Free Route Airspaces in Functional Air Space Blocks

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Abstract—**The implementation of time based operations, invented by the Single European Sky ATM Research program SESAR, enables airlines to fly along optimized waypoint-less trajectories, as long as certain predefined fixes are met within a time frame of five minutes, and assist air traffic control towards a precise air traffic flow management and subsequent an increased airspace and airport capacity. In preparation for a harmonization of the European airspace structure towards a Single European Sky, wherein time based operations will take place, Functional Airspace Blocks are invented, in which Free Route Airspaces are to be expand. However, temporal, spatial and operational constraints of those airspaces could limit the efficiency-increasing potential, mainly due to the implementation of directs instead of optimized waypoint-less trajectories. This case study analyzes different possible concepts of operations for an efficient utilization of todays airspace structure in Europe. On average, the operation along directs between entry and exit points has not paid of. In most cases, the operation along airways or navaids, which have been chosen with minimum distance to an optimum waypoint-less trajectory, was more efficient regarding ground distance and time of flight, than today's implementation of directs.**

Keywords*— *Free Route Airspace, Functional Air Space Blocks, Trajectory Optimization, Concepts of operations

I. INTRODUCTION

One of SESAR's inventions with prospect of a raising air traffic efficiency, an increased safety level and an acceptable environmental impact is summarized in Time Based Operations (TBO). TBO describe four-dimensional trajectories with mandatory time targets to enable airlines an individual multi-criteria optimized flight planning (with non-constant, optimized speeds). In TBO, Air Traffic Control (ATC) is expected to have the access to separation-required position data of all aircraft [1, 2]. The optimum trajectory will be obtained as compromise between all air traffic stakeholders. These considerations assume two facts: first, the optimum trajectory is known to all stakeholders before the aircraft is airborne. Second, the aircraft is allowed to operate along the desired route. The first challenge is a research question since three decades [3]. The second task, however, is not less exacting, because it requires the collaboration of several stakeholders with different intensions. With respect to a successful implementation of optimized routes in TBO, waypoint-less free routes are indispensable. The establishment of those operations is planned in Free Route Airspaces (FRA) [4], where aircraft can follow a freely planned route between defined entry and exit points (E and X wp) and intermediate points (I wp), without constraints by the air traffic services (ATS) route network, but under "control by exception" by ATC [5]. The operation of optimized free routes would be an efficient instrument to get closer to SESAR's ambitious goals and to distribute aircraft more evenly in the airspace [6–8]. This optimum is non-predictable and it's implementation hardly makes it possible for ATC to monitor the airspace [5]. As a consequence, nowadays orthodromes (known as Direct Routing (DCT)) between entry and exit points are flown in FRA [9]. The procedure of DCT follows the Route Availability Document (RAD), provided by EUROCONTROL based on COMMISSION REGULATION (EU) No 255/2010 and No 677/2011. However, weather conditions [10], the answer of the Earth-atmosphere system to emissions [11] and en-route charges require a trajectory optimum, which could be different from the orthodrome [10].

At the same time, an adaptation of the airspace structure with a view to a Single European Sky (SES) with as few handovers as possible and uniform overflight charges is in progress. As an intermediate step, the European airspace is structured into nine Functional Airspace Blocks (FAB) [12, 13], taking into account the route system and frequent traffic flows, from which the Functional Airspace Block Europe Central (FABEC) forms the center above the Low Countries, France, Switzerland and Germany. In FABEC, the Free Route Airspace program, which is a stepwise implementation approach of FRA, has been elaborated. As an example for the Maastricht Upper Area Control Center (MUAC), this results in three phases of FRA implementation [14]. After finishing the first phase in December 2017 (FRA is available within the Flight Information Region (FIR) between 23:00 - 05:00, in the upper airspace from FL 245 to FL 660), in December 2018 FRA will be additionally available on weekend between Friday 23:00 and Monday 05:00. The removal of the ATS route network and DCTs (according to RAD Appendix 4) is contemplated for Spring 2020 [14]. Table I summarizes the implementation phases of FRA in MUAC. Thereby, conventional ATS routes are still available at all times below FL 245 and ATC is accredited to switch to conventional operations along the ATS route at all times. Hence, parallel operations are expected [14]. To facilitate the transition between conventional operations, DCT and multi-criteria optimized waypoint-

TABLE I
IMPLEMENTATION PHASES OF FREE ROUTE AIRSPACES (FRA) IN MAASTRICHT UPPER AIRSPACE CENTER (MUAC) [14].

Phase	FRA operations [UTC]	time of implementation
(1)	23:00 - 05:00	December 2017
(2)	23:00 - 05:00	
	Fr. 23:00 to Mo. 05:00	December 2018
(3)	full-time	Spring 2020

less free routing (MCOFR), several intermediate ideas have been developed and tested in this case study. Furthermore, the fuel saving potential of DCTs compared to ATS routes (originally planned along the Minimum Time Track, MTT) and to MCOFR is assessed for 13 widespread city pairs above FABEC.

Several studies have been published, discussing the benefit of DCTs, compared to conventional air traffic operations along the ATS route network in Europe [4, 10, 15–19]. Following analyses by EUROCONTROL, each year approximately 7.5 million NM distance flown, 45,000 tons of fuel or EUR 37 million could be saved [16]. Some studies already focus on the benefit in small regions [4, 15, 19] and their geographical characteristics. Others predict some overall benefits, integrated over the whole European airspace [16–18]. In all studies, FRA routes are considered as DCTs, wind- or multi-criteria optimized routes have not been analyzed. However, the benefits of DCTs between E and X wp and I wp in FRA and of multi-criteria optimized routes in FRA, compared to the benefit of initially wind optimized ATS routes in FRA have not been analyzed so far. Albeit the efficiency-raising potential of both, DCTs and multi-criteria optimized trajectories, compared to the ATS route network in a well established FRA, strongly depends on the ATS route network structure, on the geographical orientation of each single trajectory, on the degree of FRA implementation (i.e. the phase of implementation), on the position of E and X wp and I wp and finally, on current weather conditions, there is interest in a decision support on how to operate in FRA most efficiently.

In this study, we identified the most important input variables and most effective traffic flows and geographical regions for FRA in FABEC. Therefore, we analyzed flight paths between 13 widespread city pairs in FABEC, at different times of the day under several boundary conditions, representing different implementation phases of FRA, i.e., different concepts of operations (ConOps). Some of those represent possible intermediate steps towards an optimum implementation of FRA free route flight planning. A conceivable disaggregation of today's ATS route structure towards a free choice of waypoints within the navigational aid (navaid) infrastructure, such as used in the Area navigation (RNAV) concept, would be conceivable as a temporary solution. Beside conventionally planned routes (ATS routes), DCTs and MCOFRs, adaptions of MCOFRs and ATS routes to the current navaid infrastructure are considered in the analysis. For the generation of the flight paths, we used different flight planning tools (compare Table III) and identified differences in the optimization strategies, even under the consideration of identical optimization goals. For comparability, we modeled the flight performance of all flight paths with our flight performance model COALA (compare subsection II-D) considering a target true air speed and a cruising altitude for a maximum specific range. The results of COALA are evaluated against ground distance, fuel flow and time of flight.

Conventional flight planning tools like Lido/Flight 4D by Lufthansa Systems [20], JetPlan.com and the Air Traffic Simulator (TAAM) by Jeppesen are often limited in the airspace structure to the ATS route network or to the navaid infrastructure. For some applications, DCTs between last waypoint of the SID and first waypoint of the STAR are also possible. However, neither could be different ConOps of the FRA implemented in FABEC, nor differences between night and day could have been extracted. Thus, those commercial products are limited to the current state of the art of flight operations. Beside classical trajectory optimization tools, such as the TOolchain for Multicriteria Aircraft Trajectory Optimization (TOMATO) [21, 22], the Air Traffic OPtimizer (AirTOp), the flight performance model, developed by [23], or the Air Traffic Simulator BlueSky [24], most approaches focus on cruise phase only [25–30] utilizing the BADA performance model [26, 27, 31]. Thereby, speed and altitude are assumed as constant and defined as state parameters. Ng et al. and Serafino [26, 27, 31] use the optimum control approach for vertical trajectory optimization and reduce the modeling of the flight performance to a manageable number of parameters [26, 27, 31], whereas Grabbe et al. and Sridhar concentrated on the lateral path optimization [25, 28–30]. These approaches are restricted in searching for optimum trajectories along the ATS route network, the navaid infrastructure, waypoint-less trajectories or DCTs. To the best of our knowledge, algorithms for implementing intermediate solutions, e.g. best combination between different ConOps have not been published yet. For this reason, we developed a method to find best solutions by adapting a multi-criteria optimized waypoint-less free routing (MCOFR) to an arbitrary waypoint structure. The MCOFR shapes up as the optimum solution assuming weather conditions are perfectly known before flight. The method is called ORANI (Optimized Route Adaption to the Navaid Infrastructure) and has already been used for the possibility to implement MCOFRs in today's air traffic operations [10].

II. DIFFERENT CONOPS IN FABEC

In this case study, 13 trajectories between widespread city pairs with great circle distances between $362\ \mathrm{m} \leq d_{\mathrm{GC}} \leq 2327\ \mathrm{km}$ are modeled in both directions (compare Table II and Figure 1). To consider flights taking place solely in FABEC, a very short distance flight (e.g. route No *4* between Leipzig and Cologne) is analyzed. Note, only the adapted trajectories are allowed to fly DCTs in FRA at night.

The trajectories are optimized according to specific target functions, derived from the ConOps (listed in Table III), and compared with each other.

TABLE II
CITY PAIRS AND GREAT CIRCLE DISTANCE d_{GC} OF THE ANALYZED TRAJECTORIES. DEPARTURE AND DESTINATION ARE DELINEATED AS ICAO AIRPORT CODES. THE LAST ROW DENOTES GREAT CIRCLE DISTANCES d_{GC} [KM].

No.	Departure	Destination	d_{GC} [km]
1	LFBO	EDDT	1328
2	EDDH	LFML	1186
3	EDDM	LFPG	684
4	EDDP	EDDK	362
5	EDDM	EHAM	665
6	EDDC	LPFR	2327
7	EIDW	LSZH	1240
8	EDDF	LIRF	958
9	EHAM	LOWW	962
10	LPPT	LSGG	1498
11	EGLL	LKPR	1047
12	EKCH	LEMD	2010
13	EGLL	LEVC	1332

TABLE III
ANALYZED CONOPS FOR THE IDENTIFICATION OF THE MOST EFFICIENT IMPLEMENTATION OF FRA IN FABEC. THE THIRD COLUMN DISTINGUISHES BETWEEN TRAJECTORY SIMULATIONS AT NIGHT (DIFFERENT WEATHER DATA, AIRSPACE CLOSURES, AIRWAY RESTRICTIONS) AND THE IMPLEMENTATION OF DCT IN FABEC FOR THE ADAPTED TRAJECTORIES. THE IMPLEMENTATION PHASES ARE SUMMARIZED IN TABLE I.

ConOps	Implementation Phase	Transition to FRA	Flight Planning Tool
1 MCOFR	(3)	Night	TOMATO
2 Navaids	(1),(2)	DCT	ORANI
3 JetPlan NAV	(1),(2)	Night	JetPlan.com
4 ORANI ATS	(1),(2)	DCT	ORANI
5 JetPlan ATS	(1),(2)	Night	JetPlan.com
6 ATS	(1),(2)	Night	TOMATO
7 DCT	(1),(2)	Night	ORANI

Figure 1. Overview of simulated city pairs in this case study in FABEC (blue polygon). Colors indicate trajectories within FABEC (green), with either departure or destination outside FABEC (red) and with both airports outside FABEC (blue).

A. Conventional Flight Planning with JetPlan.com

JetPlan.com is a flexible and modular online flight-planning tool developed by Jeppesen. The degree of optimization strongly depends on the number and type of the available input parameters. Airline specific target functions, e.g. the cost index, route modes (e.g. navaid optimized, optimized jet airways, national route programs, restrictive/non-restrictive routing) and the performance (e.g. time optimized, fuel optimized, cost optimized, several climb and descent modes) as well as regulative restrictions can be considered. JetPlan.com can either use weather forecasts or assume the International Standard Atmosphere (ISA) neglecting wind and regional effects. A constant wind component can also be considered. However, it is quite evident, that detailed weather information is not available during that early stage of flight planning (at least 24 hours in advance) for which JetPlan is used by dispatchers. In the current study, flight paths along the ATS route network (JetPlan ATS, ConOps 5 in Table III) and waypoint structure (JetPlan NAV, ConOps 3 in Table III) from 12^{th} of June, 2018 consider a possible solution for conventionally filed flights during daytime in FRA implementation phases (1) and (2). Whereas JetPlan ATS only follows the ATS route network, the JetPlan Nav mode allows for the use of navaids, in case they are closer to the orthodrome, than the closest ATS route. Due to different optimization functions between the JetPlan.com and TOMATO, differences between both ATS routes are expected. On the one hand, TOMATO additionally considers climate sensitive areas (i.e. costs due to emissions depend on longitude and latitude according to their Global Warming Potential [32]) [33], on the other hand, only an AIRAC cycle from November, 17^{th}, 2017 is available to TOMATO and ORANI, whereas JetPlan.com probably used the AIRAC valid on 12^{th} of June, 2018.

B. Toolchain for Multi-criteria Aircraft Trajectory Optimization

Multi-criteria optimized waypoint-less free routing (MCOFR, ConOps 1 in Table III)) and optimized routes along the ATS route structure (ConOps 6 in Table III)) have been modeled with the simulation environment TOMATO [11, 21], which includes an aircraft type specific performance model COALA (Compromised Aircraft performance model with Limited Accuracy). TOMATO optimizes the trajectories iteratively. The lateral path is optimized applying an A* algorithm respecting sublayers of wind direction and wind speed, ATC en-route charges, as well as prohibited or restricted areas, at an initially predefined altitude, which is iteratively adapted to the optimum one. At the bottommost layer, a geodesic grid provides the spatial structure on which the optimization algorithm operates. This can be an arbitrary grid, adapted to the city pair (to avoid effects due to meridian convergence), the Aeronautical Information Regulation And Control (AIRAC) Cycle, or the navaid infrastructure. For the purpose of optimization, the edge costs are expressed in monetary values. Those path influencing factors, that are not already available in the form of fees or costs, (e.g., the effect of winds, their accelerative or decelerative implication), are transformed into cost values [8, 21]. The initial lateral path is used by COALA for flight performance modeling (compare Paragraph II-D). The trajectory as output of both sub models is assessed regarding safety, costs and environmental impacts (please compare [8, 21] for more details). After the assessment, the determined performance and cost data are available for the next iteration step with benefits for both sub models (e.g., by using different cruising altitudes, speeds, flight path angles and lateral coordinates). TOMATO iteratively estimates the required fuel mass by taking the fuel burn of the last iteration as an input parameter for the next step.

In this case study, the MCOFR is an optimum between the last point of the Standard Instrument departure Route (SID) and the first waypoint of the Standard Terminal Arrival Route (STAR) and is supposed to be the shortest route regarding air distance, which will be reflected in minimum fuel and time. Differences to DCTs are expected in strong wind fields or along states with divergent en-route charges.

C. Optimized Route Adaption to the Navaid Infrastructure

The procedure of adapting a waypoint-less route to the navaid infrastructure (ConOps 2 in Table III, the model is called ORANI and is described in [10]). ORANI has been enhanced to the ATS route network (ConOps 4 in Table III)) with oneway conditions, altitude restrictions, time specific closures (ConOps 6 in Table III) and wind conditions. Although the MCOFR is already optimized with respect to the wind speed and direction, the selection of waypoints in the vicinity of the MCOFR does not ensure optimum wind conditions anymore. Restrictions to a grid of waypoints might cause a wind optimized route along waypoints at some distance from the MCOFR. Furthermore, SIDs and STARs are added to the waypoint database. SIDs and STARs are chosen according to optimum headwind conditions during takeoff and landing and minimum distance to the last waypoint of the SID and to the first waypoint of the STAR, respectively.

ConOps 2 in Table III constitutes an adaption of MCOFR to the navaid infrastructure which is defined in list $WP_{\text{NAV}} \ni wp_i$

$$WP_{\text{NAV}} = \begin{bmatrix} wp_1 \\ wp_2 \\ \vdots \\ wp_i \end{bmatrix}. \tag{1}$$

Therefore, the following procedure is applied (compare Fig. 2): MCOFR is discretized in list $WP_{\text{MCOFR}} \ni \hat{wp}_h$

$$WP_{\text{MCOFR}} = \begin{bmatrix} \hat{wp}_1 \\ \hat{wp}_2 \\ \vdots \\ \hat{wp}_h \end{bmatrix} \tag{2}$$

with waypoints $\hat{wp}_h$ (λ_h, φ_h) between the last waypoint of the chosen SID (λ_{dep}, φ_{dep}) and the first waypoint of the chosen STAR (λ_{dest}, φ_{dest}). All waypoints are defined by longitude λ_i [°] and latitude φ_i [°]. The discretization takes place with a step size of $\Delta\lambda = \Delta\varphi = 0.25°$. In case of adapting MCOFR to the ATS route network (ConOps 4 in Table III) a binary matrix $WP_{k,l} \in \{0,1\}$ with

$$kl = \begin{cases} 1 & \text{included in ATS Route} \\ 0 & \text{else} \end{cases} \tag{3}$$

is used to identify ATS route specific connections between wp_i. Given that matrix $D_{\text{NAV}\,o,p} \ni d_{o,p}$ contain great circle distances [NM] between all waypoints wp_i

$$D_{\text{NAV}\,o,p} = \begin{bmatrix} 0 & d_{1,2} & \cdots & d_{1,p} \\ d_{2,1} & 0 & \cdots & d_{2,p} \\ \vdots & \vdots & \ddots & \vdots \\ d_{o,1} & d_{o,2} & \cdots & 0 \end{bmatrix}, \tag{4}$$

it follows that matrix $D_{\text{AIRAC}\,q,r} \ni d_{m,n}$ is the hadamard product of $D_{\text{NAV}\,o,p}$ and $WP_{k,l} \in \{0,1\}$:

$$D_{\text{AIRAC}\,q,r} = D_{\text{NAV}\,o,p} \circ WP_{k,l} \in \{0,1\} \tag{5}$$

and contains great circle distances [NM] between all waypoints $wp_{m,n} \in WP_{\text{AIRAC, m,n}} \subset WP_{\text{NAV}}$ which are defined as ATS routes

$$WP_{\text{AIRAC, m,n}} = \begin{bmatrix} wp_{1,1} & wp_{1,2} & \cdots & wp_{1,n} \\ wp_{2,1} & 0 & \cdots & wp_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ wp_{m,1} & wp_{m,2} & \cdots & wp_{m,n} \end{bmatrix}. \tag{6}$$

Finally, $WP_{\text{NAV,x}}$ and $WP_{\text{AIRAC,x,}\,m,n}$ are subsets of WP_{NAV} and $WP_{\text{AIRAC}\,m,n}$ fulfilling

$$-x \leq |d_{h,i}| \leq x \tag{7}$$

and

$$-x \leq |d_{h,m,n}| \leq x, \tag{8}$$

respectively. In Equations 7 and 8, $d_{h,i}$ [°] and $d_{h,m,n}$ [°] are distances between wp_i and $\hat{wp}_h$ and $wp_{m,n}$ and $\hat{wp}_h$, respectively. Here, $x = 0.5°$ is a good estimate, but depends on the number of waypoints in the database.

Furthermore, waypoints $wp_{i,min} \in WP_{\text{NAV,min}} \subset WP_{\text{NAV,x}}$ are those waypoints with minimum distance between wp_i and $\hat{wp}_h$. Accordingly, $wp_{i,2min} \in WP_{\text{NAV,2min}} \subset WP_{\text{NAV,x}}$ are those waypoints with second minimum distance between wp_i and $\hat{wp}_h$. In the same way, $wp_{m,n,min} \in WP_{\text{AIRAC,min}} \subset WP_{\text{AIRAC,x,}\,m,n}$ and $wp_{m,n,2min} \in WP_{\text{AIRAC,2min}} \subset WP_{\text{AIRAC,x,}\,m,n}$ are defined as waypoints with minimum and second minimum distance between MCOFR and ATS routes, respectively. In case no waypoint can be found within WP_{AIRAC} fulfilling Equ. 3 and 8, $wp_{i,min} \in WP_{\text{NAV,x}}$ or $wp_{i,2min} \in WP_{\text{NAV,x}}$ on condition of Equ. 7 are chosen.

Let matrix W_{wind} contain wind vectors $\vec{w}_i$ [m s^{-1}], which are given by the Grib2 weather data at each waypoint wp_i by linear interpolation. W_{wind} is used to estimate those waypoints $wp_{\text{NAV,optwind},s} \in WP_{\text{NAV,optwind}} \subset WP_{\text{NAV,min}} \cup WP_{\text{NAV,2min}}$ and $wp_{\text{AIRAC,optwind},t} \in WP_{\text{AIRAC,optwind}} \subset WP_{\text{AIRAC,x, m,n}}$ with optimum wind conditions, which are selected for further investigations.

Strong heading changes are avoided by excluding waypoints with small angles between three consecutive waypoints in ConOps 2 . Therefore, matrices $M_{\beta,\mathrm{NAV}} \subset WP_{\mathrm{NAV}} \ni \beta_i$ and $M_{\tilde{\beta},\mathrm{AIRAC}} \subset WP_{\mathrm{AIRAC,\,m,n}} \ni \tilde{\beta}_i$ with angles

$$\beta_i = \angle\, wp_{i-1}\, wp_i\, wp_{i+1}$$

are used for WP_{NAV} in ConOps 2 and in some cases

$$\tilde{\beta}_i = \angle\, wp_{m-1,n-1}\, wp_{m,n}\, wp_{m+1,n+1}$$

are used for WP_{AIRAC} in ConOps 4 and the minimum heading change within three consecutive β_i and $\tilde{\beta}_i$, respectively, are chosen

Furthermore, ORANI is used to calculate ConOps 7 in Table III as DCT between those E and X wp, which are closest to $\hat{wp}_h$ along the MCOFR. For routes No 7 and 8 in Table III, a concept of transition between DCT and ATS route has been developed, considering the fly-by time of each wp. In both cases, ORANI decides on the basis of the time of flight and the location at each waypoint wp_i, whether a transition between DCT and ATS route is necessary/ possible or not. Regarding the transition between ATS route (FABEC day or outside FABEC) and DCT (FABEC, night) (No 7 in Table III), ORANI selects those E and X wp along $-x \leq |d_{q,r}| \leq x$ with minimum distance to $wp_{m,n}$ and assumes DCT between this E and X wp and (λ_{dest}, φ_{dest}) or the last possible E and X wp, in case (λ_{dest}, φ_{dest}) is not in FABEC. Short haul flights might not be able to find an appropriate E and X wp due to low cruising altitudes and due to a short time of flight during cruise. In case of a transition between DCT (FABEC at night) and ATS route (FABEC day or outside FABEC), ORANI estimates the first required E and X wp on the ATS route depending on the time of flight and/or location and assumes a DCT between (λ_{dep}, φ_{dep}) and the chosen E and X wp.

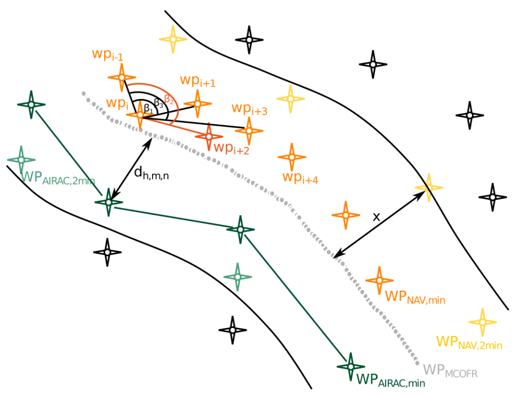

Figure 2. Procedure of ORANI's waypoint adaption of MCOFR (grey) to the navaid infrastructure (yellow) and to the ATS route structure (turquoise), after filtering the solution space (Eq. 7) and large heading changes (β).

The ATS route as an adaption to the MCOFR will be shorter and will need less fuel and time, than the ATS routes calculated by JetPlan.com and TOMATO, because it is strongly oriented along the MCOFR ($\hat{wp}_h$) and allows $wp_i \in WP_{\mathrm{NAV}}$.

D. Flight Performance Model COALA

For comparability, all trajectories are re-calculated with the flight performance model COALA to assure a level playing field for the different flight planning tools. COALA has been developed for a precise physically realistic trajectory calculation [34]. COALA needs atmospheric weather information (density ρ [kg m^{-3}] at several pressure levels p_i [Pa], relative humidity rH [a.u.], Temperature T [K], wind component in the direction of West u [m s^{-1}], wind component in the direction of North v [m s^{-1}]), which might be provided as grib2 formatted weather data modeled by GFS with a spatial resolution of 0.25 degrees. Unless provided as an input variable, COALA derives the optimum true airspeed v_{TAS} [m s^{-1}], optimum climb angle γ [°], optimum climb rate ω [m s^{-1}] and optimum cruising altitude z [m] from target functions, which are controlled by a proportional-integral-derivative (PID) controller using the lift coefficient c_L is controlled variable and achieves the 4D trajectory by the integration of the dynamic equation. Therefore, all acting forces, i.e. lift F_L [N], drag F_D [N], weight F_G [N], thrust F_T [N] and acceleration F_A [N] as net result of all forces acting on the aircraft (described by Newton's Second Law [35]), are respected, assuring only physically possible trajectories by considering unsteady flows at each time step [34, 36]. The target function focusses on a minimization of F_A. An implemented combustion chamber model allows for the calculation of significant emission quantities and precise fuel flow [11, 34].

III. Results

The results of this case study are a little bit sobering and do not allow general statements to strategically increase the efficiency of trajectories in FABEC. However, some trends conform with our expectations, from which suggestions of improvement are derived in the following. Two main statements can be concluded from our results: First, DCT between E and X wp (suggested as free routes in FABEC) are not automatically more efficient, than ATS routes, especially, when parts of the trajectory are not located inside the FRA of FABEC, as a matter of time or space. Detours via E and X wp often hamper the benefit of the DCT. For example, in FRA implementation phases (1) and (2), where aircraft follow those DCTs inside FABEC and follow ATS routes outside FRA in FABEC (ConOps 4, night), only five of 13 trajectories hold a benefit in ground distance (8 km, on average). Considering ORANI's adapted MCOFR route to the navaid infrastructure outside FABEC (or at daytime) and DCTs inside FABEC (ConOps 2, night), seven of 13 trajectories hold a mean benefit in ground distance of 24 km. Averaged over all trajectories, the night scenario (DCT implementation in FABEC) did not reduce the ground distance (compare Table IV and Figure3). However, DCT between E, X and I wp during the whole flight (ConOps 7, FRA implementation phase (3)) could reduce the detour factor by 0.08, compared to ORANI's ATS trajectories (ConOps 4).

The second finding indicates, that DCT's are not the cost minimum, which could be achieved in waypoint-less FRA,

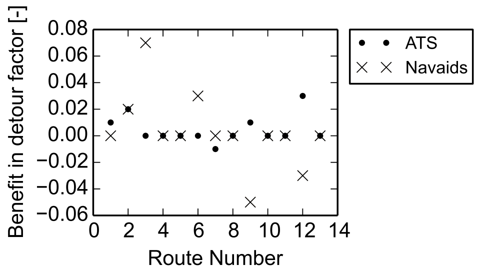

Figure 3. Benefit in detour factor due to implementation of DCTs in FABEC for flights at nights. Positive values denote shorter ground distances with FRA implementation in FABEC. Dots correspond to ConOps 4, crosses denote ConOps 2. The corresponding city pairs are listed in Table II.

TABLE IV
DETOUR FACTOR AVERAGED OVER DAY- AND NIGHT (I.E. TRANSITION TO FRA) SCENARIOS OF ALL OPTIMIZED TRAJECTORIES CONSIDERING DIFFERENT CONOPS. THE CONOPS CAN BE TAKEN FROM TABLE III.

ConOps	Day	Night
1 MCOFR	1.11	1.14
2 Navaids	1.21	1.22
3 JetPlan NAV	1.25	1.26
4 ATS ORANI	1.23	1.23
5 JetPlan ATS	1.30	1.30
6 TOMATO ATS	1.23	1.24
7 DCT	1.15	1.15

such as MCOFR in ConOps 1. Mean detour factors of MCOFR in Table IV originate from the ground distance as subject of investigation. Following Figure 4, the time of flight is shortest for MCOFR, which are optimized with respect to wind conditions, amongst others.

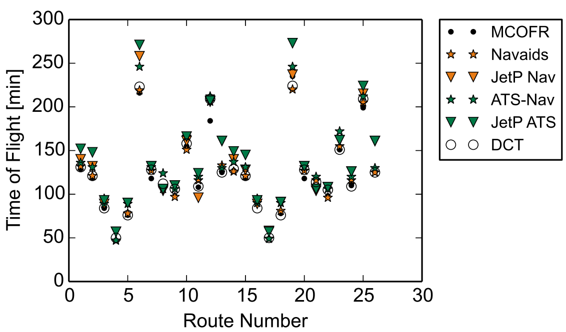

Figure 4. Time of flight of 13 simulated trajectories on daytime (Routes No 1 to 13) and night time (Routes No 14 to 26) following different target functions. In general, conventionally filed trajectories (JetPlan.com) result in long flight times, whereas multi-criteria optimized trajectories are the fastest.

Suggestions, such as an increasing detour factor with increasing share of waypoints, of which at least two consecutive ones are following an ATS route, could not be proven in this case study (Figure 5), because some city pairs (e.g. Route No *12* EKCH-LEMD) are more directly connected via ATS routes than others (e.g. Route No *5* EDDM-EHAM). Even statements on the efficiency of the ATS route structure and their connectivity to E and X waypoints in FRA according to the geographical location (North, East, West South of FABEC) or to the orientation (North-South or East-West) of the analyzed city pairs are not easily to find. Slight tendencies towards more efficient East-West orientated trajectories (advantageous ATS route structure) and trajectories either in the South of FABEC (high number of E and X waypoints) at night or with a large portion of cruise flight above Germany (dense waypoint structure) at daytime could have been extracted.

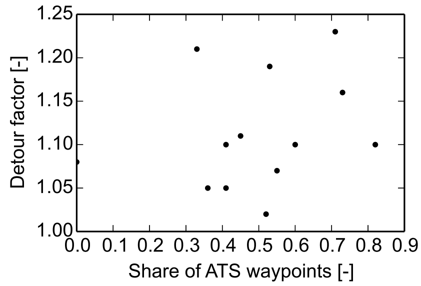

Figure 5. Detour factor compared to the great circle distance of 13 trajectories on daytime as function of the share of waypoints, of which at least two consecutive ones are on an ATS route. Due to a heterogenous ATS route network, no significant trend can be detected, which would indicate, that ATS routes are generally inefficient.

In the following, the ground distances between EHAM and LOWW Route No 9 (great circle distance in Table II) following different ConOps are analyzed in Table V and illustrated in Figures 6 and 7). The example shows a typical solution for the implementation of DCTs in FABEC, amongst the analyzed city pairs. The flights between EHAM-LOWW started 11.30 UTC (Figure 7) and 22.40 UTC (Figure 6). A comparison of trajectories at nighttime along the ATS route network (ConOps 3 to 6) show significant differences in both flight time and ground distance (Table V). While JetPlan.com (green) chooses night and day the SID, STAR and route in the North of MCOFR, TOMATO (blue) decides for ATS routes, which are South and closer to the MCOFR outside FABEC and DCTs inside FABEC (Figure 6). Anyhow, the TOMATO route is shorter than the JetPlan solution (Table V). However, JetPlan.com considers the common ATC rule, guiding eastward flights in the North and westward flights in the South. Furthermore, JetPlan may be aware of airport-specific runway allocations, whereas TOMATO only searches for the cost minimum. The navaid optimized trajectory by JetPlan.com is very similar to the airways optimized trajectory, which is why it is not shown in Figure 6. The ATS route, combined with Navaids by ORANI (ConOps 4, red) is closest to the MCOFR (black) at night and daytime. The red line indicates the FABEC boundary, within which ORANI chooses entry and exit points for the FRA implementation at night. Due to an already very small detour factor of 1.14 at daytime in ConOps 4 and a relatively large number of entry and exit points along the flight over Germany, the detour slightly increases in FRA implementation, measured by a detour factor of 1.19.

In general, it can be stated, that those trajectories, generated

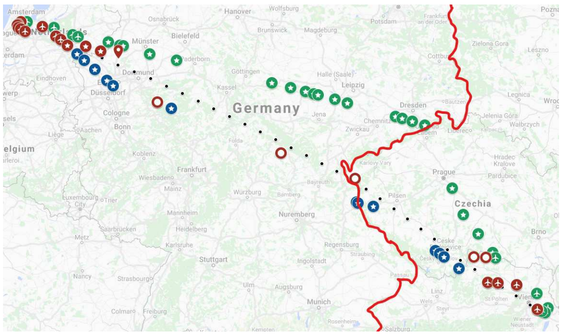

Figure 6. Different ConOps simulated for the city pair Amsterdam (EHAM) to Vienna (LOWW), route No *9* at night with FRA implementation (DCT in FABEC) in ConOps 4 (ATS ORANI, red) and ConOps 6 (TOMATO ATS route, blue). Black dots: MCOFR (ConOps 1), green stars: Airways optimized route from JetPlan.com (ConOps 5) red circles denote E and EXI wp. The red line indicates the FABEC boundary.

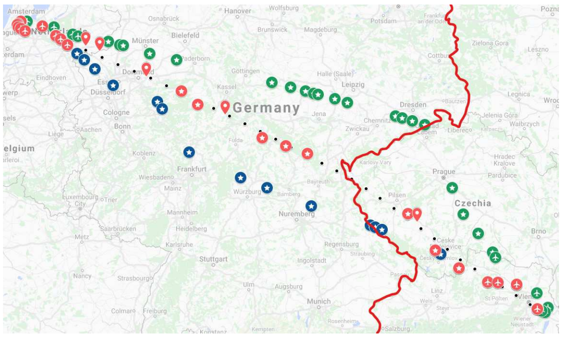

Figure 7. Trajectory optimization between Amsterdam (EHAM) and Vienna (LOWW), route No *9* at daytime without DCTs in FABEC. Green: JetPlan.com, airways optimized. Blue: TOMATO ATS-Route. Red: ORANI ATS with Navaids, from which red stars are waypoints along an ATS route, red markers indicate waypoints of the navaid infrastructure and red circles denotes E and EXI wp. The red line indicates the FABEC boundary.

TABLE V
GROUND DISTANCES GD [KM] AND TIME OF FLIGHT [MIN] OF TRAJECTORIES BETWEEN EHAM AND LOWW (ROUTE NO 9 IN TABLE II) OPTIMIZED WITH DIFFERENT CONOPS AT NIGHT AND DAYTIME. THE IMPLEMENTATION OF DCTS IN FABEC DID NOT HOLD SHORTER DISTANCES ALONG THE NAVAID ROUTE AND THE ATS ORANI ROUTE.

ConOps	GD Day	GD Night	Time of flight Day	Time of flight Night
1 MCOFR	976	975	87	87
2 Navaids	1109	1143	98	105
3 JetPlan NAV	1195	1172	110	108
4 ATS ORANI	1152	1147	106	105
5 JetPlan ATS	1195	1172	110	108
6 TOMATO ATS	1066	1065	92	92
7 DCT	1149	1148	106	105

by JetPlan.com are the longest. Even the option JetPlan NAV (ConOps 3) mostly uses the conventional ATS route structure (compare Table IV for averaged values and Table V for two single trajectories). Detour factors of 1.31 and 1.26 averaged over all airways optimized (ConOps 5) and navaid optimized (ConOps 3) trajectories, respectively, compared to the great circle distance (compare Table III) have been estimated (compare Table IV). The detour factors vary between 1.19 and 1.39 in the airways optimized scenario and 1.18 and 1.43 in the navaid optimized scenario. ATS routes generated by TOMATO (ConOps 6) and by ORANI (ConOps 2) are shorter, but still have a detour factor of 1.06 and 1.23, respectively (compare Table IV). Beside the MCOFR with the shortest flight time and the shortest air distance, DCT between SID and STAR (ConOps 7) are most efficient, followed by the "Navaids" scenario (ConOps 2). As elaborated, DCTs between FABEC specific E wp and EXI waypoints (FRA implementation phase (1) and (2) night) should be considered carefully (Figure 3). Assuming a good weather prediction, often even ATS routes are closer to wind optimum minimum time tracks than those DCTs.

IV. CONCLUSION

In this study, the implementation of DCTs in FABEC, when FRA is allowed, has been exemplified and compared with multi-criteria optimized waypoint-less free routing (MCOFR), conventional ATS routes, and possible intermediate steps between ATS routes and waypoint-less routes. These intermediate steps are a combination of convenient ATS routes and waypoints of the navaid infrastructure (ConOps 4) and a selection of navaids without constraints in terms of airways (ConOps 2). The identification of those waypoints had been achieved by an adaption of the MCOFR to the respective set of available waypoints. The analysis of 13 city pairs and 7 ConOps yielded in the suggestion, that DCTs in FRA are not always the most efficient solution, due to missing E and EXI wp along the MCOFR or the corresponding adapted trajectory. A benefit in distance could have been identified in the South of FABEC and over Germany. Especially for short distances, adverse SIDs and STARs already cause a significant detour, compared to DCT between departure and destination. The potential in route reduction due to adapted departure and arrival routes should be taken into account. From this follows, that timely restricted opening times of FRA are not as efficient as possible. A fact, which is supported by an increased controller's workload mainly due to parallel operations of FRA and conventionally filed flights. The implementation of waypoint-less free routes could increase the airspace capacity by far and meanwhile reduce fuel burn and time of flight. The identification of the MCOFR may seem as one of the great challenges in Air Traffic operations, due to external and internal interferences as cause of uncertainties in input variables (weather data, aircraft mass) and state parameter (aircraft behavior). However, the process is subject to constant improvement. Recent investigations in using aircraft surveillance data as flying weather stations [37] could improve the availability of accurate and actual weather data for in-flight trajectory optimization by far. Anyhow, waypoint-less free routes, as already operated in Northern Europe, and parts of Eastern Europe (Ukraine, Croatia) induce a significantly increased controller's workload, that needs to be compensated first by implementing intelligent decision support tools [38]. This study is only a case study analyzing 13 city pairs in Europe at two different daytimes. Since the results are not to generalized, further research will be done by applying a large number of flights to the developed algorithm. Before, some minor issues will be corrected: For example, time dependent airways closures and altitude restrictions in the ATS route structure will be implemented in TOMATO and ORANI. Furthermore, the distance between wp in the Navaid ConOps will be oriented on 60 NM, which is a common maximum between wp in today's operations. Therewith, detours due to frequent heading changes will be avoided. No night flight bans are considered in the analysis. Furthermore, investigations will be advanced in the adaption of departure and arrival routes regarding safe operations with minimum detours. Furthermore, an adaption of E, X and I waypoint to the expect multi-criteria optimized traffic flow would increase the efficiency of DCTs in FRA by far.

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