Impact of Optimized Trajectories on Air Traffic Flow Management

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Multi-criteria trajectory optimization is expected to increase aviation safety, efficiency and environmental compatibility, although neither the theoretical calculation of such optimized trajectories nor their implementation into today's already safe and efficient Air Traffic Flow Management reaches a satisfying level of fidelity. The calibration of the underlying objective functions leading to the virtually best available solution is complicated and hard to identify, since the participating stakeholders are very competitive. Furthermore, operational uncertainties hamper the robust identification of an optimized trajectory. These uncertainties may arise from severe weather conditions or operational changes in the airport management. In this study, the impact of multi-criteria optimized free route trajectories on the Air Traffic flow Management is analyzed and compared with a validated reference scenario which consist of real flown trajectories during a peak hour of Europe's complete air traffic in the upper airspace. Therefore, the TOolchain for Multi-criteria Aircraft Trajectory Optimization TOMATO is used for both the multi-criteria optimization of trajectories and for the calculation of the reference scenario. First, this paper gives evidence for the validity of the simulation environment TOMATO, by comparison of the integrated reference results with those of the commercial fast-time Air Traffic Optimizer AirTOp. Second, TOMATO is used for the multi-criteria trajectory optimization, the assessment of the trajectories and for the calculation of their integrated impact on the Air Traffic flow Management, which in turn is compared with the reference scenario. Thereby, significant differences between the reference scenario and the optimized scenario can be identified, especially considering the taskload due to frequent altitude changes and rescinded constraints given by waypoints in the reference scenario. The latter and the strong impact of wind direction and wind speed cause wide differences in the patterns of the lateral trajectories in the airspace with significant influence on the airspace capacity and controller's taskload. With this study, the possibility of a successful 4D free route implementation into Europe's upper airspace is proven even over central Europe during peak hours, when capacity constraints are already reaching their limits.

I. Introduction

The air transport system is a fast-developing entity with highly dynamic input parameters and an increasing number of variables. Very high safety requirements and certification standards are complicating the implementation of new procedures which are dealing with those general conditions. For this reason, research programs such as Single European Sky ATM Research (SESAR)[1] and Next Generation Air Transportation System (NextGen)[2] are focusing on challenging targets for the adaption of aviation to future requirements. Beside an increasing competition pressure and inevitable improvements in efficiency, aviation stakeholders are requested to increase the aviation environmental compatibility without adversely affecting safety and

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security of the air transport system. Optimization potential for those conflicting targets has been found on almost every air traffic planning level ranging from aircraft network design,[3] fleet assignment[4] and trajectory optimization[1,2,5] to air traffic flow management.[6] Trajectory optimization can be applied in the flight planning phase (dispatch) as well as during the flight, when actual input parameters, such as weather conditions, restricted areas and airport capacities are known. Regardless of the planning level, flight performance modeling is necessary for a reliable optimization of the air traffic system, because it is the smallest unit each air traffic optimization should be based on. Within the framework of the research program ProfiFuel (Improved planning and realization of flight profiles with the lowest ecological footprint and minimum fuel consumption), the potential and the boundary conditions of this 4D Trajectory Management is investigated.

In Europe, the reduction of the air traffic environmental impact and the increase in aviation efficiency and safety (regarding both airlines and air navigation service providers (ANSPs)) are already regulated by law,[7] forcing air traffic stakeholders to cooperate in finding a solution that satisfies competitive partners.

Area Navigation (RNAV) provides a solution approach for this 4D Trajectory Management by contributing a framework for both airlines and ANSPs.[1,8,9] The first step towards this action, the "Time-based operations" focus on the deployment of airborne trajectories,[1,9] considering all constraints inflicted by the highly complex and dynamic environmental conditions,[10] which requires refraining from Standard Atmospheres and focuses on the use of high-resolution real weather data. Time-based operations aspire to create free routings to enable optimized trajectories[1,9] under real weather conditions. Free routes are freely planned routes between a defined entry point and a defined exit point of a Free Route Airspace (FRA), constrained by published or unpublished waypoints.[1] In many European air traffic control sectors, FRA is already implemented, at least at night.[11,12] Therewith, the ground for innovative concepts, e.g. the 4D Trajectory Management, is prepared and several application ideas have already been formulated in the SESAR Master plan,[1] in the SESAR Solutions Catalogue[9] and in the SESAR Concept Of Operations (CONOPS) Step 1.[13]

Meeting the challenging requirements of the 4D Trajectory Management with non-constant speeds and cruising altitudes, the concept of Performance Based Navigation (PBN) has been developed to strategically deconflict free routes by allowing airspace planners to take credit for the aircraft's navigation performance.[14,15] With these rules of action, aircraft shall be able to safely meet their planned times of departure and arrival and adhere to their optimum flight paths from gate to gate with minimum disruptions, assuming aircraft are equipped with voice and data communications, RNAV and required navigation performance (RNP) capabilities.[14–16]

However, these targets implicate conflicting goals in a multi-criteria optimization, due to diverging targets between airlines and ANSPs, as well as between environmental, economic and safety issues.

A. 4D Trajectory Management

Airlines are focusing on efficiency by minimizing the number of planes and employees and the fuel burn, whereas the revenue passenger miles, number of departures and passengers and the available ton-miles shall be maximized.[17] On a planning level, this strategy will have a reducing effect on the environmental impact as well. On the level of a single trajectory, competitive applications are necessary. Taking safety requirements as additional constraints, a multiple-criteria optimization approach becomes unavoidable. Due to the increasing weight of the environmental compatibility of the flight, the aircraft emissions have to be calculated precisely. For emissions as products of incomplete combustion (NO_x, HC, BC), a combustion chamber model is necessary, which requires precise information about thrust, speed, acceleration forces and the aircraft's attitude.[3,5,18] The TOolchain for Multi-criteria Aircraft Trajectory Optimization TOMATO has been exclusively developed for this purpose. This simulation environment includes a multi-criteria trajectory optimization considering an exact trajectory calculation based on analytically solvable target functions and a combustion chamber model, which is unique at the current state of the art. In summary, airlines' targets are found specifically on the network and trajectory level and can be applied with simulation environments such as TOMATO for different airline business models (e.g. different network structures and cost indices), resulting in diverse target functions in the trajectory optimization.

B. Air Traffic Flow Management

Airlines cooperate with ANSPs for a safe operation and management of the air traffic flow. ANSPs are measured against the same performance targets (safety, efficiency and ecological impact), with different KPIs.

However, when comparing the different target functions of airlines and ANSPs, a significant competition between airlines and ANSPs is not quantifiable.

The main focus of ANSPs' assessment is based on safety measures (e.g. prevention of loss of separation and runway incursions) as well as Safety Management System maturity. One of the most important group of ANSP KPIs is summarized in the KPI *capacity utilization*, measuring the operational efficiency of ANSPs, i.e. ensuring that resources (e.g. available airport or airspace capacity) are optimized within the given conditions of the system (i.e. weather, airport maintenance constraints etc.)[19]. *Capacity utilization* quantifies the amount of available capacity that is being used to supply the current demand. Concentrating on the upper air space, the available capacity is restricted by separation minima for conflict avoidance, usually five nautical miles in the horizontal and 1000 feet in the vertical direction. With the implementation of the 4D Trajectory Management, aircraft will not be constrained by waypoints and flight levels any more. Hence, air traffic will be more homogeneously distributed in the upper air space.[20–22] Therewith, the available capacity (i.e. the maximum number of aircraft per sector and time) will increase considerably. For operating with a high *capacity utilization* in a 4D Trajectory Management, the sector size or the number of aircraft per sector could be increased. However, the KPI *complexity* (i.e. the adjusted density, vertical interactions, horizontal interactions and speed interactions[23]) is expected to increase due to the implementation of the 4D Trajectory Management. Keeping *complexity* on an acceptable level tends toward a manageable and dynamic sector size so that the KPI *traffic variability* of daily and weekly traffic (i.e. the ratio between the peak traffic and average traffic, measured in number of flights[19]) may decrease or be kept on a constant level. Due to an expected increased *complexity*, the KPI *productivity*, measuring the number of IFR flight hours per Air Traffic Control Officer (ATCO), the average number of annual working hours for ATCOs, the number of aircraft controlled, the number of controlled flight hours, the number of controlled kilometers and the directions/requests from the control center, may be stressed, due to an increased communication between pilots and ANSPs. Furthermore, the cost efficiency as costs per IFR flight hour, the flight efficiency as deviation from the optimum trajectory and environmental factors influence the KPI *quality of service*, which is a measure of the delay and airport capacity. The attributable delay KPI records the causal reasons for a delay and allows the ANSP to assess its influence in mitigating the delay and improving the efficiency.[19]

To conclude: the impact of 4D trajectories on the Air Traffic Flow Management can be assessed by ANSP's KPIs *capacity utilization*, *complexity* and *productivity*, influenced by controller's taskload, total fuel burn, total time of flight in the air spaces and necessary changes in the airspace capacity. Differences between the reference scenario and the optimized trajectories represent the potential of an efficiency improvement of airlines and ANSPs.

C. State of the Art

Several air traffic flow simulation environments have been developed, each with a specific scope, but none of them considers safety issues on the ATFM level. Furthermore, restrictive approximations in the aircraft performance modeling and a deficient quantification of the emissions, restrict all of them in the applicability to a multi-criteria trajectory optimization. The commercial fast-time air traffic simulator AirTOp[24] generates conventional waypoint-based trajectories in a dynamic airspace structure and iteratively considers conflict detection and conflict resolution.[25] AirTOp has been applied to reroutings around volcanic ash clouds[26] and in estimating the influence of restricted airspaces on the air traffic system.[27] However, due to approximations in the aircraft performance modeling (which is limited to BADA performance tables) and missing quantification of the emissions AirTOp is not suitable for the deconfliction of 4D optimized trajectories. The same restrictions apply to the Test bench for Agent-based Air Traffic Simulation (TABATS), which simulates trajectory scenarios considering weather-dependent lateral rerouting around thunder cells[28–30] but also concentrates on BADA performance tables. TABATS has been developed for the trajectory synchronization with the aim of predicting arrivals enabled by full automation and focuses on the simulation of trajectory scenarios considering lateral rerouting around thunder cells and speed adjustments with a specialized airport slot allocation routine.[28–31] Grewe et al.[32] concentrated on the climate assessment of trajectories considering future aircraft technologies and uncertainties in the quantification of the emissions. Here, the impact on ATFM was not in focus. Within the framework of the research project ATM4E, Matthes et al.[33] developed a multidimensional optimization tool for trajectories and their impact on the air traffic network and demand. Unfortunately, the implemented methodology is not completely published. Regarding the flight performance modeling, the commercial flight planning tool Lido/Flight 4D, developed by Lufthansa Systems,[34] is also able to simulate trajectories assuming ambient thermodynamical conditions defined in the International

Standard Atmosphere (ISA). Hence, special weather phenomena and parameters, which are required for the precise quantification of the engine emissions and their environmental impact, as well as the formation of condensation trails depending on location and size of ice-supersaturated regions cannot be modeled. The Airspace Simulator TAAM, developed by Jeppesen is also restricted to ISA with unknown precision. The open source Open Air Traffic Simulator BlueSky has been developed to visualize, analyze and simulate the air traffic. It includes an aircraft performance model independent of BADA[35] using only public performance data, especially Jane's All the World's Aircraft database. This promising project is still in the development stage. However, hard restrictions regarding the aircraft performance and flexibility regarding the aircraft type are expected. The optimization capability of the model is unknown. The scenario-based modeling tool Nest by EUROCONTROL provides sector counts, airport demand, number of flights between airport pairs, etc. of a set of trajectories, imported into NEST in a so6 format.[36] The research project REACT4C of the German Aerospace Center (DLR) published interesting findings regarding ecological trajectory optimization[37] using cost functions. However, details in trajectory optimization and emission quantification are not published. Hence, the accuracy of multi-criteria trajectory optimization cannot be estimated. Matthes et al.[38] published further development in the subsequent project AMT4E without any results. Furthermore, Lovegreen et al., Skowron et al. and Sovde et al.[39–41] focused on the estimation of the impact of aviation on global climate. However, all these approaches can not be generalized due to the major impact of the assumed atmospheric conditions. When performing trajectory optimization, most approaches focus on the cruise phase only.[42–47]

The aircraft flight performance has been modeled with different granularity depending on the intended use. In an ISA performance models are available for airlines, e.g. the commercial flight planning tool 4D Lido/Flight by Lufthansa Systems, with unknown precision. The Base of Aircraft DAta (BADA) by the European Organization for the Safety of Air Navigation provides specific aircraft performance parameters and allows a performance modeling for a wide range of aircraft types.[44,47,48] In many applications of trajectory optimization, a realistic flight performance is often neglected and many static parameters are assumed e.g. constant speed and altitude. Other approaches even consider minor dependencies as compressibility effects in the calculation of the drag coefficient[49] e.g. the Enhanced Jet Performance Model (EJPM), but are restricted to a very limited number of aircraft types and to ISA atmospheric conditions. The EJPM had been used and applied for case studies on continuous descent operations,[31] for flight profiles without contrail formation[50] and the contrail life cycle,[51] for automated trajectories[31,49] and for the synchronization of automated arrivals.[28] Soler et al.[52] modeled the flight performance with a 3-degree-of-freedom dynamic model depending on true air speed, heading and flightpath angle in ISA, but with two-dimensional wind information, restricted to flight level changes during cruise, separated by 1000 feet. Hence, an optimum cannot be detected. However, all these applications use a single target function (e.g. minimum fuel flow or minimum time) for the optimization, which seems insufficient with the conflictive SESAR and NextGen targets in mind. For solving multi-criteria trajectory optimization problems, two approaches have been primarily investigated. The path-finding algorithm A* and the more general Dijkstra algorithm for searching shortest paths in a graph are employed[46,48] as well as the optimal control problem approach,[45,53–55] which is able to consider conflictive target functions and real weather conditions. The discrete input parameters are approximated by analytically solvable functions. From this follows a very constricted number of variables and sometimes the errors arising from the approximation seem too high. Furthermore, the flight performance is modeled in a very simple way. Multi-criteria optimization of trajectories in a horizontal plane has been performed under real weather conditions with a detailed horizontal flight performance modeling as a two-point boundary value problem. Parton et al.[56] and Murietta et al.[57] used multi-level optimizations in 3D grid models. Nevertheless, the flight performance is only approximated by a performance database, where fuel burn and the distance traveled are calculated depending on Mach number, indicated air speed, gross weight, temperature deviation of the ISA and altitude. This approach only considers the reduction of fuel consumption or time of flight. Howe-Veenstra et al.[58] developed smooth optimized trajectories following constant IAS or constant Mach number and a constant altitude at cruise with a single, but variable target function considering a temperature deviation of the ISA.

Besides all these ongoing researches, which focus on single aspects, we do not know of any approach, that performs a full lateral and vertical multi-criteria trajectory assessment and optimization while considering direct operating costs, fuel costs, time costs, and emissions by considering realistic, aircraft specific flight performance data. Especially the complex balance between very different multiple criteria is a fairly detailed topic that needs much more attention in order to improve the ecological impact of aviation.

The concatenation of the particular trajectory calculation and optimization with the analysis of the spacial four dimensional distribution of aircraft and conflicts is unique in the simulation environment TOMATO. To date, these tasks have been treated separately. First analyses of the capability of TOMATO showed numerical and implementational difficulties in the analysis of investigations concerning the ATFM,[20] which have been solved by analyzing the demand of individual aircraft on airspace capacity and it's impact on the controllers taskload[22] and regarding the distribution of conflicts as imminent separation infringements between individual aircraft.[21]

II. Methodology

A. Approach

In this study, the impact of multi-criteria optimized free route trajectories on the ATFM system is analyzed in detail and compared with a reference scenario which consists of 8800 flown trajectories provided as so6 m3 flight plan file by EUROCONTROL (for research purposes) to correctly reproduce the current situation during one hour in the European upper airspace on May 17$^{\text{th}}$, 2017. The reference scenario is calculated twice. First, the commercial fast-time total airspace and airport model AirTOp is used to realistically simulate these trajectories with real, historical speeds, cruising altitudes, lateral paths and level changes. This reference scenario is also used for a validation of the simulation environment TOMATO, by additionally calculating the reference scenario with TOMATO using city pairs, lateral paths departure times, aircraft types, cruising altitudes and altitude changes during cruise. For validation, the results integrated over all simulated flights in the upper European airspace during that specific hour from 12 a.m. to 1 p.m., which describe the impact of the trajectories on the ATFM system, are compared between both simulation environments.

In a third step, the trajectories are optimized with TOMATO by using only the city pairs, departure times and aircraft types provided by the so6 m3 flight plan file. For the optimized trajectories, the take-off phase is realized with maximum thrust, the climb phase is split into an initial climb phase with a maximum climb angle below the transition altitude of 1000 ft and in a climb phase with a maximum climb rate above 1000 ft. During cruise, the target function follows a maximum specific range and during descent, the lift to drag ratio is maximized.[59] Both the validated reference scenarios and the optimized trajectories are assessed by the following parameters: total fuel burn, total time of flight, total distance flown, controller's taskload and number of conflicts. Figure 1 indicates the procedure of the case study, including the input data function and analyzed results of both simulation environments.

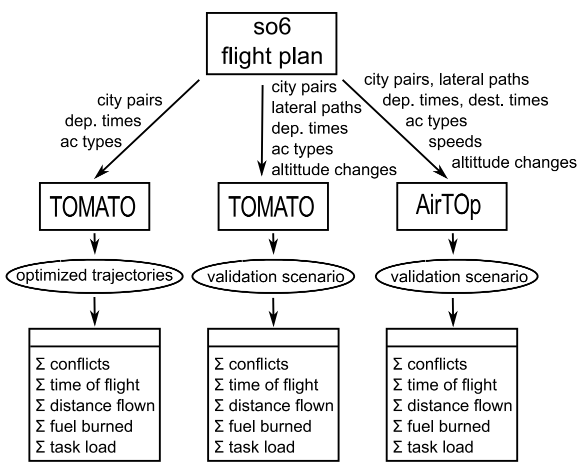

Figure 1. Procedure of the study indicating data source, programs and analyzed results.

B. TOMATO Simulation Environment

The TOolchain for Multi-criteria Aircraft Trajectory Optimization TOMATO is briefly described by Frster et al.[60] and Rosenow et al.[5,20] The trajectories are assessed by several KPIs covering safety, efficiency and ecological compatibility. All indicators are transformed into costs, enabling TOMATO to iteratively find the global optimum by changing the allowed input variables, e.g. the cruising altitude, the target function for climb and descent rates, the target function for speed or the weight of different KPIs, considering real weather conditions, given as global forecast. However, the optimum is restricted in the timely and spacial resolution within the model. The trajectories are calculated one by one.[5,20,60] Different cost components of grouped KPIs, the quantified emissions, contrail costs, and some flight performance measures for the inspection of a successful calculation of the aspired profile are summarized for each trajectory. Furthermore, each 4D trajectory is output with a variable temporal resolution, in this case study with $\Delta t = 1$ s, which is also the internal computation time step. Depending on the provided weather data, TOMATO deals with a variable spatial resolution, because the accuracy of calculation does not increase with a linear interpolation between the grid point, providing weather information.[60] In this case study, weather data are taken from the Global Forecast System (GFS) Model provided by the National Oceanic and Atmospheric Administration (NOAA)[61] with a spatial resolution of $\Delta x = 0.25$ °. Figure 2 gives an overview over the workflow in TOMATO. The resultant Air Traffic Flow can be analyzed with measures such as airspace capacity, controller's taskload, and number and characteristics of separation infringements. Therewith, the ATFM can be assessed and compared with the reference scenario.[20–22] Until now, conflict resolution is not implemented in TOMATO because, each trajectory is individually optimized and because the computational effort has already reached the limits of a personal computer.

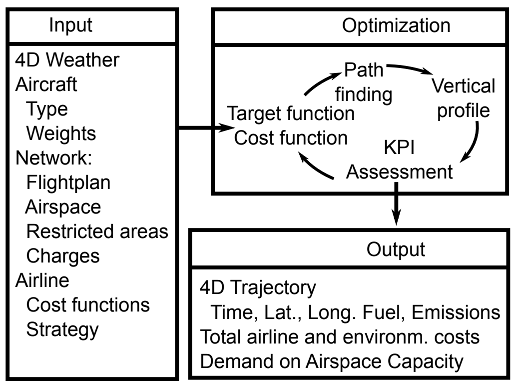

Figure 2. Workflow in TOMATO, simplified to the most important parameters and modules.

C. AirTOp Air Traffic Simulator

The fast-time air traffic simulator AirTOp generates trajectories in a dynamic airspace structure and iteratively considers conflict detection and conflict resolution.[25] AirTOp is able to manage reroutings around dynamic airspaces[26] and to estimate their influence on the air traffic system.[27] It is a multifunctional and modular platform for the simulation of gate-to-gate air traffic flows considering planned 4D trajectory synchronization and negotiation, as well as airspace planned entry load and occupancy monitoring.[24] The airspace analysis regarding the parameters time of flight, distance flown, fuel burned, occupancy, controller's taskload, altitude changes and number of conflicts is based on an Air Traffic Control (ATC) sector-specific airspace structure consisting of 632 Flight Information Regions (FIR) of different size. Therein, conflicts are defined as separation infringements of 5 NM in the lateral direction and 1000 ft in the vertical direction. The results are calculated per hour with a calculation time of two seconds. The minimum period of time of the separation infringement for the definition of a conflict is variable and set to $\Delta t = 1$ s to be comparable with the conflict detection algorithm of TOMATO. Due to the irregular airspace structure in AirTOp, a comparison of the spatial distribution of air traffic density or air traffic complexity over Europe is not possible between TOMATO and AirTOp. However, considering the same city pairs, aircraft types, cruising altitudes and altitude changes, the spatially integrated results can be compared between both models. When deconfliction is activated, different rerouting algorithms are implemented to calculate trajectories in deviation from the planned trajectories to ensure individual user defined requirements. Thereby, the conflict resolution is realized iteratively, until a possible solution for the whole ATFM is reached. However, for the sake of comparability, in this case study, deconfliction is deactivated.

III. Comparison of TOMATO and AirTOp using the validation scenario

In this paper, the simulation environment TOMATO has been prepared for a comparison of the simulated reference scenario with the reference scenario, simulated with the commercial air traffic simulator AirTOp. The results are surprisingly equal (compare Table 2), although not all input parameters and all sub models of AirTOp are known in detail by the authors. Therewith, the validity of TOMATO can be proven. Both models simulated 8800 flights with cruising pressure altitudes above 250 hPa (upper airspace). Although the internal computation time of AirTOp is unknown to the authors (nor can it be assumed that there are uniform computation time steps of all partial models), the number of potential conflicts (i.e. separation infringements of 5 NM laterally and 1000 ft vertically) is in the same order of magnitude for both models. It has to be noted that the flight performance model COALA within TOMATO has difficulties in dealing with predefined speeds at given waypoints, because it considers acceleration forces and unsteady flight attitudes[59] at each computation time step. This is why the real speeds, given by the so6 m3 flight plan, cannot be used as input parameters for COALA. Instead, the target speed is internally calculated for a maximum specific range and controlled by the lift coefficient as controlled variable.[59] These speeds are obviously similar to the true air speeds given in the flight plan. This is why the integrated time of flight is very similar in both model approaches (compare Table 2). Due to predefined lateral paths, the integrated distance flown is very similar as well. From this follows that the spatial and temporal resolution of TOMATO (0.25 degrees and 1 second, compare section B) are sufficient or at least similar to those used by AirTOp. Both models use the Base of Aircraft DAta (BADA),[62,63] provided by EUROCONTROL for the estimation of the fuel burn. For this case study, AirTOp relies on the BADA version 3,[62] whereas TOMATO uses the BADA Family 4[63] whenever possible. Performance data of aircraft which are not covered by BADA 4 are estimated with BADA 3. Nevertheless, both fuel burn estimations are very similar (with differences of $\Delta\dot{m}_f = 1.73\,\%$) and do not differ by more than the accuracy (i.e. $\Delta\dot{m}_{f,\mathrm{BADA}} = 5\,\%$) of the BADA flight performance data.[64]

Table 1. Comparison of TOMATO and AirTOp regarding the integrated results describing the simulation of 8800 trajectories and their impact on the ATFM.

	TOMATO	AirTOp
$\sum$ conflicts	$6.12 \cdot 10^2$	$5.15 \cdot 10^2$
$\sum$ flight time [h]	$1.56 \cdot 10^4$	$1.57 \cdot 10^4$
$\sum$ distance flown [NM]	$6.76 \cdot 10^6$	$6.43 \cdot 10^6$
$\sum$ fuel burned [kg]	$3.97 \cdot 10^7$	$4.04 \cdot 10^7$
$\sum$ taskload [h]	$4.51 \cdot 10^2$	$1.66 \cdot 10^3$

Large differences in the resultant controller's taskload between both models indicate uncertainties in the calculation of the controller's taskload in AirTOp, which could not be cleared completely. It could be determined, that AirTOp models the controller's taskload for conflict resolution in more detail, considering the type of conflict (i.e. the heading, speeds and altitudes of involved aircraft within a FIR). TOMATO assumes constant heading and altitude changes and the number of aircraft per artificial airspace, defined by a grid consisting of geographical coordinates with a spacial resolution of $\Delta x_{\mathrm{taskload}} = 1\ ^{\circ}$[22] (compare Figure 3). For each artificial airspace, TOMATO calculates the controller's taskload proportional to the number of aircraft within this airspace and does not consider the actual number of separation infringements in this airspace.[22] From this follows that the controller's taskload cannot be compared between both models.

IV. Impact of optimized trajectories on the ATFM

With the simulation and comparison of the reference scenario with both models, two important steps have been completed. On the one hand, the simulation environment TOMATO is validated and numerical variables such as spatial and temporal resolution are assessed (compare Section III). On the other hand, the reference scenario enables a comparison of those conventionally filed flight paths with 4D-optimized free route trajectories, which have been calculated with TOMATO in a second step. Especially the impact of those optimized trajectories on the ATFM is compared with the impact of the conventionally filed trajectories. Figure 4 indicates a more complex airspace in the reference scenario due to a more heterogeneously

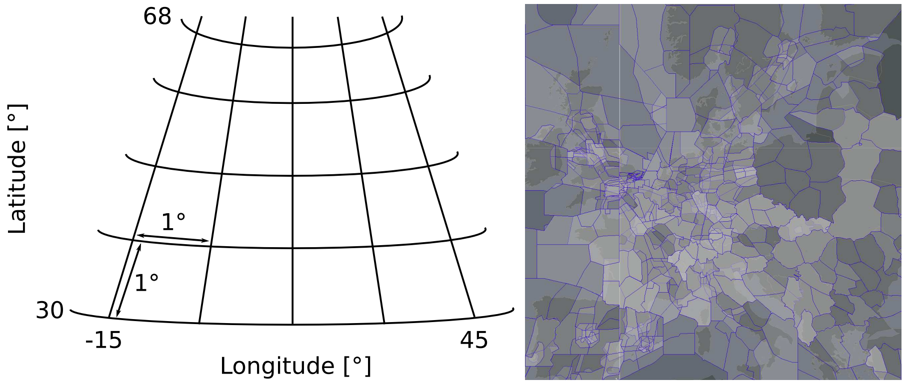

Figure 3. Airspace structure used for the calculation of the results, relevant for the ATFM of TOMATO (left) and AirTOp (right). With TOMATO, the airspace capacity (i.e. number of aircraft per airspace hour), number of potential conflicts and controller's taskload are calculated per artificial airspace defined by one degree latitude times one degree longitude (resulting in 30 to 60 nautical miles, depending on latitude), whereas flight information regions with non-equal shape and size are used in AirTOp.

distribution of aircraft per artificial airspace. Up to 58 aircraft per artificial airspace and hour are simulated over central Europe in the reference scenario (indicated by the black contours in Figure 4), whereas free routes follow their individually optimized trajectories yielding a maximum number of 42 aircraft per artificial airspace and hour. These optimized trajectories depend on the aircraft type and mass-specific flight performance.[18,59] Furthermore, non-constant air speeds and cruising altitudes spread the aircraft more widely within the airspace and therewith increase the possible airspace capacity (i.e. maximum number of aircraft, integrated over the whole European airspace)[21,22] although wind speed and wind direction are considered in the optimization function, amongst others.

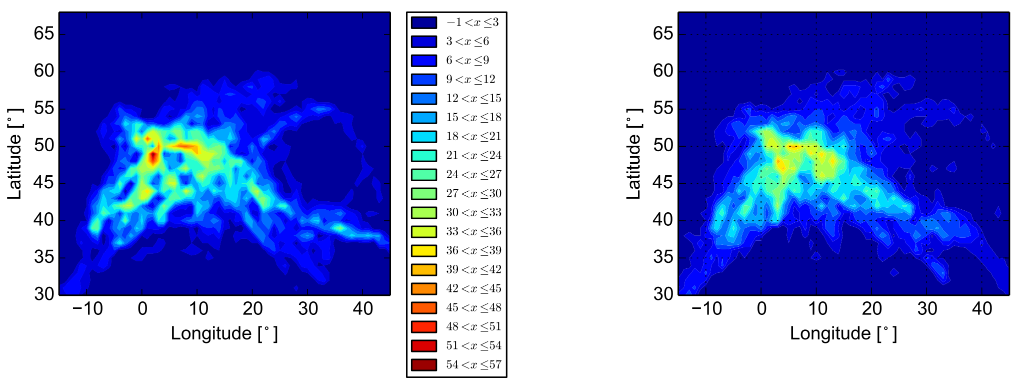

Figure 4. Heat map of airspace capacity (i.e. number of aircraft per artificial airspace defined by 1 degree latitude and 1 degree longitude) during one hour between 12 a.m. and 1 p.m. on May 17$^{\text{th}}$, 2017 above Europe (between 30 and 68 degrees latitude and -15 and 45 degrees longitude). Left: TOMATO simulated historical data of 8800 real flights, right: TOMATO optimized these trajectories considering the requested city pairs, aircraft types and departure times. Colors of dark blue, light blue, green, yellow, orange, red and black indicate zero, 10, 20, 30, 40, 50 and 60 aircraft per hour and artificial airspace, respectively.

In the scenario of optimized trajectories, 1637 artificial airspaces out of 2739 (61 degrees longitude times 39 degrees latitude) artificial airspaces are used by aircraft during this hour, whereas in the reference scenario, only 1554 artificial airspaces out of 2739 artificial airspaces are used (compare Figure 4). Nevertheless, the proportion of crowded airspaces has dropped in the optimized scenario as well and the maximum number of aircraft per hour and artificial airspace decreased significantly.

Figure 4 indicates a more equally distributed airspace capacity. Aircraft are in conflict for a significantly shorter time and distance (compare Table 2). Due to a real flight plan as reference scenario, longitudinal separation infringements can be excluded. Permanently changing speeds, altitudes and headings eliminate longitudinal separation infringements in the optimized scenario as well.

Table 2. Comparison of TOMATO's simulated real flights as reference scenario (compare Table 4) and TOMATO's multi-criteria optimized trajectories. 8800 city pairs, departure times and aircraft types on May, 17^{th} 2017 between 12 a.m. and 1 p.m. with cruising altitudes above $p_{\text{cruise}} = 250$ hPa and their integrated impact on the ATFM are simulated and optimized. Additionally, the lateral path and altitude changes are used as input parameters for the reference scenario.

	Real flights	Optimized trajectories
$\sum$ conflicts	$6.12 \cdot 10^2$	$5.85 \cdot 10^2$
$\sum$ overloaded airspaces	$2.07 \cdot 10^2$	$1.88 \cdot 10^2$
$\sum$ used airspaces	$1.55 \cdot 10^3$	$2.74 \cdot 10^3$
$\sum$ time in conflict [s]	$4.50 \cdot 10^5$	$2.57 \cdot 10^5$
mean time in conflict [s]	37.44	26.90
$\sum$ distance in conflict [m]	$3.51 \cdot 10^5$	$5.45 \cdot 10^4$
mean distance in conflict [NM]	3.46	3.22
$\sum$ flight time [h]	$1.56 \cdot 10^4$	$1.58 \cdot 10^4$
$\sum$ distance flown [NM]	$1.08 \cdot 10^7$	$6.76 \cdot 10^6$
$\sum$ fuel burned [kg]	$3.97 \cdot 10^7$	$3.54 \cdot 10^7$
$\sum$ taskload [h]	$4.51 \cdot 10^2$	$4.27 \cdot 10^2$
$\sum$ *Environmental compatibility* [€]	$1.51 \cdot 10^7$	$1.48 \cdot 10^7$
$\sum$ *Efficiency* [€]	$1.97 \cdot 10^8$	$1.19 \cdot 10^8$

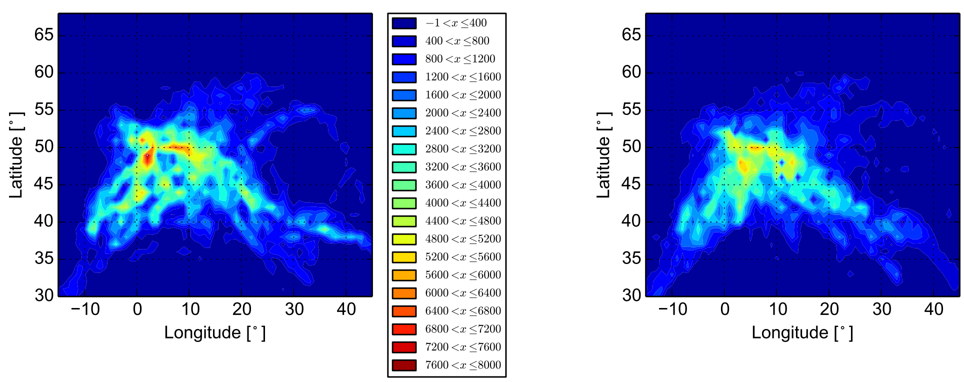

Figure 5. Heatmap of controller's taskload per artificial airspace and hour between 12 a.m. and 1 p.m. on May 17^{th}, 2017 above Europe. Left: TOMATO simulated historical data of 8800 real flights, right: TOMATO optimized these trajectories considering the requested city pairs, aircraft types and departure times. Colors of dark blue, light blue, green, yellow, orange, red and black indicate zero, 1500, 2800, 4100, 5400, 6700 and 8000 seconds, respectively.

Nevertheless, a smaller integrated controller's taskload is generated in the optimized scenario, because of fewer artificial airspaces with serious overload, which is more than 2520 seconds or 70 % of the controller's work hour. Whereas 207 airspaces with a taskload have been simulated in the reference scenario, only 188 cells with taskload of more than 2520 seconds in the optimized scenario result in a less complex ATFM when aircraft are allowed to follow their optimized flight paths. From this follows that airspace capacity would increase with the implementation of free route airspaces. In the reference scenario, the taskload exceeds values of 8265 seconds per hour and artificial airspace, whereas the maximum taskload in the optimized scenario reaches 5987 seconds (compare Figure 5). Specifically, Figure 5 indicates a more widely spread controller's taskload in the optimized scenario during the estimated peak hour, which enables an implementation of a dynamic airspace sectorization, as proposed by Gerdes et al.[65] However, the controller's taskload could increase spontaneously, a problem which probably may not only be solved by a dynamic airspace sectorization and needs reliable aircraft self-separation techniques and decision support systems for the ATC.

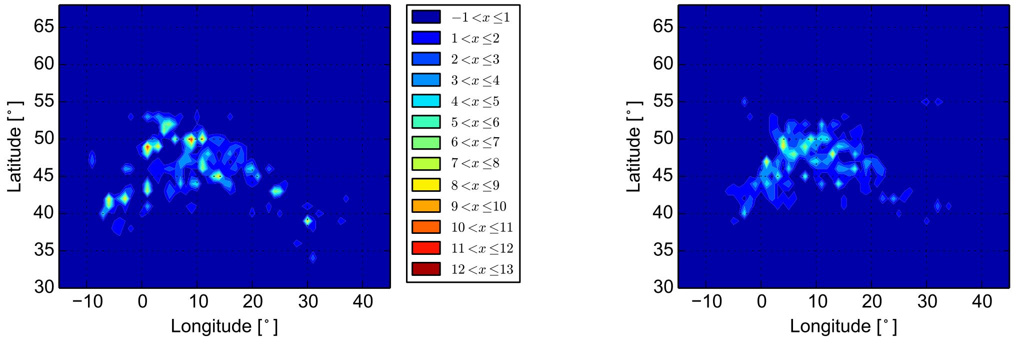

Figure 6. Heat map of the number of potential conflicts (separation infringements of 5 NM in the lateral and 1000 feet in the vertical direction) per artificial airspace and hour between 12 a.m. and 1 p.m. on May 17$^{\text{th}}$, 2017 above Europe. Left: TOMATO simulated historical data of 8800 real flights, which have been tracked in the upper European airspace between 12 a.m. and 1 p.m, right: TOMATO optimized these trajectories considering the requested city pairs, aircraft types and departure times. Colors of dark blue, light blue, green, yellow, orange, red and black indicate zero, 2, 4, 6, 8, 10 and 12 potential conflicts, respectively.

TOMATO's trajectory optimization has a positive impact on the spatial distribution of potential conflicts as well, because those conflicts are spread more widely over the European airspace and the number of conflicts per hour and artificial airspace could be reduced from twelve in the reference scenario to nine in the optimized scenario (Figure 6). From this follows that preferred flight paths are in neighbored airspaces, but do not essentially use the same artificial airspace, when 4D free routes are implemented. This has a positive effect on the ATFM-related KPI *Capacity utilization*, because high demanded airspaces above central Europe would be used more efficiently.

Airline KPIs such as *number of planes and employees*, *revenue passenger miles*, *number of departures and passengers* and *available ton-miles*[17] cannot be quantified, because they are used as input parameters (defined in the so6 m3 flight plan) for the simulation. However, KPIs describing *Efficiency*, *Safety* and *Environmental compatibility* can be quantified by the following measures: *Efficiency* includes fuel costs, direct operating costs and time costs (e.g. crew costs, delay costs, overfly charges (ATC costs), amongst others) and could be reduced by 40 % (compare Table 2) due to significant savings in fuel burn and ATC costs. The KPI *Environmental compatibility* summarizes the aviation impact on the environment (i.e. the contribution to the imbalance of the energy budget of the Earth-Atmosphere System, caused by radiative active emissions and by condensation trails) and depends on the emissions quantities, altitude,[66] latitude,[40,66] time of the day and heading[20,67] and could be reduced by 28 % (Table 2), mainly through reduced fuel burn and by the consideration of the latitude-dependent environmental costs in the lateral path finding. The KPI *Safety* is considered in the flight performance model COALA and additionally represented by the number of potential conflicts, which also could be reduced 4.5 % (Table 2), although the free route concept is applied in the optimized scenario.

The ATFM-related KPIs *capacity utilization*, *complexity*, *traffic variability* and *productivity* can be approximated by the simulation of the time-dependent and spatial variation of the controller's taskload, the number of potential conflicts and the shape of the individual trajectories (altitude changes, heading changes and speed changes). Although the optimized trajectories consist of continuous changes in altitude, heading and speed, the taskload could be reduced by 5.2 % in the optimized scenario.

V. Conclusion

The aim of this paper was to optimize a conventionally filed flight plan (i.e. a reference scenario) and compare the induced impact on the ATFM with a simulation of multi-criteria optimized trajectories. Thereby, significant differences between the reference scenario and the optimized scenario could be identified. Specifically, fuel burn, ATC charges and the environmental impact of the aircraft trajectories could be reduced, when the trajectories were optimized as 4D free routes. Even the controller's taskload could be reduced, through rescinded constraints given by waypoints in the reference scenario. The latter and the strong impact of wind direction and wind speed cause interesting differences in the patterns of the optimized lateral trajectories in the airspace with significant influence on the airspace capacity and controllers taskload.

This study suggests that even in the European airspace during a peak hour between 12 a.m. und 1 p.m. GMT, SESAR's proposed 4D free route concept is possible with a positive impact on both airline and ANSP efficiency and on the environmental compatibility. Integrated over the whole European airspace, the 4D free route concept has a further positive effect on safety, because the aircraft are more equally distributed, resulting in a reduced controllers taskload. Highly overloaded airspaces are avoided and more airspaces are used by aircraft. However, although the number of conflicts is reduced, the remaining conflicts are much more complex and difficult to solve.

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References

[1]SESAR Consortium, "The Roadmap for Sustainable Air Traffic Management - European ATM Master Plan," *EUROCONTROL*, Vol. 2, 2012.

[2]Federal Aviation Administration, "NextGen Implementation Plan 2016," 2016.

[3]Rosenow, J., Lindner, M., and Fricke, H., "Impact of climate costs on airline network and trajectory optimization: a parametric study," *CEAS Aeronautical Journal*, 2017.

[4]Jeßberger, P., Voigt, C., Schumann, U., Sölch, I., Schlager, H., Kaufmann, S., Petzold, A., Schäuble, D., and Gayet, F. G., "Aircraft type influence on contrail properties," *Atmospheric Chemistry and Physics*, Vol. 13, 2013, pp. 11965–11984.

[5]Rosenow, J., Förster, S., Lindner, M., and Fricke, H., "Multi-objective trajectory optimization," *International Transportation*, Vol. Special Edition 1, 2016.

[6]Standfuss, T., I, Temme, A., and Schultz, M., "Dynamische Luftraumoptimierung," *Deutscher Luft- und Raumfahrtkongress*, 2016.

[7]SES Single european Sky, "Verordnung (eg) Nr. 549/2004 des europäischen Parlaments und des Rates vom 10. März 2004 zur Festlegung des Rahmens für die Schaffung eines einheitlichen europäischen Luftraums," *Rahmenverordnung*, 2004.

[8]Mensen, H., *Moderne Flugsicherung*, Springer-Verlag Berlin Heidelberg, 2014.

[9]SESAR Joint Undertaking, "SESAR Solutions Catalogue," Second Edition, 2017.

[10]Abeloos, A., von Paassem, M., and Mulder, M., "An Abstraction Hierarchy and Functional Model of Airspace for Airborne Trajectory Planning Support," *Conference on human decision making and manual control*, edited by L. University, 2003.

[11]M. O'Keeffe, D. Houlihan, N. H., "AFRA Real Time Simulation Project Final Report European Free Route Airspace Developments," Tech. rep., EUROCONTROL, 2015.

[12]Eurocontrol, "Free Route Airspace Implementation Summer 2017," http://www.eurocontrol.int, November 2016.

[13]SESAR Consortium, "SESAR Concept of Operations Step 1," *D65-011*, 2000.

[14]Europäische Kommission, Generaldirektion Mobilität und Verkehr, G. E., "SESAR Modernisierung des Flugverkehrsmanagements in Europa," 2008.

[15]*European Airspace Concept Handbook for PBN Implementation*, EUROCONTROL, 2013.

[16]air navigation services organisation, C., "Introduction to the Aviation System Block Upgrade (ASBU) Modules," https://www.canso.org/sites/default/files/Introduction

[17]Rai, A., "Measurement of Efficiency in the Airline Industry using Data Envelopment Analysis," *Investment Management and Financial Innovations*, Vol. 10, 2013.

[18]Rosenow, J., Förster, S., and Fricke, H., "Continuous Climb Operations with minimum fuel burn," *Sixth SESAR Innovation days*, 2016.

[19]Civil air navigation services organisation, "Recommended Key Performance Indicators for Measuring ANSP Operational Performance," https://www.canso.org/sites/default/files/RecommendedKPIforMeasuringANSOOperationalPerformance.pdf, 2015.

[20]Rosenow, J., Förster, S., Lindner, M., and Fricke, H., "Impact of Multi-critica Optimized Trajectories on European Air Traffic Density, Efficiency and the Environment," *Twelfth USA/Europe Air Traffic Management Research and Development Seminar (ATM2017)*, 2017.

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

[22]Rosenow, J., Fricke, H., and Schultz, M., "Air Traffic Simulation with 4D Multi-Criteria Optimimized Trajectories," *Winter Simulation Conferences 2017*, 2017.

[23]ACE Working Group on Complexity, "Complexity Metrics for ANSP Benchmarking Analysis," Tech. rep., Eurocontrol, 2006.

[24]"AirTOp state-of-the-art fast time simulation software," http://www.airtopsoft.com/.

[25]Luchkova, T., Vujasinovic, R., Lau, A., and Schultz, M., "Analysis of Impacts an Eruption of Volcano Stromboli could have on European Air Traffic," *Eleventh USA/Europe Air Traffic Management Research and Development Seminar (ATM2015)*, 2015.

[26]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"*, 2016.

[27]Kreuz, M., Luchkova, T., and Schultz, M., "Effect Of Restricted Airspace On The ATM System," *WTCR Conference 2016*, 2016.

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

[29]Schultz, M., Fricke, H., Kunze, T., Mund, J., Lopez-Leonés, 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.

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

[31]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)*, 2012.

[32]Grewe, V., Matthes, S., Dahlmann, K., Gollnick, V., Niklaß, M., Linke, F., and Kindler, K., "Climate impact evaluation of future green aircraft technologies," *Greener Aviation, Brussels*, 2016.

[33]Matthes, S., Grewe, V., Lee, D., Linke, F., Shine, K., and Stromatas, S., "ATM4E: A concept for environmentally-optimized aircraft trajectories," *Greener Aviation, Brussels*, 2016.

[34]"Lido/Flight 4D," https://www.lhsystems.de/solutions-services/operations-solutions/lidoflightplanning/lidoflight4D.

[35]Metz, I., Hoekstra, J., Ellerbroek, J., and Kügler, D., "Aircraft Performance for Open Air Traffic Simulations Read More: https://arc.aiaa.org/doi/abs/10.2514/6.2016-3522 Aircraft Performance for Open Air Traffic Simulations Read More: https://arc.aiaa.org/doi/abs/10.2514/6.2016-3522 Aircraft Performance for Open Air Traffic Simulations," *Proceedings of the AIAA Modeling and Simulation Technologies Conference*, 2016.

[36]Eurocontrol, "NEST modeling tool," http://www.eurocontrol.int/services/nest-modelling-tool.

[37]V. Grewe et al., "Aircraft routing with minimal climate impact: the REACT4C climate cost function modelling approach (V1.0)," *Geoscientific Model Development*, Vol. 7, 2014, pp. 175–201.

[38]Matthes, S., Grewe, V., Dahlmann, K., Frömming, C., Irvine, E., Lim, L., Linke, F., Lührs, B., Owen, B., Shine, K., Stromatas, S., Yamashita, H., and Yin, F., "A Concept for Multi-Criteria Environmental Assessment of Aircraft Trajectories," *Aerospace*, 2017.

[39]Lovegreen, J. A. and Hansman, J. R., "Estimation of potential aircraft fuel burn reduction in cruise via speed and altitude optimization strategies," *MIT International Center for Air Transportation (ICAT)*, 2011.

[40]Skowron, A., Lee, D., and De León, R. R., "Variation of radiative forcings and global warming potentials from regional NOx emissions," *Atmospheric Environment*, Vol. 104, 2015, pp. 69–78.

[41]Søvde, O. A., Matthes, S., Skowron, A., and Lachetti, D., "Aircraft emission mitigation by changing route altitude: A multimodel," *Atmospheric Environment*, Vol. 95, 2014, pp. 468–479.

[42]Grabbe, S., Sridhar, B., and Cheng, N., "Central East pacific flight routing," *AIAA Guidance, Navigation and Control Conference and Exhibit.*, 2006.

[43]Sridhar, B. and Cheng, N. Y., "Fuel efficient strategies for reducing contrail formations in United States airspace," *Proceedings of the 29th IEE/AIAA Digital Avionics Systems Conference (DASC), Institute of Electrical and Electronics Engineers (IEEE)*, 2010.

[44]Ng, H. K., Sridhar, B., Grabbe, S., and Cheng, N., "Cross-polar aircraft trajectory optimization and the potential climate impact," *Digital Avionics Systems Conference (DASC)*, 2011.

[45]Sridhar, B., Cheng, N. Y., and Ng, H. K., "Energy Efficient Contrail Mitigation Strategies for Reducing the Environmental Impact of Aviation," *10th USA/Europe Air Traffic Management R&D Seminar, Chicago*, 2013.

[46]Zillies, J. L., Schmitt, A. R., and Vujasinovic, R., "Multi-objective 4D optimization of a trajectory-based air traffic management," *Proceedings of the Integrated Communications Navigation and Surveillance Conference*, 2013.

[47]Ng, H. K., Sridhar, B., Cheng, N. Y., and Li, J., "Three-Dimensional Trajectory Design for Reducing Climate Impact of Trans-Atlantic Flights," *AIAA Aviation*, 2014.

[48]Serafino, G., "Multi-Objective Aircraft Trajectory Optimization for Weather Avoidance and Emissions Reduction," *Modelling and Simulation for Autonomous Systems*, 2015.

[49]Kaiser, M., Schultz, M., and Fricke, H., "Enhanced Jet Performance Model," *Proceedings of the 2nd International Conference on Application and Theory of Automation in Command and Control Systems (ATACCS)*, 2011.

[50]Kaiser, M., Rosenow, J., Fricke, H., and Schultz, M., "Tradeoff between optimum altitude and contrail layer to ensure maximum ecological en-route performance using the Enhanced Trajectory Prediction Model (ETPM)," *2nd International Conference on Application and Theory of Automation in Command and Control Systems (ATACCS)*, London, 2012.

[51]Rosenow, J., Kaiser, M., and Fricke, H., "Modeling Contrail life cycles based on highly precise flight profile data of modern aircraft," *Proceedings of the International Conference on Research in Airport Transportation (ICRAT)*, 2012.

[52]Soler, M., Zou, B., and Hansen, M., "Flight trajectory design in the presence of contrails: Application of a mulitphase mixed-integer optimal control approach," *Transportation Research Part C*, 2014.

[53]Hargraves, C. and Paris, S., "Direct Trajectory Optimization Using Nonlinear Programming and Collocation," *Journal of Guidance, Control, and Dynamics*, 1987.

[54]Carretero, J. G.-H., Nieto, F. S., and Cordon, R., "Aircraft Trajectory Simulator Using a Three Degrees of Freedom Aicraft Point Mass Model," *Poster at the International Conference on Application and Theory of Automation in Command and Control Systems, Naples, Italy*, 2013.

[55]Bittner, M. and Fleischmann, B., "Optimization of ATM Scenarios Considering Overall and Single Costs," *6th International Conference on Research in Air Transportation*, 2014.

[56]Patrón, R. S. F., Botez, R. M., and Labour, D., "Flight Trajectory Optimization through Genetic Algorithms Coupling Vertical and Lateral Profiles," *Proseedings of the International Mechanical Engineering Congress and Exposition*, 2014.

[57]Murietta Mendoza, A. and Mihaela Botez, R., "Vertical Navigation Trajectory Optimization Algorithm For A Commercial Aircraft," *AIAA American Institute of Aeronautics and Astronautics*, 2014.

[58]Howe-Veenstra, R., *Commercial Aircraft Trajectory Optimization and Effciency of Air Traffc Control Procedures*, Ph.D. thesis, Master Thesis, University of Minnesota, 2004.

[59]Rosenow, J. and Fricke, H., "Flight performance modeling to optimize trajectories," *Deutscher Luft- und Raumfahrtkongress 2016*, 2016.

[60]Förster, S., Rosenow, J., Lindner, M., and Fricke, H., "A Toolchain for Optimizing Trajectories under real Weather Conditions and Realistic Flight Performance," *Greener Aviation, Brussels*, 2016.

[61](NOAA), N. W. S., 2016.

[62]Eurocontrol Experimental Center, *Coverage of European Air Traffic by Base of Aircraft Data (BADA)*, revision 3.6 ed., 2004.

[63]*User Manual for the Base of Aircraft Data (BADA) Family 4*, 2012.

[64]Poles, D., Nuic, A., and Mouillet, V., "Advanced aircraft performance modeling for ATM: analysis of Bada model capabilities," *29th Digital Avionics Systems Conference*, 2010.

[65]Gerdes, I., Temme, A., and Schultz, M., "Dynamic Airspace Sectorization using Dynamic Airspace Sectorization using Controller Task Load," *Sixth SESAR Innovation days*, 2016.

[66]Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., and Zhang, H., "Anthropogenic and Natural Radiative Forcing. In: 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 University Press*, 2013.

[67]Rosenow, J., *Optical Properties of Condenstation Trails*, Ph.D. thesis, Technische Universität Dresden, 2016.