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

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

I. Introduction

THREE performance goals, as set out by the Next Generation Air Transportation System [1] and Single European Sky ATM Research Programme (SESAR) [2], must be considered in studies of the air traffic system. These are safety, efficiency, and environmental compatibility. For the en route phase, safety is mainly set by separation requirements. Efficiency is measured by a variety of metrics such as airport capacity utilization and great circle deviation. From the economic side, air navigation costs, flight time, fuel burn [2], and depreciation charges push airlines to achieve high efficiency levels. The aviation environmental impact can in part be assessed by the amount of the aircraft engine emissions and their impact on global warming and human health. Additionally, condensation trails (contrails) with a significant influence on global warming (i.e., radiative forcing) need to be considered [3]. Contrails form in the presence of ice-supersaturated regions [4], which are dynamic layers in the upper troposphere and lower stratosphere. To avoid contrail formation, aircraft would need to bypass these ice-supersaturated regions either laterally or vertically [4], hampering flight efficiency because detours and nonoptimum flight profiles cause extra flight time and fuel burn [5]. Differences in overfly charges and air navigation charges similarly encourage detours relative to lateral trajectory optimization. In short, competing objectives must be considered in evaluating trajectories [5]. This leads to an important question: Will trajectory optimization lead to an increased pressure on airspace capacity because similar optimum vertical and lateral trajectories might be expected, or will highly aircraft specific flight performance characteristics lead to well-distinguishable trajectories with a resultant positive impact on air space capacity?

To find such multicriteria optimum flight paths, which satisfy airlines and air traffic flow management (ATFM) constraints, a highly accurate single aircraft trajectory and air traffic flow prediction are required. Until now, these aspects have been treated separately from air traffic control (ATC), ATFM, or network optimization perspectives due to the complexity and the high computational effort. Toolchain for multicriteria aircraft trajectory optimization (TOMATO) software has been developed to deal with this challenge without coarse approximations in trajectory calculation. TOMATO uses a flight performance model [5,6] independent of 2.5D base of aircraft data (BADA) performance tables.

Several air traffic flow simulation environments have been developed before TOMATO, and they were all limited to the present research question. On the one hand, the fast time air traffic simulator software, AirTOp, generated trajectories in a dynamic airspace structure and iteratively considers conflict detection and conflict resolution [7]. AirTOp had been already applied to rerouting around volcanic ash clouds [8] and to estimating the influence of restricted airspace on the air traffic system [9]. However, due to approximations in the aircraft performance modeling (which was 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 did not consider precise trajectory optimization.

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

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

At the other end of the spectrum, the airspace simulator total airspace and airport modeler (TAAM), developed by Preston Aviation Solutions (a Boeing subsidiary) [14] is able to simulate air traffic flows in the ISA. TAAM is a large-scale and fast time simulation model, and it is designed to simulate all possible aspects of ATC (ground and en route) during all phases of flight. However,

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TAAM is restricted to the ATC routing structure and cover neither the individual flight profiles nor the lateral free routes [15]. Finally, a more precise consideration of the flight performance modeling and optimization is realized in the commercial flight-planning tool, Lido/Flight 4D, developed by Lufthansa Systems, with unknown details and precision [16].

Thus, in contrast with the previously described simulation systems, TOMATO is the first air traffic simulation environment respecting the impact of individually and accurately free route multicriteria-optimized trajectories on the ATFM. This paper takes advantage of this capability using TOMATO to calculate and compare three air traffic scenarios. First, the reference scenario consists of recalculated radar-tracked four-dimensional (4-D) trajectories, specifying the tracked waypoints and altitudes of each aircraft. Second, a cost-minimized scenario is simulated, considering minimum cost performance indicators (CPIs) and minimum ecological performance indicators (EPIs), with the exception of contrails. In recognition that emission-induced EPIs are sensitive to long detours, which are often necessary for contrail avoidance [17], the impact of contrails is considered in the multicriteria trajectory optimization.

II. Properties and Workflow of TOMATO

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

As a second step, a vertical flight profile is calculated along that path, using the aircraft performance model COALA (which stands for compromised aircraft performance model with limited accuracy), which was described in more detail by Rosenow et al. [17] and Rosenow and Fricke [18]. COALA numerically solves the dynamic equations and uses target functions to calculate optimized flight-path angles γ, speeds v_{TAS}, and altitudes p at each time step. A proportional plus integral plus differential controller is used to gain those values, mainly by controlling the lift coefficient c_A, because it influences all accelerating forces. Several boundary conditions are

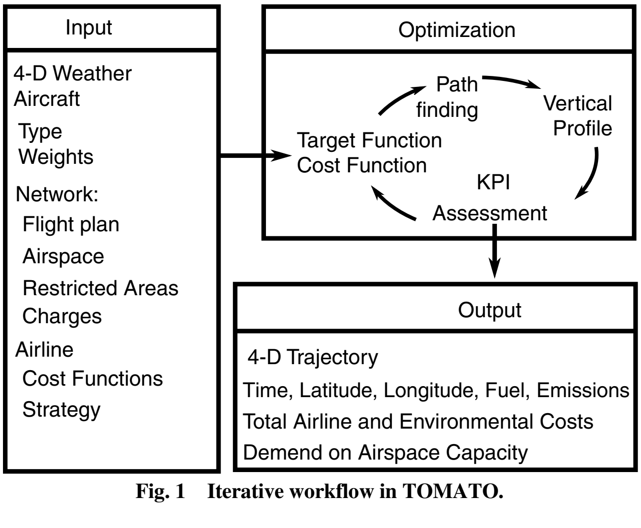

Fig. 1 Iterative workflow in TOMATO.

implemented to respect flight envelopes. The state variable speed, flight-path angle, altitude, and thrust are restricted to an aircraft-type specific codomain. The following input variables are tested for validity: the aircraft mass, (payload and fuel load cannot exceed aircraft type specific maxima), the distance between the departure and the destination, and the altitude (if predefined). Validity tests are included in the assessment: The trajectory will only be accepted if the aircraft reaches the destination airport, the cruising altitude is reached, and the top of climb is before the top of descent. The flight performance model comes together with an engine model to determine detailed performance (e.g., fuel flow) and emission data for each time step during the flight.

This optimization is done in a real three-dimensional workspace. This distinguishes TOMATO from $2.5D$ simulations, which are used by airlines today, in which fixed steps for altitude changes and level flights are often restricting the solution space. The assumption of a free route airspace allows the employment of unconstrained, continuous cruise climb operations [17].

After both optimization steps, the trajectory is assessed in terms of many different key performance indicators (KPIs) composed of cost performance indicators and ecological performance indicators, which were described in detail by Förster et al. [6] (compare Sec. II.A and Fig. 1). After the assessment, the determined performance and cost data are available for the next iteration step with benefits especially for the lateral path calculation. TOMATO iteratively considers target functions and cost functions, derived from the input parameters, and estimates the required fuel mass by varying the input parameters after each assessment step at the end of each iteration step (compare Fig. 1). With the KPI assessment, a multicriteria optimization is possible due to the use of cost functions, for which the results are assessed after each iteration step (Fig. 1). That iterative optimization process is run until a certain cancellation criteria (i.e., minimum delta that a solution has to improve or a maximum number of iterations) is met. The output makes it possible to further process the calculated trajectories (compare Fig. 1 and [6] for more details). The identification of conflicts per time step is done in a postanalysis of the trajectories. The criterion validity of TOMATO has been shown in various applications [5,6,17–19].

A. Trajectory Assessment

In the following, the main trajectory assessment parameters are introduced to illustrate the multivariability of TOMATO.

1. Trajectory Assessment Regarding Airline Costs

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

Airport and en route charges for using the air navigation services by EUROCONTROL depend on the distance flown over each flight information region, depending on a specific unit rate and the maximum takeoff mass (MTOM) of the aircraft. The departure and en route charges depend on the standardized unit rates [21], which are published monthly by EUROCONTROL [22]. Regions outside the EUROCONTROL area are assigned the mean value of all unit rates. Therewith, detours outside the European observation area (as a possible result of a cost-minimizing lateral path) are avoided. In TOMATO, any kind of airspace restriction can be formulated and activated as a polygon. For example, common en route charging regimes with uniform unit rates [e.g., FAB-EC (which stands for Functional Airspace Block Europe Central)], can be considered.

In this case study, delay costs are not considered. The comparison of the scenarios is mainly driven by costs, depending on flight time or flown distance; whereas costs for maintenance and depreciation

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

CPI		Depending on	Impact on optimization
Fuel costs	$R_{\mathrm{Fuel}} = 0.502$ €/kg	Fuel flow in kilograms per second	Yes
Pilot's salary	$R_{\mathrm{Pilot}} = 96$ €/min	t in minutes	Yes
Steward's salary	$R_{\mathrm{Steward}} = 42$ €/min	t in minutes	Yes
Insurance	$R_{\mathrm{Insurance}} = 0.03$ €/m	d in meters, n_{PAX}	Yes
ATC en route charge	$R_{\mathrm{En\text{-}route}}$	d in meters, MTOM in kilograms	Yes
ATC airport charge	R_{Airport}	MTOM in kilograms	No
Depreciation	$R_{\mathrm{Depreciation}} = 8.1 \cdot n_{\mathrm{PAX}} - 96$	n_{PAX}	No
Maintenance	$R_{\mathrm{Maintenance}} = 2.3 \cdot n_{\mathrm{PAX}} + 309$	n_{PAX}	No

(depending on aircraft type and number of passengers) as well as ATC airport charges (as functions of the MTOM and airport-specific charges), are equal for a single trajectory in each scenario (compare Table 1 for a summary). Here, n_{PAX} refers to the number of passengers in arbitrary units. The trajectories are assessed one by one. In general, the CPIs are twice the EPIs.

2. Trajectory Assessment Considering the Environmental Impact of Jet Engine Emissions

For the evaluation of the environmental impacts, the main emissions are quantified according to the current state of the art. Products of complete combustion such as carbon dioxide (CO_2), water vapor (H_2O), sulfate (SO_4), and sulfuric acid (H_2SO_4) are quantified as a linear function of fuel flow [23]. The emissions of nitrogen oxides (NO_x), hydrocarbons (HC), and carbon monoxide (CO) are estimated by following the Boeing-2 fuel flow method [24] depending on the fuel flow, thrust setting, and measured reference values; and they are estimated by the International Civil Aviation Organization [25]. For soot emissions Black Carbon (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 Ref. [26].

The cost-based assessment of the emissions according to their impact on global warming is quantified by the global warming potential (GWP) [23], which is a measure of the relative effect of the greenhouse gas impact as compared to the impact of CO_2. The GWP of the emissions depends on the latitude and altitude [27–29], which again influence the lateral and vertical trajectory optimization. Thus, converted emissions can be expressed as CO_2-equivalent emissions. The CO_2-equivalent emissions are converted into monetary values by using the European emission trading system and assuming a price of 65 €/t of CO_2 equivalent emission.

3. Trajectory Assessment Regarding Contrail Costs Depending on Daytime and Flight Path

In 2005, aviation-induced contrails contributed as much as 21% to global warming of the total aviation CO_2 emissions [23]. Assuming that approximately 10% of the total number of flights is inducing contrails [30], a rough estimation of contrail contribution to global warming can be made.

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

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

The imbalance of the energy budget mainly originates from two processes: first, the scattering of the solar radiation with a cooling effect; and second, the absorption of terrestrial radiation with a warming effect. During 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 (0500 to 0700 hrs) and sunset (1700 to 1900 hrs) contrails, which are orientated between east and west have the largest heating impact on global warming because solar radiation will radiate through the longitudinal axis of the contrail [3]. Hence, those contrails are assessed 110% of the reference value. During the day (0700 to 1700 hrs), the cooling effect will be maximum and contrails are assigned 90% of the reference value. (Although some research studies estimated an average cooling effect of contrails during the daytime [31], the net effect of individual contrails strongly depends on the contrail lifetime and the contrail microphysical properties, such as particle size and shape [3].)

4. Assessment of Safety Relevant Air Traffic Flow Concerns

Considering safety, the impact of a large number of laterally and vertically optimized trajectories on air traffic density was investigated. Therefore, the lateral distribution of the number of conflicts with a spatial lateral resolution of 0.1 deg (resulting in 3–5 n miles, depending on latitude), a vertical separation of 1000 ft, and a time resolution of 10 s have been analyzed. By simply counting the individual aircraft, which are involved in the conflict cannot be backtracked, but the estimation of the spatial behavior of crowded air spaces allowed statements regarding the air traffic density and on the spatial distribution of aircraft. The number of conflicts was increased (compared to real air traffic operations) due to nonconstant speeds in all three scenarios. This effect was amplified due to nonconstant cruising altitudes during continuous cruise climb operations in the optimized scenarios. Note that no conflict-resolution method was applied to the simulation: not even in the reference scenario. Hence, tactical conflict resolution, as the main task of ATC, was not considered. Therewith, the number of imminent conflicts should not be confused with serious separation infringements. Although short-term conflict resolution does not seem to be the main problem in today's ATFM, the air traffic density mainly influences the airspace complexity; and thereby the controller's task load and ATC efficiency. For that reason, the number of conflicts should be minimized in an efficient airspace structure.

III. Scenario Definition and Input Data

Besides precise weather information, one of the most significant variables in each aircraft trajectory simulation is the aircraft mass. Differences of up to 7% in fuel burn are identified in aircraft trajectory simulations, in which the actual takeoff mass (ATOM) is varied [32,33]. In this case study, individual values of the ATOM are composed of the seat load factor, the initial fuel mass, and the operating empty weight. The seat load factor is normally distributed around a typical aircraft specific seat configuration, which is taken from airplane manuals. A weight of 100 kg per passenger, including baggage, is assumed for the final aircraft payload. The initial fuel mass is calculated iteratively (within five iteration steps) by considering fuel burn and contingency fuel of approximately 10%. The operating empty weight is taken from airplane characteristics; e.g., [34]. With this optimistic assumption, aircraft might be lighter than in reality.

The cost index is considered in the target function for the aircraft speed and flight-path angle. Here, a maximum specific range R_{spec} is desired:

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

where TAS denotes the true air speed (in meters per second), and m_f specifies the fuel flow (in kilogramms per second) (compare with [35]). The resulting speeds are comparatively low and similar to those for minimum fuel burn, i.e., a very low cost index. The flight-path angle during climb is nonconstant and follows a maximum climb rate w (in meters per second):

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

where γ denotes the climb angle. During cruise, continuous cruise climb is implemented, following the optimum speed and altitude for maximum R_{spec} [35].

A. Flight Plan

To simulate 24 h of Europe's air traffic, a flight plan from the EUROCONTROL Demand Data Repository is used [36]. The data contain 33,816 flights, which are coordinated by the Network Manager Operations Centre. Beside flights to and from European airports, flights above the European airspace with a departure and destination in outside the European airspace are also included. Because this study focuses on the upper airspace capacity, flights with a maximum intended cruising pressure altitude beneath $p_{\text{cruise}} = 376$ hPa (flight level (FL) 250) are removed from the dataset. This procedure reduces the dataset to a total number of 13,584 flights, which are distinguishable by the flight identification, which has been successfully calculated and assessed in all three scenarios. The data are given as a So6 m3 file containing departure and destination airports and an aircraft 4-D segmented trajectory (position, altitude, time stamps), and they are synchronized by radar. The vertical discretization of the dataset is restricted to 100 ft (i. e., one flight level), whereas the lateral resolution depends on waypoints and the flight phase. The en route phase resolution can be more than 100 n miles, with 40 n miles on average. The lateral resolution is less than 3 n miles during climb and less than 10 n miles during descent.

The reference scenario in Fig. 2 gives an impression of the traffic flow, which is simulated along the waypoints and altitudes given in the So6 m3 flight plan. This figure indicates that regions with a high potential of conflicts (each indicated by a red dot) are often localized above central Europe. (A conflict is defined as imminent separation infringement of 1000 ft in the vertical and 5 n miles in the lateral direction.)

A further analysis of the flight plan yields no significant diurnal variation (Fig. 3), besides day and night traffic, because of a large number of time zones in Europe between Russia (GMT + 5) and Portugal (GMT − 1). From this insight, it is concluded that Europe's air traffic is evenly distributed throughout the day.

B. Airspace Structure

ATC en route charges in the European air space depend on the distance d flown above each EUROCONTROL member state (see Table 1). For the current case study, today's EUROCONTROL unit rate charging regime $R_{\text{En-route}}$ is implemented. Figure 4 indicates differences in the assigned unique en route charging unit rates between 10.06 €/m above southeast Europe and 106.05 €/m above Switzerland in January 2017. Further airspace structure specific parameters, such as airspace restrictions and today's route and waypoint structure, are not implemented in the current study in favor of a multicriteria free route trajectory optimization.

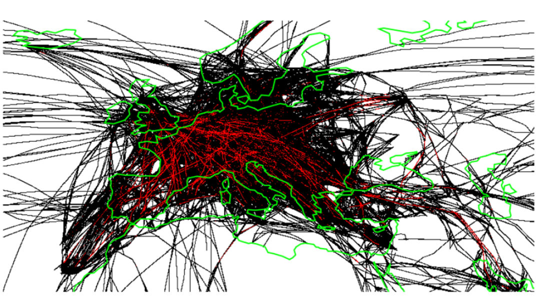

Fig. 2 Simulated trajectories along the navigational aid infrastructure (black) and conflicts (red) in the upper airspace in the reference scenario.

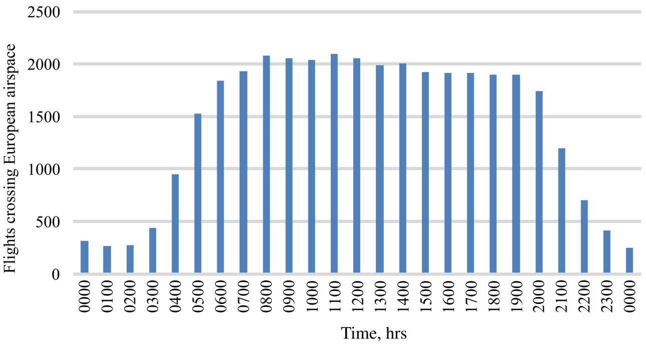

Fig. 3 Number of simulated flights per hour.

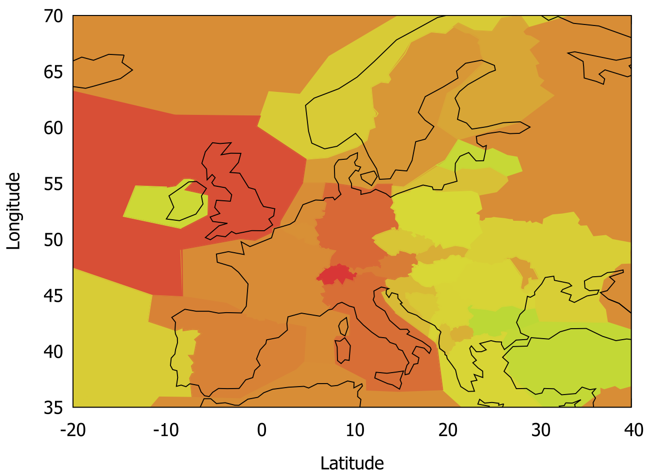

Fig. 4 Heat map of implemented en route charges between 10.06 € (yellow) and 106.05 € (red).

C. Fleet

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

D. Atmospheric Data

Corresponding to the flight plan, weather data from 25 July 2016 were extracted from Grib2 data, which was provided by the National Oceanic and Administration [37]. On that day, a typical situation in summer in the northern hemisphere [38] with relatively small and fast-moving ice-supersaturated regions offered possibilities of reroutings to avoid contrail formation. Furthermore, a realistic drift of the ice-supersaturated regions from north to southeast due to the global circulation affected by the Coriolis force was assured [39]. Weather data were only provided with a temporal resolution of 6 h. The weather dataset closest to the departure time of the flight was chosen and set constant over the whole flight. Figure 5 gives an impression of the size and location of the ice-supersaturated regions above Europe at FL 360 on 25 July 2016 at 0000 hrs, which should not be entered by aircraft in order to avoid contrail formation.

IV. Impact of Multicriteria-Optimized Trajectories on Efficiency, Environmental Compatibility, and Safety

A. Optimization Potential of a Single Trajectory

In each scenario, the trajectories have been calculated and optimized one by one. A comparison of the simulated scenarios can be done, based on individual trajectories (i.e., a single trajectory of each scenario) or based on the whole air traffic scenario (i.e., the sum of all trajectories of each scenario while additionally considering ATFM concerns as conflicts). The comparison of individual trajectories with identical departure, destination, and departure times but different optimization targets (airline cost minimized or multicriteria optimized considering contrail formation) with the reference scenario demonstrates the optimization potential of TOMATO (compare Fig. 6). Following an example of each scenario, lateral paths of trajectories from Gatwick Airport in the United Kingdom to Corfu in Greece, with different target functions, indicate cost benefits in the airline CPI cost-minimized trajectory (green).

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

This is mainly driven by 392€ higher contrail costs. Differences in the lateral path are probably caused by high ATC en route charges above Switzerland (compare Fig. 4), which are avoided in the CPI cost-minimized trajectory. This detour induces contrails (for which costs are not considered in this cost-minimizing optimization), and therewith higher EPI costs (compare Table 2 and Fig. 6). Note that the reference scenario has been assessed according to the radar-tracked flight path. It can be assumed that the flight was planned around Switzerland and, accordingly, lower ATC en route charges were paid.

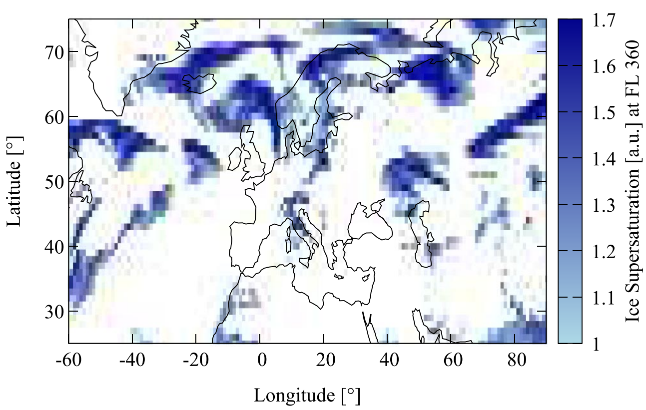

Fig. 5 Ice-supersaturated regions (blue) above Europe at FL 360 on 25 July 2016 at 0000 hrs (a.u. = arbitrary units).

Table 2 Assessment of A320 trajectories between Gatwick and Corfu using different target functions[a]

Scenario		Reference	Cost minimized	Multicriteria optimized
Total costs, €		23,570	20,464	20,178
EPI, €		1,554	1,744	1,255
Between Gatwick and Corfu	Contrail costs, €	93	485	0
CPI [€]		22,016	18,901	18,923
Between Gatwick and Corfu	Fuel costs, €	2,976	2,555	2,548
	Crew salaries, €	974	850	848
	Insurance costs, €	10,301	9,048	9,026
	ATC costs, €	2,330	1,703	1,760
Time of flight, h:min		03:03	02:40	02:39
Ground distance, km		2,289	2,010	2,005

[a]Total costs include EPI and CPI. Contrail costs are listed for comparison.

As evolved from Table 1, CPI costs are mainly driven by DOCs, depending on the time of flight, the distance flown, and fuel costs. Those cost components could be significantly reduced in the CPI cost-minimized scenario by optimizing the lateral and vertical trajectories (Table 2). A continuous climb cruise operation with optimized speeds at a higher cruising altitude results in significantly lower fuel costs (Fig. 7).

The multicriteria-optimized trajectory (blue) further considers high contrail costs in the EPI assessment, which is why the path finding algorithm avoids flight time in ice-supersaturated regions (blue grid) and finds a total cost minimum solution by completely avoiding contrail costs (Table 2 and Fig. 6). Note that contrails are not always completely avoided in the multicriteria trajectory optimization (see Table 3). This optimization step results in reduced EPI costs of 498€ (28%, as compared to the cost-minimized scenario) but in increased CPI costs by 22€ (0.11%, as compared to the cost-minimized scenario) (compare Table 2). By considering contrail costs in the optimization, ATC en route charges become less important (they increase by 66€, as compared to the CPI minimized scenario) and the algorithm finds a total cost-minimized solution by crossing Switzerland. Interestingly, on the first half of the route, the lateral multicriteria-optimized trajectory is very similar to the radar-tracked reference flight path. Differences in the vertical profile are still significant. By avoiding a detour around Switzerland, the time of flight and distance flown could be further reduced by 30 s and 5 km, respectively, inducing lower costs for crew and insurance (see Table 2).

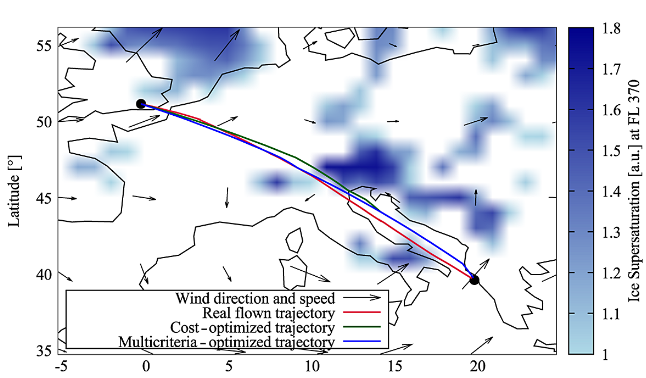

Fig. 6 Lateral paths of A320 trajectories from Gatwick to Corfu, optimized with different scenario-specific target functions, with each representing one of three scenarios (a.u. = arbitrary units).

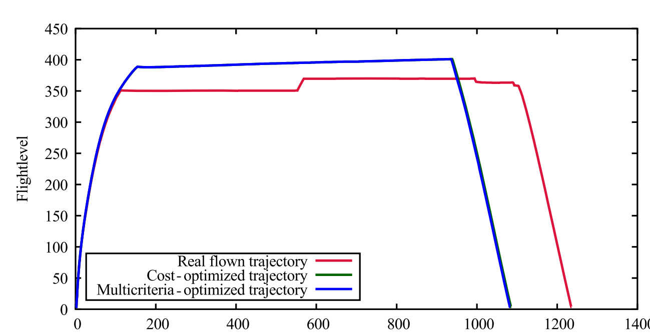

Fig. 7 Vertical profiles of three trajectories from Gatwick to Corfu with different optimization target functions in an ice-supersaturated region. Differences in distance are the result of different lateral flight paths.

Table 3 Assessment of the simulated scenarios, showing the number of conflicts

Scenario	Reference	Cost minimized	Multicriteria optimized
1000 ft	50,814	23,664	33,204
500 ft	39,708	14,395	19,968
EPI, €	7.10×10^7	1.91×10^7	1.81×10^7
CPI, €	3.47×10^8	2.09×10^8	2.10×10^8
Contrail costs, €	4.42×10^6	3.59×10^6	2.46×10^6
Fuel burn, kg	7.647×10^7	6.210×10^7	6.213×10^7

The optimization potential in the vertical profile is influenced by the flight performance optimization with the target function of a maximum specific range for the cruising altitude and true air speed results in significantly higher cruising altitudes near the aircraft's service ceiling (see Fig. 7). Inefficient step climbs in the en route phase and altitude corrections before the top of descent (TOD) (which might by the result of conflict resolution) are avoided in both TOMATO optimizations with a positive impact on fuel costs. Differences in distance are the result of different lateral flight paths.

B. Impact of Multicriteria-Optimized Trajectories on Air Traffic Flow Management

In the following, the total effect of the sum of all trajectories of each scenario is discussed (see Table 3). Therewith, the scenario's impact on capacity, environment, and airline efficiency is demonstrated. High costs in the reference scenario originate from unknown airline target functions, unknown air speeds, unknown filed flight paths (responsible for ATC en route charges), and a coarse spatial resolution of waypoint-based route structure (see Sec. III.A). Furthermore, the airline efficiency may not be realistically represented due to rough assumptions in fuel costs, crew salary, insurance costs, maintenance costs, and ATC charges for en route and airport services. All those cost functions are highly dynamic and depend on airline-specific contracts with the corresponding air traffic stakeholder. ATFM-induced requirements on speed and altitude, and specifically on the lateral path, induce longer flight paths and higher costs. The real flights are subject to prescribed flight planning processes, which are performed without such precise weather information, as used in the optimization environment TOMATO.

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

A normally distributed seat load factor and a mass of 100 kg per passenger are assumed. The fuel load is composed of the estimated fuel burn plus 10% contingency fuel. This constitutes a huge uncertainty in trajectory optimization. Errors in fuel burn up to 7% have to be considered [32]. It can be shown that both EPIs and CPIs could be significantly reduced during the free flight optimization without contrail consideration. Contrail costs could be further reduced by 1.13×10^6 € but not completely avoided, resulting in 1.5×10^4 € higher fuel costs due to detours around ice-supersaturated regions. In contrast to the example of the single trajectory, in which the time of flight, the distance flown, and the fuel costs were reduced in the multicriteria-optimized trajectory (as compared to the cost-minimized one), the majority of the flights took detours to avoid contrails. Mostly, ATC en route charges had a minor impact on cost-minimized trajectories, as compared to the benefits gained from wind speed and wind direction.

Concerning the impact of different optimization strategies on the ATFM, the number, location, and temporal distribution of conflicts within the upper airspace above 264 hPa (FL 360) were investigated. The definition of a conflict has been discussed in Sec. II.A.4. The number of conflicts per hour in the reference scenario slightly correlated with the number of flights above Europe (see Figs. 3 and 8). An afternoon slump and more distinctive morning and afternoon peaks were identified in the number of conflicts due to a decreased number of takeoffs and landings around midday. From this, it followed that an increased air traffic density in the terminal maneuvering area obviously raised the number of conflicts, although conflicts were only counted in the en route phase (upper airspace).

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

Due to a missing short-term conflict resolution, a high number of conflicts does not indicate an unsafe real air traffic scenario. A simulated comparison of a real air traffic scenario between the commercial fast time air traffic simulator AirTOp and TOMATO revealed a similar number of conflicts between the two simulation environments [40]. However, the number of conflicts may be biased due to uncertainties in the flight plan and in the identification of conflicts originating from the temporal resolution (every 10 s) and spatial resolution (0.1 deg). The variation of both parameters is influencing the number of conflicts. During a sensitivity analysis within the available computational resources, this number did not converge to a constant value. The impact of increasing the number of time steps and grid points on the number of conflicts further depends on the spatial orientation of the affected flight paths. Hence, each conflict needs a different numerical resolution and the methodology used in this study is not suitable to determine the actual collisions (i.e., intrusions) in the reference scenario. Nevertheless, we find interesting differences in the spatial patterns of the conflicts for each scenario (compare Figs. 2, 9, and 10).

Within the reference scenario (Fig. 2), the "airways" of aligned conflicts can be identified along highly frequented airways. This effect may originate from today's flight guidance procedures based on the current aeronautical information regulation and control cycle. Furthermore, the temporal resolution of the So6 m3 flight plan is not constant and has a coarse resolution in time and space (greater than 10 min). Hence, aircraft that are perfectly separated in reality could have been simulated at slightly different times and in slightly different places.

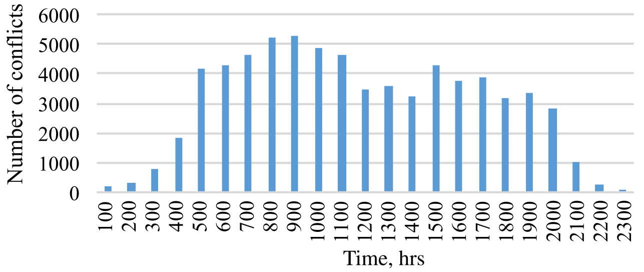

Fig. 8 Number of conflicts per hour in the reference scenario.

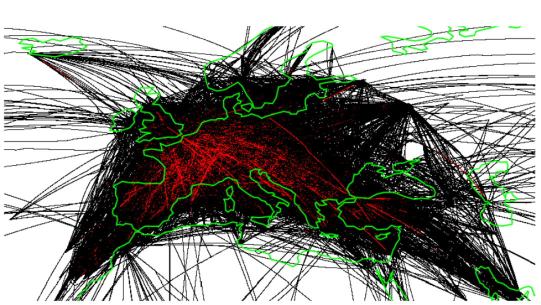

Fig. 9 Cost-minimized waypoint-less trajectories (black) and conflicts (red) in the European upper airspace. The results are integrated over a whole day.

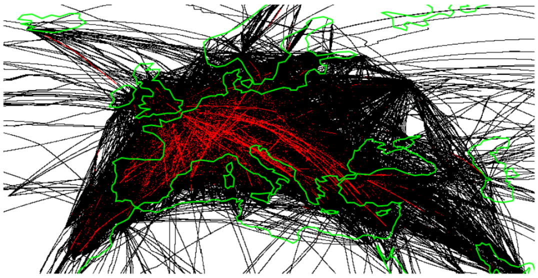

Fig. 10 Multicriteria-optimized trajectories (black) and conflicts (red) considering contrail formation.

Besides these areas, many conflicts can be detected over central Europe, where most of the European air traffic takes place. Compared to the optimized scenarios, those conflict grid points are well distributed over the whole European airspace. However, the structure of the aligned conflicts suggests a variety of longitudinal conflicts between two identical aircraft (compare Fig. 2). Our analysis shows that 92% of all conflicts resolve themselves within 10 n miles [41]. Furthermore, most of the aircraft are involved in only a single conflict during the whole flight [41]. The fuel burn calculated in the reference scenario may differ from the actual due to unknown speeds and the corresponding assumption of speeds with a maximum specific range. Because most of the emissions are proportional to the fuel flow, the EPIs (except of contrail costs) and CPIs might be defective as well. However, we suspect that the error is below 20%, which is the difference in fuel burn between the reference scenario and the cost-minimized scenario.

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

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

V. Conclusions

In this study, the trajectories from 13,584 flights were optimized with respect to cost functions for direct operating costs, fuel costs, environmental costs, and ATC charges in a flexible airspace structure using TOMATO, which is a simulation environment that calculates and considers aircraft performance, engine emissions, and the radiative impact of contrails for complex air traffic flow scenarios to improve ecological sustainability. With this case study, it was demonstrated that the free route concept, as proposed by SESAR in the key feature optimized ATM network services [2], had the potential to increase airspace capacity by more homogeneously distributing aircraft in the air space, even though all aircraft followed a cost-minimized optimum trajectory. However, the concept might not lead to a decrease in air traffic density over all of Europe (i.e., number of aircrafts per volume and time) due to favored airspaces along wind-optimum paths between high-frequency city pairs.

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

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

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

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References

[1] "NextGen Implementation Plan 2016," Federal Aviation Administration, 2016, www.faa.gov/.

[2] "European ATM Master Plan Edition 2," SESAR Joint Undertaking, 2015, www.eurocontrol.int.

[3] Rosenow, J., "Optical Properties of Condensation Trails," Ph.D. Thesis, Technical Univ. of Dresden, Dresden, Germany, 2016.

[4] Sussmann, R., and Gierens, K. M., "Differences in Early Contrail Evolution of Two-Engine Versus Four-Engine Aircraft: Lidar Measurements and Numerical Simulations," *Journal of Geophysical Research*, Vol. 106, 2001, pp. 4899–4911.

[5] Rosenow, J., Förster, S., Lindner, M., and Fricke, H., "Multi-Objective Trajectory Optimization," *International Transportation*, 1st ed., Vol. 68, 2016.

[6] Förster, S., Rosenow, J., Lindner, M., and Fricke, H., "A Toolchain for Optimizing Trajectories Under Real Weather Conditions and Realistic Flight Performance," *Proceedings of the Greener Aviation 2016*, Brussels, 2016.

[7] Luchkova, T., Vujasinovic, R., Lau, A., and Schultz, M., "Analysis of Impacts an Eruption of Volcano Stromboli Could Have on European Air Traffic," *11th USA/Europe Air Traffic Management Research and Development Seminar (ATM2015)*, Lisbon, Portugal, 2015.

[8] Luchkova, T., Kaltenhaeuser, S., and Morlang, F., "Air Traffic Impact Analysis Design for a Suborbital Point-to-Point Passenger Transport Concept," *3rd Annual Space Traffic Management Conference "Emerging Dynamics"*, Embry-Riddle, 2016.

[9] Kreuz, M., Luchkova, T., and Schultz, M., "Effect of Restricted Airspace on the ATM System," *World Conference on Transport Research 2016*, Shanghai, China, 2016.

[10] Schultz, M., Fricke, H., Kaiser, M., Kunze, T., Lopez-Leones, J., Wimmer, M., and Kappertz, P., "Universal Trajectory Synchronization for Highly Predictable Arrivals," *SESAR Innovation Days (SID)*, 2011.

[11] Schultz, M., Fricke, H., Mund, J., Lopez-Leones, J., Grabow, C., Prins, J. D., Wimmer, M., and Kappertz, P., "Uncertainty Handling and Trajectory Synchronization for the Automated Arrival Management," *SESAR Innovation Days (SID)*, 2012.

[12] Kaiser, M., Schultz, M., and Fricke, H., "Automated 4D Descent Path Optimization Using the Enhanced Trajectory Prediction Model (EJPM)," *Proceedings of the International Conference on Research in Air Transportation (ICRAT)*, Berkely, CA 2012.

[13] Schultz, M., Fricke, H., Gerbothe, T., Grabow, C., Prins, J. D., Wimmer, M., and Kappertz, P., "Modeling and Evaluation of Automated Arrival Management Considering Air Traffic Demands," *SESAR Innovation Days (SID)*, 2013.

[14] Yousefi, A., Donohue, G. L., and Qureshi, K. M., "Investigation of En Route Metrics for Model Validation and Airspace Design Using the Total Airport and Airspace Modeler (TAAM)," *5th EUROCONTROL/FAA ATM R&D Conference 2003*, Budapest, Hungary, 2003.

[15] Klein, A., and Hafner, F., "Computation and Analysis of Aircraft Proximities in NAS Airspace from Historical Data," *Digital Avionics Systems Conference*, 2005.

[16] Lido/Flight 4D (online database), Lufthansa Systems, Cologne, Germany, https://www.lhsystems.de/solutions-services/operations-solutions/lidoflightplanning/lidoflight4D [retrieved 12 Jan. 2017].

[17] Rosenow, J., Förster, S., and Fricke, H., "Continuous Climb Operations with Minimum Fuel Burn," *6th SESAR Innovation Days*, 2016.

[18] Rosenow, J., and Fricke, H., "Flight Performance Modeling to Optimize Trajectories," *Deutscher Luft- und Raumfahrtkongress 2016*, Braunschweig, Germany, 2016.

[19] Rosenow, J., Fricke, H., Luchkova, T., and Schultz, M., "Minimizing Contrail Formation by Rerouting Around Dynamic Ice-Supersaturated Regions," *Aeronautics and Aerospace Open Access Journal*, Vol. 2, 2018, pp. 105–111.

[20] Fuel Price Analysis (online database), International Air Transport Assoc., Montreal, http://www.iata.org/publications/economics/fuel-monitor/Pages/price-analysis.aspx [retrieved 28 Nov. 2016].

[21] Lindner, M., Förster, S., Rosenow, J., and Fricke, H., "Ecological Impact of Air Traffic Control En-Route Charging Zones from Multi Criteria Optimized Flight Paths," *Greener Aviation 2016*, Brussels, 2016.

[22] Monthly Adjusted Unit Rates (online database), EUROCONTROL, Brussels, http://www.eurocontrol.int/services/monthly-adjusted-unit-rates [retrieved 28 Nov. 2016].

[23] Lee, D. S., et al., "Transport Impacts on Atmosphere, Climate: Aviation," *Atmospheric Environment*, Vol. 44, No. 37, Dec. 2010, pp. 4678–4734.

[24] Schäfer, M., "Methodologies for Aviation Emission Calculation—A Comparison of Alternative Approaches Towards 4D Global Inventories," Diploma Thesis, Univ. of Munich, Munich, 2006.

[25] "Aircraft Engine Exhaust Emissions Data Bank," International Civil Aviation Organization, Montreal, 2016, www.easa.europa.eu/.

[26] Kugele, A., Jelinek, F., and Gaffal, R., "Aircraft Particulate Matter Emission Estimation Through All Phases of Flight," *EUROCONTROL*, Brussels, 2005.

[27] Myhre, G., et al., "Anthropogenic and Natural Radiative Forcing," *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge Univ. Press, New York, 2013, pp. 659–740, Chap. 8.

[28] Collins, W., Fry, W. M., Fuglestvedt, J. S., Shindel, D. T., and West, J. J., "Global and Regional Temperature-Change Potentials for Near-Term Climate Forcers," *Atmospheric Chemistry and Physics*, Vol. 13, 2013, pp. 2471–2485.

[29] Fuglestvedt, J. S., Shine, K., Bernsten, T., Cook, J., Stenke, A., Skeie, R., Velders, G., and Witz, I., "Transport Impacts on Atmosphere and Climate: Metrics," *Atmospheric Environment*, Vol. 44, No. 37, 2010, pp. 4648–4677.

[30] Spichtinger, P., "Eisübersättigte Regionen," Ph.D. Thesis, Dept. of Physics, Univ. of Munich, Munich, May 2004.

[31] Vázquez-Navarro, M., Mannstein, H., and Kox, S., "Contrail Life Cycle, Properties from One Year of MSG/SEVIRI Rapid-Scan Images," *Atmospheric Chemistry, Physics Discussions*, Vol. 15, No. 2015, pp. 7019–7055.

[32] Wickramasinghe, N. K., Brown, M., Miyamoto, Y., and Miyazawa, Y., "Effects of Aircraft Mass and Weather Data Errors on Trajectory Optimization and Benefits Estimation," *AIAA Modeling and Simulation Technologies Conference, AIAA SciTech Forum*, AIAA Paper 2016-0166, 2016.

[33] Chati, Y. S., and Balakrishnan, H., "Statistical Modeling of Aircraft Takeoff Weight," *12th USA/Europe Air Traffic Management Research and Development Seminar*, Berkely, CA, 2017.

[34] "A320/A320NEO Aircraft Characteristics, Airport and Maintenance Planning," AIRBUS S.A.S Customer Services Technical Data Support, and Service, 2014.

[35] Rosenow, J., Lindner, M., and Fricke, H., "Impact of Climate Costs on Airline Network Optimization: A Parametric Study," *CEAS Aeronautical Journal*, Vol. 8, No. 2, 2017, pp. 371–384.
doi:10.1007/s13272-017-0239-2

[36] DDR2—Web Portal (online database), EUROCONTROL, Brussels, http://www.eurocontrol.int/articles/ddr2-web-portal.

[37] NOMADS: NOAA Operational Model Archive and Distribution System (online database), National Oceanic and Atmospheric Administration, Silver Spring, MD, http://nomads.ncep.noaa.gov/ [retrieved 26 Nov. 2016].

[38] Spichtinger, P., Gierens, K. M., and Read, W., "The Global Distribution of Ice-Supersaturated Regions as Seen by the Microwave Limb Sounder," *Quarterly Journal of the Royal Meteorological Society*, Vol. 129, No. 595, 2003.

[39] Kraus, H., *Die Atmosphäre der Erde*, Springer–Verlag, Berlin, 2001, pp. 243–317.

[40] Rosenow, J., Luchkova, T., Schultz, M., and Fricke, H., "Impact of Optimized Trajectories on Air Traffic Flow Management," *Aeronautical Journal* (Under Review).

[41] Rosenow, J., and Fricke, H., "Impact of Multi-Critica Optimized Trajectories on European Airline, Network Efficiency," *Proceedings of the Air Transport Research Society World Conference*, 2017.

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