Proceedings of the 2017 Winter Simulation Conference
W. K. V. Chan, A. D'Ambrogio, G. Zacharewicz, N. Mustafee, G. Wainer, and E. Page, eds.

AIR TRAFFIC SIMULATION WITH 4D MULTI-CRITERIA OPTIMIZED TRAJECTORIES

Judith Rosenow
Hartmut Fricke

Technische Universität Dresden
Institute of Logistics and Aviation
Hettnerstraße 1-3
01069 Dresden, GERMANY

Michael Schultz

German Aerospace Center (DLR)
Institute of Flight Guidance
Lilienthalplatz 7
38108 Braunschweig, GERMANY

ABSTRACT

Today's aviation industry is faced with three conflicting goals: First, aeronautics already draws responsible for 2 % of all anthropologically induced emissions, (IATA 2013) and the need for reducing those emissions is no point of contention anymore. Second, the irresistible growth of air traffic demand challenges both, airport operations and air traffic flow management. And third, despite all changes, the expectations of safety are constantly increasing. To account for the need of improved, safe and climate friendly aircraft operations, we present a simulation environment, that is capable of optimizing trajectories regarding multiple criteria. Therewith we show the positive impact of 4 D optimized trajectories on the air traffic flow, controller's taskload and airspace complexity and emphasize the importance of an enhanced air traffic flow management considering dynamic sectorization and air space configuration.

1 INTRODUCTION

Today, the European airspace is facing multiple capacity constraints, which are regulating the demand during busy traffic periods of the day. According to current market forecasts, passenger air traffic demand will continue to grow between 4.5 percent (Airbus 2016) and 4.8 percent (Boeing 2016) annually. These capacity limits typically cause inefficiencies in flight and consequently in airport ground handling as well. To better manage rare airspace capacity, free routing performance based navigation and harmonized airspace structures are seen as efficient mitigation measures according to the Single European Sky ATM Research (SESAR Joint Undertaking 2015) and the Next Generation Air Transportation System (NextGen) (Federal Aviation Administration 2016) programs. Additionally, a growing public awareness and a better understanding of the anthropogenic environmental impact necessitates further functions for flight planing and execution, beside today's minimum fuel and time objectives. Hence, multi-criteria trajectory optimization is required allowing the aircraft to follow a 4 D waypoint free trajectory with minimum costs.

In this paper, these divergent targets are applied in a twenty four hour Air Traffic Simulation of the European air space, which is capable of exploiting the 4 D free route optimization potential and especially considering the costs of condensation trails (contrails) depending on current weather conditions. Therefore, the simulation environment TOMATO (Toolchain for Multi criteria Aircraft Trajectory Optimization) (Rosenow et al. 2016) is used and airline efficiency and ecological compatibility are optimized for flight intentions for an entire day based on departure airport, arrival airport and departure time on July 2016, considering all safety standards. As one ecological aspect, condensation trails (contrails) are considered. Contrails form in the presence of ice-supersaturated regions (Sussmann and Gierens 2001), which are dynamic layers in the upper troposphere and lower stratosphere. To avoid contrail formation, aircraft would need to bypass these ice-supersaturated regions either laterally or vertically (Sussmann and Gierens 2001), hampering flight efficiency as detours cause extra fuel burn (Rosenow et al. 2016). Therewith, competing objective functions impact the performance indicators (Rosenow et al. 2016). A trajectory optimization based on those target functions might lead to unsolvable high requirements on airspace capacity, because similar vertical and lateral trajectories are expected, since airlines will still prefer wind-optimized flight paths, which do not significantly differ between the common used aircraft types.

Dynamic input parameters, as changes in demand and weather conditions, require a simulation of the air traffic system to analyze the impact of optimized trajectories on expected challenges for the Air Traffic Management (ATM) and Air Traffic flow Management (ATFM), (i.e., the spatial and time resolution of capacity) with consequences on controller's taskload and air space complexity. Indeed, our simulation of 4 D waypoint free trajectories allows statements on the today's demand on air space capacity, complexity and on the controller's taskload. To quantify the expected changes in capacity, complexity and taskload, three different scenarios are simulated: First, the real radar tracked trajectories are simulated as a reference scenario (hereafter called real). Second, the given demand is used to minimize airline costs in the trajectory optimization, already considering environmental costs due to engine emissions (hereafter called cost optimized). And third, the trajectories are further optimized by additionally considering high costs due to the formation of condensation trails in the lateral trajectory optimization. This simulation environment has been already used by Rosenow et al. (2017), where the economic difference between several levels of trajectory optimization has been analyzed but the impact of those individual trajectories on the air traffic flow management could not have been answered disproportionately. This fact is now taken into account.

NASA is searching for methods to organize and efficiently allocate the future airspace structure considering future requirements as an increased demand, different level of automation and more important ecological concerns (resulting in more heterogenous trajectories) (Sridhar et al. 1998) (Kopardekar et al. 2007). Following this research, the Dynamic Airspace Configuration (DAC) yields a promising potential. This should be realized by restructuring the air space, as initiated by Kopardekar et al. (2007) Gerdes et al. (2016) and Standfuss et al. (2015) to consider and promote higher levels of automation as self-separation and 4 D trajectories. Furthermore, DAC should be realized by an adaptable air space to accumulate the fluctuating demand over the day. Above all, generic air spaces should be considered to promote the interchangeability among the facilities of the controllers. Therewith, the airspaces could be managed by any controller due to no need of sector specialized skills (Mogford et al. 2014). Important input parameters for those efforts to reduce the airspace complexity, e.g., the impact of optimized 4 D trajectories on capacity and traffic patterns considering the fluctuating demand over the day have been simulated in this study and will be assessed in the following chapter.

1.1 Previous Work

Several air traffic flow simulation environments have been developed, each with a specific scope. The fast time air traffic simulator AirTOp generates trajectories in a dynamic airspace structure and iteratively considers conflict detection and conflict resolution (Luchkova et al. 2015). The Test bench for Agent-based Air Traffic Simulation (TABATS), simulates trajectorie scenarios considering weather intented lateral rerouting around thunder cells (Schultz et al. 2011) (Schultz et al. 2012) (Schultz et al. 2013) also concentrates on BADA performance tables and not on trajectory optimization. Both do not focus on precise trajectory optimization. Grewe et al. (2016) concentrates on the climate assessment of trajectories considering future aircraft technologies and uncertainties in the quantification of the emissions. Basic work in multi criteria optimization is done by Sridhar et al. (2013). Contrail formation has been considered by Ng et al. (2014) and Mannstein and Schumann (2005). Aircraft flight performance has been modeled with different granularity depending on the intended use. In an ISA standard atmosphere, performance models are available for airlines, e.g. the commercial flight planning tool Lido/Flight 4D 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. Some missing dependencies as compressibility effects in the calculation of the drag coefficient had been considered by Kaiser (Kaiser et al. 2011) resulting in the Enhanced Jet Performance Model (EJPM). Soler et al. (2014) 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 there are primarily two approaches around. The path finding algorithm A* as well as the more general Dijkstra algorithm for searching shortest paths in a graph are employed (Zillies et al. 2013) (Serafino 2015) and the optimal control problem approach (Hargraves and Paris 1987) (Sridhar et al. 2013) and (Bittner and Fleischmann 2014), 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 constricted number of parameters and sometimes the errors done by the approximation seem too high. Furthermore, the flight performance is modeled in a very simple way. Patrón et al. (2014) and Murietta Mendoza and Mihaela Botez (2014) used multi-level optimizations in 3 D grid models. Anyhow, the flight performance is only approximated by a performance database, where fuel burn and the distance traveled is 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. R. Howe-Veenstra (2004) 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. The research project REACT4C of the German aerospace center (DLR) published interesting findings regarding ecological trajectory optimization (V. Grewe et al. 2014).

2 SIMULATION ENVIRONMENT TOMATO

TOMATO is a simulation environment with a very modular architecture and described by Förster et al. (2016). In the core, there are three submodules, interconnected in an iterative process (cf. Förster et al. (2016) and Rosenow et al. (2017) and the optimization cycle therein), containing two optimization steps and one assessment part. The first step is a lateral path optimization (A* algorithm) considering wind speed and wind direction, ice-supersaturated regions, ATC en-route charges, as well as prohibited or restricted areas. Each of those factors reside 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 path influencing factors are already available in 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. The second step is a vertical flight profile along the optimized lateral path, modeled with COALA (COmpromised Aircraft performance model with Limited Accuracy), which is described by Rosenow et al. (Rosenow and Fricke 2016) (Rosenow et al. 2016) and complies all safety standards. An engine model is implemented in COALA, to determine precise performance and emission data for each time step during the flight. After both optimization steps the trajectory is assessed concerning airline costs and ecological costs (Rosenow et al. 2016) (Förster et al. 2016). After the assessment, more precise performance and cost data are available for the next iteration step with benefits especially for the lateral path calculation. TOMATO iteratively improves the optimum cruising altitude and speed (if not defined by an analytically solvable target function) and the required fuel mass by varying the input parameters at the end of each iteration step.

Due to the iterative process, the optimization is done in a real 3 D workspace. In the presence of dynamical input data (e.g., weather data), the optimization is carried out in a real 4 D manner. The assumption of a free route airspace allows the employment of unconstrained, continuous cruise climb operations, as required for an optimized trajectory (Rosenow et al. 2016). Due to the use and assessment of cost functions, a multi-criteria optimization is possible. That iterative optimization process will run until a certain cancellation criteria is met, e.g., a minimum residuum or a maximum number of iterations.

The trajectories are generated and assessed one by one. A variable number of files is generated as output for further processes (Förster et al. 2016). The analysis of the air space capacity, complexity and the controller's taskload is done in a post-analysis of the trajectories. The criterion validity of TOMATO could be shown in various applications (Rosenow et al. 2016) (Rosenow and Fricke 2016) (Rosenow et al. 2016).

2.1 Airline Costs Considered In TOMATO

Airline direct operating costs (DOC) are mainly driven by fuel costs (0.502 euros per kilogram Jet A1 plus 20 % handling costs (IATA) and time costs, considering crew salaries, maintenance costs, deprecation rates, and direct or indirect compensations for delays, if necessary (Förster et al. 2016). Airport and en-route charges are estimated as function of a unique Unit Rate and the maximum take off mass of the aircraft. The departure and en-route charges depend on standardized Unit Rates (Lindner et al. 2016), which are monthly published by EUROCONTROL. A mean value of all Unit Rates is considered outside the European area to avoid detours around the European area, as a result of the lateral optimization. Any kind of airspace restrictions can be formulated and activated as polygons. Any en-route charging regime with more or less uniform Unit Rates, e.g., FAB-EC (FAB Europe Central), can be implemented in TOMATO.

2.2 Ecological Cost Factors In TOMATO

For the evaluation of the aviation environmental compatibility, the main emissions are quantified. Products of complete combustion as carbon dioxide CO_2, water vapor H_2O, sulfate SO_4 and sulfuric acid H_2SO_4 are quantified as linear function of fuel flow (Lee et al. 2010). Emissions of nitrogen oxides NO_x, hydrocarbons HC and carbon monoxide CO are estimated following the Boeing-2 fuel flow method (Schäfer 2006) depending on fuel flow, thrust setting and measured reference values, estimated by the International Civil Aviation Organization (2016). For soot emissions BC, a combustion chamber model is implemented (Kugele et al. 2005).

The cost based assessment of the emissions according to their impact on global warming is quantified by the Global Warming Potential (GWP) (Lee et al. 2010), a measure of the relative effect of the greenhouse gas impact compared to the impact of CO_2. Therewith, converted emissions can be expressed as CO_2 equivalent emissions. Global climate analyses have shown, in 2005 aviation induced contrails contributed to global warming as much as 21 % of the total aviation CO_2 emissions in the same year (Lee et al. 2010). Approximatively 10 % of the total number of flights are inducing contrails (Spichtinger 2004). Hence, aircraft flying through ice-supersaturated regions are additionally burdened with a reference value of 32 tons of CO_2 equivalent emissions per hour (Rosenow et al. 2016). This reference value is adapted depending on the time of the day (Rosenow et al. 2017). The CO_2 equivalent emissions are converted into monetary values by using the European Emission Trading System (ETS) and assuming a price of 65 euros per ton of CO_2 equivalent emission.

2.3 TOMATO Input Data

2.3.1 Flight Plan

In order to simulate twenty four hours of European's air traffic, a flight plan from EUROCONTROL Demand Data Repository (DDR2) is used and 13584 flights to and from European airports, as well as overflights with an intended cruising altitude above $p_{\text{cruise}} = 376$ hPa (FL 250) are used for all three scenarios. The data contain departure and destination airports and an aircraft 4 D segmented trajectory (position, altitude, time stamps), updated using radar traces. The vertical discretization amounts 1000 ft, the lateral resolution depends on waypoints and flight phase with averaged values of 40 NM, 3 NM and 10 NM during en-route, climb and descent, respectively.

Besides day and night traffic, the flight plan shows a weak diurnal variation, because of a large number of time zones in Europe between Russia (GMT+5) and Portugal (GMT-1) (Rosenow et al. 2017). The aircraft fleet is simulated with sixteen different aircraft types, implemented in the aircraft performance model COALA. Aircraft subtypes, not implemented in COALA (e.g., turboprop engine aircraft) are represented by the best matching turbofan aircraft available (in most cases E170, E190 and CRJ9 for short haul flights). In total, 70 % of the original aircraft assignment is maintained. Aircraft payload is normally distributed around a typical aircraft specific seat configuration. A mass of 100 kg per passenger including luggage is assumed.

2.3.2 Weather Data

Weather data is extracted form Grib2 data of 25th of July, 2016, provided by the National Oceanic and Administration ((NOAA) 2016) with a timely resolution of six hours. The weather data set, closest to the departure time of the flight is chosen and set constant over the whole flight. Rosenow et al. (2017) show examples of size and location of the ice-supersaturated regions of that data set, which are mandatory for contrail formation (Rosenow 2016).

3 CAPACITY, CONTROLLER'S TASKLOAD AND COMPLEXITY

With the results of the air traffic simulation TOMATO, the post-analysis is possible to estimate the impact of 4 D optimized trajectories on the influencing factors of air traffic complexity.

3.1 Capacity

Defining air space capacity as number of aircraft per volume and time (EUROCONTROL), the number of aircraft per air volume with a spatial lateral resolution of 1 degree (resulting in 30 to 60 nautical miles, depending on latitude), in the upper air space (>FL 250) per hour has been quantified for each scenario. This artificial air space structure contains $N_{\text{total}} = 2379$ air volumes and has been used for the post analysis, to ensure a comparability of neighbored air spaces and to analyze the spatial distribution of aircraft in the European air space. The area of those artificial grids of analysis is equal to todays EUROCONTROL upper civil sectors above Germany. The number of aircraft in the artificial air volumes is higher (with a correspondingly lower time of flight) than in today's upper civil specific sectors. Hence, a large number of air volumes will be flown through by each aircraft. However, considering present efforts of SESAR defined in the SES legislative package (SES Single European Sky 2009) to harmonize and defragment the European air space by defining Functional Airspace Blocks (FAB) based on operational requirements regardless of State boundaries, the spatial distribution of the air traffic flow becomes more and more important for an efficient organization of the air navigation services (ANS), especially considering free routes (Button and Nieva 2013) (Standfuss et al. 2015) (Cujic et al. 2015). For both the estimation of the air space complexity and a dynamical organization of the future air space, the information of the dynamical spatial distribution of 4 D optimized trajectories is far more important, than the capacity within a highly specific ATC sector.

3.2 Controller's Taskload

Together with the capacity, the controller's taskload allows conclusion to be made about the air space complexity. On one hand, the difference between taskload and capacity is a good measure of the air space complexity, because a low taskload in an air volume with a high number of aircraft attests to a well structured air space with a low complexity. On the other hand, the efficiency of the air space structure can be estimated, by means of a maximum taskload an en-route controller should be exposed to over an hour. This maximum taskload amounts 2520 seconds per hour (corresponding to 70 % of the available time per hour). Otherwise, the sector needs to be divided into several sectors, or an additional controller is required for the same sector (Brain and Netjasov 2004). Hence, the air space structure will be most efficient, if the taskload of each controller converges to 2520 seconds. In this artificial air space structure, a taskload of 2520 seconds derives from approximatively 18 aircraft per air volume, depending on flight time. Furthermore, today's air space structure is inefficient, because the structure does not follow the aircraft routing structure to avoid superfluous handovers of aircraft between different controllers (Gerdes et al. 2016). Instead, the aircraft flow follows the ATC structure. A change of paradigm by the introduction of a dynamic and adaptive sectorization will significantly increase the air space structure and will reduce the air space complexity (Sridhar et al. 1998), (Kopardekar et al. 2007), (Standfuss et al. 2015), (Gerdes et al. 2016).

In this study, the controller's taskload is estimated according to a model developed by the Deutsche Flugsicherung (DFS) called $\text{CAPAN}_{\text{neu}}$ (Groth et al. 2011). Following this model, en-route air traffic controller's tasks concentrate on monitoring, radio telephony, coordination, clearances, conflict detection and conflict resolution, each claiming a specific effort. The following en-route controllers taskload per aircraft above FL 355 are taken over this study (Groth et al. 2011): 5 seconds every two minutes for recurring monitoring, 21 seconds for radio telephony, 14 seconds for clearances, 1.5 seconds for coordination and 40 seconds for conflict resolution. The taskload for conflict detection depends on the number of aircraft in the sector and the aircraft configuration, aircraft heading and flight path angle. Because heading and flight path angle are not analyzed individually for each aircraft in each artificial air volume, the worst case is assumed: a difference in heading of 180 degrees between two altitude changing aircraft causes the highest taskload of 30 seconds per aircraft. The number of aircraft in the sector is considered by multiplying this taskload (30 seconds) with a factor of 1.2, 1.5 and 2.0 in the case of six and seven, eight and nine as well as ten and more aircraft within the air volume, respectively. Hence, en-route controllers taskload above FL 355 depends on capacity to the power of two and on the duration of aircraft within the sector. From this follows an increased air space complexity in air spaces with heterogeneous distributed capacity in neighbored sectors.

3.3 Air Space Complexity

Following Delahaye and Puechmorel (2000) the air space is a highly dynamic system, characterized by the observed position and speed of aircraft within. The complexity may be described by intrinsic metrics as geometrical properties yielding a new complexity coordinate system of the complexity evolution over time, or by entropy metrics (Delahaye and Puechmorel 2000). For the analysis of the European air traffic situation over a whole day, those metrics require a high computational effort. For a first approximation, more general complexity metrics are used and the specific measures are saved for future studies. Kopardekar et al. (2007) defined air space complexity as relation between effects of changing airspace configurations, traffic patterns and the controller's taskload. Herein, air space configuration contains the predefined and coordinated organization of routes and their associated air space structures, temporary air space reservations and the ATC sectorization. Each of those parameters is considered in the simulation environment TOMATO (cf. section 2). The traffic pattern (capacity) and controller's taskload have been estimated in the post-analysis and the air space complexity can be quantified in this study, allowing statements on the influence of 4 D optimized trajectories with different target functions on the air space complexity.

The traffic pattern is characterized by the spatial distribution of the capacity and the statistical dispersion of aircraft within the flown through artificial air volumes. This characteristic is described by the Gini coefficient GUK [0...1], based upon the Lorenz curve, which describes the proportion of the total amount of a resource, partitioned to the proportion of the total number of used artificial air volumes. Assuming an equality, the area under the Lorenz curve would be $A = 0.5$ arbitrary units. This value is set as reference value. The Gini coefficient is defined as the difference between the area under the reference Lorenz curve of equality A and the area under the scenario and time specific Lorenz curve B in relation to A:

$$GUK = \frac{A-B}{A}.$$

A Gini coefficient $GUK = 0$ denotes total equality, whereas $GUK = 1$ describes a dispersion, where all resources are allocated to a single purchaser. The Gini coefficient is an invariant metric of inequality, because it is based on the relative proportion of the frequency distribution and does not depend on the absolute number of the available values and it can be used to compare the dispersion of aircraft in the air space at one time step of different air traffic scenarios, between which the number of used air volumes N_{used} and the number of aircraft $N_{\text{A/C}}$ is similar, but not equal. However, N_{used} is an important measure with significant influence on controller's taskload and has to be analyzed supplementary. The impact of the controller's taskload on the complexity is considered in a different measure. Respecting the maximum taskload of 2520 seconds per hour and artificial air volume, our post-analysis identified a large number of overloaded air volumes (130 in the cost optimized, 133 in the contrail considered and 145 in the real scenario, on average and per hour, compare Figure 5). Following Delahaye and Puechmorel (2000), Kopardekar et al. (2007) and Sridhar et al. (1998) those situations are increasing the air space complexity and the number of overloaded air volumes should be small. On the other hand, air space complexity will be reduced, if the number of used air spaces with a controller's taskload converging to 2520 seconds is large, because of an equality dispersion of aircraft. The difference between the share of taskload and the share of capacity per air volume and time $N_{\text{Taskloaod>Capacty}}$ allows further statements on the air space complexity, because an uneven distribution of taskload and capacity leads to an increased air space complexity. The number of air volumes where taskload exceeds capacity is taken as measure of complexity and is compared between all three scenarios (Figure 5).

4 IMPACT OF 4D OPTIMIZED TRAJECTORIES ON AIR SPACE COMPLEXITY

The goal of this simulation was to estimate the impact of optimized 4D waypoint free trajectories (as invented and preferred by the research programs SESAR and NextGen) on the airspace capacity and on controller's task load to enable statements on airspace complexity and to quantify the air traffic flow. Hence the distribution of the trajectories in the European air space was analyzed. Figures 1 to 3 show heat maps of capacity per hour with values between Zero (red) and 51 (yellow) aircraft per air volume.

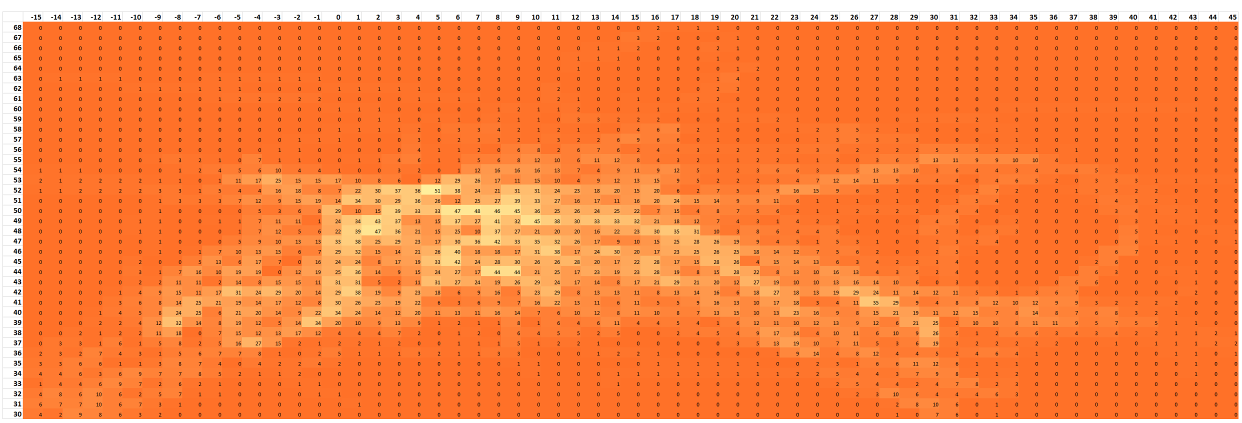

Figure 1: Heat map of simulated capacity of the real scenario as number of aircraft per artificial air volume between 8:00 and 9:00 GMT. 211 cells with high capacity (yellow) are detectable out of only 1265 used air volumes due to Aeronautical Information Publication (AIP) waypoint constraints.

Figures 1 to 3 show enforced airways in the real scenario (Figure 1) due to fixed AIP waypoints, and in the contrail scenario (Figure 3), where dedicated air spaces (i.e., ice-supersaturated regions) are more expensive. Anyhow, we can show that both multi-criteria optimized trajectories (Figure 2 and 3) are more uniformly distributed in the European airspace. This effect is reflected in our analysis of the derived complexity measures $N_{>2520}$, $N_{\text{Taskload>Capacity}}$, $N_{\text{overloaded/unused}}$ and GUK throughout the day, which increase with growing demand over daytime and reach lower values for the cost optimized scenario. In the contrail scenario, where high costs of ice-supersaturated regions are considered in the multi-criteria trajectory optimization, the number of used air spaces is maximum, the number of overloaded air volumes

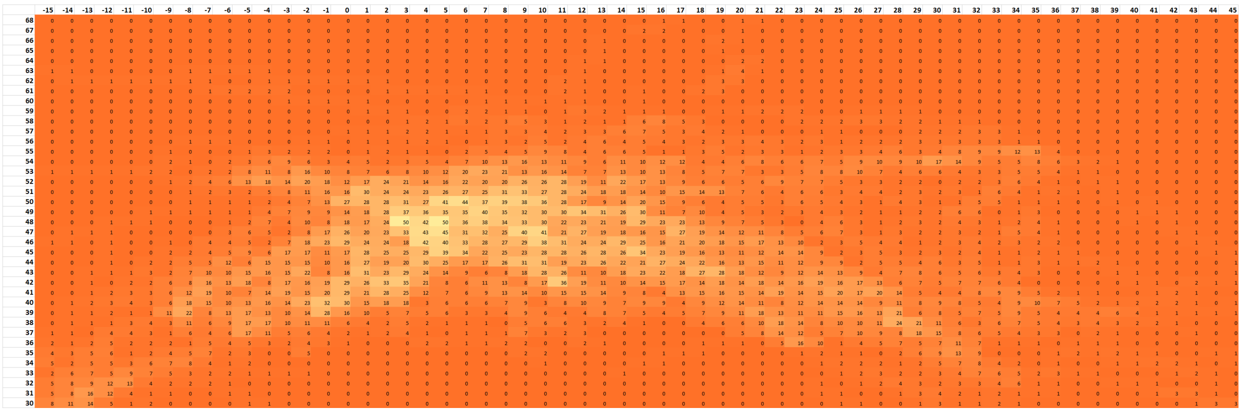

Figure 2: Simulated capacity of the cost optimized scenario (where contrail formation is not punished) as number of aircraft per artificial air volume between 8:00 and 9:00 GMT. 1336 used air volumes and only 197 with very high capacity (yellow) are detectable as result of the multi criteria trajectory optimization.

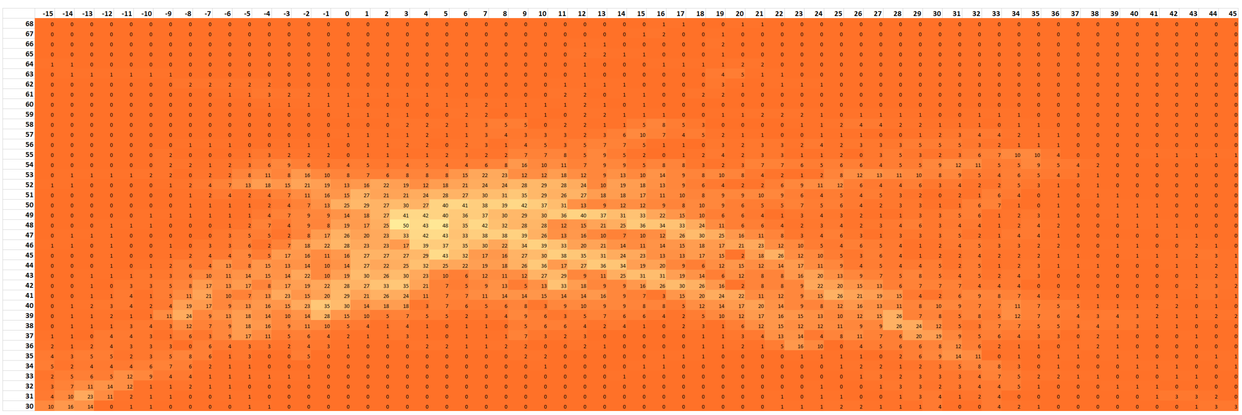

Figure 3: Capacity (i.e., number of aircraft per artificial air volume between 8:00 and 9:00 GMT) of the optimized scenario, where contrail formation is taken into account as additional cost function in the optimization. In this strongly weather dependent air space structure, 195 cells with high capacity (yellow) are detectable beside a large number (1358) of used air spaces.

is minimum, but aircraft are not evenly distributed among the airspaces (cf. Figure 6, left). Compared to the cost optimized scenario, the real scenario shows a small number of used air spaces N_{used} (cf. Figure 4, left), a large number of air spaces with high capacity (Figure 1) and high controller's taskload (Figure 5), a large number of air spaces with controller's overload $N_{>2520}$ (Figure 4, right) and a strong heterogeneity between neighbored air spaces (Figure 5, right).

Our simulation shows an interesting behavior with changing demand over daytime. While the maximum number of overloaded air volumes $N_{>2520\,\text{s}}$ appears at 9 a.m. due to morning peaks (especially short-haul flights) above central Europe, the sum of taskload across all air volumes is maximum at 11 a.m., when most of the long-haul flights of the day have been departed. At 1 p.m., the long-hauls are distributed efficiently over central Europe and N_{used} reaches maximum values.

Anyhow, in the simulation of the optimized scenarios, conflict management is not considered. Here, more separation infringements are expected due to wind optimized flight paths. The development of the Gini coefficient GUK gives evidence for an uneven distribution of aircraft in the artificial air volumes,

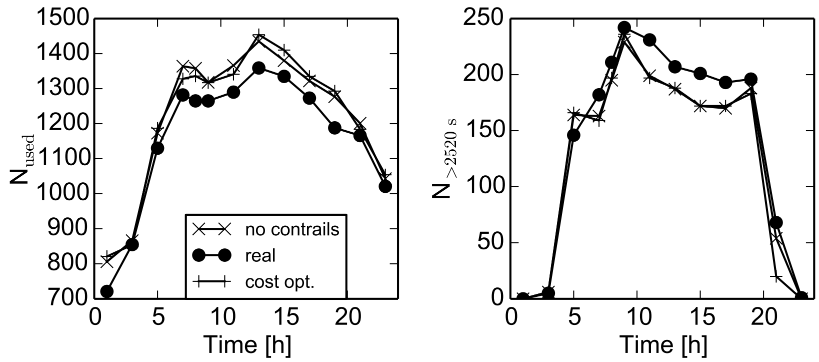

Figure 4: Left: Number of used air volumes per hour over the day in all three scenarios. Right: Number of overloaded air spaces with overloaded controllers taskload. With our optimization both the taskload and the airspace complexity could be reduced in the European airspace.

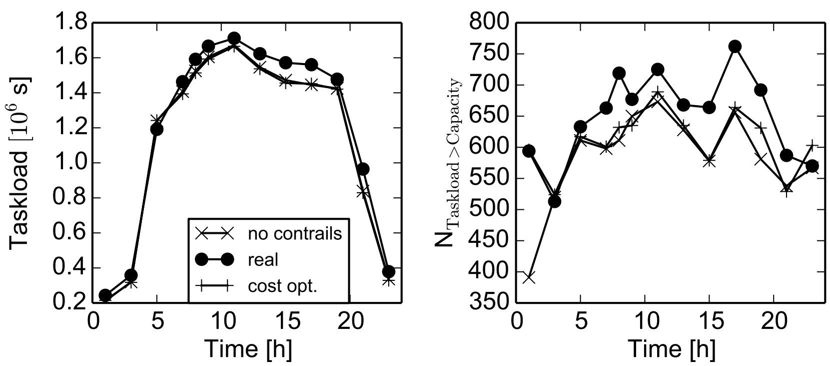

Figure 5: Left: Sum of controller's taskload per hour over the day. Right: Number of air spaces where taskload exceeds capacity, as measure of air space complexity. Both optimized scenarios show a better distribution of aircraft and taskload to the European airspace. Therewith, the airspace complexity could be reduced by considering individual aircraft performance in a 4 D waypoint free trajectory optimization.

especially in the optimized scenarios. Here, the *GUK* reaches higher values and spreads more strongly over the day as reaction of changes in demand.

5 CONCLUSION AND OUTLOOK

In this paper we could show the impact of 4 D multi-criteria optimized trajectories on the distribution of capacity and the effect on controller's taskload and air space complexity. We could confirm two theses. First: optimized trajectories will distribute the air traffic over the European air space and second: the distribution of aircraft following their optimum trajectories without conflict management is more uneven, although a high number of air volumes is used and taskload is reduced, compared to the today's air space configuration. An increased intrinsic air space complexity is expected due to a wide spectrum of speed and altitude changes of optimized trajectories. Hence, following complexity measured as dynamic density according to Delahaye and Puechmorel (2000), further investigations in an efficient air space configuration are required. For example, ideas of Kopardekar et al. (2007) like tube corridors or "highways in the sky" are promising concepts, where aircraft optimized trajectories could be better considered than in today's

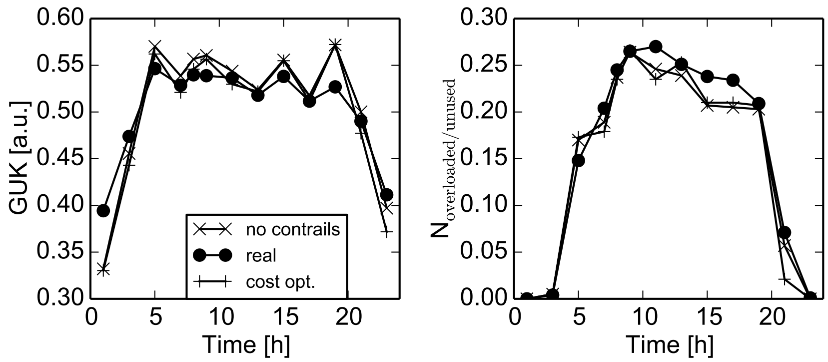

Figure 6: Left: Gini coefficient as measure of the statistical dispersion of aircraft within the used air volumes. Right: Share of overloaded air spaces per unused air space. Due to a missing air traffic flow management, the Gini coefficient shows a more uneven distribution of aircraft within the used air spaces in the optimized scenarios. However, a better distribution of aircraft to the whole European airspace has succeeded with the optimization.

trajectory management. In addition, we could emphasize the importance of a future dynamic sectorization to deal with the time dependent changes in air traffic demand and trajectories due to changing weather conditions over the day. Gerdes et al. (2016) provide a method to dynamically adapt the air space structure depending on the specific demand and flow restrictions.

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AUTHOR BIOGRAPHIES

JUDITH ROSENOW is postdoctoral researcher at Technische Universität Dresden. In 2011 she finished her Ph.D. in Aeronautical Meteorology on Optical Properties of Condensation Trails. Since 2014 she concentrates on trajectory optimization and it's application on several levels of air traffic operations. Her e-mail address is Judith.Rosenow@tu-dresden.de.

HARTMUT FRICKER is professor for Aviation Technologies and Logistics at Technische Universität Dresden. In 2001 he finished his Habilitation on "Integrated Collision Risk Modeling for airborne and ground based systems". In 2012 he was elected scientific expert to DFG. In 2013 he became SESAR External Expert. His e-mail address is Hartmut.Fricke@tu-dresden.de.

MICHAEL SCHULTZ is Head of the Department of Institute of Flight Guidance at the German Aerospace Center (DLR), Braunschweig, Germany. He holds a Ph.D. in aviation technologies and logistics from Technische Universitt Dresden. His research interests include stochastic, agent-based simulation, and their applications in the transportation sector. His e-mail address is Michael.Schultz@dlr.de.