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An approach to study concepts for conflict free direct arrival and departure trajectories to and from an airport using realistic traffic patterns

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Abstract

The study develops elements of a concept for arrival and departure operation in an extended Terminal Manoeuvring Area using user preferred trajectories and individual trajectory based separation mechanisms. It implements core parts in a simulation environment, assesses the feasibility and associated costs and finally shows limitations and additional requirements to work on in the future development of the concept. Core of the concept is the idea to allow nearly direct arrival and departure routes to and from an airport. Conflicts between climbing and descending flights are solved through insertion of an altitude constraint or level segment in the departure trajectory. The concept has been implemented in a simulation environment for two generic airports and corresponding route structures. The results are showing that the concept is feasible for the test cases and the costs arising in the simulation are given.

Keywords: TMA operations, conflict resolution, trajectories

Résumé

L'étude développe des éléments d'un concept des opérations d'arrivée et de départ dans une Terminal Zone de manœuvre étendu, utilisant utilisateur-préférée trajectoires et individuelles séparation mécanismes basée sur trajectoire. Il implémente pièces de base dans un environnement de simulation, évalue la faisabilité et les coûts associés et enfin montre ses limites et exigences supplémentaires aux travaux sur le développement futur de la notion. Cœur de la notion est l'idée de permettre près de routes directe de l´arrivée et le départ à destination et en provenance d'un aéroport. Conflits entre les vols escalade et décroissant sont résolus par l'insertion d'une altitude contrainte ou niveau segment dans le départ trajectoire. Le concept a été mis en œuvre dans un environnement de simulation pour deux aéroports générique et structures de routes correspondant. Les résultats montrent que le concept est réalisable pour les cas de test et les coûts résultant de la simulation sont donnés.

Mots-clé: TMA operation, conflict resolution, trajectory

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Nomenclature

ATM	Air Traffic Management
BADA	Base of Aircraft Data
DLR	Deutsches Zentrum für Luft- und Raumfahrt e. V.
RTA	Required Time of Arrival
s	seconds
TBO	Trajectory Based Operations
TMA	Terminal Manoeuvring Area
TrafficSim	Air Traffic Simulator

1. Introduction

Direct flight connections using great circle arc routes have been studied extensively for the en-route part of a flight. In the vicinity of airports such concepts are not developed that far. Most of the relevant studies are based on the assumption of current flow control procedures and the concept of extended TMAs for optimizing the procedurally separated in- and outbound traffic flows. The flexiGuide project of DLR is one ongoing project to create and introduce more individual and flexible approach procedures to reduce environment impacts. The flexiGuide concept expands the conventional Standard Instrumental Arrival Routes and transitions by a Late Merging Point (LMP) on each final, roughly positioned on the half way between Final Approach Fix and runway threshold.

While the main focus of the flexiGuide project is an evolutionary concept starting at the air traffic management of today the work presented here is approaching the future ATM situation from a theoretical upper bound referred to as utopia. The utopia concept for the extended TMA was introduced in Schwoch et. al. (2012). The main premise of utopia is that each arriving or departing aircraft is allowed to plan its preferred trajectory during climb and descent. The term “preferred trajectory” is interpreted for the scope of the study as shortest possible horizontal route and a fuel optimized speed and altitude profile between the origin or destination airport and the runway of the airport in focus.

The combination of the individual trajectories in a traffic scenario of course will lead to planning conflicts, i.e. at some point in time the planned 4-D trajectories between two aircraft are closer together than defined minimum separation rules allow. Then measures like e.g. conflict avoidance manoeuvres, trajectory time shifts, modified separation rules or elementary TMA route structures are introduced stepwise in the utopia concept to address and solve most if not all conflicts. This approach will not lead directly to a feasible operational concept for TMA operations but it will help to identify requirements, needs and challenges for the future development of feasible ATM concepts for the extended TMA.

The work presented here consists of two main components: The first one is a proposal for a basic TMA structure and concept to operate arriving and departing flights to and from an airport. The second one is an environment to simulate, assess and refine the concept with realistic traffic patterns of a hub airport including the results achieved so far.

The approach of this study follows the concept of an enhanced level of flow control supporting the shortest routes possible with the opportunity of minimizing the extensions of the TMAs to the level required for spacing procedures. The aim of this study is estimating possible benefits resulting from shorter flight distances, initially without taking into account other constraints like airport specific noise abatement procedures although a reduction of noise emissions is expected by the usage of near optimal trajectory profiles.

2. Operational Concept for arriving and departing traffic within an extended TMA

For this study we assume a basic operational concept with the following elements:

All aircraft are equipped with a 4-D FMS and are able to exchange information with a trajectory manager. A ground based trajectory manager (or management system) coordinates the trajectories of all arrivals and departures to and from an airport. The trajectory manager receives basic trajectory information for flights scheduled to arrive at the airport in focus.

Based on this preliminary information and the runway separation matrix required by ATC rules the trajectory manager creates an RTA for the landing threshold before the top of descent of arriving flights. Gaps in the arrival stream are allocated for departures but without assigning a specific departure to a generic gap.

Arrivals are able to reach the runway threshold within +/- 20-30 s of RTA from top-of-descent. Based on the RTA, arriving flights transmit their planned trajectory to the trajectory manager. The arrival trajectory usually includes a continuous descent from en-route flight level.

Departure take-off operations at the airport in focus are scheduled between arrival operations according to a runway separation matrix. Directly after take-off a departing aircraft sends its trajectory based on the actual take-off time to the trajectory manager. The trajectory manager checks the departure trajectory for conflicts against arrival trajectories. If a conflict is detected, a level segment or an altitude constraint is generated to keep the departure well below the conflicting arrival trajectory. The constraint is transmitted to the departing aircraft, which includes it in its trajectory. The new departure trajectory is transmitted to the trajectory manager which checks it against follow-on conflicts resulting from the trajectory change and inserts a new altitude constraint if necessary.

There are several effects which can be expected from such an operational concept: Arrivals will not get into conflict with other arriving aircraft during descent to the runway threshold due to their pre-planned separation at the runway threshold. It will be possible to separate departures against other departing flights along the departure tracks by the usage of appropriate runway separations. Conflicts between descending arrivals and climbing departures in the extended TMA of the airport can be solved by the specific insertion of level segments in the departure trajectories.

Additional issues can be studied with the implementation of the operational concept in a simulation environment:

- How many conflicts between arriving and departing flights will occur within a realistic traffic example?
- Will the conflict solution through level insertion lead to follow-on conflicts?
- What are the costs of the conflict solution in terms of flight time and model fuel consumption?

Based on the assumption that the traffic demand will not exceed the airports runway capacity at any time and the inbound traffic flow can be controlled by speed adaptions while keeping the aircraft on great circle arc routes, the generic structure of the TMA used for this study is depicted in Fig. 1.

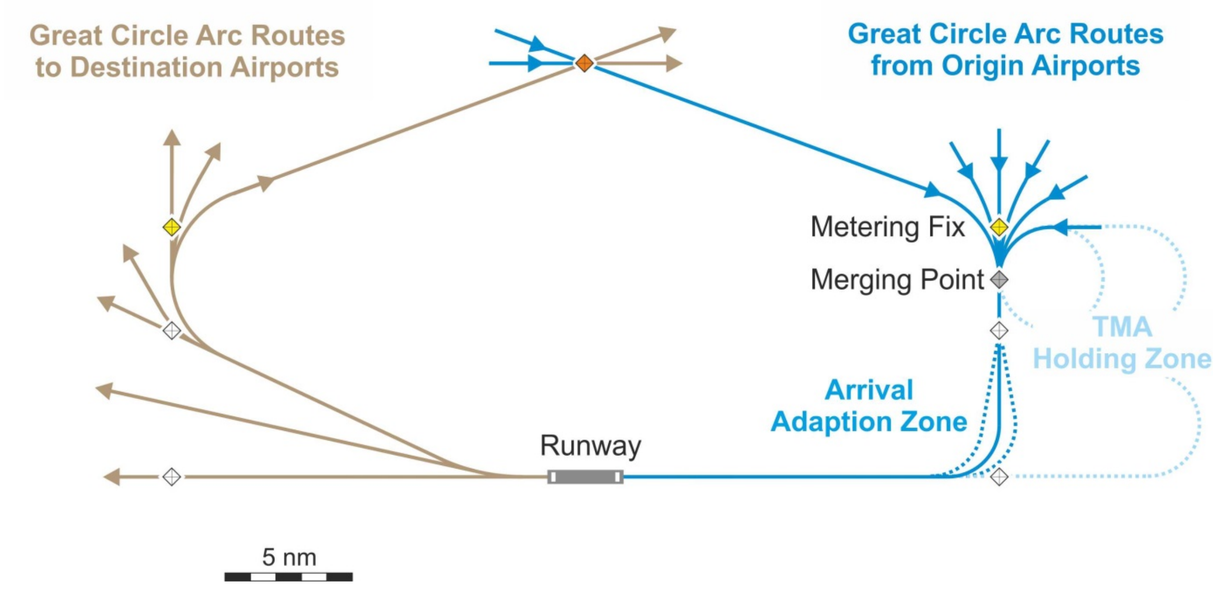


Fig. 1. Generic structure of the TMA

The radius of the TMA is about 20 nm while the cross distance between the centerline and the Metering Fix is 10nm. The nominal length of the final is approximately 15 nm. Inbound flow control is assumed to be performed by scheduling the inbound traffic at the Metering Fix as the result of the sequencing and scheduling process of the total in- and outbound flow at the runway. The controllability of target times by speed variation is limited by the flight envelope of civil aircraft. As an example the flight times of a sample distance of 200 nm before runway threshold and the metering fix can be varied by approximately 4 minutes using the high/nominal/low speed profiles of an Airbus A320 from BADA model data.

The results of the sample trajectory calculations with nominal/economic, low and high speed profiles to estimate the required arrival time accuracy at the Metering Fix are explained in more detail. Fig. 2 shows the ground speed, the flight level and the required separation times (corresponding to a 3 nm in trail separation) versus the distance to go for the runway threshold.

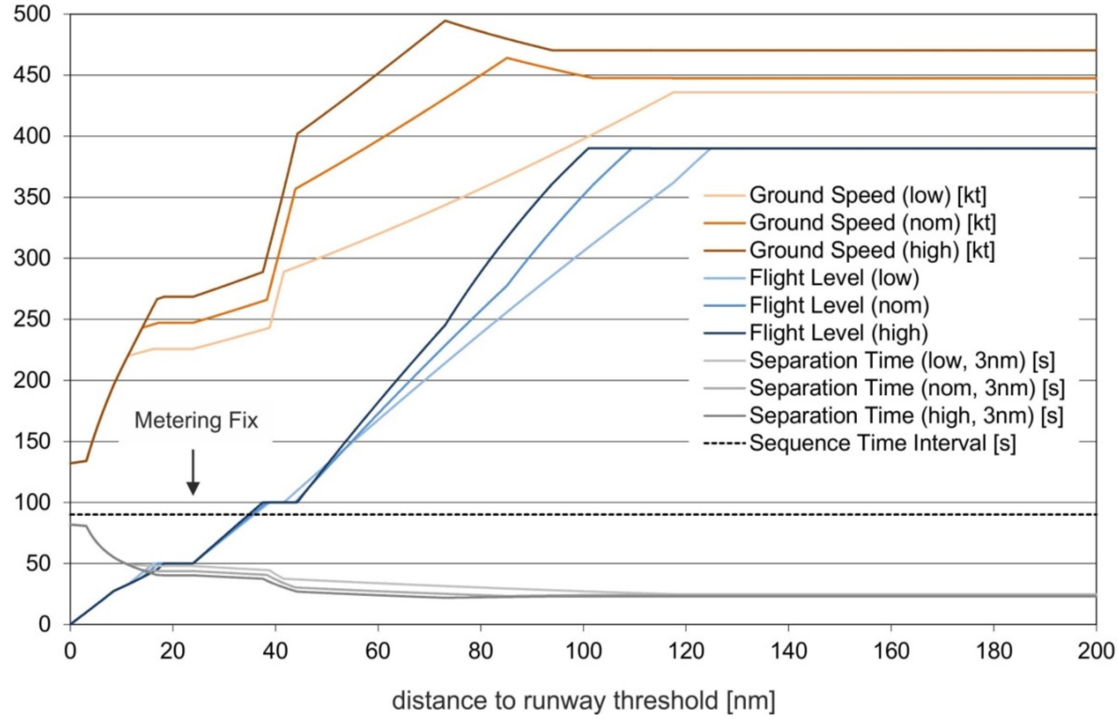


Fig. 2: Sample trajectory calculation results (BADA Airbus A320)

Assuming a maximum inbound traffic flow of 40 aircraft per hour with a corresponding average time separation of 90 s (dotted line in Figure 2), the arrival time accuracy at the Metering Fix is required to be in the range of +/- 20 s (in case of the low speed profile) according to Fig. 2. Klooster et al. (2009) have shown that with current generation avionics it is possible to meet a time constraint at a point in the approach with accuracies of less than 5 s. In conclusion the envisaged structure of the TMA seems operationally feasible. An important aspect in this context is the time compensation ability within the TMA in order to meet the originally fixed target arrival times at the runway threshold. Fig. 3 shows an example of tracks required for compensation of arrival time errors of +/-20 s at the Metering Fix. This adjustment option and in addition the proper height of arrivals near the arrival/departure crossing area abeam the runways are advantages caused by the location of the metering fixes in relation to the final approach. Compared to a solution with a short final it will lead to slightly longer flight tracks as an inefficiency trade-off. As the ground speeds are decreasing towards the runway and arrival trajectories are separated by 90 seconds it is assumed that there will be a closing effect between succeeding aircraft and there is no loss of capacity caused by the length of the common flight path.

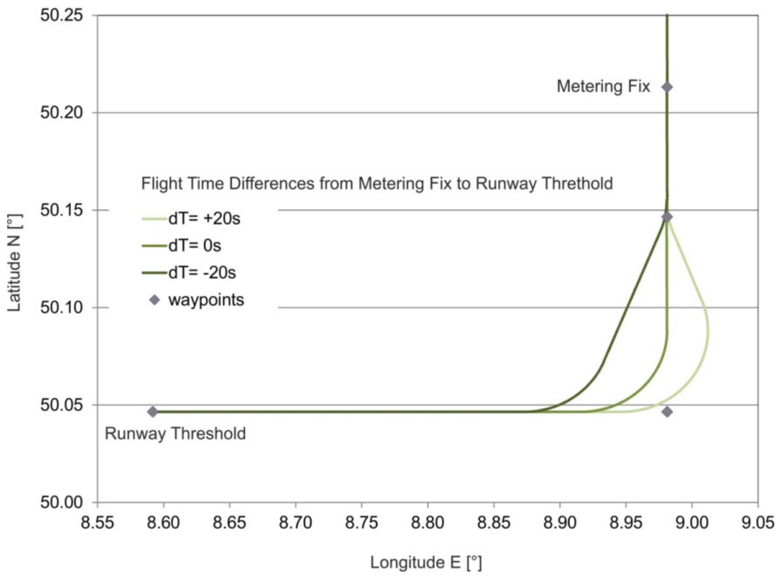
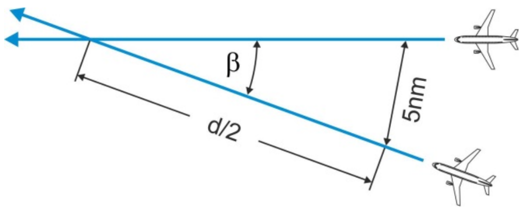


Fig. 3: TMA tracks for time compensation

In contrast to other approaches (e.g. Valenzuela, 2012) this study is using trajectory conflict resolution in the vertical plane only while keeping the aircraft on the original great circle arc routes. Some simple considerations should give a broad outline of the differences in costs of resolution manoeuvres in the vertical plane versus manoeuvres in the lateral plane. In the case of two crossing trajectories at the same flight level and the same time like sketched in Fig. 4 the additional fuel costs and the additional time required by vertical and lateral resolution manoeuvres are estimated. The vertical manoeuvre consist of a descent segment 1000 ft below the original altitude, a level segment with a length depending on the crossing angle of the two trajectories assuming a minimum cross separation of 5 nm if the vertical separation is less than 1000 ft and a climb segment back to the original flight level. For the lateral resolution manoeuvre an additional track length of 5 nm before the crossing point is assumed.



	β [°]	d [nm]
V5	5	114.6
V15	15	38.3
V45	45	13.1

Fig. 4: Geometry of the assumed trajectory conflict case and required lengths of level segments

For the sample calculations the BADA 3.9 model data of the Airbus A320 are used. The additional fuel required for the resolutions manoeuvres at different flight levels and the additional time required are depicted in Fig. 5. V45, V15 and V5 are the vertical resolution cases according to Fig. 4 and L denotes the lateral resolution case.

In all cases the estimated BADA model fuel costs and the additional time for the lateral resolution manoeuvres are significantly higher than those for the vertical resolution manoeuvres. This may enforce the approach to resolve the trajectory conflicts in the vertical plane whenever suitable.

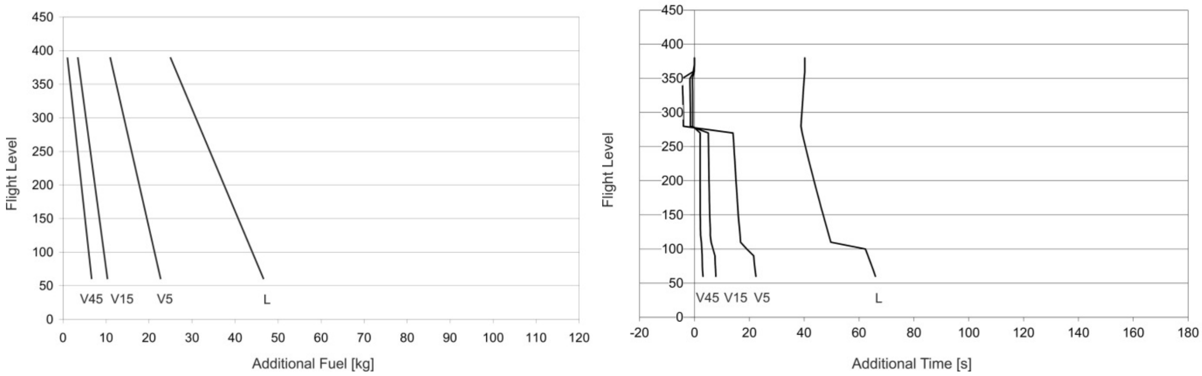


Fig. 5: Additional BADA model fuel and model flight time required for resolution manoeuvres (A320 model data)

For the envisaged simulations the generic TMA structure depicted in Fig. 6 is used. A generic airport with two parallel independent runways with a length of 4000 m and a runway centerline spacing of 2000 m is assumed.

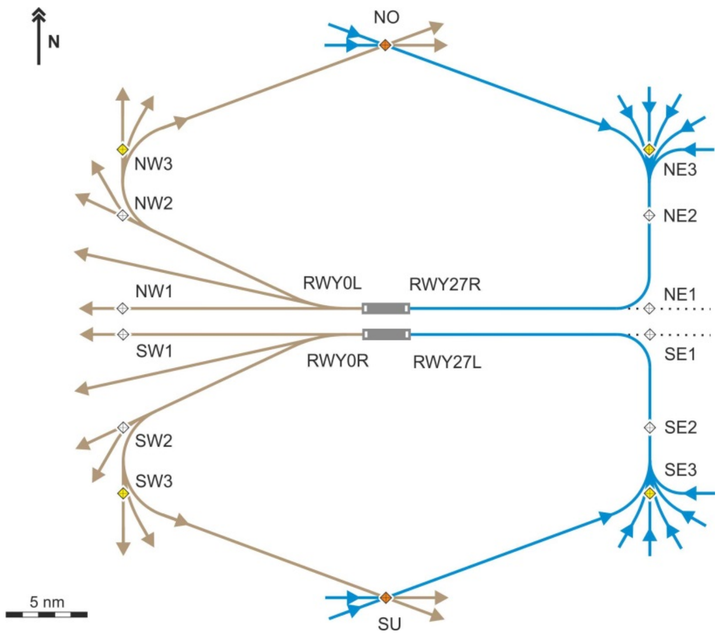


Fig. 6: Generic TMA structure for simulations

The en-route part of the flight is outside the scope of this study, it is assumed here that flights between two busy airports can be separated either by vertical separation or by lateral offset route segments.

3. Assessment Concept and Simulation Setup

The overall purpose of the assessment concept is to evaluate and further develop novel approaches to extended TMA operation in a real world traffic demand environment. Real world traffic demand represents the traffic structure of an airport in terms of aircraft mix as well as spatial and temporal distribution of arrivals and departures. Depending on the airport in focus a new idea to organise the traffic around an airport may have different effects.

Real world traffic demand data (Origin/Destination pairs and times, aircraft types, CFL) for this study were taken from the EUROCONTROL Demand Data Repository (EUROCONTROL 2012). The en-route parts of the recorded flight plans for one complete day were combined with the proposed generic runway and TMA structure using the scenario generator RouGe (Sulkowski, 2013). The resulting runway-to-runway flight plans for each flight were taken as approximation for user preferred flight plans because at that stage they did not consider the intents of other flights.

In a first stage of de-conflicting, the runway threshold times at the airport in focus were sequenced using a runway capacity simulation model (Karbowy, 2008). Aircraft types were arranged in 5 categories reflecting their wake vortex class and their speed performance: Heavy, Medium Jet, Medium Prop, Light Jet and Light Prop. Using today's separation requirements, arrival and departure speeds as well as longitudinal radar and wake vortex separations the following time separation values were used for sequencing on one runway:

Arrival/Arrival	90 s to 210 s	Departure/Departure	70 s to 160 s
Departure/Arrival	64 s to 72 s	Arrival/Departure	50 s to 60 s

Pairwise runway operations were considered independent if the two aircraft use different runways on the airport in focus. From the operational concept point of view in this sequencing process the arrival position in the runway-threshold-sequence is established well before top-of-descent and in addition gaps in the arrival sequence are foreseen for departures. These gaps were filled with departures during operation. A departure gap itself is quite fixed in the concept due to the arrival sequence planning time horizon. In order to avoid loss of departure slots departures should be interchangeable between the neighbouring gaps and there should always be a departure ready to take an available gap. That may require an adaption of ground queuing processes on the airport and at the runway.

The result of the first stage of de-conflicting was a scenario with conflict free runway threshold times, but with no information on other possible conflicts along the trajectories in the extended TMA. Hence in the second stage of de-conflicting, arrival and departure trajectories were calculated considering routing information, RTAs and aircraft performance. The trajectory calculations were performed with the DLR proprietary tool TrafficSim. The TrafficSim algorithms are based on an Advanced Flight Management System and for this study BADA performance data were taken as input (Edinger & Schmitt 2012).

It has to be underlined here, that in the studied operational concept most trajectories will be computed on-board, i.e. they will have much higher prediction accuracy than ground based trajectory calculations due to the more precise information on aircraft weight, flight intention, thrust settings etc. available on board. The TrafficSim trajectories, although based on BADA data, were used here as substitutes for on board trajectories which were transmitted to the trajectory management system on ground.

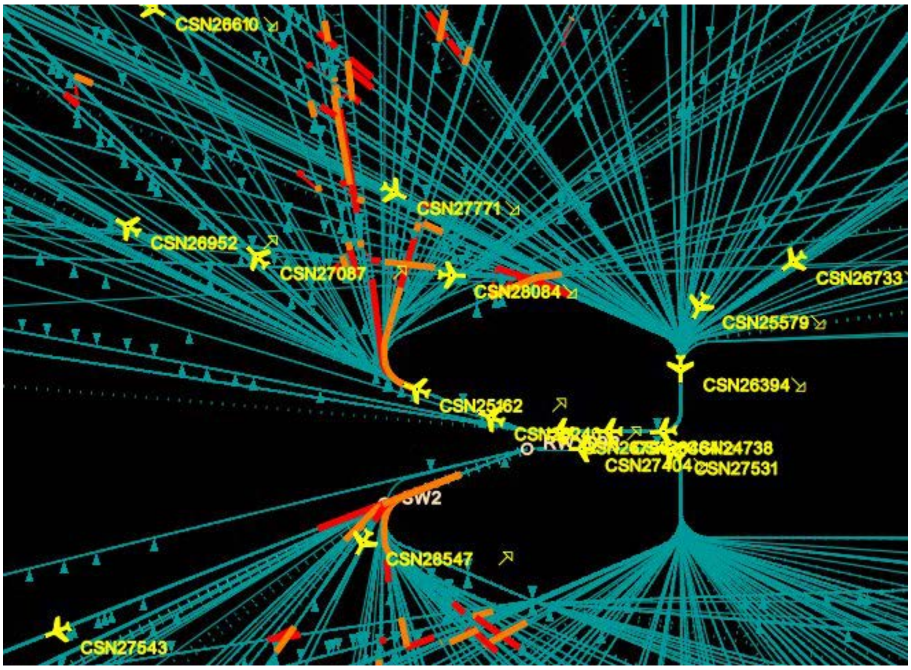


Fig. 7: Typical trajectory and conflict depiction for one complete day of traffic (1264 flights, conflicts detected in red and orange)

The pairwise conflict detection was performed using the technique from (Kuenz & Peinecke, 2009) which is implemented in TrafficSim. It looks for conflicts between trajectories violating vertical and horizontal separation values. The current separation minima are 5 nm horizontal and 1000 ft vertical, in the study values down to 3 nm horizontal and up to 3000 ft (if at least one of the two a/c is climbing or descending) were used.

The conflicts detected were classified. Conflicts of both aircraft in level were outside the scope of the study and hence ignored at this stage. Arrival/arrival and departure/departure conflicts were analysed in order to improve the operational concept with measures to avoid these types of conflicts. The main focus was laid on conflicts between descending arrivals and climbing departures.

Conflict resolution by inserting a departure level segment

The paradigm to solve conflicts between arriving and departing aircraft is to suspend the climb of the departing aircraft so that the approaches of the arriving aircraft are not disturbed and continuous descent operations can be performed. The departing aircraft will always be able to execute a level segment during its climb phase, thus the conflict resolution will be applicable in 100% of the arrival/departure conflicts. The conflict area itself can be avoided e.g. by the insertion of a level segment of 5 nm into the departure trajectory. Additionally a vertical safety buffer of 3,000 ft is introduced, following the separation minima for climbing or descending aircraft. Examples for integration of level segment constraints for the departing aircraft are depicted in Figure 8.

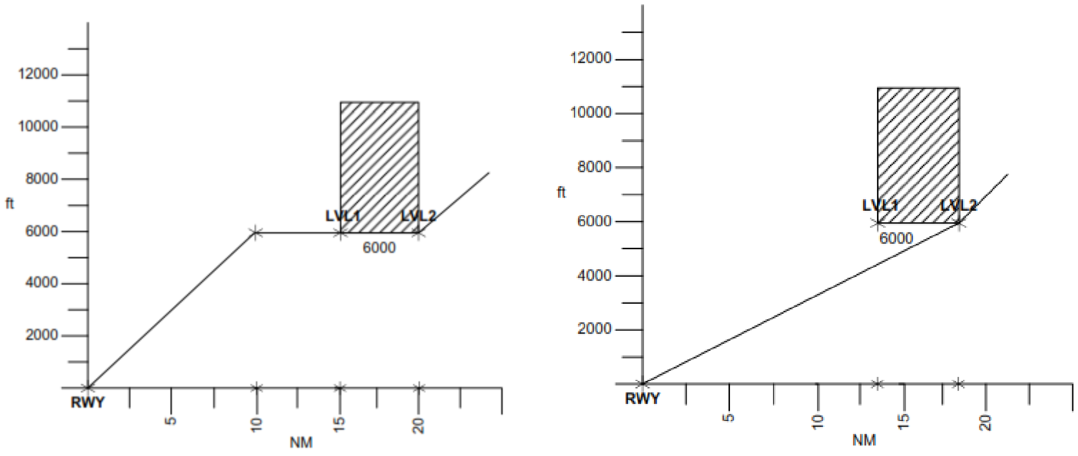


Fig. 8: Insertion of departure level segment and two different ways to comply

Due to the conflict detection, a conflict at 9000 ft was detected whereby a level segment at 6000 ft is introduced, bounded by points LVL1 and LVL2. The conflicting arriving aircraft can pass above the conflict area while maintaining vertical separation. This method, however, may lead to some different implementations of the idea of the level segment. Two of the observed implementations are depicted in Figure 8.

Figure 8 demonstrates on the left hand that a much longer segment is flown as actually calculated. In this case, the first waypoint is not served directly by the aircraft, but rises early to the determined restrictive altitude and retains this until the second waypoint has been passed. Then the aircraft climbs further to cruising altitude. In the second case, the aircraft is climbing directly to the second waypoint of the segment. Due to the reduced rate of climb, the restrictive altitude is not achieved up to this point. However, the conflicts are resolved in both cases.

The subsequent step is the calculation of a new altitude which is assigned to the departing aircraft within the segment. For this purpose, the altitude of the arriving aircraft at the end of the conflict is used, which is also an output of the conflict detection. Using this altitude and the introduction of a vertical safety buffer of 3,000 ft, the altitude of the departing aircraft within the level segment can be determined.

According to these calculations, the coordinates for the two waypoints and the constraining altitude of the level segment are available.

4. Results

For this study the concept was implemented for two existing European hub airports and the results in terms of number and duration of potential conflicts, cost of conflict resolutions and flight time variation are given.

For airport 1 with 1265 flights a day a conflict detection limit of 3 nm longitudinal and 3000 ft vertical led to 21 conflicts between arriving and departing flights. They were solved by inserting level segments in the departure trajectories. One additional conflict occurred and again was solved accordingly.

The cost of the level insertion was 53 seconds additional flight time and 35 kg additional BADA model fuel per departure affected (median values). The minimum time between lift-off and start of conflict was 6 minutes, the average time between lift-off and start of conflict was 8.5 minutes (Zilger, 2012). Conflicts usually were starting at altitudes of 15000 ft and above. These numbers serve as a first estimate of the time interval available for trajectory transmission air to ground, conflict detection and resolution on ground, trajectory transmission ground to air and trajectory implementation on board. It is expected that the short time interval available for the level off procedure envisaged will put a challenge on the cockpit crew during the climb phase in the future environment. On the other hand the character of the trajectory change is known in advance which facilitates the implementation.

For airport 2 with 1274 flights a day a conflict detection limit of 3 nm longitudinal and 3000 ft vertical led to 52 conflicts between arriving and departing flights. The minimum altitude where a conflict between arrival and departure trajectories occurred was 11500 ft, the maximum 31000 ft and the median value was 18650 ft. These values are a result of the basic route structure of the TMA which left airspace below the departure trajectory to implement a vertical conflict solution manoeuvre.

The average conflict duration between descending and climbing aircraft pairs was 15 s (airport 1) and 19 s (airport 2). These values indicate a requirement on the accuracy of the prediction and execution of arrival and departure trajectories.

In both airport scenarios a number of departure conflicts between succeeding departures arose despite the runway time separations implemented. These conflicts were caused by slow turboprop aircraft followed by faster jet aircraft on the same route on the edges of the departure funnel some 5 to 20 nm after take-off. Replacing turboprops by jet aircraft in the scenarios eliminated the conflicts. Other possible ways of solving these conflicts would be an increase of departure/departure runway separations or a departure sequence optimization. Both methods could lead to a runway capacity drop. On the arrival hand a few arrival/arrival separation conflicts were observed as overtaking cases of slow aircraft before reaching the metering fix. Possible actions to resolve these conflicts are again increasing the runway separation, sequence optimization or replacing the aircraft types.

All results were obtained using nominal BADA profiles and standard atmospheric conditions. The introduction of variations in these parameters may lead to different results.

5. Conclusions and Outlook

A basic concept for TMA operations was developed in order to enable short nearly direct routes for arrivals and departures. In the concept conflicts between trajectories are solved by sequencing runway landing and take-off times and by inserting vertical level segments into departure trajectories where necessary. Some preliminary considerations were made on costs of conflict solution manoeuvres and available controllability times for arrivals. The concept was implemented in a simulation environment for realistic one day traffic samples of two European hubs. The results are indicating that the core element of the concept seems to be feasible, i.e. the conflict resolution between climbing departures and descending arrival through insertion of a level segment in the departure trajectory. The associated requirements are precise trajectory predictions and an upper bound for the duration of the trajectory negotiation process. The concept is suboptimal for the integration of slower aircraft because of the long common flight paths especially for consecutive departures.

The approach to use realistic traffic patterns of European hub airports in combination with generic airport and TMA route structures in a simulation environment has been proven successful for the assessment of the concept. The setup will be used for the further development of this and other concepts.

Possible directions of research for further development of the concept are e.g. the introduction of more traffic from and to surrounding airports, of minimum noise routings for departures, of more realistic aircraft weights and profiles and of uncertainties in wind predictions.

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