Multicriteria-Optimized Trajectories Impacting Today's Air Traffic Density, Efficiency, and Environmental Compatibility

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Abstract

Todays air traffic system is faced with airspace capacity constraints that can cause inefficiencies in flight and in airport ground handling. Free routing performance based navigation and harmonized airspace structures are seen as efficient mitigation measures to save distance and fuel, as far as free routes are implemented as optimized and predictable trajectories. In this case, an monitoring of the air traffic system is expected due to an improved predictability of those trajectories. In this paper we present a trajectory optimization model for 3D free routes considering multiple targets, including operational costs, time costs, environmental costs and expected external costs of condensation trails. The model is applied for a case study which looks at optimization of trajectories for an entire day based on departure airport, arrival airport and departure time in July 2016. The resulting trajectories are evaluated against the number of conflicts. The case study shows that today's air traffic demand already stresses the free route capacity when considering efficiency, ecological compatibility and safety standards.

I. Introduction

Three performance goals, as set out by the NextGen [1] and SESAR [2], must be considered in studies of the air traffic system. These are safety, efficiency and environmental compatibility. For the en-route phase safety is mainly set by separation requirements. Efficiency is measured by a variety of metrics such as airport capacity utilization and great circle deviation. From the economic side, air navigation costs, flight time, fuel burn [2] and depreciation charges push airlines to achieve high efficiency levels. The aviation environmental impact can in part be assessed by the amount of the aircraft engine emissions and their impact on global warming and human health. Additionally, condensation trails (contrails) with a significant influence on global warming (i.e. radiative forcing, RF) need to be considered [3]. Contrails form in the presence of ice-supersaturated regions [4], which are dynamic layers in the upper troposphere and lower stratosphere, as shown in Figure 4. To avoid contrail formation, aircraft would need to bypass these ice-supersaturated regions either laterally or vertically [4], hampering flight efficiency as detours and non optimum flight profiles cause extra flight time and fuel burn [5]. Differences in overfly charges and air navigation charges

*A thank you or further information

similarly encourage detours relative to lateral trajectory optimization. In short, competing objectives must be considered in evaluating trajectories [5]. This leads to an important question: Will trajectory optimization lead to an increased pressure on airspace capacity because similar optimum vertical and lateral trajectories might be expected, or will highly aircraft specific flight performance characteristics lead to well distinguishable trajectories with a resultant positive impact on air space capacity?

i. Simulation Environments

To find such multi-criteria optimum flight paths, which satisfy airlines and Air Traffic Flow Management (ATFM) constraints, a highly accurate single aircraft trajectory and air traffic flow prediction is required. Until now, these aspects have been treated separately from Air Traffic Control (ATC), ATFM or network optimization perspectives due to the complexity and the high computational effort. The TOolchain for Multicriteria Aircraft Trajectory Optimization software (TOMATO) has been developed to deal with this challenge without coarse approximations in trajectory calculation. TOMATO uses a flight performance model [6, 5] independent of 2.5D BADA performance tables.

Several air traffic flow simulation environments have been developed before TOMATO all limited to the present research question. On the one hand the fast time air traffic simulator AirTOp generates trajectories in a dynamic airspace structure and iteratively considers conflict detection and conflict resolution [7]. AirTOp had been already applied to rerouting around volcanic ash clouds [8] and to estimate the influence of restricted airspaces on the air traffic system [9]. However, due to approximations in the aircraft performance modelling (which is limited to BADA performance tables) and restrictions regarding the quantification of the emissions (due to missing information of the conditions within the engine combustion chamber), AirTOp does not consider precise trajectory optimization.

The Test bench for Agent-based Air Traffic Simulation (TABATS) has been developed for the trajectory synchronization for highly predictable arrivals enabled by full automation and focuses on the simulation of trajectory scenarios under realistic weather conditions (i.e. lateral rerouting around thunder cells and speed adjustments) with a specialized airport slot allocation routine [10, 11, 12, 13]. However, TABATS also concentrates on BADA performance tables and is limited in the quantification of the emissions.

By using the BADA performance tables, an analytical solution specifying aircraft performance is impossible, mainly because of the following assumptions and approximations: First, these tables are only available for three different aircraft reference weights. Thus, actual aircraft weight cannot be considered. Second, the significant influence of the atmospheric conditions on the aircraft performance is not implemented. Here, only the International Standard Atmosphere (ISA) with a course correction depending on a temperature deviation at sea level is used. Third, the aircraft true air speed cannot be influenced. A constant reference speed has to be assumed. Furthermore, vertical movements are restricted between common flight levels. As a result, trajectory optimization is significantly limited. Furthermore, only rough estimates of the required flight performance for a dedicated flight manoeuvre are possible with those tables. One of the reasons for these approximations might be the complexity of the aircraft drag polar, mainly depending on Mach number, air density and angle of attack.

At the other end of the spectrum, the Airspace Simulator TAAM, developed by Preston Aviation Solutions (a Boeing subsidiary) [14] is able to simulate air traffic flows in ISA. TAAM is a large scale and fast time simulation model and designed to simulate all possible aspects of the ATC, (ground and enroute) during all phases of flight. However, TAAM is restricted to the ATC routing structure and does neither cover individual flight profiles nor lateral free routes [15]. Finally, a more precise consideration of the flight performance modelling and optimization is realized in the commercial flight-planning tool Lido/Flight 4D, developed by Lufthansa Systems, with unknown details and precision.

Thus, in contrast with the above described simulation systems, TOMATO is the first air traffic simulation environment respecting the impact of individually and accurately free route multi-criteria optimized trajectories on the ATFM. This paper takes advantage of this capability using TOMATO to calculate and compare three air traffic scenarios. First, the reference scenario consists of recalculated radar tracked 4D trajectories, specifying the tracked waypoints and altitudes of each aircraft. Second, a cost minimized scenario is simulated, considering minimum Cost Performance Indicators (CPIs) and minimum Ecological Performance Indicators (EPIs), with the exception of contrails. In recognition that emission induced EPIs are sensitive to long detours which are often necessary for contrail avoidance [19] the impact of contrails are considered in the multi-criteria trajectory optimization.

II. Properties and workflow of TOMATO

The architecture of the TOMATO simulation environment is very modular and described in Förster et al. [6]. The core is composed of three sub modules that are interconnected in an iterative process (Figure 1). For complexity reasons, the overall optimization has been split into two parts. The first step is lateral path optimization completed by employing the A* algorithm in the presence of winds and ice-supersaturated regions. Furthermore ATC en-route charges, as well as prohibited or restricted areas, are considered in the lateral trajectory optimization. Each of those factors resides on its individual layer that spans the whole Earth and can be enabled and disabled if necessary. At the bottommost layer, a geodesic grid provides the spatial structure on which the optimization algorithm operates. Edge costs are expressed in monetary values. Some of the factors influencing the lateral path are already available in the form of a fee or cost. To express the effect of winds, their accelerative or decelerative implication is transformed into a cost value by applying a factor that expresses the estimated costs per time unit.

As a second step, a vertical flight profile is calculated along that path, using the aircraft performance model COALA (COmpromised Aircraft performance model with Limited Accuracy), which is described in more detail by Rosenow et al. [20, 19]. COALA numerically solves the dynamic equations and uses target functions to calculate optimized flight path angles γ, speeds v_{TAS} and altitudes p at each time step. A proportional plus integral plus differential controller is used to gain those values, mainly by controlling the lift coefficient c_A, because it influences all accelerating forces. Several boundary conditions are implemented to respect flight envelopes. The state variables speed, flight path angle, altitude and thrust are restricted to aircraft type specific co-domain. The following input variables are tested for validity: the aircraft mass, (payload, and fuel load cannot exceed aircraft type specific maxima), distance between departure and destination and altitude (if predefined). Validity tests are included in the assessment: The trajectory will only be accepted if the aircraft reaches the destination airport, the cruising altitude is reached and the top of climb is before the top of descent. The flight performance model comes together with an engine model to determine detailed performance (e.g. fuel flow) and emission data for each time-step during the flight.

This optimization is done in a real 3D workspace. This distinguishes TOMATO from 2.5D simulations, which are used by airlines today, where fixed steps for altitude changes and level flights are often restricting the solution space. The assumption of a free route airspace allows the employment of unconstrained, continuous cruise climb operations

[19].

After both optimization steps the trajectory is assessed in terms of many different Key Performance Indicators (KPIs), composed of Cost Performance Indicators (CPIs) and Ecological Performance Indicators (EPIs) which are in detail described by Förster et al. [6] (compare Section i and Figure 1). After the assessment, the determined performance and cost data are available for the next iteration step with benefits especially for the lateral path calculation. TOMATO iteratively considers target functions and cost functions, derived from the input parameters and estimates the required fuel mass by varying the input parameters after each assessment step at the end of each iteration step (compare Figure 1). With the KPI assessment, a multi-criteria optimization is possible due to the use of cost functions, whose results are assessed after each iteration step (Figure 1). That iterative optimization process is running until a certain cancellation criteria (i.e., minimum delta that a solution has to improve or a maximum number of iterations) is met. The output makes it possible to further process the calculated trajectories (compare Figure 1 and [6] for more details). The identification of conflicts per time step is done in a post-analysis of the trajectories. The criterion validity of TOMATO has been shown in various applications [5, 20, 19, 6, 43].

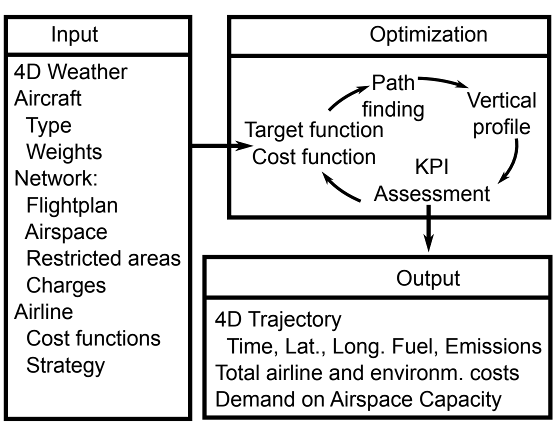

Figure 1: *Iterative workflow in TOMATO.*

i. Trajectory Assessment

In the following, the main trajectory assessment parameters are introduced to illustrate the multi-variability of TOMATO.

i.1 Trajectory assessment regarding airline costs

Airline Direct Operating Costs (DOC) are mainly driven by fuel costs and time costs. For this study, the fuel price is taken from the IATA fuel price monitor in December 2016 for Europe and is set to 0.502 € per kilogram Jet A1 plus 20 % handling costs. Flight time dependent costs are extracted from analyses of different airline cost studies including cost factors and linear relationships describing crew salaries, maintenance costs, deprecation rates, and direct or indirect compensations for delays, if necessary [6]. Crew salaries depend on flight time [6].

Airport and en-route charges for using the air navigation services by EUROCONTROL depend on the distance flown over each Flight Information Region (FIR), depending on a specific unit rate and the maximum take off mass (MTOM) of the aircraft. The departure and en-route charges depend on the standardized unit rates [22], which are monthly published by EUROCONTROL [23]. Regions outside the EUROCONTROL area are assigned the mean value of all unit rates. Therewith, detours outside the European observation area (as a possible result of a cost minimizing lateral path) are avoided. In TOMATO, any kind of airspace restriction can be formulated and activated as a polygon. For example, common en-route charging regimes with uniform unit rates, e.g. FAB-EC (Functional Airspace Block Europe Central) can be considered.

In this case study, delay costs are not considered. The comparison of the scenarios is mainly driven by costs, depending on flight time or flown distance, whereas costs for maintenance and depreciation (depending on aircraft type and number of passengers) as well as ATC airport charges (as function of MTOM and airport specific charges) are equal for a single trajectory in each scenario (compare Table 1 for a summary). Here, n_{PAX} refers to the number of passengers in arbitrary units. The trajectories are assessed one by one. In general, the CPIs are twice the EPIs.

Table 1: *Cost performance parameters (CPI) for the trajectory assessment, differentiated according to their dependency on flight time t and flown distance d with impact on the optimization.*

CPI	Rate	depending on	Impact on optimization
Fuel costs	$R = 0.502$ €/kg	$\dot{m}_f$ [kg/s]	yes
Pilot's salary	$R = 96$ €/min	t [min]	yes
Steward's salary	$R = 42$ €/min	t [min]	yes
Insurance	$R = 0.03$ €/m	d [m], n_{PAX}	yes
En-route charge		MTOM [kg] d [m]	yes
Airport charge		MTOM [kg]	no
Depre-cation	$R = 8.1 \cdot n_{\mathrm{PAX}} - 96$	n_{PAX}	no
Mainte-nance	$R = 2.3 \cdot n_{\mathrm{PAX}} + 309$	n_{PAX}	no

i.2 Trajectory assessment considering the environmental impact of jet engine emissions

For the evaluation of the environmental impacts, the main emissions are quantified according to current state of the art. Products of complete combustion such as carbon dioxide CO_2, water vapour H_2O, sulphate SO_4 and sulphuric acid H_2SO_4 are quantified as a linear function of fuel flow [24]. Emissions of nitrogen oxides NO_x, hydrocarbons HC and carbon monoxide CO are estimated following the Boeing-2 fuel flow method [31] depending on fuel flow, thrust setting and measured reference values, estimated by the International Civil Aviation Organization (ICAO) [32]. For soot emissions BC, the Boeing-2 fuel flow method needs further information about the combustion, which is estimated by a combustion chamber model providing the required combustion chamber inlet pressure p_3 and temperature T_3 according to [33].

The cost based assessment of the emissions according to their impact on global warming is quantified by the Global Warming Potential (GWP) [24], a measure of the relative effect of the greenhouse gas impact compared to the impact of CO_2. The GWP of the emissions depends on latitude and altitude [25, 26, 27], which again influences the lateral and vertical trajectory optimization. Thus, converted emissions can be expressed as CO_2 equivalent emissions. The CO_2 equivalent emissions are converted into monetary values by using the European Emission Trading System (ETS) and assuming a price of 65 € per ton CO_2 equivalent emission.

i.3 Trajectory assessment regarding contrail costs depending on daytime and flight-path

In 2005, aviation induced contrails contributed to global warming as much as 21 % of the total aviation CO_2 emissions [24]. Assuming that approximately 10 % of the total number of flights are inducing contrails [34], a rough estimation of contrail's contribution to global warming can be made.

In this study, aircraft flying in ice-supersaturated regions are additionally burdened with a reference value of 32 tons of CO_2 equivalent emissions per flight hour in the ice-supersaturated region [5]. This reference value is adapted depending on the time of the day.

Contrail radiative forcing as an induced imbalance of the Earth- atmosphere energy budget depends on the position of the sun relative to the spatial orientation of the contrail [3]. This relationship can be described by the time of the day and by the aircraft heading (i.e. the flight path).

The imbalance of the energy budget mainly originates from two processes: First the scattering of the solar radiation with a cooling effect and second the absorption of terrestrial radiation with a warming effect. During night, the contrail will always heat the atmosphere and flights with induced contrails are weighted with the reference value of 32 tons of CO_2 equivalent emissions. During sunrise (5 a.m. to 7 a.m.) and sunset (5 p.m. to 7 p.m.) contrails, which are orientated between East and West have the largest heating impact on global warming, because solar radiation will radiate through the longitudinal axis of the contrail [3]. Hence, those contrails are assessed 110 % of the reference value. During day (7 a.m. to 5 p.m.) the cooling effect will be maximum and contrails are assigned 90 % of the reference value. (Although some research studies estimated an average cooling effect of contrails during the daytime [35], the net effect of individual contrails strongly depends on contrail life time and contrail microphysical properties, such as particle size and shape [3].)

i.4 Assessment of Safety Relevant Air Traffic Flow Concerns

Considering safety, the impact of a large number of laterally and vertically optimized trajectories on air traffic density was investigated. Therefore, the lateral distribution of the number of conflicts with a spatial lateral resolution of 0.1 degree (resulting in three to five nautical miles, depending on latitude), a vertical separation of thousand feet and a time-resolution of ten seconds have been analyzed (compare Figures 8 to 10, where the location of conflicts per scenario are highlighted in red). By simply counting the number of conflicts, the conflict involved aircraft cannot be backtracked, but the estimation of the spatial behavior of crowded air spaces allows statements regarding the air traffic density and on the spatial distribution of aircraft. The number of conflicts is increased (compared to real air traffic operations) due to non-constant speeds in all three scenarios. This effect is amplified due to non-constant cruising altitudes during continuous cruise climb operations in the optimized scenarios. Note, that no conflict resolution method is applied to the simulation, not even in the reference scenario. Hence, tactical conflict resolution, as the main task of ATC, is not considered. Therewith, the number of imminent conflicts should not be confused with serious separation infringements. Although short term conflict resolution does not seem to be the main problem in todays ATFM, the air traffic density mainly influences the airspace complexity and thereby the controller's taskload and ATC efficiency. For that reason, the number of conflicts should be minimized in an efficient airspace structure.

III. Scenario Definition and Input Data

Besides precise weather information, one of the most significant variables in each aircraft trajectory simulation is the aircraft mass. Differences up to 7 % in fuel burn are identified in aircraft trajectory simulations, where the Actual Take-Off Mass (ATOM) is varied [28, 29]. In this case study, individual values of ATOM are composed of the seat load factor, the initial fuel mass and the operating empty weight. The seat load factor is normally distributed around a typical aircraft specific seat configuration, taken from airplane manuals. A weight of 100 kg per passenger including baggage is assumed for the final aircraft payload. The initial fuel mass is calculated iteratively (within five iteration steps) considering fuel burn and contingency fuel of approximatively 10 %. The operating empty weight is taken from airplane characteristics, e.g. [42]. With this optimistic assumption aircraft might be lighter than in reality.

The Cost Index (CI) is considered in the target function for aircraft speed and flight path angle. Here, a maximum specific range R_{spec} is desired

$$R_{\text{spec}} = \frac{TAS}{m_f} \tag{1}$$

where TAS denotes true air speed [$\mathrm{m\,s^{-1}}$] and m_f specifies the fuel flow [$\mathrm{kg\,s^{-1}}$] (compare [30]). The resulting speeds are comparatively low and similar to those for minimum fuel burn, i.e. a very low cost index. The flight path angle during climb is non constant and follows a maximum climb rate w [m s^{-1}].

$$w = \sin\gamma \cdot TAS \tag{2}$$

where γ denotes the climb angle. During cruise, continuous cruise climb is implemented, following the optimum speed and altitude for maximum R_{spec} [30].

i. Flight plan

In order to simulate twenty-four hours of Europe's air traffic, a flight plan from EUROCONTROL Demand Data Repository (DDR2) is used. The data contains 33816 flights, coordinated by the Network Manager Operations Centre (NMOC, previously called CFMU). Beside flights to and from European airports, over flights above the European airspace are also included. Since this study focuses on the upper airspace capacity, flights with a maximum intended cruising pressure altitude beneath $p_{\text{cruise}} = 376$ hPa (FL 250) are removed from the data set. This procedure reduces the data set to a total number of 13584 flights, distinguishable by the flight ID, which has been successfully calculated and assessed in all three scenarios. The data is given as a So6 m3 file containing departure and destination airports and an aircraft 4D segmented trajectory (position, altitude, time stamps), synchronized by radar. The vertical discretization of the data set is restricted to 100 ft (i.e. one flight level), whereas the lateral resolution depends on waypoints and flight phase. The en-route phase resolution can be more than 100 NM, with 40 NM on average. The lateral resolution is less than 3 NM during climb and less than 10 NM during descent.

The reference scenario in Figure 8 gives an impression of the traffic flow, simulated along the waypoints and altitudes given in the So6 m3 flight plan. This Figure indicates that regions with high potential of conflicts (each indicated by a red dot) are often localized above Central Europe.

A further analysis of the flight plan yields no significant diurnal variation (Figure 2), besides day and night traffic, because of a large number of time zones in Europe between Russia (GMT+5) and Portugal (GMT-1). From this insight, it is concluded that Europe's air traffic is evenly distributed throughout the day.

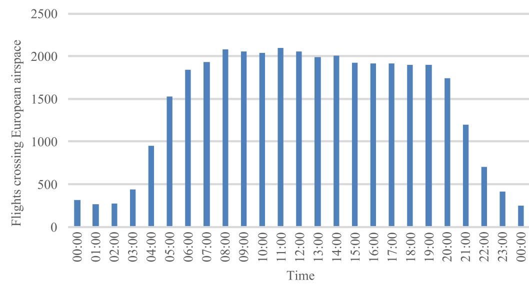

Figure 2: *Number of simulated flights per hour.*

ii. Airspace structure

ATC en-route charges in the European air space depend on the distance d flown above each EUROCONTROL member state (see Table 1). For the current case study, today's EUROCONTROL unit rate charging regime $R_{\text{En-route}}$ is implemented. Figure 3 indicates differences in assigned unique en-route charging unit rates between 10.06 € per meter above South-East Europe and 106.05 € per meter above Switzerland in January 2017. Further airspace structure specific parameters, such as airspace restrictions and today's route and waypoint structure are not implemented in the current study in favour of a multi-criteria free route trajectory optimization.

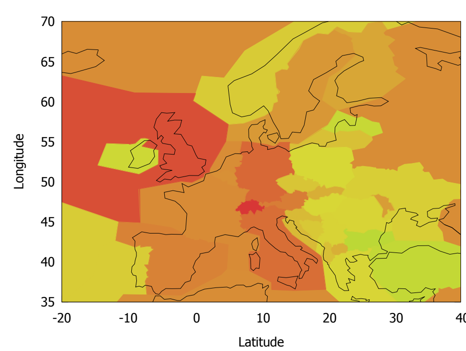

Figure 3: *Heat map of implemented en-route charges between 10.06 € (yellow) and 106.05 € (red).*

iii. Fleet

The aircraft requireing flight assignment is obtained from the given flight plan. The set of flights contains 9673 short haul flights with distances below 500 kilometres, which corresponds to 26 % of all flights. Sixteen common aircraft types are implemented in COALA. Aircraft subtypes are matched to those aircraft types, implemented in COALA. Aircraft with turboprop engines (inducing differences in the combustion chamber) are not yet considered in TOMATO. Those aircraft types are represented by the best matching turbofan aircraft, which is implemented in COALA (in most cases E170, E190 and CRJ9). In total, 70 % of the original aircraft assignments are maintained.

iv. Atmospheric Data

Corresponding to the flight plan, weather data from the 25th of July, 2016 is extracted form Grib2 data, provided by the National Oceanic and Administration NOAA. On that day a typical situation in summer in the Northern hemisphere [37] with relatively small and fast moving ice supersaturated regions offering possibilities of reroutings to avoid contrail formation. Furthermore, a realistic drift of the ice-supersaturated regions from North to South East due to the global circulation affected by the Coriolis force is assured [38]. Weather data is only provided with a temporal resolution of six hours. The weather data set closest to the departure time of the flight is chosen and set constant over the whole flight. Figure 4 gives an impression of size and location of the ice-supersaturated regions above Europe at FL 360 on 25th of July, 2016, 12. a.m. which should not be entered by aircraft in order to avoid contrail formation.

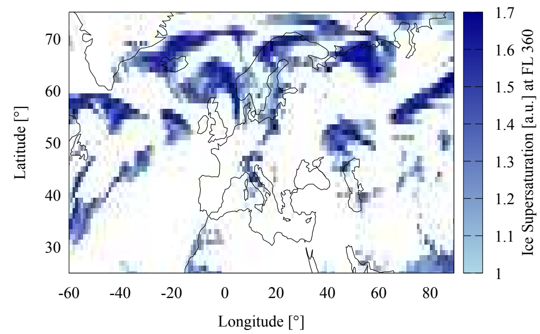

Figure 4: *Ice-supersaturated regions (blue) above Europe at FL 360 on 25th of July, 2016, 12. a.m..*

IV. Impact of multi-criteria optimized trajectories on efficiency, environmental compatibility and safety

i. Optimization potential of a single trajectory

In each scenario, the trajectories have been calculated and optimized one by one. A comparison of the simulated scenarios can be done based on individual trajectories (i.e. a single trajectory of each scenario) or based on the whole air traffic scenario (i.e. the sum of all trajectories of each scenario while considering additionally ATFM concerns as conflicts). The comparison of individual trajectories with identical departure, destination and departure time but different optimization targets (airline cost minimized or multi-criteria optimized considering contrail formation) with the reference scenario demonstrates the optimization potential of TOMATO (compare Figure 5). Following an example of each scenario, lateral paths of trajectories from Gatwick, United Kingdom to Corfu, Greece, with different target functions, indicate cost benefits in the airline CPI cost minimized trajectory (green).

Beside the minimization of ATC en-route charges, the optimum utilization of wind direction and wind speed is used in this free route concept. A benefit of 3115 € (15 %, compared to the reference scenario) in CPI costs and 421 € (14 %) in fuel costs could be achieved. Although the CPI are minimized, 190 € (10 %) higher EPI costs are calculated for the CPI cost minimized trajectories.

This is mainly driven by 392 € higher contrail costs. Differences in the lateral path are probably caused by high ATC en-route charges above Switzerland (compare Figure 3), which are avoided in the CPI cost minimized trajectory. This detour induces contrails (which costs are not considered in this cost-minimizing optimization) and therewith higher EPI costs (compare Table 2 and Figure 5). Note, the reference scenario has been assessed according to the radar tracked flight path. It can be assumed that the flight was planned around Switzerland and accordingly lower ATC en-route charges were paid.

As evolved from Table 1, CPI costs are mainly driven by DOC, depending on time of flight, distance flown and fuel costs. Those cost components could be significantly reduced in the CPI cost minimized scenario, by optimizing the lateral and vertical trajectory (Table 2). A continuous climb cruise operation with optimized speeds at higher cruising altitude results in significantly lower fuel costs (Figure 6).

The multi-criteria optimized trajectory (blue) further considers high contrail costs in the EPI assessment, which is why the path finding algorithm avoids flight time in ice-supersaturated regions (blue grid) and finds a total cost minimum solution by completely avoiding contrail costs (Table 2 and Figure 5). Note, contrails are not always completely avoided in the multi-criteria trajectory optimization (see Table 3). This optimization step results in reduced EPI costs of 498 € (28 %, compared to the cost minimized scenario) but in increased CPI costs by 22 € (0.11 %, compared to the cost minimized scenario) (compare Table 2). By considering contrail costs in the optimization, ATC en-route charges become less important (they increased by 66 €, compared to the CPI minimized scenario) and the algorithm finds a total cost minimized solution by crossing Switzerland. Interestingly, on the first half of the route, the lateral multi-criteria optimized trajectory is very similar to the radar tracked reference flight path. Differences in the vertical profile are still significant. By avoiding a detour around Switzerland, time of flight and distance flown could be further reduced by 30 seconds and 5 kilometres, respectively, inducing lower costs for crew and insurance (see Table 2).

The optimization potential in the vertical profile is influenced by the flight performance optimization with the target function of a maximum specific range for the cruising altitude and true air speed results in significantly higher cruising altitudes near the aircraft's service ceiling (see Figure 6). Inefficient step climbs in the en-route phase and altitude corrections before the TOD (which might by the result of conflict resolution) are avoided in both TOMATO optimizations with positive impact on fuel costs. Differences in distance are the result of different lateral flight paths.

Table 2: *Assessment of A320 trajectories from Gatwick, UK to Corfu, Greece, using different target functions. Total costs include EPI and CPI. Contrail costs are listed for comparison.*

Scenario	Reference	Cost min.	multi-crit. opt.
Total costs [€]	23570	20464	20178
EPI [€]	1554	1744	1255
from which			
Contrail costs [€]	93	485	0
CPI [€]	22016	18901	18923
from which			
Fuel costs [€]	2976	2555	2548
Crew salaries [€]	974	850	848
Insurance costs [€]	10301	9048	9026
ATC costs [€]	2330	1703	1769
Time of flight [hh:mm]	03:03	02:40	02:39
Ground distance [km]	2289	2010	2005

ii. Impact of multi-criteria optimized trajectories on ATFM

In the following, the total effect of the sum of all trajectories of each scenario is discussed (see Table 3). Therewith, the scenario's im-

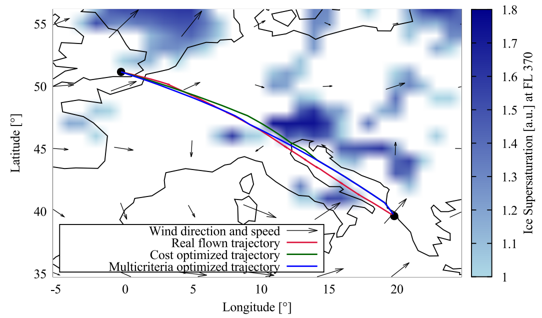

Figure 5: *Lateral paths of A320 trajectories from Gatwick, United Kingdom to Corfu, Greece, optimized with different scenario-specific target functions each representing one of three scenarios.*

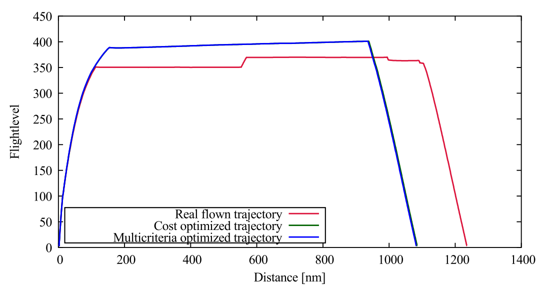

Figure 6: *Vertical profiles of three trajectories from Gatwick, United Kingdom to Corfu, Greece with different optimization target functions in an ice-supersaturated region. Differences in distance are the result of different lateral flight paths.*

pact on capacity, environment and airline efficiency is demonstrated. High costs in the reference scenario originate from unknown airline target functions, unknown air speeds, unknown filed flight paths (responsible for ATC en-route charges) and a coarse spatial resolution of waypoint-based route structure (see Section i). Furthermore, the airline efficiency may not be realistically represented due to rough assumptions in fuel costs, crew salary, insurance costs, maintenance costs and ATC charges for en-route and airport services. All those cost functions are highly dynamic and depend on airline-specific contracts with the corresponding air traffic stakeholder. ATFM induced requirements on speed and altitude and specifically on the lateral path induce longer flight paths and higher costs. The real flights are subject to prescribed flight planning processes, which are performed without such precise weather information, as used in the optimization environment TOMATO.

Finally, no coupling with turnaround processes and no delay costs are considered in this study. The optimized flights are not under time pressure. They do not have to reach connecting flights and do not have to stick to an airport slot. The values are only used for comparability and should be interpreted with care. Furthermore, the aircraft masses are unknown in the reference scenario. Therefore, the same assumptions are made as for the optimized scenario.

A normally distributed seat load factor and a mass of 100 kg per passenger is assumed. Fuel load is composed of estimated fuel burn plus 10 % contingency fuel. This constitutes a huge uncertainty in trajectory optimization. Errors in fuel burn up to 7 % have to be considered [28]. It can be shown, that both EPIs and CPIs could be significantly reduced during the free flight optimization without contrail consideration. Contrail costs could be further reduced by $1.13\ 10^6$ € but not completely avoided, resulting in $1.5\ 10^4$ € higher fuel costs due to detours around ice-supersaturated regions. In contrast to the example of the single trajectory, where time of flight, distance flown, and fuel costs where reduced in the multi-criteria optimized trajectory, compared to the cost minimized one, the majority of flights take detours to avoid contrails. Mostly, ATC enroute charges have a minor impact on cost-minimized trajectories, compared to benefits gaining from wind speed and wind direction.

Concerning the impact of different optimization strategies on the ATFM, number, location and temporal distribution of conflicts within the upper airspace above 264 hPa (FL 360) were investigated. The definition of a conflict has been discussed in Section i.4. The number of conflicts per hour in the reference scenario slightly correlates with the number of

Table 3: *Assessment of the simulated scenarios.*

Scenario	Reference	Cost min.	multi-crit. opt.
Number of conflicts			
1000 ft	50814	23664	33204
500 ft	39708	14395	19968
EPI [€]	$7.10\ 10^7$	$1.91\ 10^7$	$1.81\ 10^7$
CPI [€]	$3.47\ 10^8$	$2.09\ 10^8$	$2.10\ 10^8$
Contrail costs [€]	$4.42\ 10^6$	$3.59\ 10^6$	$2.46\ 10^6$
Fuel burn [kg]	$7.647\ 10^7$	$6.210\ 10^7$	$6.213\ 10^7$

flights above Europe (see Figures 2 and 7). An afternoon slump and more distinctive morning and afternoon peaks are identified in the number of conflicts due to a decreased number of take-offs and landings around midday. From this it follows that an increased air traffic density in the terminal manoeuvring area obviously raises the number of conflicts, although conflicts are only counted in the enroute phase (upper airspace).

Table 3 gives the number of conflicts of all scenarios under two different criteria regarding the vertical separation requirement. Therein, an already reduced vertical separation minimum of 1000 ft is compared with a vertical separation of 500 ft, which is often proposed by the Traffic collision avoidance system (TCAS) in emergency cases. In this way a huge number of conflicts were detected, even in the reference scenario.

Due to a missing short-term conflict resolution, a high number of conflicts does not indicate an unsafe real air traffic scenario. A simulated comparison of a real air traffic scenario between the commercial fast time Air Traffic Simulator AirTOp and TOMATO revealed a similar number of conflicts between the two simulation environments [41]. However, the number of conflicts may be biased due to uncertainties in the flight plan and in the identification of conflicts originating from the temporal resolution (every 10 seconds) and spatial resolution (0.1 degrees). The variation of both parameters is influencing the number of conflicts. During a sensitivity analysis within the available computational resources this number did not converge to a constant value. The impact of increasing the number of time steps and grid points on the number of conflicts further depends on the spatial orientation of the affected flight paths. Hence, each conflict needs a different numerical resolution and the methodology used in this study is not suitable to determine the actual collisions (i.e. intrusions) in the reference scenario. Nevertheless, we found interesting differences in the spatial patterns of the conflicts for each scenario (compare Figures 8, 9 and 10).

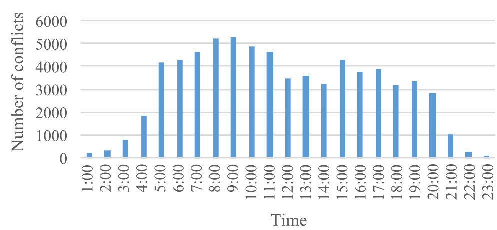

Figure 7: *Number of conflicts per hour in the reference scenario.*

Within the reference scenario (Figure 8) "airways" of aligned conflicts can be identified along highly frequented airways. This effect may originate from today's flight guidance procedures based on the current Aeronautical Information Regulation And Control (AIRAC) cycle. Furthermore, the temporal resolution of the So6 m3 flight plan is not constant and too course (> 10 minutes). Hence, aircraft that are perfectly separated in reality could have been simulated at slightly different times and in slightly different places.

Beside these areas, many conflicts can be detected over Central Europe, where most of the European air traffic takes place. Compared to the optimized scenarios, those conflict grid points are well distributed over the whole European airspace. However, the structure of the aligned conflicts suggest a variety of longitudinal conflicts between two identical aircraft (compare Figure 8). Our analysis showed that

92 % of all conflicts resolved themselves within 10 NM [40]. Furthermore, most of the aircraft are involved in only a single conflict during the whole flight [40]. The fuel burn calculated in the reference scenario, may differ from the actual due to unknown speeds and the corresponding assumption of speeds with a maximum specific range. Since most of the emissions are proportional to the fuel flow, the EPIs (except of contrail costs) and CPIs might be defective as well. However, we suspect that the error is below 20 %, which is the difference in fuel burn between the reference scenario and the cost minimized scenario.

Within the cost minimized scenario, the number of conflicts with a vertical separation minimum of 1000 ft decreased to 46 %, compared to the reference scenario due to the free route concept and a more homogeneous distribution of aircraft in the air space. (Aircraft are modeled to fly along aircraft specific optimum flight paths with respect to wind direction and wind speed using the whole airspace without constraints due to a waypoint based trajectory management.) Despite the identical optimization function in each scenario, Figure 9 indicates an even distribution of cost minimized trajectories in the European airspace. However, lots of highly frequented airspaces can be detected in the optimized scenarios. These free routes may also result in capacity stress and increased controller's workload. By minimizing operational costs, CPI costs could be reduced by 40 %, compared to the reference scenario. This benefit results from decreased distance and time of flight.

When contrail formation should be reduced (Figure 10), aircraft are encouraged to fly around ice-supersaturated regions, resulting in airspace bottlenecks, where many optimized routes converge. This effect is reflected in the number of conflicts (1000 ft vertical separation) in the multi-criteria optimized scenario (reduced to 65 %, compared to the reference scenario), where lots of narrow "airways" of conflicts can be detected. From this it follows, that with the growing demand on future air traffic: contrail formation will not always be avoidable. Detours around ice-supersaturated regions cause higher fuel burn ($3\ 10^4$ kg = 0.05 %, compared to the cost minimized scenario), higher CPI costs ($1\ 10^6$ € = 0.05 %, compared to the cost minimized scenario) but lower EPI costs ($1\ 10^6$ € = 5.34 %, compared to the cost minimized scenario). Contrail costs could be reduced by $1.13\ 10^6$ € = 32 %, compared to the cost minimized scenario.

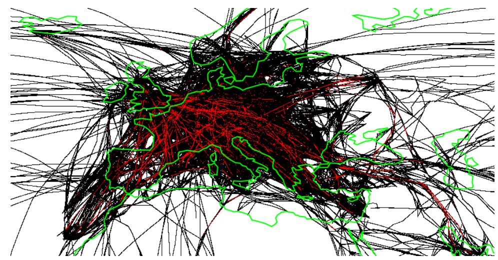

Figure 8: *Simulated trajectories along the navaid infrastructure (black) and conflicts (red) in the upper airspace in the reference scenario. A conflict is defined as imminent separation infringement of 1000 ft in the vertical and 5 NM in the lateral direction.*

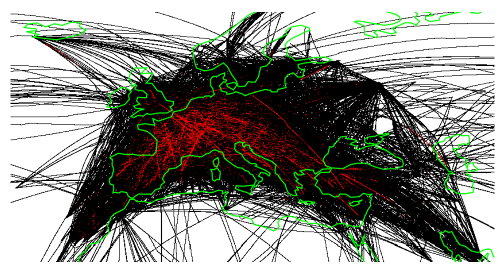

Figure 9: *Cost minimized waypoint-less trajectories (black) and conflicts (red) in the European upper airspace. The results are integrated over a whole day.*

V. Conclusion

In this study, the trajectories from 13584 flights were optimized with respect to cost functions for direct operating costs, fuel costs, environmental costs and ATC charges in a flexible airspace structure using TOMATO, a simulation environment which calculates and considers aircraft performance, engine emissions

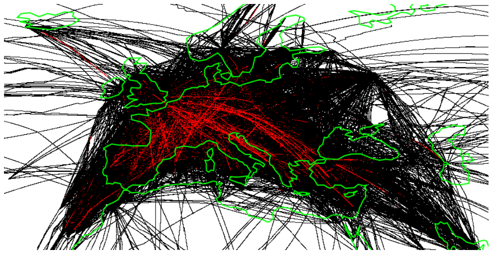

Figure 10: *Multi-criteria optimized trajectories (black) and conflicts (red) considering contrail formation.*

and the radiative impact of contrails for complex air traffic flow scenarios to improve ecological sustainability. With this case study it was demonstrated, that the free route concept, as proposed by SESAR in the Key Feature optimized ATM network services [2], has the potential to increase airspace capacity by more homogeneously distributing aircraft in the air space, even though all aircraft follow a cost minimized optimum trajectory. However, the concept might not lead to a decrease in air traffic density over all of Europe (i.e. number of aircrafts per volume and time), due to favoured airspaces along wind optimum paths between high frequency city pairs.

In addition, asa caveat, note that the results are strongly weather dependent and that the consideration of high costs for contrail formation may cause narrow air corridors as a result of the flight planning strategies used by the airline depending on the number and size of the ice-supersaturated regions.

i. Outlook

During flight planning, airlines are optimizing trajectories in a 2.5 dimensional manner by trying to follow wind optimum flight paths according to an assumed optimal gain in cruising altitude and by considering airline specific target functions. Constraint by today's airway system with fixed waypoints, flight levels, constant true air speeds and a rough discretization of available weather data; this procedure might be as precise as possible. However, often ATC does not know the airline specific target functions and tries to permit the requested trajectory as far as the total effects on air traffic flow and separation requirements allow.

A simulation environment like TOMATO, which considers both trajectory optimization and air traffic simulation offers the possibility for ATC to fully understand and consider the airline intensions more closely. TOMATO can be used by airlines for trajectory optimization and by ATC for the visualization of the requested airline inquired trajectories as well as for an indication of areas with high potential of conflicts. However, additional work needs to be done to develop TOMATO into a satisfactory decision support system by including conflict detection and avoidance algorithms, airport slot planning, and the coupling between trajectory and turnaround.

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