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Impact of multi-criteria optimized trajectories on European airline efficiency, safety and airspace demand

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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. These capacity limits cause inefficiencies in flight and airport ground handling. Current market forecasts predict an annual growth in passenger air traffic demand between 4.5 percent and 4.8 percent. This growth will be realized by an increasing number of aircraft movements reflected in an expected annual growth of jet airplanes by 3.3 percent with a negative impact on airspace capacity. To better manage the rare airspace capacity, the Single European Sky ATM Research (SESAR) and the Next Generation Air Transportation System (NextGen) program suggest free route airspaces, a Performance Based Navigation (PBN) and harmonized airspace structures as efficient concepts of improvement in air traffic efficiency. Beside today's minimum fuel and time objectives, a growing public awareness of the anthropogenic environmental impact necessitates further functions for flight planning and execution. Additionally, today's high safety standards must not be negatively influenced by the introduction of free route airspaces. In this paper, we present a trajectory calculation model capable of exploiting a 4D free route optimization potential while considering the divergent targets of safety, efficiency and environmental compatibility. In particular, the environmental effects of condensation trails depending on the time of the day are carefully considered. To further estimate the impact of free routes on airspace demand and on safety issues, the model is implemented in the simulation environment TOMATO, and the European flight intentions have been optimized for an entire day based on departure airports, arrival airports and original departure times July 2016. The resulting trajectories are evaluated against the number, location and duration of separation infringements. Despite constantly changing air speeds and cruising altitudes induced by the optimization target functions, the number and duration of separation infringements could be reduced by 30% due to optimized lateral and vertical trajectories. The results of this case study show a high potential for an increased airspace capacity under free routing conditions. Furthermore, fuel burn (20%) and airline direct operational costs (40%) could be significantly reduced.

1. Introduction

Today's air traffic system is facing three conflicting performance areas as set out by the relevant worldwide research programs NextGen (Federal Aviation Administration, 2016) and SESAR (SESAR Joint Undertaking, 2015). These are safety, efficiency and environmental compatibility. For the en-route phase, safety is mainly set by minimum separation requirements which impact the existing scarce airspace capacity. Efficiency is 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 depending on flight time and fuel burn (SESAR Joint Undertaking, 2015) put stress on airlines to achieve high efficiency levels. Considering instruments like the European Emission Trading System (ETS) the environmental impact of aviation is already being assessed on the basis of aircraft engine emissions. Additionally, condensation trails (contrails) with a significant influence on the radiation budget of the Earth's atmosphere (i.e., radiative forcing, RF) (Sausen et al., 2005; Myhre et al., 2013) will also need to be considered in the future (Rosenow, 2016). Contrails form in the presence of ice-supersaturated regions (Sussmann and Gierens, 2001), which are dynamic layers in the upper troposphere and lower stratosphere. To avoid contrail formation, aircraft would need to bypass these ice-supersaturated regions either laterally or vertically (Sussmann and Gierens, 2001), hampering flight efficiency since detours cause extra fuel burn (Rosenow et al., 2016a) and since different overfly charges may accumulate. Today differences in overfly charges and in

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air navigation charges already lead to detours during a lateral trajectory optimization when airlines attempt to avoid expensive upper airspaces such as Switzerland (compare Fig. 3). Thus, highly competing objective functions impact the performance indicators of a trajectory (Rosenow et al., 2016a). Additionally, a trajectory optimization might lead to unsolvable, high requirements on airspace capacity because similar vertical and lateral trajectories with non-constant air speeds are expected and since airlines will still prefer wind-optimized flight paths which do not significantly differ between the commonly used Aircraft types.

To find such multi-criteria optimum flight paths, which satisfy airline's efficiency intensions as well as Air Traffic Management (ATM) constraints, both highly accurate single aircraft trajectories and air traffic flow prediction are required. Until now, these aspects have been treated separately either on the flight planning level or for Air Traffic Flow Management (ATFM) purposes initiated by different stakeholders. Generally, aircraft type specific 2.5D performance tables by BADA (EUROCONTROL) are used and include coarse approximations regarding the trajectory calculation and assessment (Rosenow et al., 2016a; Förster et al., 2016). The TOolchain for Multi-criteria Aircraft Trajectory Optimization TOMATO has been developed to precisely solve this catenation. TOMATO is an air traffic simulation environment based on an accurate trajectory optimization which includes the estimation of engine emissions and provides a trajectory and ATFM assessment (compare Table 2). In the present case study, the air traffic flow scheme and a historic European EUROCONTROL flight plan set were used for optimization trials. For comparison and assessment, these trials were split into three scenarios:

- An airline, cost-minimized scenario (i.e., the sum of ecological costs and direct operating costs is minimized, and contrail formation is not considered in the optimization but in the assessment).
- A multi-criteria, optimized scenario considering contrail costs.
- A reference scenario wherein the lateral route is taken from the EUROCONTROL flight plan.

In this case study, the trajectories are analyzed with respect to number, location and duration of separation infringements mainly induced by non-constant air speeds and altitudes. Therewith, the influence of optimized free routes on airline and network efficiency can be approximated. In the first studies with TOMATO, only the number of aircraft within a defined spatial grid had been analyzed, which merely allowed statements about imminent separation infringements, the airspace capacity, controllers' workload (Rosenow et al., 2017a) and typical patterns of airways caused by different optimization strategies (Rosenow et al., 2017b). Now for the first time, an extensive post analysis of each individual trajectory allows for the estimation of actual separation infringements.

Several air traffic flow simulation environments have been developed, each with a specific scope. On the one hand, the fast-time air traffic simulator AirTOp (Online. Available: http:a) generates trajectories in a dynamic airspace structure and iteratively considers conflict detection and conflict resolution (Luchkova et al., 2015). AirTOp has been applied for rerouting around volcanic ash clouds (Luchkova et al., 2016) and for estimating the influence of restricted airspaces on the air traffic system (Kreuz et al., 2016). 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 of 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 (Schultz et al., 2011, 2012, 2013; Kaiser et al., 2012). However, TABATS also concentrates on BADA performance tables and is limited in the quantification of the emissions.

Grewe et al. (2016) concentrate on the climate assessment of trajectories considering future aircraft technologies and uncertainties in the quantification of emissions. Grewe et al. do not focus on the impact of optimized trajectories on ATFM. In the framework of the research project ATM4E, Matthes et al. (2016) have developed a multi-dimensional 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 (Online. Available: https), is also able to simulate trajectories assuming an International Standard Atmosphere ISA without wind information. Hence, special weather phenomena, like ice-supersaturated regions cannot be modeled. The Airspace Simulator TAAM, developed by Jeppesen, is also able to simulate air traffic flows in ISA. Anyhow, the impact of adverse weather conditions is already parameterized.

Considering single trajectory optimization, most approaches focus on cruise phase only (Grabbe et al., 2006; Ng et al., 2011, 2014; Sridhar et al., 2013; Sridhar and Chen, 2010; Zillies et al., 2013), utilizing the BADA performance model (Ng et al., 2011, 2014; Serafino, 2015) or neglecting a realistic flight performance. Thereby, speed and altitude are assumed as constant and defined as static parameters. Ng et al. and Serafino use the optimum control approach for vertical trajectory optimization and reduce the modeling of the flight performance to a manageable number of parameters (Ng et al., 2011, 2014; Serafino, 2015), whereas Grabbe et al. and Sridhar concentrate on the lateral path optimization (Grabbe et al., 2006; Sridhar et al., 2013; Sridhar and Chen, 2010; Zillies et al., 2013). Table 1 summarizes the literature review by the most important categories and indicates the complexity of

Table 1

Summary of current trajectory optimization and environments and their key features. TOMATO is the onlyknown tool chain which considers the precise 4d flight performance of each flight phase and air traffic flow (atfm).

Study	(Grabbe et al., 2006; Sridhar et al., 2013)	(Online. Available: http:a)	(Ng et al., 2011, 2014)	Grewe et al. (2016)	TOMATO
	(Sridhar and Chen, 2010; Zillies et al., 2013)	Schultz et al. (2013)	Serafino (2015)	Matthes et al. (2016)	
Optimizing Cruise	X	X	X	X	X
Whole Flight	–	–	–	X	X
Lateral	–	X	–	X	X
Vertical	X	–	X	X	X
ATFM	–	X	X	–	X
Assuming BADA	X	X	–	–	–
ISA	X	X	X	–	–

Table 2
Output of TOMATO consists of a full 4d trajectory, assessment indicators and data for atfm considering airspace demand, separation infringements and controller's taskload of all optimized flights. Emissions and contrails are explained in section 2.3 and section 2.5, respectively.

4D Trajectory
Latitude [∘], longitude [∘]
Altitude [ft, m, FL], time [s]
Speeds (TAS, GS) [m s − 1], Mach number
Air distance [m, NM], ground distance [m, NM]
Fuel burn [kg s − 1], remaining fuel [kg]
Emissions
CO2, H2O, SO4 [kg s − 1]
H2SO4, NOx [kg s − 1]
HC, CO [kg s − 1], Contrails [0,1]
Assessment
Delay costs [euros]
Time of flight [s]
Fuel costs [euros]
ATC costs [euros]
Maintenance costs [euros] Deprecation costs [euros]
Σ total costs [euros]
Σ EPI [euros], CPI [euros]
Emission costs [euros]
Time costs [euros]
ATFM
Number of separation infringements within grid
Location of separation infringement
Number of aircraft in separation infringement
Aircraft IDs involved in separation infringement
Begin of separation infringement
End of separation infringement
Distance flown in separation infringement
Mean heading in separation infringement
Controller's task load

aircraft trajectory optimization and capacity analyses which is applied in TOMATO for the first time.

TOMATO is in no way restricted to the type of target function in the multi-criteria optimization procedure as long as aircraft type-specific flight performance envelopes are not exceeded. Where freely planned trajectories without Air Traffic Service (ATS) route constraints are burdened with time stamps for an efficient Air Traffic Flow Management, TOMATO can be perfectly used for the simulation of Performance Based Navigation (PBN) procedures. Therefore, free routes are simulated with TOMATO unless a navaid infrastructure is restricting the solution space of the path finding algorithm. Free routes are freely planned routes between a defined entry point and a defined exit point of a so-called Free Route Airspace (FRA) or a Flight Information Region (FIR). Free routes are described by published or unpublished waypoints (position data) (Eurocontrol, 2012). In many European air traffic control sectors, FRA has already been implemented, at least at night (O'Keeffe and Houlihan, 2015; Eurocontrol, 2017). Free routes significantly differ from directs (great circle navigation) between defined entry points and exit points because they may fully utilize actual wind speed and wind direction and overfly charges. However, for this precise optimization, accurate and up-to-date weather information is required, which is not (often) utilized in today's operations. For that reason, aircraft mostly follow orthodromes to ensure the shortest air distance. For safety reasons, those directs are only allowed in the upper airspace (above 250 hPa).

The fuel saving potential of a full implementation of orthodromes in the European upper airspace has been quantified between 4.5 10^4 tons (Agency, 2016) and 5 10^5 tons per year (Bucuroiu, 2017). The EASA consider a proportion of flight time flown in Free Route Airspace at 8.5% (Agency, 2016). Other studies specify the fuel saving potential of directs in the upper airspace of smaller regions, such as six tons per day in the Czech Republic (Kraus, 2011) (corresponding to roughly 2 10^3 tons per year) or 3.7 10^3 tons per year in the Maastricht Upper Air Control Center (Lebutte and Roman, 2017). This promising saving potential will increase significantly if actual weather information is considered in the design of free routes along the fuel minimum flight path during the whole flight, allowing for optimum climb and descent profiles. In TOMATO, a perfect weather data provision and a free route concept in all airspaces are assumed in the multi-criteria trajectory optimization. From this follow large differences in fuel burn, time of flight and distance flown between the reference scenario and the optimized situation.

2. TOMATO simulation environment

In this case study, three different air traffic scenarios have been calculated and compared with our air traffic simulation environment called TOMATO. First a reference scenario is estimated by a recalculation of the flight plan according to historical 4D trajectories. Hereby, the given coordinates of the flight plan and the recorded altitudes have been complied for each aircraft. The aircraft's true air speed, however, is chosen according to the optimum speed for a maximum specific range. This speed is constantly changing. Secondly, a multi-criteria optimized flight plan is simulated, aiming at minimum cost regarding all implemented efficiency-related and ecological key performance indicators, except for contrails since their avoidance would usually require long detours (Rosenow et al., 2016b). And third, contrails are then supplementary considered in the multi-criteria trajectory optimization.

2.1. Properties and workflow of TOMATO

The architecture of the TOMATO simulation software is very modular and described in Förster et al. (Förster et al., 2016). The core is composed of three sub modules which 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 enroute 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 path finding is done by employing the A* algorithm where edge costs are expressed in monetary values. While most of the path influencing factors are already available in the form of a fee or cost, the accelerative or decelerative implication of wind speed and direction is transformed into a cost value by applying a factor that expresses the estimated costs per time unit. The 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. (Rosenow et al., 2016b; Rosenow and Fricke, 2016). An engine model allows for the determination of detailed performance and emission data for each timestep during the flight. Therewith, the 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 tend to restrict the solution space. The assumption of a free route airspace allows the employment of unconstrained, continuous cruise climb operations (Rosenow et al., 2016b).

After both optimization steps, the trajectory is assessed in terms of many different Key Performance Indicators (KPI), composed of Cost Performance Indicators (CPIs) and Ecological Performance Indicators (EPIs) which are described by Förster et al. (Förster et al., 2016) in detail (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 (compare

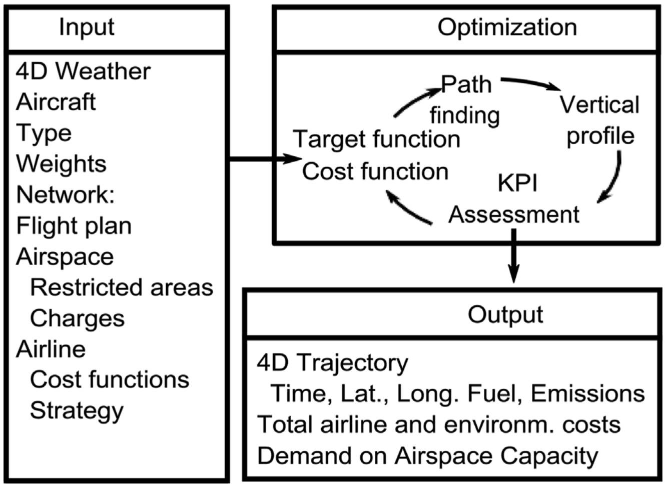

Fig. 1. Workflow in TOMATO simplified to the most important parameters, variables and modules.

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). Table 2 summarizes the most relevant output parameters of TOMATO. The automated trajectory optimization, the parameters Top Of Climb (TOC), Top Of Descent (TOD) and time of flight are used for monitoring. For the post analysis regarding ATFM, separation infringements are counted and analyzed individually. Additionally, the airspace is divided into an artificial grid with the grid size of 1 latitude and 1 latitude. Therein, the number of separation infringements, the number of aircraft and the controller's task load is calculated. Both the trajectories and the assessment is provided as output for further post analyses (compare Fig. 1 and Förster et al. (Förster et al., 2016) for more details), e.g., the identification of separation infringements per time step. The criterion validity of TOMATO could be shown in various applications (Rosenow et al., 2016a, 2016b; Rosenow and Fricke, 2016).

For validation purposes, TOMATO has been compared with the commercial air traffic simulator AirTOp. Therefore, a 24-h European reference scenario has been calculated in TOMATO and AirTOp (Rosenow et al., 2018). The results were evaluated for the following parameters: Number of separation infringements, time of flight, distance flown, fuel burn and controller's task load, which were in the same order of magnitude in both simulations (Rosenow et al., 2017c).

2.2. *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 European IATA fuel price monitor (Online. Available: http:b) from December 2016 and is set constant to 0.502 euros per kilogram Jet A1 plus 20% handling costs. Flight dependent costs include cost factors such as crew salaries, maintenance costs, deprecation rates and direct or indirect compensations for delays when necessary (Förster et al., 2016). Airport and en-route charges for using the air navigation services by EUROCONTROL are also implemented (Lindner et al., 2016). Any kind of airspace restrictions can be formulated and activated as polygons. A common en-route charging regime with uniform unit rates as intended by the SES, for example FAB-EC (FAB Europe Central), can be used in TOMATO.

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

2.3. *Assessment of the environmental impact: EPI*

For the evaluation of the environmental compatibility of aviation, the main emissions are quantified according to current scientific state-of-the-art technology. Products of complete combustion such as carbon dioxide CO_2, water vapor H_2O, sulphate SO_4 and sulphuric acid H_2SO_4 are quantified as a linear function of fuel flow (Lee et al., 2010). Emissions of nitrogen oxides NO_x, hydro-carbons HC and carbon monoxide CO are estimated following the Boeing-2 fuel flow method (Schäfer, 2006) which depends on fuel flow, thrust setting and measured reference values estimated by the International Civil Aviation Organization (ICAO) (International Civil Aviation Organization, 2016). 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 Kugele et al. (2005).

The cost-based assessment of the emissions according to their impact on global warming is quantified by the Global Warming Potential (GWP) (Lee et al., 2010), a measurement 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. In 2005 global climate analyses have show that of the total aviation CO2 emissions in the same year, aviation induced contrails contributed as much as 21% to global warming (Lee et al., 2010). Approximately 10% of the total number of flights are inducing contrails (Spichtinger, 2004). Hence, aircraft flying through ice-supersaturated regions are additionally burdened with a reference value of 32 tons of CO_2 equivalent emissions per hour (Rosenow et al., 2016a). This reference value is adapted depending on the time of the day (compare Section 2.5). The CO_2 equivalent emissions are converted into monetary values by using the European Emission Trading System (ETS) and by assuming a price of 65 euros per ton of CO_2 equivalent emission.

2.4. *Radiative forcing of contrails depending on time of day and flightpath*

The radiative forcing of contrails as an induced imbalance of the Earth's atmospheric energy budget depends on the position of the sun relative to the spatial orientation of the contrail (Rosenow, 2016). This relationship can be described by the time of day and by the aircraft direction (i.e., the flight path). The imbalance of the energy budget mainly originates from two processes. Firstly, from the scattering of the solar radiation with a cooling effect and secondly, from the absorption of terrestrial radiation with a warming effect. During the 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.–7 a.m.) and sunset (5 p.m.–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 (Rosenow, 2016). Hence, flights producing those contrails are punished with 110% of the reference value. During the day (7 a.m.–5 p.m.), the cooling effect will be at its maximum and flights are punished with 90% of the reference value. Although some research studies estimate an average cooling effect of contrails during the day (Va'zquez-Navarro et al., 2015), the net effect of individual contrails strongly depends on contrail lifetime and contrail microphysical properties, such as particle size and shape (Rosenow, 2016). For this reason and for increasing the importance of contrail costs in the trajectory assessment, flight inducing contrails during the day are punished anyway.

2.5. *Methodology of identifying separation infringements*

Despite the high costs of analyzing each individually optimized trajectory, the influence of trajectory optimization on airspace capacity is very important for meeting the safety demands of the simulation. In the first studies using TOMATO, only the position of the aircraft within a grid with a spatial resolution of 0.1 degrees (resulting in three to five nautical miles, depending on latitude) had been analyzed (Rosenow et al., 2017a, 2017b). In this paper, however, the trajectories are analyzed with respect to separation infringements, number of aircraft and distance flown during the infringement and the duration and location of the infringement. Thereby each trajectory has been analyzed individually and each infringement (which is defined as a loss of separation of 5 nautical miles in the lateral and 1000 feet in the vertical direction) has been followed until the separation between the aircraft exceeds the defined infringement separation requirements.

3. TOMATO input data

3.1. Flight plan

Twenty-four hours of Europe's air traffic are simulated using a flight plan from EUROCONTROL Demand Data Repository (DDR2). The data contains 33 816 flights coordinated by the Network Manager Operations Center (NMOC, previously called CFMU) (Online. Available: http:c). Beside flights to and from European airports, overflights 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 pcruise = 376 hPa (FL 250) are removed from the simulation. As the target function could not be estimated for each time step of all of the flights due to some numerical issues, a total number of 13 584 flights with identical departure, arrival and departure time for each scenario were successfully calculated and assessed within all three scenarios. Only those flights are assessed and post-analyzed with respect to separation infringements and then compared to the three scenarios. Nevertheless, it is assumed that a realistic simulation has been chosen, representing enough aircraft movement for an applicable proof of separation infringements along optimized free routes. The simulated trajectories and their influence on airspace capacity and controller's task load are discussed in Rosenow et al., 2017a, 2017b. 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. Unfortunately, speeds are not provided. The vertical discretization of the flight plan amounts to 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 is 40 NM. The mean lateral resolution is less than 3 NM during climb and less than 10 NM during descent.

Except for the amount between day and night traffic, an analysis of the flight plan yields no significant diurnal variation (Fig. 2) because of the multiple time zones within Europe spanning from Russia (GMT + 5) to Portugal (GMT-1). A high number of short haul flights, namely 9673 (26% of all flights), are shorter than 500 km.

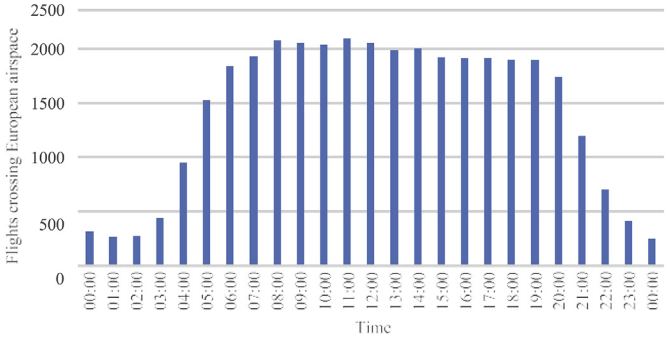

Fig. 2. Number of simulated Flights over Europe on July 25th, 2016 as a Function of Greenwich Mean Time in Intervals of one Hour.

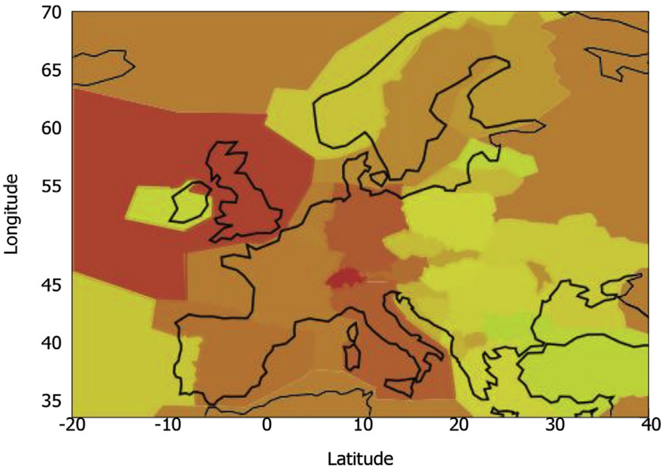

Fig. 3. Heat Map of Implemented En-route Charges for all EUROCONTROL Member States in January 2017. Unit Rates between 10 euros (yellow) and 100 euros (red) are considered in TOMATO. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.2. Airspace structure

En-route charges in European airspace are calculated depending on the distance flown above each EUROCONTROL member state. For the current case study, the current EUROCONTROL unit rate charging regime has been implemented.

Fig. 3 shows a heat map representing the unique en-route charging unit rates assigned in each member state in January 2017. In the current study, airspace restrictions as well as the current route and waypoint structure have not been implemented.

3.3. Fleet

The aircraft to flight assignment is obtained from the given flight plan. In total there are 16 aircraft types implemented in COALA. Aircraft with turboprop engines and other, not implemented aircraft types are represented by the best equivalent turbofan aircraft implemented in COALA, which in most cases are the E170, E190 and CRJ9 for short haul flights. If a given aircraft subtype matches the implemented COALA aircraft type, the flight will be optimized using this aircraft performance data. In total, 70% of the original aircraft assignment has been maintained.

Aircraft payload is normally distributed around a typical aircraft specific seat configuration.

3.4. Weather data

Corresponding to the flight plan, weather data from July 25th, 2016 were chosen since this day showed typical weather for the summer in the Northern Hemisphere (relatively small and fast moving ice-supersaturated regions offering re-routing possibilities (Spichtinger et al., 2003)). Furthermore, a realistic drift of the ice-supersaturated regions from north to southeast is assured due to the global circulation distracted by the Coriolis force (Kraus, 2001). Weather data was extracted from Grib2 data distributed by the National Centers for Environmental Information, NESDIS, NOAA, U.S. Department of Commerce (National Oceanic and Atmospheric Administration, 2016). Weather data was only provided with a timely resolution of 6 h. Because TOMATO cannot handle dynamic effects during lateral path finding, the weather data set closest to the departure time of the flight was chosen and set constant over the whole flight. Fig. 4 gives an impression of the size and location of the ice-supersaturated regions at a constant pressure level.

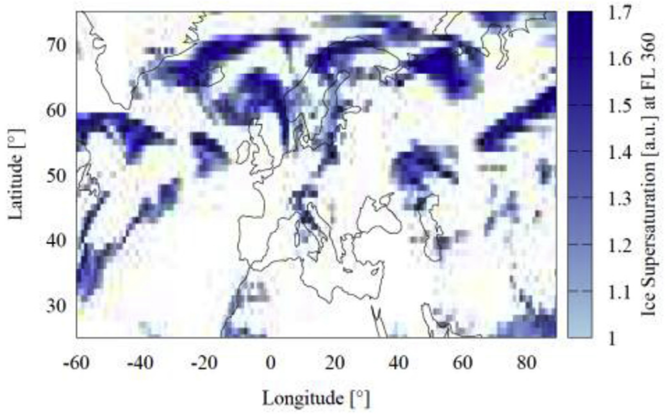

Fig. 4. Size and Location of Ice-Supersaturated Regions (blue) above Europe on July 25th, 2016 at 12. a.m. at FL 360 which should not be passed by Aircraft in Order to Avoid Contrail Formation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4. Modeling results

4.1. Airline efficiency

For each scenario, the trajectories have been calculated, optimized and analyzed one by one. A comparison of the simulated scenarios has been done for the sum of all trajectories on the day of each scenario (compare Table 3). Therewith, the impact of our free routing involving optimizing safety, environment and airline efficiency can be shown. Non-optimum cruising altitudes, waypoint induced detours and non-wind optimal flight paths in the reference scenario cause high direct operating costs (CPI) and high environmental costs (EPI); these originate from unknown air speeds and a course spatial resolution of the underlying flight plan (compare Section 3.1). Furthermore, overfly charges are calculated according to the tracked path which might deviate from the planned path used for charging in today's operations. Non-optimum speeds and altitudes might also lead to overestimations in fuel burn due to model restrictions of COALA (e.g., COALA solves the dynamic equation of motion for a point mass model). The weather data in TOMATO was observed and the modeled data by the Global Data Assimilation System (GDAS) was used and therefore may not represent the exact situation of that day. Finally, the costs probably do not represent realistic airline numbers and the values are only used for comparability. The number of separation infringements in the reference scenario is caused by unknown air speeds which have been replaced by optimized ones. Both EPIs and CPIs could therefore be significantly reduced during the free routing, cost-minimum optimization (CPI and EPI were reduced by 39.77% and 73% respectively) even when contrail formation sensitive areas (ice-supersaturated layers) are subjected to high costs in the lateral path finding. Still, CPI and EPI were reduced by 39.49% and 75%. By minimizing contrail formation contrail costs could be reduced by $1.13\,10^{6}$ euros, resulting in $1.51\,10^{4}$ euros higher fuel costs. The number of separation infringements is minimal in the airline cost-minimum scenario. Here the trajectories are well distributed in the airspace because each aircraft is flying along its cost-minimum trajectory with its optimum air speed. However, due to equal target functions in the trajectory optimization per scenario (e.g., optimum utilization of wind fields, consideration of ATC overfly charges, eventual avoidance of ice-supersaturated layers, etc.) and similar aerodynamic and technical aircraft properties, aircraft follow similar routes in the optimized scenarios. Thereby, a more uneven statistical lateral distribution of aircraft within the used airspaces can be detected in the optimized scenarios compared to the real flights (Rosenow et al., 2017a).

Table 3
Assessment of all simulated scenarios. The number of separation infringements is subdivided in short and long separation infringements, which are dissolved within a range of more or less 10 nautical miles respectively. Although contrail costs are already included in epi, they are listed separately, indicating that epi excluding contrail costs would be minimal in the cost-minimized scenario. Note the costs of the reference scenario may not represent realistic airline costs as explained in section 1 and section 4.1.

Scenario	Reference Flights	Cost Minimized	Contrails Considered
Separation Infringements			
< 10 NM	12020	9566	10498
> 10 NM	3631	1101	1400
Total	15651	10667	11898
EPI [euros]	$7.10\,10^{7}$	$1.91\,10^{7}$	$1.81\,10^{7}$
CPI [euros]	$3.47\,10^{8}$	$2.09\,10^{8}$	$2.10\,10^{8}$
Contrail Costs [euros]	$4.42\,10^{6}$	$3.59\,10^{6}$	$2.46\,10^{6}$
Fuel Burn [kg]	$7.647\,10^{7}$	$6.210\,10^{7}$	$6.213\,10^{7}$

Network efficiency, number, location and duration of separation infringements within the European airspace are investigated. The definition of separation infringements has been discussed in Section 2.5 (5 nautical miles laterally and 1000 feet vertically). The temporary distribution of separation infringements correlates with the timely variation of the number of flights over Europe (compare Figs. 2 and 5). Table 3 contains the number of separation infringements and distinguishes between longitudinal separation infringements which have not been resolved within 10 nautical miles and short separation infringements which have been resolved within 10 nautical miles. Remember, no conflict management has been implemented into TOMATO as of now. The infringements are resolved due to different trajectories.

In Table 3 a large number of separation infringements can be detected, especially in the reference scenario whose trajectories are constrained by the ATS route. Most of the infringements are resolved within 10 nautical miles (76%, 89% and 88% in the reference, cost-minimized and contrails-considered scenario). The higher number of longitudinal separation infringements in the reference scenario might be caused by AIP waypoint constraints which force aircraft to follow identical routes. Furthermore, due to missing data in the reference flight plan, the true air speeds for simulating the reference scenario are calculated with TOMATO following a maximum specific range. Therewith, the speeds in our reference scenario fluctuate, which is highly unrealistic and causes a significantly higher number of separation infringements.

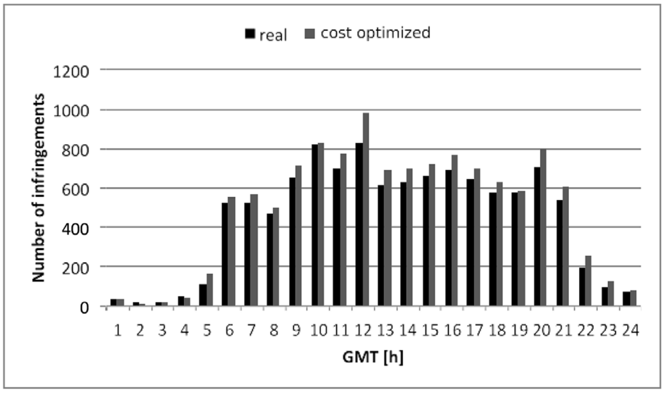

Fig. 5. Number of Separation Infringements per hour over the day (GMT) in the Reference Scenario (black) and the Cost-minimized Scenario (gray). A Weak Correlation to the Number of Flights over Europe (Fig. 2) can be Identified but with more Distinctive Morning and Afternoon Peaks due to More Departures in Central Europe at these Times.

Within the cost-minimized scenario, the number of separation

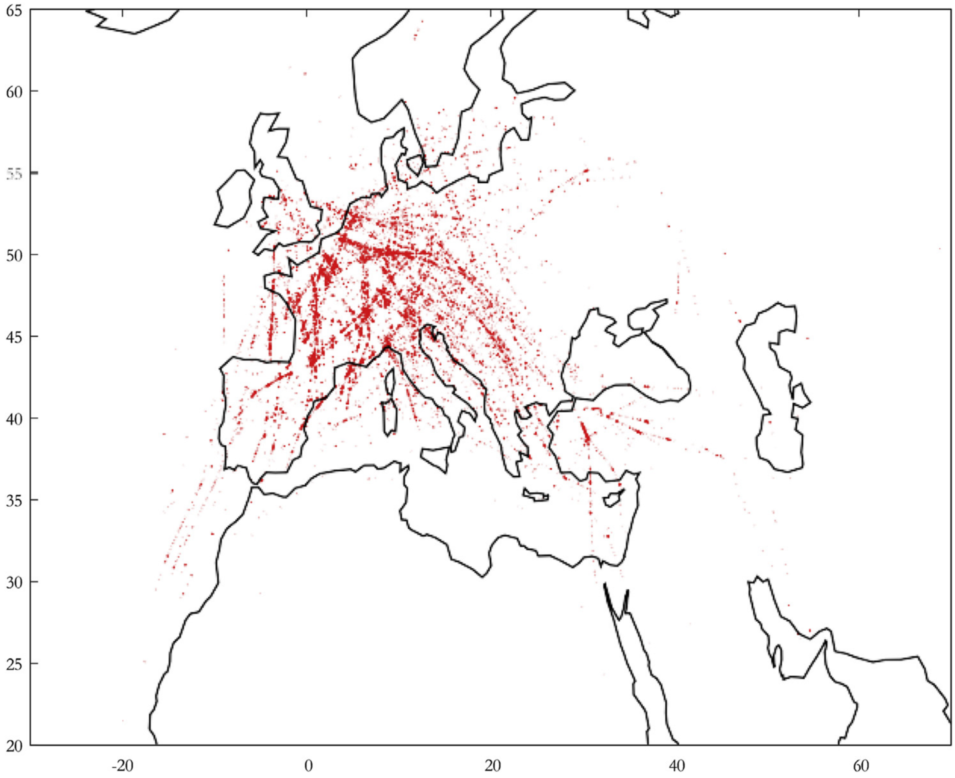

Fig. 6. The Reference Scenario: Simulated Separation Infringements (red) between 13 584 Flights over Europe on July 25th, 2016. The Trajectories are simulated along a Real SO6 m3 Flight Plan defining Departure, Destination, Departure Times, Waypoints, Altitudes and Aircraft Types. A large Number of Separation Infringements (15 651) are caused by AIP Waypoint Constraints and by Unknown True Air Speeds which are replaced by Optimized Airspeeds Calculated with the Flight Performance Model COALA. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

infringements decreased by 32% from 15 651 separation infringements in the reference scenario to 10 667 in the cost-minimized scenario; compare Table 3. This is 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 without constraints due to a waypoint-based trajectory management.

When contrail formation needs to 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 separation infringements in the third scenario, which was only reduced by 24% compared to the reference scenario; compare Table 3. Plus, narrow “airways” of separation infringements can be detected (Fig. 8). Especially when considering the growing demand for

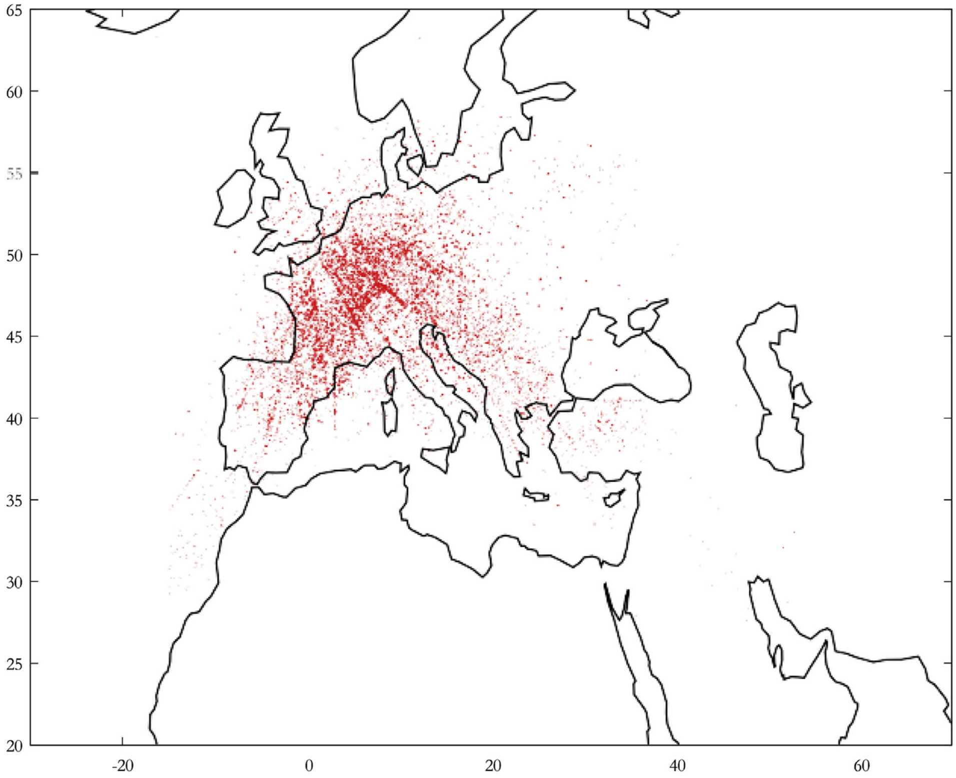

Fig. 7. Separation Infringements (red) between 13 584 Multi-Criteria Opti-mized Trajectories during 24 h over Europe on July 25th, 2016 Without the Intension of Avoiding Contrail Formation. Departure, Destination and Departure Times are taken from the SO6 m3 Flight Plan by EUROCONTROL and are Identical with the Flights in the Reference Scenario. Compared to the Reference, Non-Optimized scenario (Fig. 6), a smaller Number of Separation Infringements (10 667) are generated due to More Evenly Distributed Trajectories over the European Airspace. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

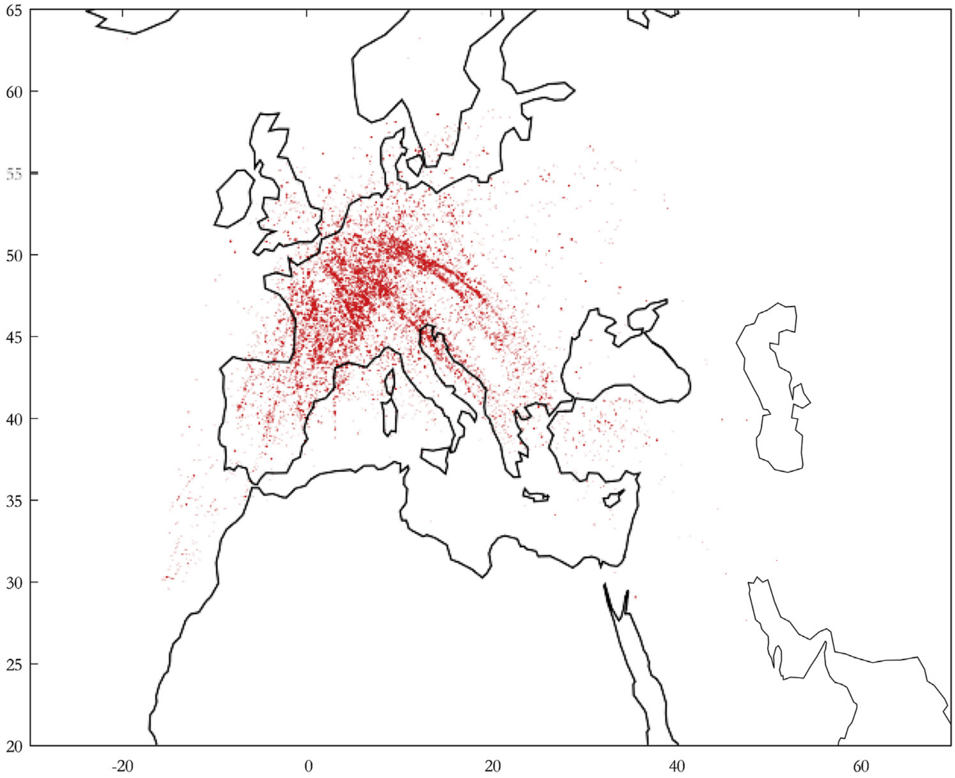

Fig. 8. Simulated Separation Infringements (red) between 13 584 Multi- Criteria Optimized Trajectories over Europe on July 25th, 2016 considering expensive Contrail Formation in the Lateral Path Finding. Departure, Destination and Departure Times are taken from the SO6 m3 Flight Plan by EUROCONTROL. Due to Expensive Ice-Supersaturated Regions, which are intended to be avoided, 11 898 Separation Infringements (10% more than in the Cost-Minimized Scenario but 24% less than in the Reference scenario) are generated over the entire day. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

air traffic, it can be concluded that contrail formation will not always be avoidable.

4.2. Longitudinal separation infringements

In order to understand the large number, the separation infringements are analyzed according to their duration, location and distance flown in conflict. As shown in Table 3, only a small fraction was identified as longitudinal infringements (longer than 10 nautical miles). Those longitudinal infringements are longest within the reference scenario (distances are twice as long and the duration of the infringement is more than twice as long; compare Figs. 9 and 10). Considering only longitudinal separation infringements, mean values of the distances flown in conflict are 96, 49 and 63 nautical miles in the reference, cost-minimized and contrail-considered scenario. Meanwhile, the mean duration of two aircraft flying below the separation requirement is 16, 6 and 8 min in the reference, cost-minimized scenario and contrail-considered scenario. These measures show the significant influence of contrail avoidance on trajectory optimization. Since it is hard to predict the locations of ice-supersaturated layers, the efficiency of rerouting around those layers should be scrutinized. Just the same, enforced waypoints or routes are not recommendable when aircraft are required to fly with optimized, non-constant speed in order to increase airline efficiency and reduce the aviation ecological impact.

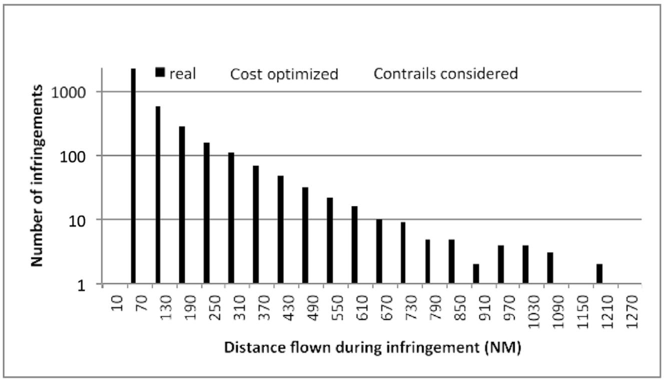

Fig. 9. Number of Longitudinal Separation Infringements over Distance flown during Conflict. Trajectories within the Reference Scenario (black) are Longer (up to 2000 nautical miles) in Conflict than the Optimized Ones (maximum 1000 nautical miles, orange and gray).

4.3. Short separation infringements

As pointed out, aircraft which share an identical route over a long distance do not cause most of the separation infringements. In the reference scenario, a successful conflict management is assumed for avoiding this hazard. The generated separation infringements in our simulation are caused by non-constant speeds.

In the optimized scenarios, identical trajectories are very unlikely because each aircraft is allowed to fly along its optimized lateral and vertical route. Nevertheless, the question arises as to whether the large number of infringements is caused by two identical aircraft coming too close again and again or whether different aircraft pairs mainly cause the infringements. This is the reason why the short separation infringements are analyzed with respect to the number of infringements per aircraft and the number of aircraft which are in conflict with a single aircraft. Fig. 11 shows that most of the aircraft are involved in only one or two separation infringements during the whole flight, but in the reference scenario, aircraft are involved in up to 17 infringements during the flight. Still, no recurring separation infringements between an identical aircraft pair could be identified. From this follows that most separation infringements are caused by different aircraft pairs, which is a challenge for the conflict management.

More significant differences between the scenarios are detectable when considering the altitude where separation infringements are generated. Due to optimized cruising altitudes with respect to a maximum specific range (Rosenow and Fricke, 2016), aircraft fly in higher altitudes in the optimized scenarios (Fig. 12). Ac- cording to an underlying conflict management of the reference scenario, separation

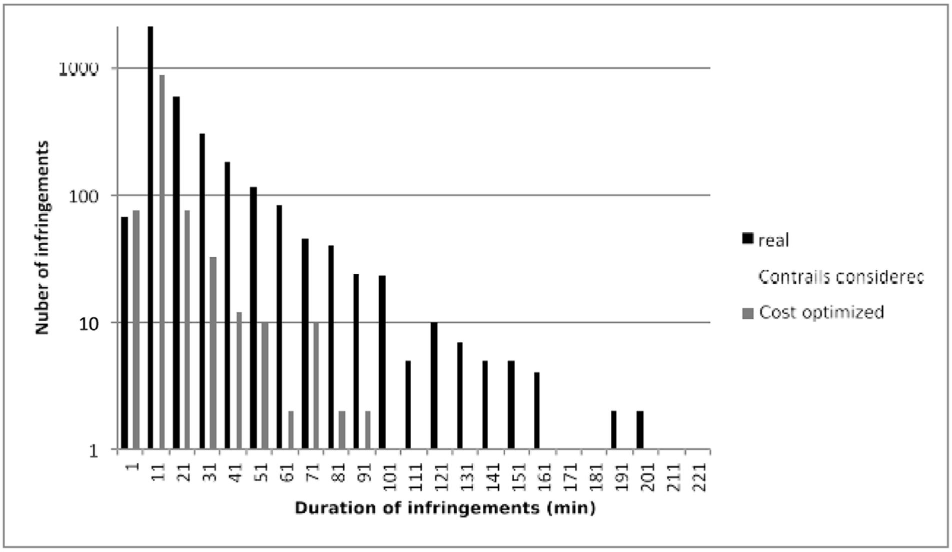

Fig. 10. Number of Longitudinal Separation Infringements over the Duration of Conflict. Trajectories within the Reference Scenario (black) are Longer (maximum 2000 min) in conflict than the optimized ones (maximum 870 min, orange and gray).

infringements are distributed over a wider altitude range whereas optimized trajectories are concentrated on a narrower range of conflict-ridden altitudes. This is an interesting fact considering the smaller number of separation infringements in the optimized scenarios. As a consequence, although optimized trajectories are concentrated on a small range of cruising altitudes, their better lateral distribution shows the potential of increasing future airspace capacity when free routing would be possible.

5. Summary

Three air traffic scenarios, each with a specific target function, have been simulated with TOMATO. Using the output parameters listed in Table 2, the scenarios are assessed and compared with each other on three different levels. The analysis of the 4D trajectories provides an insight on differences in speed, altitudes, climb and descent angles and lateral paths resulting from specific target functions.

The comparison of the trajectory assessment integrated over all trajectories of each scenario (Table 3) enables the most efficient, the safest (regarding the potential of separation infringements) and the most ecologically friendly scenario to be identified. With the assessment, the impact of high contrail costs during path finding on fuel flow and the number of separation infringements could be identified. By saving $1.13\,10^6$ euros in contrail costs, higher fuel costs of $1.51\,10^4$ euros and 1231 more separation infringements have to be accepted.

Note these results are strongly affected by the assumptions of several cost indicators which in reality are far more heterogeneous and dynamic. For example, non-dynamic costs for fuel, fuel handling, CO_2 in the ETS, crew (e.g., steward and pilot and supplements for delays), ATC en-route charges and airport charges are assumed and therefore do not represent a realistic airline operation procedure. However, these assumptions are kept constant for all scenarios. Hence, a relative comparison of the results is possible.

With the ATFM post-analyzing tool of TOMATO, the dynamics of the number of separation infringements along the day of operation could be evaluated (compare Fig. 5). Thereby, no surprising anomalies

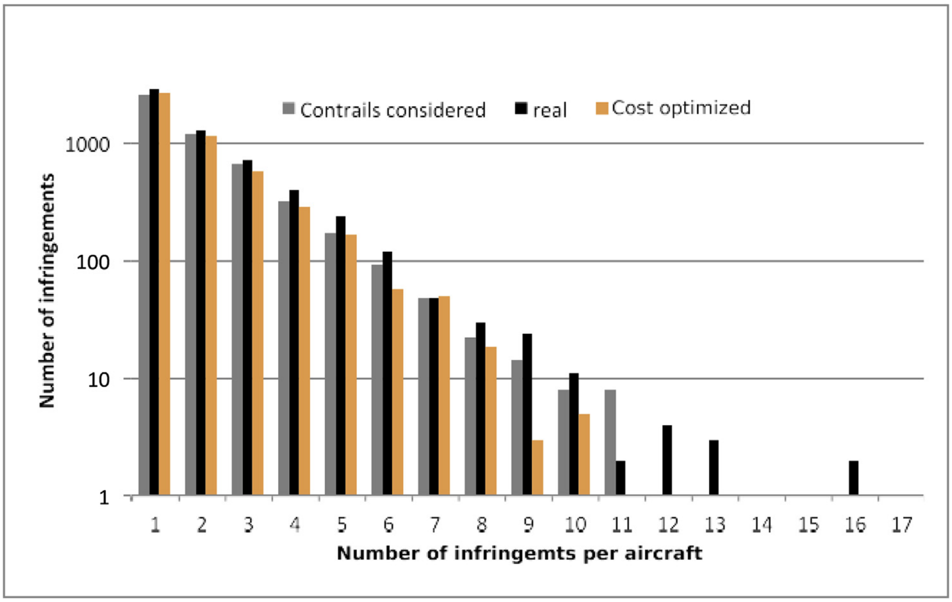

Fig. 11. Number of Separation Infringements per Aircraft. Most of the Aircraft are involved in only a Single Conflict during the Whole Flight.

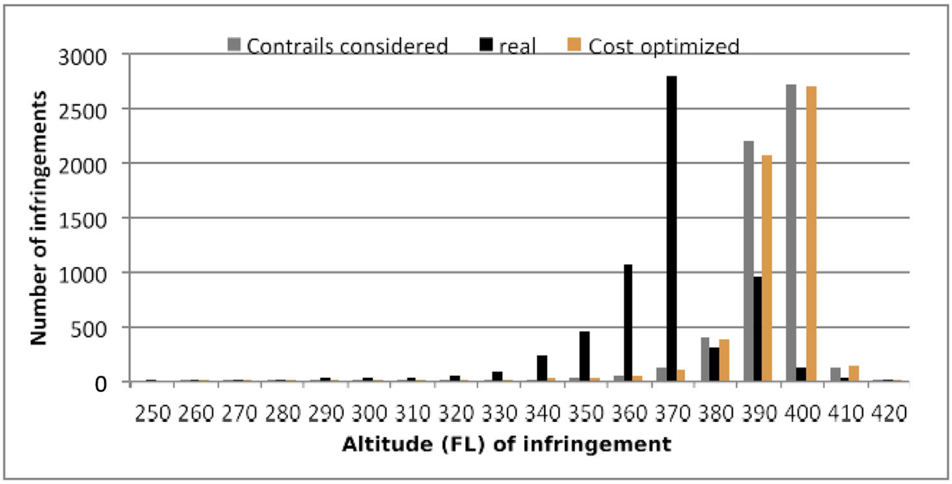

Fig. 12. Number of Separation Infringements over altitude (FL). Higher Cruising Altitudes in the Optimized Scenarios cause higher Altitudes of Separation Infringements. Trajectories within the Reference Scenario (black) are distributed to a wider range of Altitudes during Cruise.

could be identified. With the increasing number of aircraft movements, the number of separation infringements increases as well. The distribution of separation infringements integrated over the entire day of operation localizes the airways between waypoints in the reference scenario (Fig. 6) and preferred airspaces between ice-supersaturated layers in the contrail-avoidance scenario (Fig. 7) whereas the cost-minimized, unrestricted-free-route scenario (Fig. 8) is best distributed over the entire European airspace. In general, the number of separation infringements correlates with the number of aircraft in an artificial airspace (compare Fig. 12). The number of longitudinal separation infringements as function of the distance flown in conflict (Figs. 9 and 10) yield more long-distance separation infringements in the reference scenario due to stringed aircraft along the airways between AIP waypoints. Furthermore, it is for this reason that the number of separation infringements per aircraft is at its maximum in the reference scenario (compare Fig. 11) whereas permanent path deviations in the optimized scenario lead to a small probability of a recurring separation infringement for each individual aircraft.

6. Conclusion and outlook

With the air traffic simulation environment TOMATO, the simulation and evaluation of a complex, 24-h traffic scenario over a entire continent is possible. The total number of 13 584 flights could be optimized with respect to cost functions for direct operating costs, fuel costs, environmental costs and ATC 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 in order 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 (SESAR Joint Undertaking, 2015) will lead to increased airline efficiency (because optimized trajectories are subject to reduced direct operational and ecological costs) and to increased network efficiency (because optimized trajectories are better distributed laterally in the airspace). This conclusion is based on flying laterally and vertically optimized trajectories while considering wind speed and wind direction and also the environmental compatibility. The intention of avoiding contrail formation often results in a higher probability of separation infringements due to enforced rerouting around ice-supersaturated layers. Nevertheless, these results are strongly weather dependent. Depending on the number and size of the ice-supersaturated regions and as airlines attempt to avoid the high costs of forming contrails, narrow airway corridors could result as a consequence. Considering this complexity and comparing historical flight paths with the optimized ones, a high potential in multi-criteria trajectory optimization and cost savings could be identified.

In order to reduce the aviation ecological impact and to increase airline efficiency, free routing should be implemented and solutions for reducing controllers' task, which are induced by inconstant speed, load should be developed. Beside the negative effect on controller's task load due to non-constant speed, we found that the controller's task load might be reduced in the optimized scenario due to more widely distributed trajectories (Rosenow et al., 2017a). However, similar targets in the trajectory optimization sometimes result in similar (wind-optimized) trajectories in the vicinity of strong wind fields. Hence, the optimized scenario may include a more imbalanced dispersion of aircraft in used airspaces (Rosenow et al., 2017a), but it still has less separation infringements and less overloaded airspaces.

However, enforced waypoints are not recommendable when aircraft fly with their optimized, non-constant speed in order to increase airline efficiency and reduce the aviation eco-logical impact. Optimized trajectories have the potential of self-separation due to aircraft specific optimized trajectories. Because the optimized trajectories are concentrated on a narrower range of cruising altitudes and still have a lower conflict potential, there is a promising potential of increasing the airspace capacity by introducing optimized free route trajectories.

Although the shape of separation infringements in Figs. 6–8 suggest several consecutive separation infringements between identical aircraft pairs along long distances (i.e., longitudinal separation infringements), our analysis show that in the cost minimized scenario, 89% of all separation infringe-mints between two aircraft are resolved within 10 NM and are generated between different aircraft pairs.

The air traffic simulation environment TOMATO is the first module that can be used by both airlines for trajectory optimization and by ATC for the visualization of the exact airline inquired trajectories and for the indication of areas with high potential of separation infringements. The identification and analysis of separation infringements and aircraft involved in those separation infringements is the first step towards full conflict management which will iteratively avoid those infringements during trajectory optimization. Therefore, the identified positions of separation infringements will be considered during lateral and vertical path finding. In the second step, we aim to further develop TOMATO into a satisfactory decision support system before concentrating on the air traffic flow simulation by considering airport slot planning. The implementation of dynamic input parameters, especially in the lateral path finding, will improve the optimization in the third step.

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