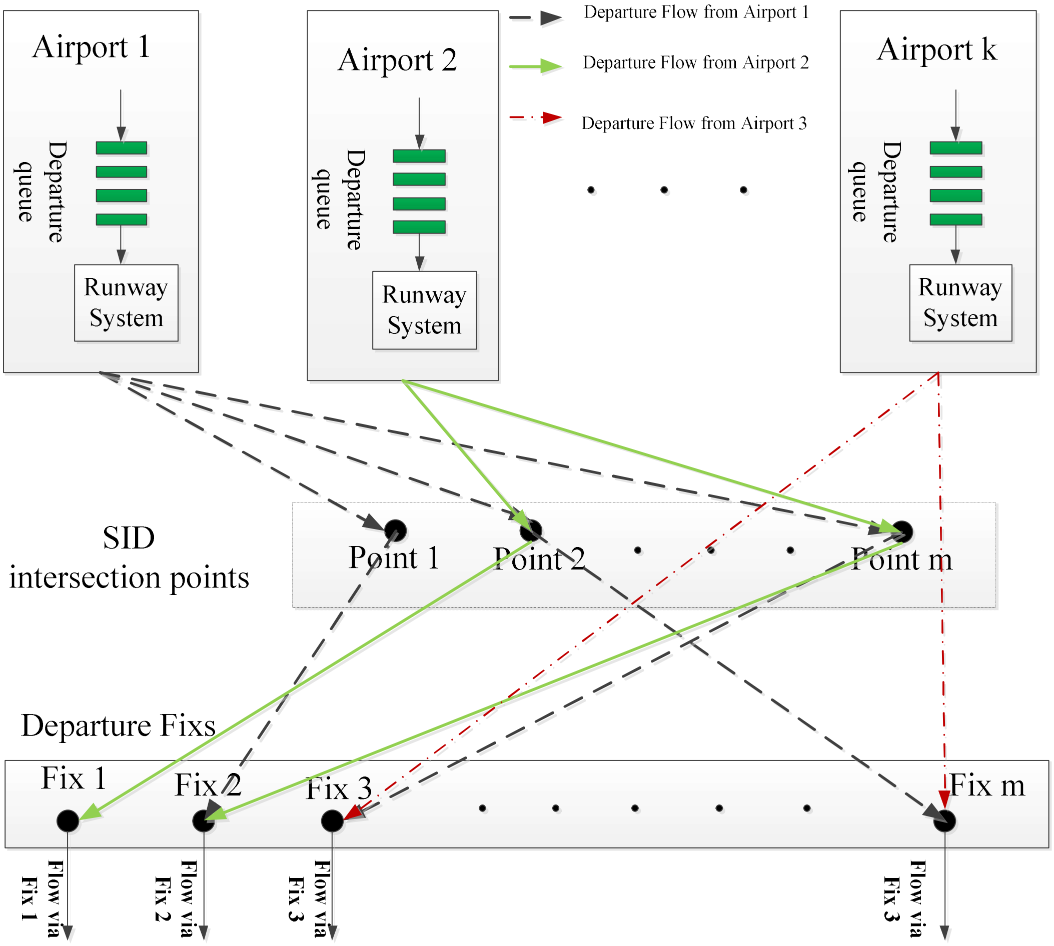


Figure 8-2: The sketch map of departure slot assignment for metroplex areas.

8.2. SUPPORTING PROCEDURES AND SYSTEMS

Departure sequencing in CDM system has two levels: sequencing for single airport and collaboration for multi airports. Departure sequencing for single airport is aimed at achieving the preliminary flight schedule according to runway and surface constraints. Collaboration for multi airports is mainly aimed at achieving the traffic merging with specific separations in the busy route area. The main mission of departure sequencing is to sort departure flights according to the established procedures and rules, and determine the specific orders and time slots.

8.2.1. BRIEF OPERATIOANAL PROCEDURES OF CDM

The CDM system has a planning horizon. Two hours before EOBT, the flight will be involved into the departure sequencing process. Considering the traffic flow measures from adjacent ANSP, airspace capacity parameters, EOBT and TOBT, the Calculated Time Over (CTO) of flight on the intersection (usually the terminal gate) is assigned first. Then, the CTOT is calculated according to CTO. 90 minutes before EOBT, CDM system will publish the CTOT and CTO of this flight to related systems. At the single airport level, the CDM system will calculate COBT according to gate position, runway operation, surface situation and CTOT. COBT is published to airline and airport operator. The COBT should be confirmed by airlines no later than 55 minutes before COBT. If COBT is not confirmed within the specified time, CDM system would set it non-executable and reassign a new COBT. To guarantee the stability of departure sequencing, CTOT and COBT are locked at 55 minutes before COBT, unless there are new immediately effective traffic flow measures, operational deviations or human interventions. Besides, a concept of "waiting pool" is introduced into the CDM process. The handling rules of waiting pools are as follow:

- If airlines neither confirm COBT nor provide a new EOBT no later than 55 minutes before COBT, the flight will be put into waiting pool automatically.
- If ground services are not accomplished before COBT and there is no estimated time, the flight will be put into waiting pool automatically.
- If a flight is not pushed back with 5 minutes after COBT, it will be put into waiting pool by controller.
- If a flight stops taxiing and cannot determine a TTOT, it will be put into waiting pool by controller.
- When flights in waiting pool provide new EOBT or report ready, CDM system will re-assign departure slots to them. The new assigned departure slots will not occupy the locked ones.

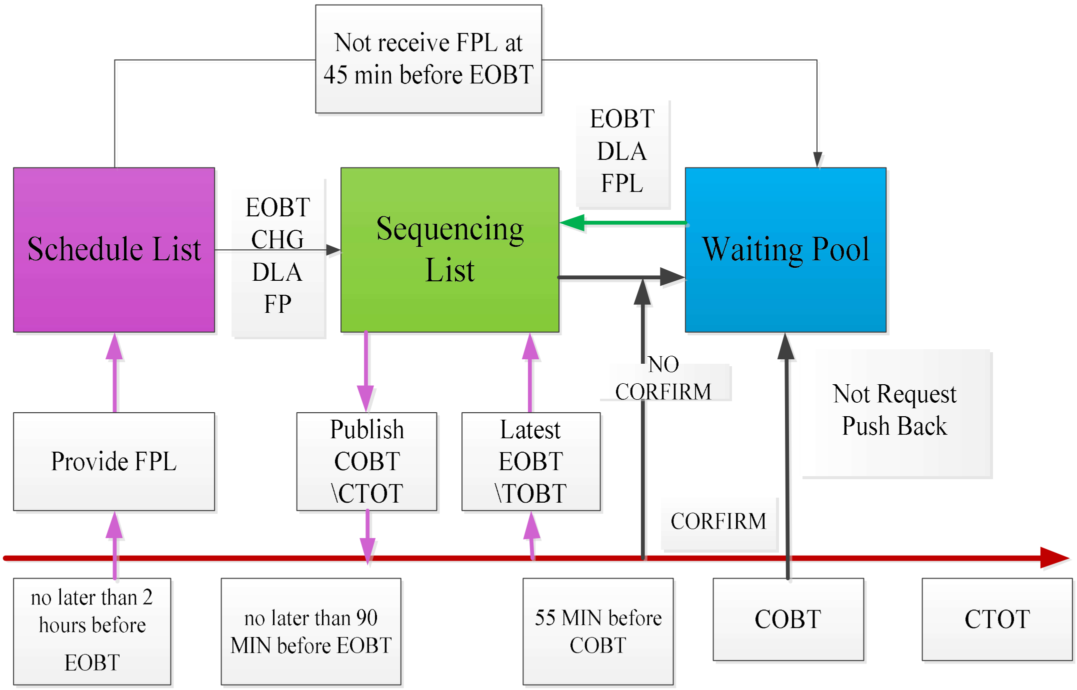


Figure 7-3: The departure sequencing process for CDM system

Currently, the participants of CDM include ATC, airport and airline. Within the CDM process, the responsibilities of each participant are as follow:

1. ATC

- Publish the information of flow control, COBT/CTOT for departures and Estimated Landing Time (ELDT) for arrivals to airports and airlines.
- Generate the COBT and CTOT based on CDM system, and conduct the sequencing for departure flights in controlled area. According to operational situation, adjust the sequencing results.
- Monitor the operational situation in controlled area, and propose the traffic management measures (e.g. miles-in-trail) for adverse weather, military activities and equipment failure.

2. Airport

- Arrange the ground services according to the COBT from CDM system.
- Provide the operational information to ATC and airlines, such as gate assignment information and capacity information.
- Monitor the operational situation in airport, and announce the situation impacting the operation to ATC and airlines in time.

3. Airline

- Monitor the flight operation and provide the flight plan and dynamic information to ATC and ground service organization.
- Arrange the ground services according to the confirmed COBT.

8.2.2. MAJOR ELEMENTS OF CDM IN METROPLEX AREAS

According to the operational procedures, major elements of CDM in metroplex areas are listed in below:

1. **Information Sharing Platform**

For CDM system, the information sharing platform is an important element and foundation. In the collaboration process, the participants, such as airport, airlines and ATC, share their operational information through this platform. Therefore, all participants can timely and accurately understand the overall situations. It will improve the utilization of airspace in metroplex areas on the basis of guaranteeing operation safety.

2. **Key events and departure sequencing**

The key events indicate the whole process before flight departure. As the all related information is shared on the platform, participants are able to catch the key events precisely. Departure sequencing function considers the factors from different aspects and participants, and then sorts the departure flights scientifically.

3. **Variable taxi time**

Taxi time is used to calculate the COBT as CTOT is assigned. In one airport, the taxi time may be selected as a fixed time, e.g. 10 minutes or 15 minutes. This inaccurate taxi time causes the inaccurate COBT and the aircraft may have more waiting time at runway heads or taxiway. Therefore, a precise taxi time calculated by a surface manager (Chapter 4.3) is helpful to reduce the fuel burnt on ground, as well as promote the operational efficiency. The variable taxi time is calculated for each departure flight based on the stand or gate, the assigned runway and the chosen taxi route.

4. **Collaboration under adverse situation**

As airports or airspace encounter the special situation, such as adverse weather, runway close, the operational capacity may decrease seriously. At this time, participants should start a full collaboration and jointly plan to relieve the impact.

5. **Collaborative management of navigation data**

Participants should update the navigation data into information sharing platform, such as the modified Standard Instrument Departure (SID). This will improve the availability of predicted trajectory and the Estimated Time of Over (ETO) and lead an accurate departure slot assignment.

6. **Unified management of flight plan and dynamic**

CDM system is able to establish the flight plan list for each operation day and update the status and data of each flight according to AFTN messages, electronic flight strip system and monitoring data. The main functions of unified management of flight plan and dynamic are:

- Establishment of flight plan data
- Modification of flight plan data
- Check of flight plan data
- 4d-trajectory calculation
- Management of flight plan status

9. SUMMARY

To save kerosene and the associated reduction of climate-impacting emissions, there is no one big solution that will transform air traffic into a completely environmentally friendly and sustainable transport medium in one fell swoop. Instead, many small steps are needed that, taken together, will reduce greenhouse gas emissions from aircraft. This concept presents a wide variety of solutions, each of which can only provide a small component, but which, taken together, will make an important and tangible contribution to making this transport segment more environmentally friendly. To this end, solutions were presented, some of which can be implemented immediately, but some of which require further research and development until they can be seamlessly and safely integrated into air traffic and its control.

The solutions relate in particular to the areas of airspace organization, its design and efficient use, and to support systems for air traffic controllers and pilots that will help them to optimally manage traffic both in the air and on the ground without increasing ATCOs' workload. The MergeStrip System allows ATCOs to continuously inform flight crews with track miles information, enabling them to fly fuel- and noise-optimal approach procedures. These procedures make it possible to reduce both noise pollution and CO_2 emissions, especially in the vicinity of airports, which will benefit the residents of these traffic hubs in particular. Another approach procedure that enables smooth and thus efficient traffic flow, especially at highly congested airports, is the point merge procedure. It has already proven at various airports that by efficiently shaping the approaching traffic, holding patterns and delay procedures can be reduced through equalizing traffic peaks that are otherwise responsible for additional fuel consumption and thus increased CO_2 emissions.

Metroplex airport constellations present another challenge for efficient air traffic management. Metroplex refers to areas where several airports are located so close together that their approach and departure areas overlap. These overlaps impose continuous constraints on the management of traffic, since the arrivals and departures of each airport must be coordinated not only with each other but also with the corresponding movements of neighboring airports. These arrangements cost time and it is not always possible for controllers and pilots to find optimal sequences and distributions to guide traffic. The associated delays inevitably lead to additional consumption of kerosene and increased CO_2 emissions.

At these points, the use of planning support systems for air traffic controllers lends itself to helping not only air traffic control, but also flight crews and airlines. Systems such as AMAN, DMAN and SMAN can not only help controllers with general coordination, but also calculate solutions to guide traffic flows on approach, departure and on the ground in such a way as to minimize delays, which always mean increased fuel consumption and thus CO_2 emissions. Some of these systems with general support functions are already available on the market. Therefore, the GreAT project focuses on the coordinated cooperation of these planning systems. It has been shown that local optimizations for one aviation sector are more often associated with disadvantages for other sectors. However, to find global optima in flight control, these systems must coordinate with each other. This concept shows that this is possible in some places in a simple master-slave procedure, but for optimal traffic flows, procedures from the field of AI should also be applied.

The GreAT project shows that there are solutions for the interaction of airspace design, procedures for pilots and air traffic controllers, and the use of planning systems specially and individually tailored to airports and their surroundings, which enable near-optimal guidance and control of air traffic. In this way, we will be able to reduce the environmental impact to an absolutely necessary minimum already in the near future.

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