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FUEL EFFICIENT AND NOISE-REDUCED APPROACH PROCEDURES USING LATE MERGING OF ARRIVAL ROUTES

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This paper introduces a concept for more fuel-efficient and noise-reduced management of arrival traffic at hub airports. A central element of the proposed system is a modified airspace and route structure, featuring the late merging of arrival routes to support user-preferred flight profiles such as CDAs. Also, new airborne and ground-based automation is developed which will be closely integrated for better air-ground cooperation. This contribution discusses the roles of the human operators in interaction with the newly developed automated systems and operational environment. Aim of the overall concept and tools, which are currently being investigated in the DLR project FAGI, is a significant improvement of ATM with respect to fuel consumption and noise emissions, while eliminating the negative impact on capacity, which is today's penalty for implementing continuous descent approaches in high traffic situations.

1. INTRODUCTION

Worldwide civil aviation traffic is expected to grow annually at rates between three and five percent [1]. This development will soon cause the capacity limits of today's airports and air traffic management, especially in Europe, to be reached [2]. To make the growing air traffic more efficient, more environmentally-friendly and more sustainable, current flight planning and guidance techniques have to be improved and new technologies have to be developed and implemented in the near future.

A key potential for further improving the efficiency of arrival management at airports can be seen in the better exploitation of new 4D capabilities of modern Flight Management Systems (FMS). Using these 4D-FMS capabilities of such 'equipped' aircraft, pilots can nowadays plan and execute fuel saving and low noise approach trajectories (especially CDAs), exhibiting remarkable precision in time and space.

However, most of these advanced FMS-capabilities still remain unutilized under today's standard approach procedures in high traffic Terminal Manoeuvring Areas (TMAs). The reason for that is the difficulty for Air Traffic Control (ATC) to integrate the individual user-preferred trajectories into a safe and efficient overall traffic planning. Existing solutions of this coordination problem remain unsatisfactory so far. This is also related to insufficient integration of the concerned airborne and ground automation. On those occasions where the new 4D-capabilities are already used today for realizing highly efficient approaches like CDAs, the noise reductions and fuel savings are usually bought at the price of a significant break-in of airport capacity [3]. This capacity reduction is unacceptable for large airports during periods of high traffic, due to economic reasons.

Analysing the weaknesses of current operations, the early merging of arrival paths on very few arrival routes is one of the main reasons why all aircraft have to fly similar speed profiles from an early phase of the approach procedure onwards. While this uniform speed reduces the control complexity from the ATC point of view, it leads to inefficient trajectories for individual aircraft, i.e. increased fuel burn and noise emissions. This is related to differing optimal approach profiles due to different performance data. Based on results of the DLR project FAGI, this paper proposes a new route structure with a late merging of arrival traffic in combination with a time-based (4D) guidance to overcome this problem. The late merging of otherwise independent arrival routes allows each aircraft to fly its user-preferred approach profile as long as possible. The time-based planning with absolute overfly times, as opposed to today's relative guidance, supports the coordinated guidance of all arrival traffic to the central late merging point. A further aim of the project is to shorten the flight time of the arriving aircraft by allowing direct approaches with customized trajectories and approach procedures.

The demand to facilitate user-preferred trajectories and integrate these into a coherent overall traffic planning will initially increases the complexity of the air traffic control problem. This is exacerbated by the fact that 'unequipped' aircraft, without 4D-FMS and with significantly lower navigation precision, must also be integrated into the traffic picture. An effective solution for the treatment of such unequipped aircraft is a core requirement for the practical implementation of the concept. A new combination of two different approach patterns via direct or path stretching approaches can constitute a key element of this solution and is detailed in this paper.

In order to cope with the new demands, the question how the human operators can be supported in performing their tasks in the best way is crucial. New automation in terms of advanced arrival managers (AMAN) is necessary to help the controller with appropriate time-based planning functions for all aircraft, matching with their respective equipage standards. Such automation is developed and tested in the FAGI project in the form of DLR's arrival manager 4D-CARMA (4-Dimensional Cooperative Arrival Manager). Among other things, 4D-CARMA provides data link based negotiation functions to coordinate user-preferred trajectories with 'equipped' aircraft while also proposing radio-based clearances to the controller in order to guide 'unequipped' aircraft according to ground-based 4D-planning.

The paper is structured as follows: The new route structure and the late merging concept are presented in section 2. Section 3 describes how time-based guidance with modern FMS along these routes is already implemented today and how it will improve in the near future. Section 4 details the related requirements for the ground-based arrival manager and how they are satisfied by 4D-CARMA. Section 5 discusses important changes within the human-automation relation and effects on operator role before Section 6 concludes.

2. ROUTE STRUCTURE

In this chapter we first motivate the new route structure with late merging of arrivals. Then we describe how 4D-equipped aircraft can benefit from the new route structure before we show the integration of unequipped aircraft without high precision 4D-FMS capabilities and data link.

2.1. Late Merging

The use of CDA approaches promises a noise reduction of up to 5dB [3] while at the same time allowing fuel savings However, due to different approach speeds of different aircraft types and because of flight operational uncertainties, the implementation of Continuous Descent Approaches requires an increased separation between aircraft when two consecutive aircraft start the descent at cruising altitude on the same arrival route. This would result in a significant reduction of the runway capacity in the region of 50% [5]. With this drawback CDA approaches are currently only acceptable at nighttimes, but not in high traffic situations.

Ren et al [6] showed that regaining some of the lost capacity is possible with CDA approaches if a Modified Three Degree Deceleration Approach (MTDDA) is used. However, this implies that constraints for the speed profile are necessary and no *ideal* idle descent is allowed.

The Late merging concept presented in the following aims at avoiding the negative effect of CDAs on capacity but does not require a homogenous speed profile or speed constraints at top of descent (TOD). Instead, it relies on a modified route structure, where sequent aircraft use different lateral routes to a so called *late merging point* (LMP).

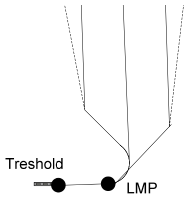

Fig 1: Late merging of different approach routes

Within the concept, the aircraft co-use only a short common flight segment starting near the LMP and ending at the runway threshold (see Fig 1). Therefore speed and especially deceleration constraints respectively time constraints are only necessary on the last flight segment (if at all) resulting only in a slight increase of the separation (i.e. loss of capacity) or in a decrease of the flight efficiency. In Fig 1 the solid lines represent fixed routes, the dashed lines show routes which are flexible with respect to strategic path stretching which is necessary only when upstream flow control sends too many aircraft.

Taking a larger view, Fig. 2 shows the structure of a larger share of airspace surrounding the airport, termed "Extended Terminal Manoeuvring Area" (ETMA). There are several routes starting at different ETMA entries. These can be fixed routes (solid lines) or variable routes which allow a path stretching (dotted lines). Depending on the traffic situation, a direct approach to the LMP may be permitted (blue dashed lines).

Before the aircraft are starting their CDA at the TOD, they should be on separated routes. Therefore, the different routes are assigned to the aircraft when the aircraft are entering the extended TMA (ETMA), see Fig 2.

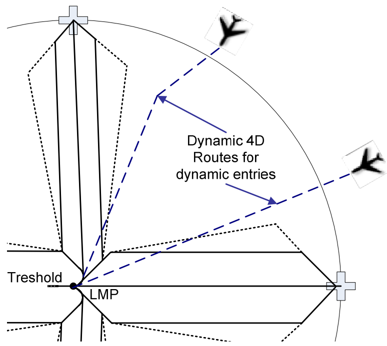

Fig 2: RNAV Routes to the Late Merging Point

The lateral separation between the routes allows each aircraft to choose an individual optimal (i.e. user preferred) approach profile. The lateral separation is transferred into a time based separation just shortly before reaching the LMP, i.e. the aircraft normally has to maintain a time constraint only at the LMP.

The *Late Merging Concept* requires a high predictability of landing times, i.e. there is no real flexibility to adapt the target landing time when having passed the TOD. Present on board systems already permit to maintain a time constraint very precisely (section 3), but the uncertainty of other events remains and may counteract these precision:

- Short-term gaps for outbounds may be necessary if the runway is used in mixed mode.
- Unequipped aircraft without 4D-FMS and without own capabilities to meet a required time of arrival autonomously must be integrated.

Currently ATC designs buffers for this uncertainties, by using the minimal separation plus a buffer time. If the buffer time is too large, this will decrease efficiency. If, however, the buffer time is too small subsequent even more expensive interventions may be necessary. In case the deviations only occur in exceptional situations, ATC may decide as the case arises. If they occur frequently, the underlying concept has to take these buffers into account.

In order to gain the flexibility to react to uncertainties and unforeseen events, the FAGI concepts features two different procedures to approach the LMP that can be used simultaneously supporting each other: A direct approach and an approach via a path stretching area.

2.2. Direct-to-LMP Approach

The first procedure assumes direct lateral paths to the LMP without the necessity of a path stretching area near the LMP in order to compensate deviations from the planned (negotiated) trajectory (see Fig 1 and Fig 2). This requires high precision 4D capabilities of aircraft, i.e. the onboard FMS used. Equipped aircraft get a time constraint for the LMP early, which is fixed no later than starting the final descent after having left the level segment in the last sector before reaching the TMA. Every parameter change would reduce the efficiency of an already optimized trajectory.

A short buffer, however, is also designed for the equipped aircraft. After they have left their cruising level, a first CDA segment is flown until they reach a short level segment (e.g. FL 80). It is the last time for adjustment of the target time by changing the IAS, which in turn influences the descent rate and the position of the TOD (see Fig 6).

2.3. Path-Stretching-Area Approach

The second procedure assumes an approach to the LMP via a trombone pattern (see Fig. 3) to be able to adjust the arrival time of the aircraft. The grey paths in Fig 3 visualize the possibilities to move the "turn to base" point on the trombone. By shortening the trombone length, an earlier time of arrival is possible. An extension of the trombone enables a later time of arrival. In order to shorten the trombone length a detour of round about two NM on the downwind and on the final segment is already planned from the beginning. This variation of this detour, however, enables the flexibility to compensate short-term events (e.g. outbounds, pilot and controller deviations) without touching the highly accurate Direct-To-LMP approaches.

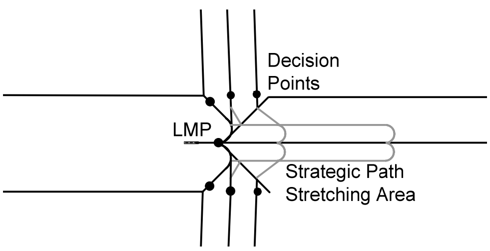

Fig 3: RNAV Routes to the Late Merging Point

2.4. Simultaneous Operation

Both methods presented above are simultaneously in operation. Each aircraft can be guided via the Direct-To-LMP or via the path stretching approaches. The same routes can be used for both methods until the decision point is reached where it has to be decided between Direct-To-LMP and path stretching (see Fig 3). The separation at the intersection points are implemented by vertical separation. The direct approaches then fly below the aircraft which are using path stretching approaches. Therefore, a suitable altitude constraint is issued both at the LMP and at the decision point.

The decision whether to use the direct or the path-stretching variant can be taken at short notice, in general until the aircraft has reached the trombone altitude constraint at the decision point. Normally, however, the FMS equipment and the traffic demand determines which method is used. Aircraft, which can perform a high precision 4D approach, use the Direct-To-LMP pattern. Unequipped aircraft use the trombone path stretching area. Equipped aircraft which do not comply with their negotiated trajectory can be reintegrated into the traffic flow via the trombone. This concept offers an incentive to modernize the aircraft fleet as a side effect, because the equipped aircraft will fly shorter routes on average.

3. ADVANCED FLIGHT MANAGEMENT SYSTEM – AFMS

It has been pointed out in the last chapter that FMS' ability to reach the LMP at a predetermined time with high accuracy is crucial for the route structure concept. This section will discuss the ability of DLR's own Advanced FMS (AFMS) for accurate flight along predetermined 4D-trajectories as well as the time-accuracy of today's standard FMS. It will also explain the Advanced CDA (ACDA) procedure developed by DLR and why such highly-efficient procedure cannot be fully exploited in today's operational environment but will be much better supported in the FAGI concept.

3.1. AFMS

Within the Programme for Harmonized Air traffic Management Research in Eurocontrol (PHARE), an Advanced Flight Management System (AFMS) with a high-level human machine interface has been developed and since then continually improved by the Institute of Flight Guidance at the DLR. By means of strategic trajectory planning and a corresponding guidance module, the AFMS allows planning of highly accurate 4D-trajectories and following them with little deviations autonomously.

Fig 4 shows the in- and output data of the AFMS. Generation of 4D-trajectories is performed based on a list of waypoints describing the route from actual position to the destination, altitude and time constraints, the aircraft's performance data, and an accurate weather forecast. Using the descent parameter given by the pilot the AFMS allows predicting standard and LDLP approaches (so-called Low Drag-Low Power) as well as CDA.

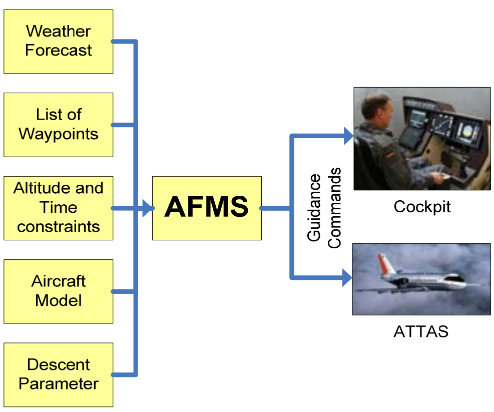

Fig 4: In- and output of AFMS

Once a 4D-trajectory is generated, the AFMS provides guidance commands to fly along the calculated trajectory. A 4D-trajectory consists of a lateral route with altitude and time information for every waypoint. If an appropriate connection to the autopilot is available, these commands are directly forwarded to the aircraft that will automatically follow the trajectory. If such a connection is not available, the guidance commands can be displayed as instructions to be carried out by the pilot. The AFMS guidance commands control the aircraft in all four dimensions (lateral, vertical and time).

3.2. ACDA

The phrase "Continuous Descent Approach" is often used non-stringently. German Airports like Stuttgart, Nuremberg, Hamburg, Hanover, and Munich offer usage of CDAs with an intermediate level flight between 2000 ft and 5000 ft with a maximum length of one NM [7]. London Heathrow classifies arrivals as CDA if it contains, at or below an altitude of 6000 ft, no more than one level flight no longer than 2.5 NM. A level flight is interpreted as any segment of flight having an altitude change of not more than 50 ft over a track distance of 2 NM or more [8].

Even the phrase "Advanced Continuous Descent Approach" is not used consequently in literature. DLR's ACDA has the following advanced features compared to a standard CDA (see also Fig 5):

- Commencing the ACDA from an altitude where the aircraft is silent on the ground (usually above FL100) there is no further level flight until touchdown.
- Descents are performed with engines idle. Thus, sink rate and flight path angle are not necessarily constant while descending. Idle thrust does not only reduce noise emissions of the engines but also reduces noise immissions on the ground and fuel consumption due to higher and therefore more economical flight profiles.
- The vertical profile can be specified independently of the lateral path. This enables the implementation of special procedures like curved approaches.

The ACDA starts from a level flight at an altitude where the aircraft is silent on the ground, usually above FL100. This level flight is reached from the aircraft's cruising altitude via another idle descent and is used as the last opportunity to alter the aircraft's trajectory.

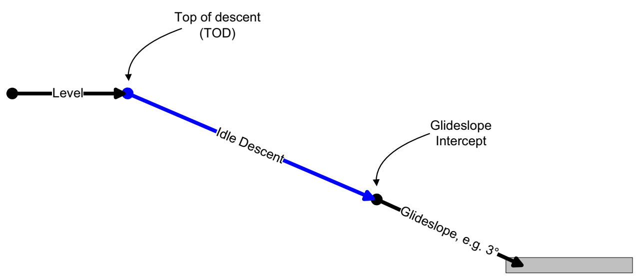

Fig 5: ACDA vertical profile

Once the idle descent of the ACDA has been commenced, it is hardly possible for the aircraft to react to ATC instructions. Since the ACDA is flown with the engines idle, this procedure represents the optimum profile for the airplane in terms of noise and fuel consumption. Any deviation from the predetermined approach profile due to ATC instructions would lead the aircraft away from its optimum profile and thus create more noise and higher fuel consumptions. Additionally, ATC does not know when the aircraft is planned to use which descent rate or speed, because this highly depends on the aircraft type, current weight, or even specific operational procedures used by different airlines, making the aircraft's behaviour hardly predictable for ATC. To compensate for this, ATC had to create a generous margin around aircraft performing CDA within today's fixed approach route structure, which significantly reduces capacity.

3.3. ACDA Calculation of AFMS

The main task when calculating a 4D-trajectory for an ACDA is to predict an appropriate position for the top of descent (TOD). First, the AFMS calculates the glideslope intercept point by means of glideslope angle, intercept altitude and runway threshold position and elevation. The AFMS calculates the TOD by stepping backward from the glideslope intercept point, implying an idle descent to the glideslope intercept (see also Fig 5).

The foreseen airspeeds depend on phase of flight and type of aircraft. Optimum speeds for different flight phases are published for most transport aircraft by Eurocontrol in the Base of Aircraft DAta (BADA, current version 3.6) [9].

For a precise prediction and guidance along 4D-trajectories the AFMS must also consider the aircraft configuration. The higher drag and lift coefficients of extended flaps otherwise would lead to deviations which might not be acceptable in a 4D trajectory-based traffic management.

Fig 6 depicts an example of an ACDA calculated for the Airbus A330-300. The TOD is in FL80 where the aircraft is in clean configuration. The descent starts idle with constant 250kts. This is followed by an energy sharing phase where the aircraft both descents and decelerates. The glideslope is intercepted at 3000ft with 170kts, flaps just coming out to position 2. At 1800ft above ground level the aircraft is configured for landing (flaps full, gear down). Flying the standard glideslope approach the aircraft will need thrust to hold the landing speed on the very last part before landing.

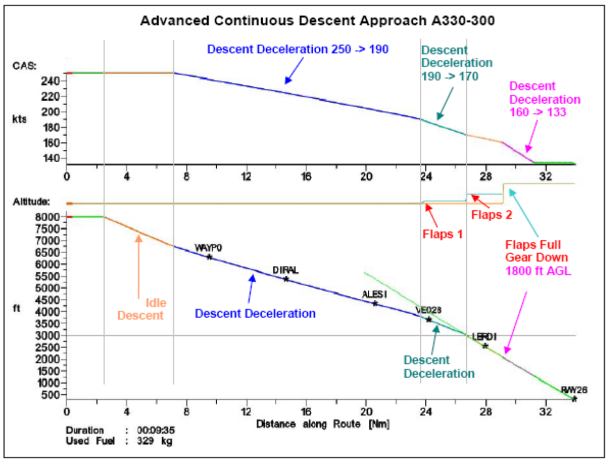

Fig 6: ACDA of A330-300

Deviations may occur during the execution of an ACDA due to

- insufficient or imprecise aircraft performance data
- jitter in the configuration points
- bad weather forecast
- …

When forced to deviate from the predicted trajectory because of unforeseen influence described above, the AFMS guidance functionality tries to hold the time deviation at minimum and in exchange accumulate the altitude error. The altitude error is compensated when intercepting the glideslope. This type of readjustment depends on whether the aircraft is too high or too low [10].

Being in time and having a positive altitude error (too high) means that the aircraft has too much energy left. Since the engines are idle in descent there is no way out with the thrust. Therefore, the AFMS reacts by increasing the drag. If the AFMS detects a positive altitude error when intercepting the glideslope it brings forward dynamically the configuration times for flaps and gear.

A negative altitude error (too low) implies a lack of kinetic energy. An early reaction in form of setting higher thrust should be avoided because

- Slow response times of jet engines make a closed loop control difficult.
- Even small changes of the engine speed are felt disturbing by the passengers.

A negative altitude error is corrected by insertion of a less steep segment. Only in extreme cases this segment will be a level segment. In order to get rid off the missing energy, the AFMS brings forward the point of leaving idle thrust. Thus, there is no new phase of closed loop low power control but a small extension of the thrust phase just before landing.

3.4. Precision in Time of FMS

The AFMS prediction and guidance capabilities have been validated in several simulation runs using the A330-300 Full Flight Simulator in Berlin and flight trials with DLR's test aircraft ATTAS, a VFW614 twin engine jet [11].

During both simulator and flight trials, the altitude error in general stayed within +/-150 ft, while the time error remained within +/-5 sec. On two occasions during the flight trials the time error reached rather bad 10 sec; this was in both cases due to an imprecise weather forecast and could be mitigated with a more precise weather forecast containing wind on a finer 3D-grid and also vertical wind components. With a sufficiently accurate weather forecast, ACDA have hence been proved to be feasible with a precision in time of 5 sec.

Of the FMS used in today's airline aircraft, 32% are capable of meeting one time constraint in their route with a precision of +/-6 sec., 11% are nowadays capable to do so during a descent or climb [12]. This group, which will continue to grow further, could already substantially profit from the new concepts and procedures developed in FAGI today. FMS manufacturers do not state the capability of their devices to calculate ACDAs, but since it is a newly developed (nevertheless already proven under real world conditions) procedure by DLR, this functionality still has to be included into standard FMS.

4. ARRIVAL MANAGER – 4D-CARMA

During the last decade, the Institute of Flight Guidance has developed Arrival Managers (AMAN) for different kinds of applications on various European airports. The latest development is 4D-CARMA to assist controllers at civil airports in organizing the multitude of arrivals. It is the latest implementation of DLR's previous arrival managers COMPAS [13] and 4D-Planner [14], both research projects in close cooperation with the Deutsche Flugsicherung GmbH (DFS). The new design of 4D-CARMA for FAGI will be specifically optimized to support control of the two different arrival flows via direct or trombone approaches (section 2) and supports them in the time-based merging or aircraft at the late merging point LMP.

4.1. Features of 4D-CARMA

Taking different constraints into account, e.g. separation criteria, target times, and runway allocation, 4D-CARMA uses actual radar data and additional information of all arriving aircraft and calculates sequences with conflict free trajectories from the actual position to the runway threshold. Furthermore, this AMAN provides advisories for the controller to guide the aircraft through the Terminal Manoeuvring Area (TMA).

4D-CARMA calculates first the shortest and the longest possible flight route in the Terminal Manoeuvring Area (TMA) from the actual aircraft position to the allocated runway. On the basis of these two legs a time-based window between the earliest and the latest arrival time (without holdings) is estimated and a sequence for all arriving aircraft is created. Taking wake vortex safety distances into account, 4D-CARMA calculates the target times of arrival and finally generates the trajectories.

In cooperation with DLR's Departure Manager (DLR-DMAN) and the AMAN-DMAN Coordinator (ADCO) 4D-CARMA support mixed mode operations on runways by taking departures into account within the arrival sequence optimization process. To integrate out-bound traffic into the arrival flow, the ADCO generates "*arrival free intervals*" (AFI) into the planned arrival sequences.

For a common overview of the planned arrival and departure sequence 4D-CARMA provides real-time time-lines for each runway showing aircraft labels ordered by its scheduled arrival respectively departure time. Fig 7 shows the time-line which was used during the OPTIMAL[1] validation trials for dual threshold operations [15]. On the right side, we see brown labels which mark the inbounds scheduled for the right runway 25R. DAL20, a heavy B772 aircraft, should land on the right runway at 7:21 a.m. The blue labels visualize the take-off times of the departures scheduled for the mixed mode runway 25R. On the time-line's left side, we see the inbounds scheduled for the normal threshold 25L (solid lines) and for the displaced

[1] The project "Optimised Procedures and Techniques for Improvement of Approach and Landing" (OPTIMAL) was funded by the European commission within the sixth framework programme.

threshold 26L (dashed lines). The pink areas in the middle of the time-line show the arrival free intervals, which are reserved for departures.

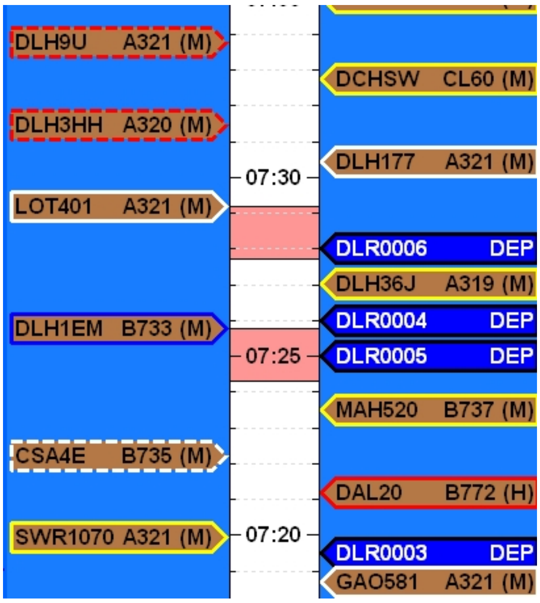

Fig 7: Time-line of 4D-CARMA

Furthermore, 4D-CARMA supports various kinds of human-machine-interfaces (HMI) for controllers to handle the growing aviation traffic in the vicinity of larger airports. Conventional radar displays can be upgraded to show the sequence position of each arriving aircraft next to the common aircraft label to assist controller at the planning and guiding exercise without treating him to distract his attention from the radar display. If required 4D-CARMA generates controller advisories on the basis of calculated trajectories or generates clearances for appropriately equipped aircraft. The controller gets an advisory stack (see Fig 8) with a time-based counter assisting him in giving guidance advisories at the right time in the radar-display or on an additional device, so that the arriving aircraft precisely follow the planned trajectory.

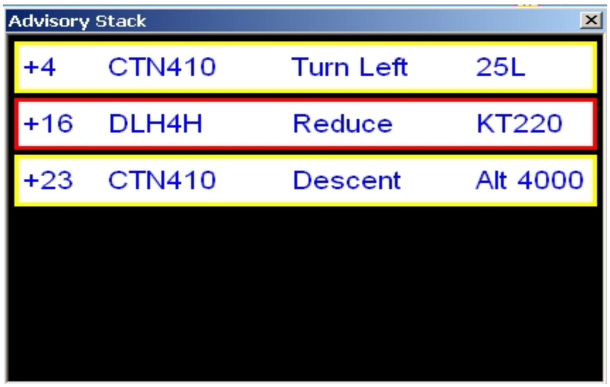

Fig 8: Advisory Stack of 4D-CARMA

Fig 8 shows an example of the advisory stack contents. The CTN410 pilot should start his left turn in four seconds in order to exactly meet the planned target time at the threshold. Therefore, the controller should give the advisory via voice a little bit earlier. It is up to the controller to decide when he gives the command. This depends on the priority of the other advisories in the stack, on the current traffic situation, or maybe on the pilot.

There will be deviations from the exact time, but 4D-CARMA will detect this and adapt the next advisories to the new situation. If the aircraft turns too early the next reduce command will be given earlier or a smaller target speed value will be chosen. In an analogous manner 4D-CARMA handles the case when an aircraft turns too late. Validation trials with three different European controller teams showed that the exact timing of the command is not so important [15]; more important is the information that an advisories should soon be issued. Currently no advisory de-conflicting algorithm is implemented in 4D-CARMA, so it could happen that the controller is advised to give speed and descent commands to two different aircraft at the same time. The controller is used to this situation. It is his daily practice, but ongoing work will investigate whether a de-confliction of the advisories could make the controllers' work easier.

4.2. 4D-CARMA and the Non-Equipped Aircraft

Due to its modular implementation, 4D-CARMA uses different functionalities and thereby diverse modules to handle equipped (with 4D-FMS and data link) and unequipped aircraft. Fig 9 shows the interaction chain how 4D-CARMA handles unequipped aircraft. It is initiated with an update of the aircraft's radar data inducted by the module Radar Interface (RIfc). The Lateral Path Predictor (LPP) determines all lateral paths, which lead from the aircraft's present position to one of the runway threshold the aircraft may use. The Arrival Interval Calculation (AIC) module calculates for each lateral path an earliest and a latest arrival time at the assigned threshold.

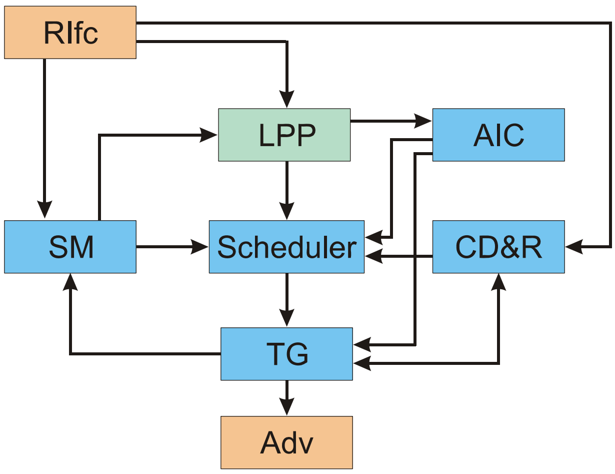

Fig 9: Interaction chain for unequipped aircraft

Based on the aircraft's positions, the calculated arrival intervals, the controller inputs etc. the Scheduler identifies sequence constraints (e.g. DLH344 before AFR321). The optimal arrival sequence, which minimizes the specified evaluation criteria (e.g. stability and compactness) and satisfies the constraints (e.g. no arrival before earliest possible arrival time, sequence constraint, blocked arrival times), is determined by a heuristic tree search algorithm. The AMAN derives from the optimal sequence for each aircraft an arrival runway (i.e. the corresponding threshold), an arrival route and target times (for the LMP and, if necessary, other significant waypoints).

The task of the Trajectory Generator (TG) is to calculate a trajectory for each aircraft, which uses the assigned route, meets the calculated target times and has no conflicts with the trajectories of other aircraft. The last task is performed by module Conflict Detection and Resolution (CD&R). If no conflict free trajectory is found a re-planning of the Scheduler with further constraints is necessary. From the trajectories, the advisories are derived and appropriately displayed to the controllers (Adv).

This interaction chain is repeated again and again. Deviations of the aircraft from the trajectory (task of Status Monitor - SM) or adapted controller advisories are detected by 4D-CARMA via radar data. This leads to an update of the planning, e.g. adapted advisories, adapted trajectories or adapted arrival sequences. The same is true if the controller enters new sequence constraints.

4.3. 4D-CARMA and the AFMS-Equipped Aircraft

Contrary to the handling of unequipped aircraft, Fig 10 shows the corresponding interaction chain of 4D-FMS equipped aircraft. The Route Assignment (RA) module is comparable to the LPP. It detects possible routes from the actual aircraft position to the late merging point. Using data link and the on board FMS capabilities the Air Ground Communicator (AGC) determines arrival time intervals at the runway thresholds. The Scheduler calculates sequence constraints and an arrival sequence of the equipped aircraft which minimizes the evaluation functions.

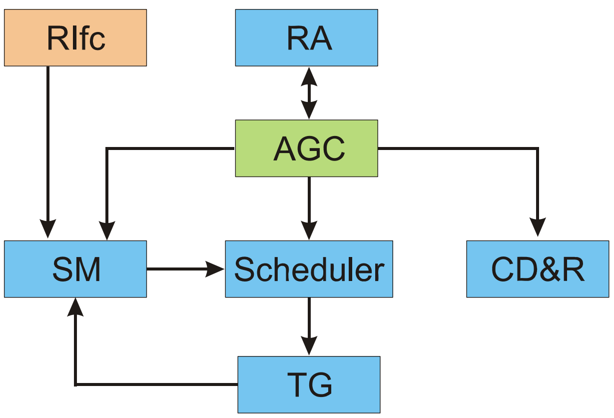

Fig 10: Interaction chain for equipped aircraft

The optimal sequence results in target times at the LMP, the runway threshold and in other individual flight constraints like specific altitudes or speeds at real or virtual waypoints. These are transmitted to the aircraft via data link from the Air Ground Communicator module to the aircraft to enable the 4D-FMS calculating precise approach trajectories.

Depending on the available data link capabilities the resulting on board trajectory is transmitted to the ground AMAN for conformance monitoring purposes. If no appropriate bandwidth is available, the ground module Trajectory Generator has to calculate the trajectory which results from the ground constraints.

The ideal case works as follows: 30 minutes before touch down a contract between air and ground is established and the resulting trajectory is not touched any more. The status monitor, however, has to check whether the aircraft is conform to the negotiated trajectory and whether no conflicts with other trajectory are possible. In those cases, the controller is informed and has to decide whether the current plan should be kept or whether a planning update is necessary.

4.4. Data-Link and Air-Ground-Communication

One unit of the aircraft-ground-integration is the partly automated air-ground communication with data-link. Basic and advanced information like constraints or complete trajectories information is transmitted from aircraft and management tools. In addition, clearances could be granted and accepted or rejected without using voice radio and reduce blocking times of voice radio frequencies.

In FAGI project it is planned that the ground management tools contacts an arriving aircraft a few minutes before it approaches the virtual border of the Extended TMA. The air ground communication module (AGC in Fig 10) starts with sending a “First Contact Initial Handshake” with a set of actual and general information about the flight conditions around the destination airport (Fig 11):

- Local weather conditions incl. QMH, visibility, wind speed and direction,
- Path stretching procedure,
- Supported approach procedures.

This automated communication does not substitute today’s initial hellos via radio voice, but it will reduce the length of spoken messages and spare the cockpit crew entering data into the FMS which it needs following the allocated STAR and for trajectory calculation.

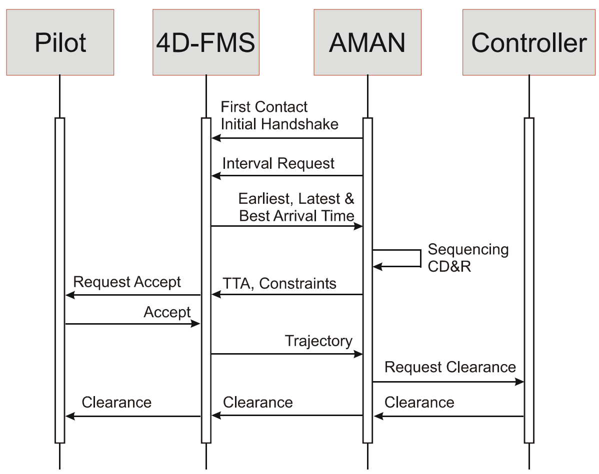

Fig 11: Sequence diagram with the flow of semi-automatic air-ground-communication

To find the best trajectory possible, the AMAN has to consider all arriving aircraft. Therefore 4D-CARMA sends an “Initial-Request” for one or more selected STARs to get an interval for possible landing times (earliest and latest time of arrival). Additionally the FMS sends its preferred landing time for that STAR. The FMS answers with an “Earliest, Latest, and Best Arrival Time” message. On the data-basis of these focused time-windows, 4D-CARMA plans an arrival sequence with the according landing times ("Sequencing and Conflict Detecting and Resolution" – CD&R, Fig 11).

To meet the Target Time of Arrival (TTA) aircraft have to observe flight constraints at real or virtual waypoints. 4D-CARMA transmitted these individual constraints with the "TTA and Constraints" message to the current aircraft to enable the FMS calculating precise approach trajectories. For that the FMS needs an accept input by the flight crew. If the bandwidth of the available data-link is sufficient, the airborne FMS sends its high-precision trajectory with the "Trajectory" message to the AMAN which uses the information for potential conflict detection and resolution with non-equipped aircraft. When the FMS trajectory data arrives at the AMAN, 4D-CARMA checks the on board trajectory against the ground constraints of the "TTA, Constraint" message.

5. HUMAN AND AUTOMATION

While the presented automation can technically contributes to significant performance improvements, the human operator continuous to play a central and indispensable role in all aspects of the system's operations. This is true for both air and ground side.

From a technical viewpoint, route structure and concept presented in section 2 are designed to support user-preferred trajectories, fuel efficient and noise-reduced approaches through the late merging of arrival routes. Much of the potential of the concept to realize that goal lies in the better exploitation and integration of advanced airborne and ground automation. This was presented in section 3 and 4 with DLR's AFMS and Arrival Manager 4D-CARMA. However, the implementation of the concept and overall system performance achieved will strongly depend on acceptability of new procedures and roles in human factors terms. Compatibility with human cognitive capabilities, preferences and constraints has to be ensured.

It is thus a primary concern in FAGI to design all systems and procedures to optimally support the human operators' tasks. The acceptability of new operator roles with respect to human factors issues such as workload, situation awareness and trust etc. will be thoroughly investigated. In order to support the design and validation process, the FAGI project has integrated human factors knowledge from the beginning and has built on the expertise and feedback of operational subject matter experts (controllers and pilots) from the early development phases onwards.

5.1. Impact of 4D-Paradigm

A considerable impact on human operators' task requirements and modified roles within the concept is obviously connected with the change from today's relative guidance to a paradigm of 4D time-based planning with absolute overflight times. This change concerns both controllers and pilots. Technically, absolute 4D planning is a key enabler for the coordinated guidance of all aircraft to the central late merging point. From a human factors perspective, however, 4D planning is generally hard to grasp for human beings due to its mathematical complexity. Even automatically generated 4D-plans are difficult and cognitively expensive to monitor and verify if not adequately supported by effective automation and interfaces. This is exacerbated whenever decisions over extensive trajectory segments have to be made [17] by human operators and is most difficult where potential consequences for downstream positions (controller view) or later flight segments (pilot view) may have to be taken into account. In this context, also the visualization of the potential future traffic situations and of the factor time especially in controller displays is another important research topic. Existing display representations concentrate mainly on the visualization of current state information, and might have to be extended to projective information.

Under the 4D-paradigm, reliance on automation support to cope with the computational complexity of 4D-planning will necessarily be greater than in today's operational environment. Reliance must be calibrated and well-balanced, however, and must not result in complacency. Eventually, it has to be noted that 4D-CARMA and AFMS are designed to the role of support systems, with the ability to generate highly efficient proposals for trajectory and traffic planning. However, the ultimate responsibility for the safety of operation, however, remains with the operator, which must consequently be provided with adequate technical means and authority to assume this role.

In order to identify the functional requirements for 4D-guidance within the concept, extensive scenario writing and development of use cases has been carried out within FAGI. Numerous nominal and non-nominal scenarios have been developed. These scenarios describe the guidance of both unequipped and equipped aircraft and specify the human tasks and roles during the interaction with their respective automated systems and human counterparts on air/groundside.

With regard to the guidance of unequipped aircraft, that is aircraft without own 4D-FMS/data link, which will be guided through individual clearances along a 4D-trajectory calculated by 4D-CARMA (section 4.2), the development can already build on experience and results from recent human in the loop (HIL) validation experiments within the EU project OPTIMAL, where related procedures and interface elements were tested successfully.

For the guidance of equipped aircraft (with own 4D-FMS/data link), previous work from the German KATM project KOPIM (cooperative implementation) will serve as a basis for protocols and procedures [16]. Controllers and flight crew of equipped aircraft will negotiate, with the help of AMAN and 4D-FMS, a target time and 4D-trajectory to the late merging point. The aircraft can then execute this trajectory autonomously as long as the overall traffic plan remains stable. To support the controller in monitoring the equipped aircraft's progress and its conformance to the contract an important issue is the development of procedures and interface elements which are essential to maintain operators' situation awareness.

5.2. Mixed Equipage Levels

Building on experiences from OPTIMAL and KOPIM, the simultaneous handling of unequipped and equipped aircraft within the same airspace and route structure is a new concept element in FAGI. It is a new requirement especially for the air traffic controller, which will have both aircraft types simultaneously under his responsibility. The consequences of this new requirement in terms of workload and performance will be investigated during the upcoming validation experiments. In general, processing of equipped aircraft is expected to lower workload on the ground. This concerns mainly the later flight phases, once the trajectory has been negotiated. From the controller perspective, however, the distinction between two different categories of aircraft, which will be processed according to different procedures, has also a potential to increase control complexity. It could thus make situation awareness more difficult to maintain.

To prevent confusion, the distinction has to be adequately supported by the system and interface. The human-machine interfaces developed in FAGI must ensure that the categorisation of each aircraft is unambiguous. The applicable procedures must always be clear. The unambiguity of HMI gets even more important as switches of individual aircraft between the two sets of procedures are possible within the FAGI concept. For example, an 'equipped' aircraft (with 4D-FMS/data link) which was formerly on a direct-to-LMP approach (section 2.2) may be diverted to the trombone (standard for approach unequipped, (section 2.3) due to violation of the 4D-contract. The equipped aircraft will then be treated according to standard procedures for unequipped aircraft and this must be instantly recognizable.

5.3. Dual-Modality Communication

Closely related to different procedures in FAGI for equipped/unequipped aircraft is the requirement for human operators to act within a dual-modality environment with data link and voice communication [19,20]. The issue concerns the flight crews of equipped aircraft and even more so the controllers. Flight crews of equipped aircraft will e.g. negotiate and exchange trajectory information via the data link medium. In parallel they will maintain radio contact with the controller for other tasks (e.g. handovers, short term conflict resolution). Controllers will guide equipped aircraft mainly via data link clearances. They will at the same time control unequipped aircraft exclusively via radio communication. Only flight crews of unequipped aircraft will be experience minor changes compared to today, apart from the fact that there will be no party line information on the voice channel for the equipped aircraft.

Existing research has shown that voice radio and data link exhibit different communication characteristics with different strength and weaknesses [21, 22, 23]. This affects their suitability for certain tasks from a human factors point of view. On the one hand, data link messages appear more suitable to transmit greater amounts of numerical data. This is why they are preferable for the negotiation of trajectory data and overfly times of equipped aircraft in FAGI. Data link messages also often show higher message quality (less error prone, misunderstanding/read back errors). They offer the potential to parallelize communication with different aircraft from a controller point of view and handle multiple open message transaction at a time, which can be cognitively highly demanding however. Also congestion of radio channels may be alleviated by data link. This improvise the chances of giving radio clearances to unequipped aircraft with good timing and precision enabling better adherence to 4D-planning. On the other hand, preparation, transmission and response time for data link messages is generally higher [21] which has been discussed as a potential source of additional controller workload, Continuous switching between modalities adds an additional "modality monitoring task" to the task of the operator, and, due to the different response times of data link and voice, causes a need to for setting different "mental timers" [21].

In FAGI the usage of data link as a medium for communication between ground and equipped aircraft introduces the technical possibility of having direct communication between airborne and ground automation, that is between AMAN and FMS, potentially without the need of human involvement (see Fig 12). Such direct inter-automation communication can be curse or blessing from a human factors point of view. On the positive side it enables the repetitive exchange of routine data between air and ground without continuously interrupting human operators work flows. It may thus help to avoid additional workload. On the negative side there would be a potential for leaving the human operator out of the loop if significant information was exchanged between system and the human operator was bypassed. Fig 12 highlights the differences in information flow with regard to the guidance of unequipped and equipped aircraft and illustrates that in the case of unequipped aircraft all transmitted information will be exchanged between human operators due to the absence of data link, while equipped aircraft communication allows system to system transactions.

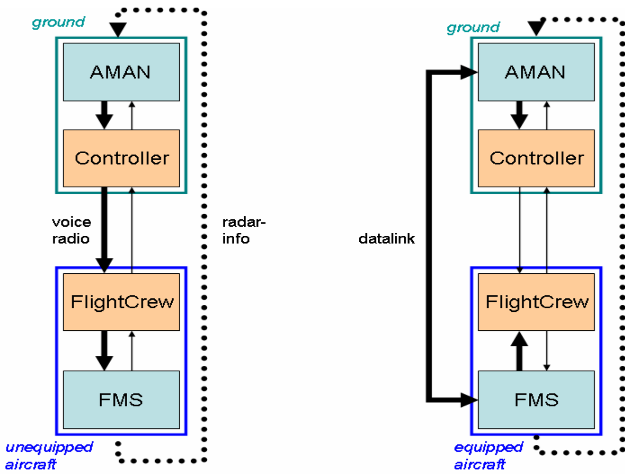

Fig 12: Information flow with voice and data link

5.4. Validation

FAGI validation planning applies the guidelines of the E-OCVM (European operational concept validation methodology) in order to demonstrate fitness for purpose of its central concept elements and technical systems. Several workshops with external subject matter experts in combination with extensive experimental trials in simulators and with DLR's test aircraft will serve to evaluate if FAGIs objectives according to defined human factors criteria and key performance areas have been met and where further developments are necessary.

Experimental HIL validation will include simulations with flight crews and for different controller positions such as feeder, pick-up, and sector positions. First experiments are scheduled for the next months and will proceed from the feeder position handling the LMP vicinity to the more upstream positions.

6. CONCLUSIONS

This paper presents a concept for more fuel-efficient and noise-reduced management of arrival traffic at hub airports. As a key element of the concept a modified airspace and route structure is proposed which was developed in the DLR project FAGI. This route structure features the late merging of arrival routes to better support user-preferred flight profiles and especially CDAs. New airborne and ground-based automation is developed within FAGI for the time-based guidance of aircraft within the new operational environment and will be validated in upcoming experimental trials. Important issues about the interaction with the newly developed automated systems are discussed. Aim of the overall concept and tools is a significant improvement of ATM with respect to fuel consumption and noise emissions, while eliminating the negative impact on capacity, which is still connected with the provision of CDAs and user-preferred trajectories today.

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