

Impact of Multi-criteria Optimized Trajectories on European Air Traffic Density, Efficiency and the Environment

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Abstract—Today, the European airspace is facing multiple capacity constraints, which are regulating demand during busy traffic periods of the day. According to current market forecasts, passenger air traffic demand will continue to grow between 4.5 percent [1] and 4.8 percent annually [2]). These capacity limits typically cause inefficiencies in flight and consequently in airport ground handling as well. To better manage rare airspace capacity, free routing performance based navigation and harmonized airspace structures are seen as efficient mitigation measures according to the Single European Sky ATM Research (SESAR) and the Next Generation Air Transportation System (NextGen) programs. However, a growing public awareness and a better understanding of the anthropogenic environmental impact necessitates further functions for flight planing and execution, beside today's minimum fuel and time objectives. In this paper we present a trajectory calculation model capable of exploiting the 3D free route optimization potential while considering these divergent targets, especially the costs of condensation trails depending on the time of the day. The model was implemented in the simulation environment TOMATO for a case study, which optimized the European's flight intentions for an entire day based on departure airport, arrival airport and departure time on July 2016. The resulting trajectories are evaluated against the number of separation infringements. The case study shows that this anticipated air traffic demand already stresses the free route capacity when considering the required airline efficiency, ecological compatibility and safety standards.

keywords: *Contrails, Air Traffic Simulation, Trajectory Optimization, Trajectory Assessment*

I. INTRODUCTION

Three conflicting performance areas, as set out by the relevant worldwide research programs NextGen [3] and SESAR [4] are facing today's air traffic system. These are safety, efficiency and environmental compatibility. For the en-route phase, safety is mainly set by minimum separation requirements, impacting existing scarce airspace capacity. Efficiency is however set and measured by a variety of metrics such as airport capacity utilization and great circle deviation.

From the economic side, air navigation costs per flight and by flight time and fuel burn [4] stress airlines to achieve high efficiency levels. The aviation impact on the environment should be assessed by the amount of the aircraft engine emissions. Additionally, condensation trails (contrails) with a significant influence on the radiation budget of the Earth-atmosphere system (i.e. radiative forcing, RF) must be considered [5]. Contrails form in the presence of ice-supersaturated regions [6], which are dynamic layers in the upper troposphere and lower stratosphere. To avoid contrail formation, aircraft would need to bypass either laterally or vertically these ice-supersaturated regions [6], hampering flight efficiency as detours cause extra fuel burn [7]. Therewith, competing objective functions impact the performance indicators [7]. This trajectory optimization based on these target functions might lead to unsolvable high requirements on airspace capacity, because similar vertical and lateral trajectories are expected, since airlines will still prefer wind-optimized flight paths, which do not significantly differ between the common used aircraft types.

To find such multi-criteria optimum flight paths, satisfying at best both airlines and Air Traffic Management (ATM) constraints, a highly accurate single aircraft trajectory and air traffic flow prediction is required. Until now, these aspects have been treated separately on Air Traffic Control (ATC) and respective Air Traffic Flow ATFM/Network Optimization level due to the complexity and the high computational effort. The TOolchain for Multicriteria Aircraft Trajectory Optimization TOMATO has been developed to precisely solve this catenation without coarse approximations regarding the trajectory calculation (e.g. 2.5D BADA performance tables). The air traffic flow scheme [8] and a historic European EUROCONTROL flight plan set were used in the present case study for optimization trials. For assessment, these trials were split into one scenario without contrail consideration (i.e. airline cost optimized), one with contrail avoidance intent and a reference

scenario.

Several air traffic flow simulation environments had been developed, each with a specific scope. On the one hand the fast time air traffic simulator AirTOP [9] generates trajectories in a dynamic airspace structure and iteratively considers conflict detection and conflict resolution [10]. AirTOP had been applied to reroutings around volcanic ash clouds [11] and to estimate the influence of restricted airspaces on the air traffic system [12]. However, due to approximations in the aircraft performance modeling (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 focusses 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 [13–16]. 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 of the aircraft performance is impossible, mainly because of the following assumptions and approximations: First, these tables are available for three different aircraft reference weights. Therewith, the important actual aircraft weight can not be considered. Second, the significant influence of weather on the aircraft performance is not implemented. Here, only the International Standard Atmosphere (ISA) with a course consideration of a temperature deviation at sea level is used. Third, the aircraft true air speed can not be influenced. A constant reference speed has to be assumed. Furthermore, vertical movements are restricted between common flight levels. Therewith the trajectory optimization potential is significantly limited. One of the reasons for this approximations might be the complexity of the aircraft drag polar, mainly depending on Mach number, air density and angle of attack. Furthermore, quick approximations of the required flight performance for a dedicated flight manouever are possible.

Grewe et al. [17] concentrated on the climate assessment of trajectories considering future aircraft technologies and uncertainties in the quantification of the emissions. Here, the impact on air traffic simulation was not in focus. In the framework of the research project ATM4E, Matthes et al. [18] developed a multidimensional optimization tool for trajectories and their impact on the air traffic network and demand. This intention covers parts of the study, presented in this paper. Regarding the flight performance modeling, the commercial flight planning tool Lido/Flight 4D, developed by Lufthansa Systems [19], is also able to simulate trajectories assuming ISA. Hence, special weather phenomena, like ice-supersaturated regions can not be modeled. The Airspace Simulator TAAM, developed by Jeppesen is also able to simulate air traffic flows in ISA.

II. SIMULATION ENVIRONMENT TOMATO

Three air traffic scenarios have been calculated and compared. First, a reference scenario is estimated by a recalculation of the flight plan according to the historical 4D trajectories. Hereby, the given coordinates of the flight plan and the recorded altitudes must be complied by each aircraft. Second, a multi-criteria optimized flight plan is simulated, considering minimum costs regarding all implemented Key CPIs and EPIs, but not contrails, because of long detours, which are often necessary for contrail avoidance [20]. And third, contrails are considered in the multi-criteria trajectory optimization.

A. Properties and workflow of TOMATO

The architecture of the TOMATO simulation software is very modular and described in Förster et al. [8]. The core is composed of three submodules that are interconnected in an iterative process. For complexity reasons, the overall optimization has been split into two parts. The first step is a lateral path optimization 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.

Lateral pathfinding is done by employing the A* algorithm, which will always find the optimal path if there exists one. Edge costs are expressed in monetary values. Some of the path influencing factors are already available in form of a fee or cost. To express the effect of winds, their accelerative or decelerative implication will be transformed into a cost value by applying a factor that expresses the estimated costs per time unit.

Second, a vertical flight profile will be calculated along that path, using the performance model COALA (COMpromised Aircraft performance model with Limited Accuracy), which is described in more detail by Rosenow et al. [20, 21]. It comes together with an engine model, that allows to determine detailed performance and emission data for each time-step during the flight. Therewith, the optimization is done in a real 3D workspace. This distinguishes the TOMATO from 2.5D simulations, which are used by airlines today, where fixed steps for altitude changes are restricting the solution space. The assumption of a free route airspace allows the employment of unconstrained, continuous cruise climb operations [20].

After both optimization steps the trajectory can be assessed in terms of many different Key Performance Indicators (KPI), composed of Cost Performance Indicators (CPI) and Ecological Performance Indicators (EPIs) which are in detail described by Förster et al. [8] (compare Fig. 1 and the optimization cycle therein). 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 estimates the optimum cruising altitude and speed

(if not defined by an analytically solvable target function) and the required fuel mass by varying the input parameters after each assessment step at the end of each iteration step (compare Fig. 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 (Fig. 1). That iterative optimization process will run until a certain cancellation criteria is met. This can be a minimum delta that a solution has to improve or a maximum number of iterations. A number of files will be generated as output which allow to further process the calculated trajectory (compare (Fig. 1) and [8] for more details). The estimation of separation infringements per time step is done in a post-analysis of the trajectories. The criterion validity of TOMATO could be shown in various applications [7, 20, 21].

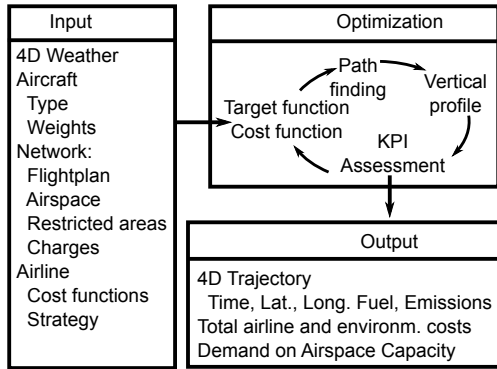


Figure 1. Workflow in TOMATO, simplified to the most important parameters and modules.

B. Quantification of airline costs: CPI

Airline direct operating costs (DOC) are mainly driven by fuel costs and time costs. The fuel price is taken from the IATA fuel price monitor [22] in December 2016 for Europe and is set constant to 0.502 euros per kilogram Jet A1 plus 20 % handling costs. Flight dependent costs are extracted from analyses of different airline cost studies including cost factors and linear relationships describing crew salaries, maintenance costs, depreciation rates, and direct or indirect compensations for delays, if necessary [8]. Airport and en-route charges for using the air navigation services by EUROCONTROL depend on the distance flown over each Flight Information Region, depending on a unique Unit Rate and the maximum take off mass of the aircraft. The departure and en-route charges depend on the standardized Unit Rates [23], which are monthly published by EUROCONTROL [24]. Regions outside the EUROCONTROL area are assigned by the mean value of all Unit Rates. Therewith, airline's detours outside the European observation area as a possible result of airline cost minimizing strategies are avoided. Any kind of airspace restrictions can be formulated and activated as polygons. A common en-route charging regime with uniform Unit Rates, for example FAB-EC (FAB Europe Central), as intended by the SES, can be used in TOMATO.

The trajectories are assessed one by one. The sum of all CPIs represents two-thirds of the total costs (resulting in one third for Ecological Performance Indicators EPI).

C. Assessment of the environmental impact: EPI

For the evaluation of the aviation environmental compatibility, the main emissions are quantified according to scientific knowledge's state of the art. Products of complete combustion as carbon dioxide CO_2 , water vapor H_2O , sulfate SO_4 and sulfuric acid H_2SO_4 are quantified as linear function of fuel flow [25]. Emissions of nitrogen oxides NO_x , hydrocarbons HC and carbon monoxide CO are estimated following the Boeing-2 fuel flow method [26] depending on fuel flow, thrust setting and measured reference values, estimated by the International Civil Aviation Organization (ICAO) [27]. 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 [28].

The cost based assessment of the emissions according to their impact on global warming is quantified by the Global Warming Potential (GWP) [25], a measure of the relative effect of the greenhouse gas impact compared to the impact of CO_2 . Therewith, converted emissions can be expressed as CO_2 equivalent emissions. Global climate analyses have shown, in 2005 aviation induced contrails contributed to global warming as much as 21 % of the total aviation CO_2 emissions in the same year [25]. Approximately 10 % of the total number of flights are inducing contrails [29]. Hence, aircrafts flying through ice-supersaturated regions are additionally burdened with a reference value of 32 tons of CO_2 equivalent emissions per hour [7]. This reference value is adapted depending on the time of the day (compare Section II-D). The CO_2 equivalent emissions are converted into monetary values by using the European Emission Trading System (ETS) and assuming a price of 65 euros per ton of CO_2 equivalent emission.

D. Radiative forcing of contrails depending on daytime and flightpath

The radiative forcing of contrails 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 [5]. This relationship can be described by the time of the day and by the aircraft heading (i.e. the flightpath). 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 [5]. Hence, those contrails are punished with 110 %

of the reference value. During day (7 a.m. to 5 p.m.) the cooling effect will be maximum and contrails are punished with 90 % of the reference value. Although some research studies estimated an average cooling effect of contrails at daytime [30], the net effect of individual contrails strongly depends on contrail life time and contrail microphysical properties, such as particle size and shape [5]. That's why, and for reasons of increasing the importance of contrail costs in the trajectory assessment, contrails induced at daytime are punished anyway.

E. Assessment of separation infringements

Considering safety aspects of the simulation, the influence of trajectory optimization on airspace capacity should be investigated. Due to restrictions in computing capacity, a complex analysis of the airspace capacity is not possible in this case study. Instead, heat maps of separation infringements 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 timely resolution of ten seconds have been estimated (compare Fig. 8 to 10, where all conflicts per scenario are shown). Therewith, the conflict effected aircraft can not be backtracked, but the spatial behavior of conflict affected cells allows statements of the airspace capacity.

III. TOMATO INPUT DATA

A. Flight plan

In order to simulate twenty four hours of European'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) [31]. Beside flights to and from European airports, overflights above the European airspace are also included. Since this study focusses on the upper airspace capacity, flights with a maximum intended cruising pressure altitude beneath $p_{cruise} = 376$ hPa (FL 250) are removed from the simulation. Due to some numerical problems during the optimization of some flights, where the target function could not be estimated for each time step, a total number of 13584 flights with identical flight IDs (i.e. identical departure, arrival and departure time) have been successfully calculated and assessed during all three scenarios. Only those flights are assessed and checked according to conflicts between the three scenarios. These flights are compared between the three scenarios. Nevertheless it is assumed, that a realistic simulation is chosen representing enough aircraft movements for a applicable proof of separation infringements along optimized free routes. 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 amounts 1000 ft (flight level) and the lateral resolution depends on waypoints and flight phase. The en-route phase resolution can be more than 100 NM, but on average 40 NM. According to some test data of randomly chosen flights the resolution is less than 3 NM during climb and less than 10 NM during descent.

Figure 8 gives an impression of the traffic flow, simulated along the waypoints and altitudes given in the real radar adjusted SO6 m3 flight plan. Therein, regions with high conflict potential (red) can be already localized above Central Europe.

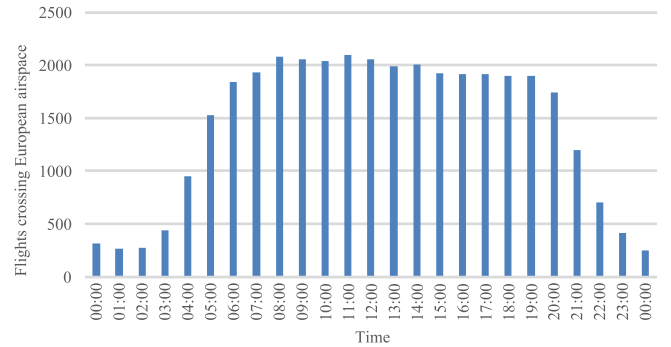


Figure 2. Number of simulated flights over Europe on 25th July, 2016 as function of Greenwich Mean Time in intervals of one hour.

A further analysis of the flight plan yields no significant diurnal variation (Fig. 2), besides day and night traffic, because of a large number of time zones in Europe between Russia (GMT+5) and Portugal (GMT-1).

B. Airspace structure

En-route charges in the European air space are calculated depending on the distance flown above each EUROCONTROL member state. For the current case study, the today's EUROCONTROL Unit Rate charging regime is implemented. Fig. 3 shows the actual assigned unique en-route charging Unit Rates as heat map for each member state in January 2017. In the current study, airspace restrictions, as well as the today's route and waypoint structure are not implemented.

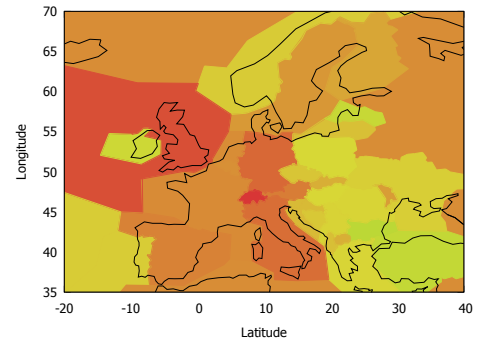


Figure 3. Heat map of implemented en-route charges for all EUROCONTROL member states in January 2017. Unit Rates between 10.06 euros (yellow) and 106.05 euros (red) are considered in TOMATO.

C. Fleet

The aircraft to flight assignment is obtained from the given flight plan. As more than 26 % of all flights are shorter than 500 kilometers, a high number of 9673 short haul flights exists in the flight plan. In total, there are sixteen aircraft

types implemented in COALA. If a given aircraft subtype matches the implemented COALA aircraft type, the flight will be optimized using this aircraft performance data. Aircraft with turboprop engines with differences in the combustion chamber (which are not yet considered) and other not implemented aircraft types will be represented by the best matching turbofan aircraft which is implemented in COALA (in most cases E170, E190 and CRJ9 for short haul flights). In total, 70 % of the original aircraft assignment is maintained.

Aircraft payload is normally distributed around a typical aircraft specific seat configuration. A weight of 100 kg per passenger is assumed.

D. Weather data

Corresponding to the flight plan the weather data of 25th of July, 2016 has been chosen, because of a typical situation in Summer on the Northern hemisphere [32] with relatively small and fast movements of the ice supersaturated regions offering possibilities of rerouting. Furthermore, a realistic drift of the ice-supersaturated regions from North to South East due to the global circulation distracted by the Coriolis force is assured [33]. Weather data is extracted from Grib2 data, provided by provided by the National Oceanic and Administration NOAA [34]. Weather data is only provided with a timely resolution of six hours. Because TOMATO can not handle dynamic effects during lateral path finding, the weather data set, closest to the departure time of the flight is chosen and set constant over the whole flight. Fig. 4 gives an impression of size and location of the ice-supersaturated regions at a constant pressure level.

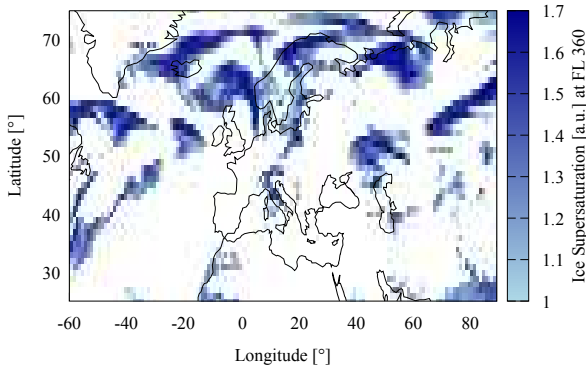


Figure 4. Size and location of ice-supersaturated regions (blue) above Europe on 25th of July, 2016, 12. a.m. which should not be passed by aircraft for avoiding contrail formation.

IV. SCENARIO ASSESSMENT

For 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 (a single trajectory of each scenario) or based on a composition of the whole air traffic scenario (the sum of all trajectories of each scenario). First of all, the total effect of the sum of all trajectories of each scenario is discussed (compare

Table I). Therewith, the scenario's impact on the capacity, environment and airline efficiency can be shown. High costs in the reference scenario (real) originate from unknown airspeeds and a coarse spatial resolution of the underlying flight plan (compare Section III-A) and are not representing a realistic airline efficiency. The values are only used for comparability. 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 $1.13 \cdot 10^6$ euros, resulting in 1.51^4 euros higher fuel costs.

TABLE I
ASSESSMENT OF THE SIMULATED SCENARIOS. THE NUMBER OF SEPARATION INFRINGEMENTS CORRESPONDS TO 1000 FT AND 500 FT VERTICAL SEPARATION REQUIREMENTS.

Scenario	Real flights	Cost optimized	Contrails considered
separation infringements			
1000 ft	50814	23664	33204
500 ft	39708	14395	19968
EPI [euros]	$7.10 \cdot 10^7$	$1.91 \cdot 10^7$	$1.81 \cdot 10^7$
CPI [euros]	$3.47 \cdot 10^8$	$2.09 \cdot 10^8$	$2.10 \cdot 10^8$
Contrail costs [euros]	$4.42 \cdot 10^6$	$3.59 \cdot 10^6$	$2.46 \cdot 10^6$
Fuel burn [kg]	$7.647 \cdot 10^7$	$6.210 \cdot 10^7$	$6.213 \cdot 10^7$

V. TRAJECTORY ASSESSMENT

A comparison of individual trajectories is in focus with respect to lateral and vertical differences, resulting in a different assessment. Fig. 5 shows the lateral path of a single city pair under constant boundary conditions, but with different target functions, i.e. scenarios. In the cost optimized trajectory (green), the benefit of wind direction and wind speed (not precisely known during real flight planning) is used as well as the free flight procedure resulting in 250 euros (7.2 %) less fuel costs, 1619 euros (6.8 %) less CPI costs and 441 euros (15 %) EPI cost benefit, mainly caused by significantly higher cruising altitudes of the optimized trajectories. The multi-criteria optimized trajectory further considers high contrail costs, which is why the lateral optimization reduces the flight time in ice-supersaturated regions (blue grid). This last optimization step results in reduced CPIs of 1525 euros (6.4 %) and reduced EPIs (1120 euros (39 %)), compared to the reference scenario (compare Table II). The optimization potential can be further seen in the vertical profiles (Fig. 6). Here, the influence of 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 aircrafts service ceiling. Differences in distance are the result of different lateral flight paths.

VI. SEPARATION INFRINGEMENTS

As a measure of capacity concerns, the number, location and timely distribution of separation infringements within the upper airspace above 264 hPa (FL360) are investigated. The

TABLE II

ASSESSMENT OF A SINGLE A320 TRAJECTORY FROM CORFU, GREECE TO MANCHESTER, UNITED KINGDOM IS SHOWN DUE TO MULTI-CRITERIA OPTIMIZATION, ECOLOGICAL COSTS CAN BE REDUCED BY 45 %, WHEN CONTRAIL FORMATION IS CONSIDERED. OPERATIONAL COSTS MIGHT BE REDUCED TO 19 % WITHOUT CONCERNING CONTRAIL FORMATION.

Scenario	Real flights	Cost optimized	Contraails considered
EPI [euros]	5017	4121	2714
CPI [euros]	35127	28329	28582
Contrail costs [euros]	2501	2155	736
Fuel costs [euros]	5096	3986	4011

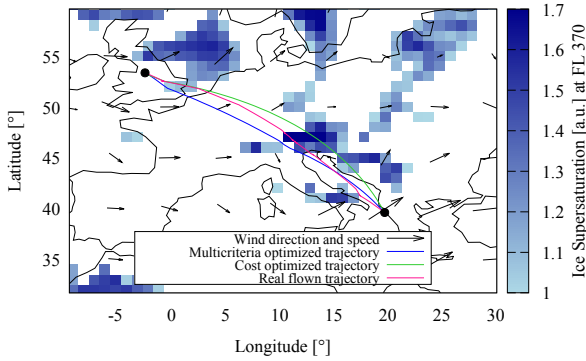


Figure 5. Lateral paths of three trajectories in an ice-supersaturated environment (blue, grids), each representing one scenario. Differences between the actually flown real trajectory (magenta, reference scenario) and the multi-criteria optimized trajectories with (blue) and without (green) lateral adjustments for reasons of contrail avoidance show the optimization potential of today's flight operations by using TOMATO. An A320 flight from Vilnius, Lithuania to Malaga, Spain is shown.

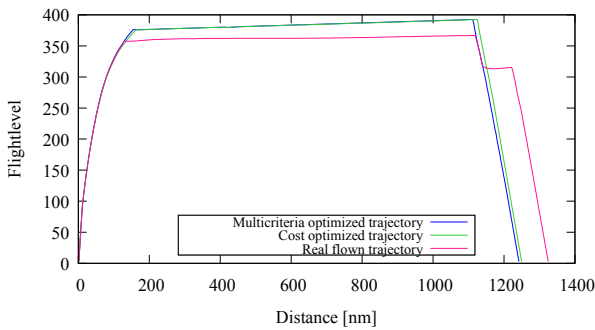


Figure 6. Vertical profiles of three trajectories in an ice-supersaturated region. High cruising altitudes of the optimized trajectories are caused by the target function of a maximum specific range. Furthermore, the optimized trajectories avoid level flights during descent.

definition of separation infringements has been discussed in Section II-E. The temporary distribution of separation infringements correlates with the timely variation of the number of flights over Europe (compare Fig. 2 and 7). Table I gives the number of “conflicts” of all scenarios under two different criteria regarding the vertical separation requirements. Therein,

a huge number of conflicts can be detected, even in the real scenario. From this follows an incomplete delimitation of separation infringements, originating from the timely (every 10 seconds) and spacial resolution (0.1 degrees) during conflict detection. The variation of both parameters is influencing the number of conflicts. With 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, different conflicts need a different numerical resolution and the methodology used in this study is not suitable to determine real conflicts of the historical scenario. Anyhow, we could find interesting differences in the patterns of the separation infringements for each scenario (compare Fig. 8, 9 and 10).

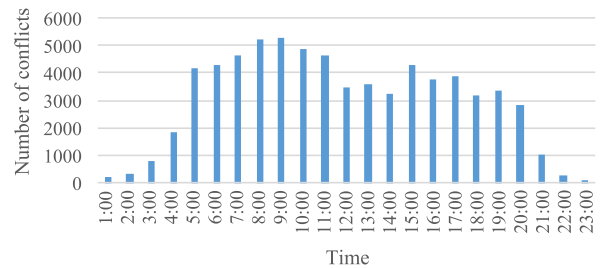


Figure 7. Number of separation infringements in the upper airspace per hour over time of the day in the cost optimized scenario without lateral reroutings for contrail avoidance. A weak correlation to the number of flights over Europe (Figure 2) can be identified, but with more distinctive morning and afternoon peaks due to more departures in Central Europe at these times.

Within the real scenario “airways” with aligned grid points of separation infringements can be identified between often used waypoints. This effect may originate from the today’s flight guidance based on routes between these waypoints. Furthermore, the timely resolution of the SO6 m3 flight plan is not constant, at least more than ten minutes, which is far too course. Hence, aircraft which are perfectly separated in reality could have been simulated at slightly different times and in slightly different places. Beside these airways of conflicts many separation infringements can be detected over Central Europe, where most of the European air traffic takes place. Compared to the other scenarios, those grid points are well distributed the whole European airspace.

Within the cost optimized scenario, the number of conflicts decreased to 46 % due to the free flight approach within the trajectory optimization. Although all aircraft are suspected to fly along optimum flight paths with respect to wind direction and wind speed, the whole airspace can be used now, without constraints due to a waypoint based trajectory management. Conflicts mainly occur over Central Europe. Nevertheless lots of unlikely “airways” of separation infringements can be detected between frequently demanded city pairs.

When contrail formation should be reduced, aircraft are encouraged to fly around ice-supersaturated regions, resulting in airspace bottlenecks, where many optimized routes meet. This effect is reflected in the number of conflicts in the third sce-

nario (reduced to 65%, compared to the reference scenario), where lots of narrow “airways” of separation infringements can be detected. From this follows under consideration of the growing demand on future air traffic: contrail formation will not always be avoidable.

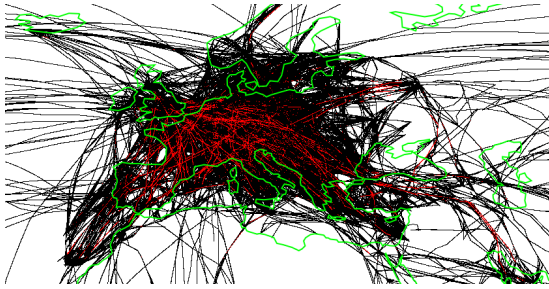


Figure 8. The reference scenario: detail of the heat map of simulated air traffic (black) and separation infringements (red) in the upper airspace of 13584 flights over Europe on 25th of July, 2016. The trajectories are simulated along a real SO6 m3 flight plan defining departure, destination, departure times, waypoints, altitudes and aircraft types.

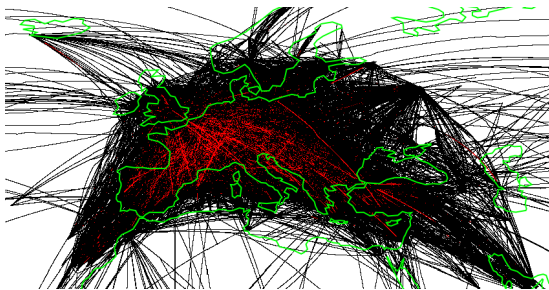


Figure 9. Detail of the heat map of 13584 multi-criteria optimized trajectories (black) and separation infringements (red) in the upper airspace over Europe on 25th of July, 2016 without the intension of avoiding contrail formation. Departure, destination and departure times are taken from the SO6 m3 flight plan by EUROCONTROL.

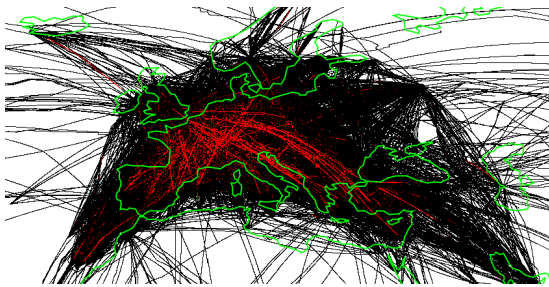


Figure 10. Detail of the heat map of 13584 multi-criteria optimized trajectories (black) and separation infringements (red) in the upper airspace over Europe on 25th of July, 2016 considering expensive contrail formation during the lateral path finding. Departure, destination and departure times are taken from the SO6 m3 flight plan by EUROCONTROL.

VII. CONCLUSION

With the TOOLchain for Multicriteria Aircraft Trajectory Optimization, TOMATO, the simulation and evaluation of a complex traffic scenario is possible. The total number of 13584

flights could be optimized with respect to cost functions for direct operating costs, fuel costs, environmental costs and ATC cost charges in a flexible airspace structure. TOMATO is the first simulation environment, which accurately calculates the aircraft performance, the engine emissions and the radiative impact of contrails for a complex air traffic flow scenario to improve the aviation ecological sustainability. With this case study it has been shown, that free flight procedures, as proposed by SESAR in the Key Feature optimized ATM network services [4] might not always lead to a decrease in airspace capacity (i.e. number of aircrafts per volume and time). This conclusion is based on flying laterally and vertically optimized trajectories by considering wind speed and wind direction and also the environmental compatibility (i.e. contrail formation), which results in a higher probability of separation infringements, due to the consideration of contrail formation. Anyhow, these results are strongly weather dependent. Especially, the consideration of high costs for contrail formation may cause narrow airway corridors in consequence of cost minimizing strategies of all participants, depending on number and size of the ice-supersaturated regions. By accepting this complexity, a high potential in multi-criteria trajectory optimization and cost savings could be identified by comparing historical flight paths with the optimized ones.

A. Outlook

During flight planning, airlines are optimizing trajectories in a 2.5 dimensional way by trying to follow wind optimum flight paths according to an assumed optimal gain in cruising altitude and by considering airline specific target functions. Reflecting the todays airway system with fixed waypoints, flight levels and a rough discretization of available weather data, this procedure might be as precise as possible. However, often the ATC does not know the airline specific target functions and tries to permit the inquired trajectory as far as the total affected air traffic flow and separation requirements are considered. A simulation environment, as TOMATO, which covers both trajectory optimization and air traffic simulation would offer the possibility to ATC to fully understand and consider the airline intension more closely. TOMATO can be used by airlines for trajectory optimization and by ATC for the visualization of the exact airline inquired trajectories as well as for the indication of areas with high potential of conflicts. Anyhow, more work has to be done in the further development of TOMATO into a satisfactory decision support system, by including conflict detection and avoidance algorithms in air traffic flow scenarios, as well as airport slot planning.

ACKNOWLEDGMENT

This work has been done in the framework of the research project MEFUL, financed by the Federal Ministry for Economic Affairs and Energy and by Lufthansa Cargo AG.

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