Proceedings of the 2018 Winter Simulation Conference
M. Rabe, A. A. Juan, N. Mustafee, A. Skoogh, S. Jain, and B. Johansson, eds.

COUPLING OF TURNAROUND AND TRAJECTORY OPTIMIZATION BASED ON DELAY COST

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ABSTRACT

This study successfully implements flight specific delay costs in an air traffic simulation with a multi-criteria trajectory optimization and exemplifies a coupling of turnaround and trajectory optimization of historical real flights. Therein, delay costs and detour costs for the reduction of contrail formation are individually calculated for each flight and considered in a flight specific multi-criteria trajectory optimization with the air traffic simulation environment TOMATO. Detours in the optimized trajectories are mainly caused by the intent of avoiding contrail formation. With this case study, the historical flight plan could be stretched and departures and arrivals could be more homogeneously distributed during the analyzed three hours while at the same time ecological costs could be saved by 15 per cent. Therewith the promising potential of System Wide Information Management between airports, airlines, air traffic control and customers could once again be shown.

1 INTRODUCTION

Aircraft trajectories are functions in a four-dimensional space constricted by aerodynamic and flight performance limitations in speed and altitude. In addition, economic, environmental and operational constraints affect all stakeholders. To master future expected capacity constraints during peak hours in air spaces with extremely high traffic density, trajectory based operations are invented by Next Generation Air Transportation System (NextGen) and by the Single European Sky ATM Research (SESAR) program as first step towards a harmonization of the European air space (Joint Planning and Development Office 2011). With a time prioritization for arrivals at airports, initial trajectory-based operations are deployed by defining time stamps which describe the aircraft trajectory in a four-dimensional way and enable a controlled time of arrival (SESAR Joint Undertaking 2015). Therefore, all stakeholders are called upon to contribute to a System Wide Information Management (SWIM) (International Civil Aviation Organization 2016) and to apply an interoperable exchange of flight and flow information right before each flight for a collaborative environment (International Civil Aviation Organization 2012).

Competitive target functions (e.g. airline's cost index, preferred routes, Air Traffic Control (ATC) instructions, runway capacity limits or airport ground handling constraints) and unpredictable impact factors, such as weather phenomenons or geo-political restrictions, strongly increase the complexity of a precise 4D trajectory prediction. High punctuality demands are made on the involved parties (airlines, airport, network manager and ATC provider) which often cannot be adhered over the whole day of operation. For example, in 2016, only 80 % of all flights were less than 15 minutes late (Performance Review Commission 2017). However, origin of most delays is during the aircraft turnaround (Mueller and Chatterji 2012; Performance Review Commission 2017). Averaged over the whole flight, the average time variability (measured as standard deviation of all European flights during 2016) amounts 5.3 minutes (Performance Review Commission 2017), around a mean delay of 15 minutes. The standard deviation of departure and

978-1-5386-6572-5/18/$31.00

arrival delay reaches 16.6 and 18.6 minutes (Mueller and Chatterji 2012). Note, in 2009, the average predictability of the airborne trajectory 20 minutes before arrival was 30 seconds (Bronsvoort et al. 2009), giving aircraft ground handlers the opportunity to react to delayed arrivals with a fast turnaround (Schultz 2018a). Furthermore, airlines implement time buffers to achieve target values of punctuality (Schultz 2018b).

For example, in order to secure an efficient and safe Air Traffic Flow and Capacity Management (ATFCM), for flights planned to enter into airspace sectors anticipated as significant demand/capacity imbalances, departures slots are allocated by the Network Management Operation Center NMOC. Allocated departures slots may induce specific delays (ATFCM delays). For such flights (regulated flights), imposed slot adherence of take-off-time is -5 min + 10 min. For Collaborative Decision Making (CDM) airports (most of the major hubs in Europe), ATFM slot allocation is coordinated with Airport CDM systems, to optimize turnaround operations.

Delays are expensive. Time dependent costs influence crew salaries, airport charges for parking positions and compensation for missing connecting flights, to name some of the concerned (International Air Transport Association 2017). Airline delay cost dependencies are summarized and parameters are updated by Cook and Tanner (2015). Departure delay may be caused for four reasons: airline, reactionary (as respond on already delayed arrivals), en-route (ATFM induced) and weather (at destination) (International Air Transport Association 2017). Although operational resilience is currently a subject of research and major concern for airport planners, sometimes, the share of reactionary delay (as part of the average departure delay per flight) increases with daytime and reaches a maximum value of 66 % at 9 p.m. (Eurocontrol 2016). En-route and weather influenced delays only share 8 % of the delays but the local turnaround, caused by airlines, airport operators, ground handlers and other parties induced 35 % of all departure delays in 2016 where the averaged (over all European flights) departure delay per flight reached 11.2 minutes (Performance Review Commission 2017). Hence, the initiators of delay are non linearly coupled; an already delayed aircraft causes additional trouble at the airport with extra delay costs. However, to ensure a continuous demand and a maximum use of resources, any system to be operated needs to reach a certain limit of acceptable level of delay in order to be profitable.

Delays are unavoidable. Even in a fully automated operation, weather conditions will change in an unpredictable manner, disregarding from the difficulty to reliably predict weather conditions along the whole flight. In addition, airline target functions might change between the flight planning process and the day of operation (Rosenow et al. 2018). Subsequent, aircraft speed, climb and descent profile will change (as reaction on a different cost index). In Free Route Airspaces (FRA), as intended by (Bucuroiu 2017), the preferred flight path will change, because weightings of the multi-criteria trajectory optimization will be adapted. For example, the formation of condensation trails could be burdened with high environmental costs causing lateral and vertical deviations from the originally flight plan to avoid ice-supersaturated regions in the atmosphere. Exactly those spontaneous modifications of the planned flight path often lead to delays. The induced delay costs must be overcome by saving environmental costs. Otherwise, increased direct operating costs due to inefficient and higher cruising speeds could be accepted to avoid delay.

The resulting cost-benefit analysis culminates in a complex, non linear optimization problem, which has been solved in the case study by using the Toolchain for Multi criteria Aircraft Trajectory Optimization (TOMATO) (Foerster et al. 2016 ; Rosenow 2017a). In this paper, a real air traffic scenario, described by 128 flights from and to Boston Logan International Airport (BOS) during three hours on April 17th, 2018, is assessed and optimized. The coupling between the air-to-air trajectory and the ground-to-ground trajectory is exemplified by the economic balance between delay costs induced by decreased environmental costs due to contrail avoidance. For each flight, a total minimum of delay costs and contrail costs is estimated, by a variation of the weighing function of contrail costs in the multi-criteria trajectory optimization.

For the first time, a coupling between ground operations and flight operations is simulated and the boundaries of environmental friendly trajectory optimization on the airport ground handling is demonstrated. Therefore, the weighting function has been analyzed from different points of view, always under hard constraints. In former studies, mainly the environmental part of the trajectory assessment has never been considered, although it contains the most unpredictable impact factors. The focus of the project Turnaround Integration in Trajectory And Network (TITAN) (Zerkowitz 2012), was the identification of improvement opportunities in the communication between aircraft turnaround stakeholders (Katsaros et al. 2012) and the integration possibilities for the business trajectory. However, in TITAN the aircraft was still considered as stationary. During turnaround, the trajectory continues to evolve but only in the time dimension only (Zerkowitz 2012). Neither the network level, nor environmental issues are developed in detail. Other studies end at the airport slot allocation and are not interested in the effect of trajectory deviations on the delay costs (Schultz et al. 2011; Schultz et al. 2012; Schultz et al. 2013; Ivanov et al. 2017; Pellegrini et al. 2017). Other authors focus on the absorption of delays, neglecting negative effects as increased costs by gaining speed (Belkoura et al. 2012). The restrictions may result from the necessity to precisely model the individual aircraft trajectory in order to assess competitive cost factors of the trajectory. In order to consider different weightings of the cost functions physically reliable modifications regarding flight path or speed are required. Therefore, an aircraft performance model with optimization potential is essential. Those highly complex and aircraft type specific models are rare. Matthes et al. (2016) developed a performance model for the development of environmental friendly trajectories based on BADA performance tables which is a rough approximation of the aircraft performance (Rosenow et al. 2017). Here, delay costs were not considered. The Air Traffic OPtimizer (AirTOp) would be able to the couple trajectory and ground operations, but also relies on BADA performance tables and is restricted to the implementation of a Standard Atmosphere (Rosenow et al. 2018b). Commercial products, such as Lido flight 4D by Lufthansa or the Air Traffic Simulator (TAAM) by Jeppesen only consider a Standard Atmosphere without any wind information. Therewith, weather effects cannot be reproduced.

In TOMATO, the Compromized Aircraft performance model with Limited Accuracy (COALA) (Rosenow and Fricke 2016; Rosenow et al. 2016; Rosenow et al. 2017) is implemented. COALA uses highly resolved weather data (in Grib2 format) and only falls back to the BADA flight performance model for fuel flow, and maximum thrust during climb with uncertainties in fuel flow of around 5 % (Poles et al. 2010). This is the "limited accuracy" in COALA. Using the implemented jet engine combustion model, COALA is able to quantify several emission species (Rosenow et al. 2016) which can be transferred into external environmental costs by using the Global warming potential with parameters published by Myhre et al. (2013). Additionally, COALA calculates the environmental impact of condensation trails (contrails) depending on both flight performance characteristics and atmospheric conditions. By weighting the environmental impact, the trajectory can be optimized regarding minimum contrail formation. This feature makes COALA unique among the available ones.

2 SIMULATION AND ASSESSMENT OF OPTIMIZED TRAJECTORIES

2.1 Simulation Environment TOMATO

The air traffic simulation environment TOMATO is described by ((Förster et al. 2016) and (Rosenow et al. 2017)). For this case study, the toolchain has been extended by flexible weighting of contrail costs between zero and 54 tons of CO_2 equivalent emissions per contrail hour (compare Section 2.3) in order to manipulate the trajectory regarding minimum contrail costs and minimum delay costs. Furthermore, the quantification of delay costs is improved by the sum of linear functions depending on pilot and crew salaries, number of passengers (PAX) and amount of delay in minutes. In TOMATO, the trajectory is assessed regarding several key performance indicators, some of them can be manipulated as input variables for the weighting function of the multi-criteria trajectory optimization. The weightings are considered in the lateral path finding algorithm, amongst wind data, ice-supersatured regions, restricted areas and overfly charges (Förster et al. 2016). Other weightings, such as the cost index, the impact of insalubrious and radiative active emissions and thrust ratings to protect the engines, are considered in the vertical trajectory optimization. The key performance indicators are summarized in Direct Operating Costs (DOC) including delay costs und Environmental Costs (EC) which in turn contain contrail costs. TOMATO has been validated by a comparison with the Air Traffic Optimizer AirTOp using a reference scenario (Rosenow et al. 2018a).

In TOMATO, the flight performance model (COALA) analytically solves the dynamic equation of motion by considering all acceleration forces at each time step. Therewith, only physical possible trajectories are generated. For optimization purposes, target functions for speed and altitude are derived from the weighting of the multi-criteria optimization. The target values are controlled by a proportional plus integral plus differential controller and the lift coefficient is used as controlled variable (Rosenow and Fricke 2016; Rosenow et al. 2016). The implemented jet engine combustion model in COALA quantifies the emission species as well as exhaust temperature and exhaust volume flow rate, which is important for the estimation of conditions of contrail formation, together with the quantification of the number of soot particles (Rosenow 2016). With the additional analysis of the relative humidity above ice the exact duration of contrail formation can be estimated.

2.2 Quantification of Delay Costs

In this case study, delay costs mainly depend on the sum of four cost components: A linear cost rate is used for each pilot per minute delay (2.34 €/min). This applies for each steward per minute delay (1.02 €/min). The slope of crew salaries are derived from European airlines Cook and Tanner (2015). Due to missing availability of data the delay-specific costs per passenger are taken from European airline delay cost reference values which has been updated and extended in 2015 by Cook and Tanner (2015). Therein, passenger delay costs are split into hard and soft costs per passenger and per minute delay (Cook and Tanner 2015). Hard costs are considering passenger rebooking, compensation and care. Soft costs reflect subjective factors such as loss of market share due to unpunctuality. Cook and Tanner (2015) derived three scenarios for each passenger delay factor with differences between low and high scenario of approximatively 100 %. Those scenarios are used to approximate the impact of the scheduled turnaround time (STT) according to the Computerized Reservations Systems (CRS) on the delay costs. Expectancy, aircraft type-specific values of the turnaround time are taken from the Aircraft Characteristics for Airport Planning. For example, the Fullserving Turnaround Time (FTT) of an Airbus A320 aircraft amounts 44.2 minutes, compared to an Outstation Turnaround Time (OTT) of 21.6 minutes (AIRBUS S.A.S 2014). FTT differs from OTT in the boarding and deboarding procedure of 150 passengers through one door and one passenger boarding bridge (compared to 180 passengers through two doors and two stairways), as well as in additional processes such as refueling, toilet serving and potable water serving (AIRBUS S.A.S 2014). If the delay exceeds the difference between fullserving and outstation turnaround time, the high passenger delay cost scenario will be used in the trajectory assessment, to consider expected higher costs for ground handling due to a missed arrival slot and to respect reactionary delay costs. On the other hand, low passenger delay cost factors will be used if the STT is still longer, than the sum of delay and OTT. Therewith, the impact of the STT on the delay costs is considered in the simulation. Furthermore, with STT and OTT airlines are given the opportunity to proceed a fast turnaround to compensate delay.

2.3 Quantification of Contrail-Costs and Environmental Costs

Contrails are ice particles at flight level developed from condensed water vapor (Schumann 2005). For contrail formation, the ambient atmosphere has to be cold enough to counterbalance the exhaust heat, which works against condensation (Schmidt 1941; Appleman 1953). The threshold temperature is derived from the Schmidt-Appelman-criterion (Schmidt 1941; Appleman 1953). In an ice-supersaturated ambient atmosphere contrails will form into long living artificial cirrus clouds, which are considered as contrails in this study (Brewer 1946; Schumann 1996; Sussmann and Gierens 2001). For the assessment of contrails the following assumptions are applied: In 2005, aviation induced contrails contributed to global warming as much as 21 % of the total aviation CO_2 emissions (Lee et al. 2010). Approximatively 10 % of the total number of flights are inducing contrails (Spichtinger 2004). Hence, the impact of a contrail induced in one hour, can be estimated. In the assessment of this study, aircraft flying in ice-supersaturated regions are additionally burdened with a reference value of 32 tons of CO_2 equivalent emissions per flight hour in the ice-supersaturated region (Rosenow et al. 2016). This reference value is adapted depending on the time of the day following 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 €per ton CO_2 equivalent emission. Figure 1 shows size and position ice-supersaturated regions over the United States as one criterion of contrail formation on April 17th, 2018, 12 p.m. at 200 hPa. Due to the significant size of the ice-supersaturated regions on this specific day it is expected that not all flights will be able to avoid contrail formation.

Additionally, the most important jet engine emissions are quantified using the implemented jet engine combustion model (Rosenow et al. 2017). Furthermore, a cost based assessment of those emissions is derived by the Global Warming Potential (GWP) (Lee et al. 2010). GWP measures the relative environmental effect of a specific substance, compared to the impact of the same amount of emitted CO_2. Therewith, converted emissions can also be expressed as CO_2 equivalent emissions and converted into monetary values using the ETS.The quantified emission costs and the contrail costs are summarized in the environmental costs (EC).

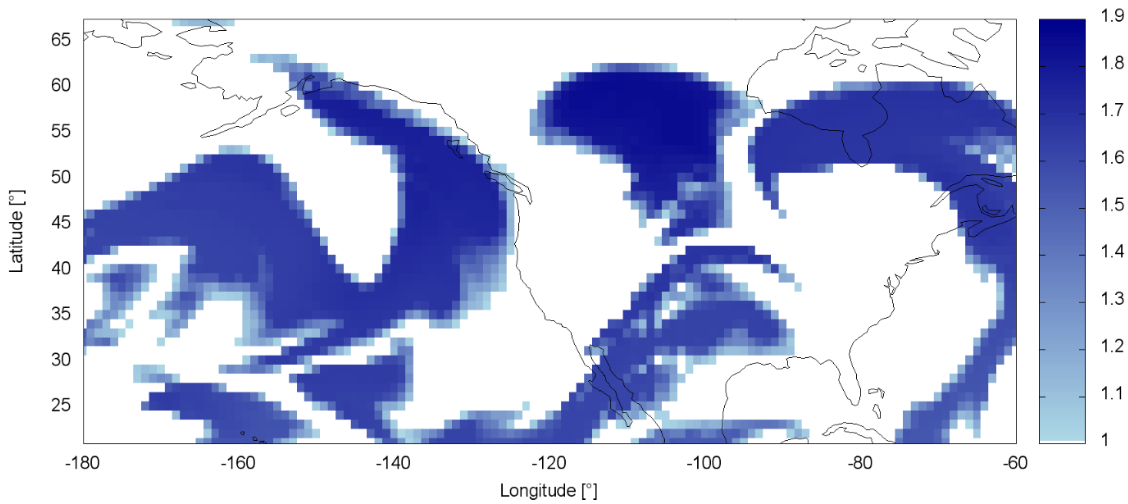


Figure 1: Location of ice-supersaturated regions over the United States as one criterion of contrail formation on April 17th, 2018, 12 p.m. at 200 hPa. Axes denote longitude and latitude [°].

The derived global optimum for contrail costs of the analyzed trajectories are simulated for climb and descent profiles and true air speeds with a maximum specific range. From this follows a relatively low cruising speed for the benefit of nearly minimized fuel consumption (Rosenow et al. 2016). To reduce the amount of delay costs, speeds could be increased up to a maximum aircraft type specific cruising Mach number. For the contrail minimum scenario several speed adjustments have been proceeded. The scenarios are also considered in the global assessment.

3 IMPACT OF CONTRAIL COSTS ON DELAY COSTS

The aim of this study was to estimate an optimum flight specific detour around ice supersaturated regions, considering the Schmidt-Appelman-criterion to gain a minimum sum of contrail costs and delay costs. Therefore, the simulated flights were individually analyzed and a weighting factor for contrail costs was varied in nine simulation runs (each multi critically optimized the trajectories) between zero and 54 tons of CO_2 equivalent emissions per contrail hour (see Table 1 for extremum and mean scenarios and their expected impact on trajectory optimization). It is expected, the higher the contrail costs, the higher the possibility, that a detour around ice-supersaturated regions is considered in the path finding algorithm, i.e. the longer the flight distance and time of flight. In order to find a guaranteed solution, the contrail costs must not be set to infinity. In the 54 tons scenario, the algorithm already did not find a solution for one flight which has been removed in all scenarios. The heuristic in the path finding algorithm A* to find the minimum distance is based on the great circle distance. That's why, the algorithm does not accept unrealistically long detours. Large ice supersaturated regions at cruising altitude (as shown in Figure 1) cause trajectories, where contrail formation is unavoidable. Therewith, the following extremum values are considered in the costs assessment:

Table 1: Impact of extremum contrail cost weightings on the trajectory.

Contrail cost weighting	Impact on trajectory optimization
0 t CO_2 eq. emissions:	Minimum time track
32 t CO_2 eq. emissions:	balanced contrail and delay costs
54 t CO_2 eq. emissions:	minimum possible contrail formation

Additionally, the real flown trajectories on the specific day were simulated as reference scenario. Due to a significant detour factor (quotient of actual flight distance divided by great circle distance) of the reference scenario, the optimum contrail induced detour was estimated on the bases of multi critically optimized trajectories. Since one of the Efficiency Key Performance Indicators, the "average horizontal en route flight efficiency of the actual trajectory" is defined as the distance flown compared to the great circle distance (The European Comission 2013), the ground distance is also evaluated in the study.

3.1 Trajectory Specific Optimum Contrail Induced Detours

Contrail formation could have been avoided between Boston Logan International Airport (BOS) and Los Angeles International Airport (LAX) with a Boeing B787 aircraft (compare Figure 2). The aircraft departure was already 30 minutes late, which is why high passenger delay costs are assumed (compare Section 2.2).

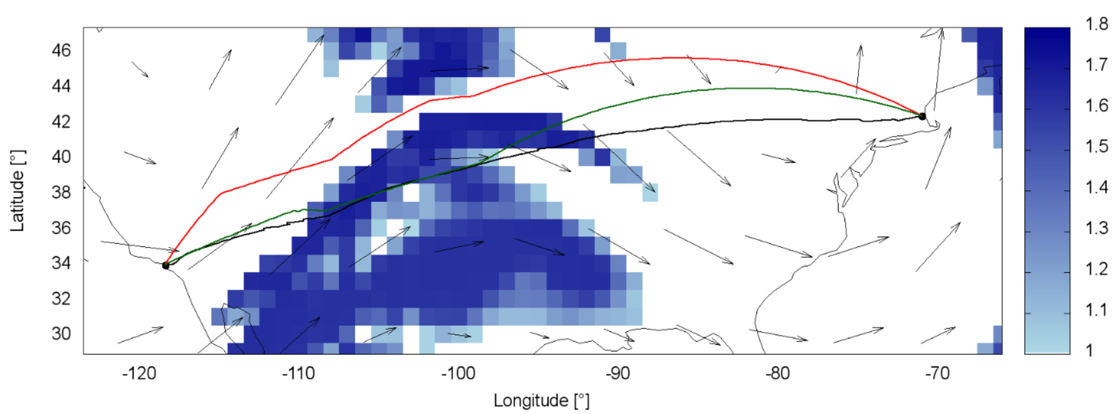


Figure 2: Optimized trajectories from Los Angeles to Boston in an ice-supersaturated (blue squares) atmosphere: Black: originally filed, green: multi-critically cost optimized (contrail costs= 32 t) and red: complete contrail avoidance. Black arrows mark wind speed (length) and wind direction.

In Figure 2, ice supersaturated regions at cruising altitude (between 210 and 180 hPa) are shown in blue. Note, only if the Schmidt-Appelman-criterion is satisfied, contrails will be induced. Hence, contrail formation is very unlikely in low altitudes. The impact of increasing detours around those regions is reflected in the delay costs and in flight time (compare Table 2). Furthermore, the detour induces additional fuel burn, direct operating costs (DOC) and environmental costs (EC). Hence, the cost minimum trajectory with cruising speeds for a maximum specific range (32 t CO_2 eq. emissions) includes 1360 € contrail costs, 1147 € delay costs and a flight time of 7.02 hours. The minimum time track (zero t CO_2 eq. emissions) would cause 7 % more contrail costs, 1.3 % more DOC and 3 % more EC by only saving 0.34 % delay costs. Complete contrail avoidance were estimated for a contrail cost weighting higher than 32 t CO_2 eq. emissions (compare Table 2). Strong headwinds in the second half of the flight cause a northern optimum trajectory. As soon as contrails are avoided, the ground distance does not increase with increasing contrail costs function, because the algorithm does not find different solutions.

In this special case, a speed increase yield reduced DOC and reduced delay costs (compare Table 2). Obviously, the increase in EC and in fuel burn does not overcome the benefit of the reduced flight time. Hence, the detour around the ice-supersaturated is short enough to compensate additional fuel burn by saved contrail costs, when cruising speed is increased as well.

Table 2: Optimum contrail cost weighting (in t CO_2 eq. emissions) for a single trajectory between BOS and LAX, where contrail formation could have been avoided. The last line lists those costs derived with increased cruising speed up to maximum Mach number in the 40 tons scenario.

Contrail cost weighing [t CO_2 eq. emissions]	Contrail costs [€]	Delay costs [€]	EC [€]	DOC [€]	Flight time [h]	Ground distance [km]
0 t CO_2 eq. emissions	1462	1143	3397	86362	6.98	4256.92
32 t CO_2 eq. emissions	1360	1147	3298	85214	7.02	4358.50
40 t CO_2 eq. emissions	0	1155	1947	86213	7.02	4358.50
Mach max	0	953	1967	83511	6.35	4358.50

Another example shows the behavior of the simulation, when contrail formation is not avoidable. Figure 3 shows an Airbus A320 flight from Boston (BOS) to Cyril E. King Airport (STT) on April 17th, 2018 at 6 a.m. which has to pass an ice-supersaturated region during cruise. The scheduled turnaround time of this flight is long enough to assume low passenger delay costs (compare Section 2.2). Obviously, the path finding algorithm does not find a contrail free solution, even for a very high contrail cost weighting of 56 t CO_2 eq. emissions. A relatively small detour (indicated as black line in Figure 3) enables the saving of a few minutes of contrail formation (compare Table 3). Again, the speed increase has a positive effect on both contrail costs and delay costs. However, this statement should not be generalized. Often, additional fuel costs and EC hamper the saved time costs (compare Figure 5). This applies especially to flights without delay. This example flight shows the effect of contrail induced detours on ground distance (compare Table 3), which is increasing with increasing contrail costs function. Hence, the overall efficiency is significantly hampered by contrail induced detours.

Table 3: Optimum contrail cost weighting for a single trajectory between Boston and Cyril E. King Airport STT. Contrail formation could not completely be avoided. The last line corresponds to costs with increased cruising speed up to maximum Mach number in the 56 tons scenario.

Contrail cost weighing [t CO_2 eq. emissions]	Contrail costs [€]	Delay costs [€]	EC [€]	DOC [€]	Flight time [h]	Ground distance [km]
0 t CO_2 eq. emissions	200	268	720	26350	3.79	2740.70
32 t CO_2 eq. emissions	194	268	715	26520	3.79	2744.28
56 t CO_2 eq. emissions	188	269	726	26261	3.79	2753.36
Mach max	181	203	724	25704	3.52	2751.46

3.2 Global Optimum Contrail Induced Detour

After examining two individual trajectories and analyzing the effect of different strategies in trajectory optimization on contrail costs and delay costs the whole scenario of 128 flights in the United States from and to Boston during three hours on April, 17th, 2018 is contemplated (compare Table 4). Low contrail cost weightings lead to reduced time of flight only for trajectories affected by contrails. Therefore, flight time

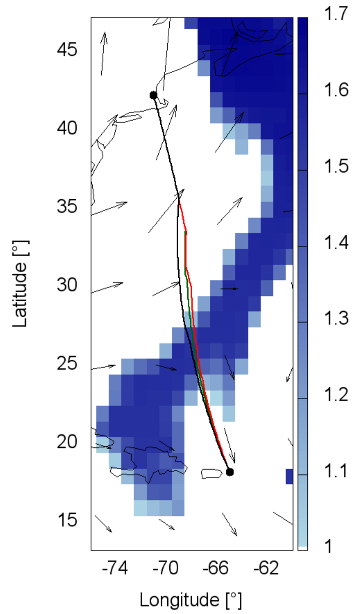


Figure 3: Optimized trajectories from Boston (BOS) to Cyril E. King Airport (STT) in an ice-supersaturated (blue squares) atmosphere. Contrails cannot be completely avoided, only a few minutes of contrail formation can be saved (black) by a short detour, compared to the cost minimized trajectory (red). The green line indicates the optimized trajectory with a contrail cost weighting of 6 t CO_2 eq. emissions. Black arrows mark wind speed (length) and wind direction during the first flight hour.

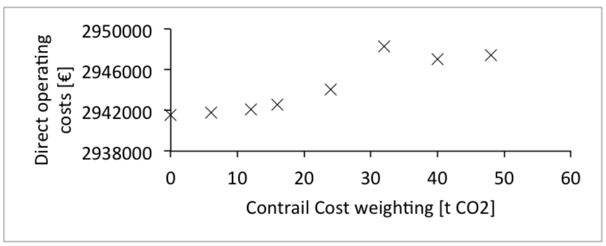
is only slightly reduced in Table 4 unless speed is increased which causes additional fuel and emissions. The additional emissions are reflected in slightly higher environmental costs (EC) (last row in Table 4). Compared to the 56 tons scenario, contrail costs are further reduced in the speed increased scenarios because contrails are assessed per contrail hour. Due to the effect of wind speed and wind direction, minimum ground distance is detected in a scenario with very low contrail cost weighting (6 t CO_2 eq. emissions), but not with zero tons CO_2 eq. emissions.

In the minimum time track scenario, 41 flights induced contrail costs and 57 flights were delayed. Eighteen contrail flights could be saved assuming 40 t CO_2 eq. emissions with an unchanged number of 57 delayed flights. The 56 t CO_2 eq. emissions simulation still calculated 27 flights with contrails but 66 with delay. The number of delayed flights could be reduced to 38 when cruising with maximum Mach number was assumed. In this case study, the simulation with a high contrail cost weighing of 40 t CO_2 eq. emissions per contrail hour, yielded a minimum sum of direct operating costs and environmental costs (Figure 5, right) which would be of interest for airlines with respect to an increased efficiency. In that scenario, significantly reduced contrail formation is achieved (compare Table 4 and Figure 4, right) and contrail costs are in the same order of magnitude as delay costs (Figure 5, left). However, due to significantly increasing delay costs considering contrail costs of 32 t CO_2 eq. emissions per contrail hour and higher, direct operating costs are consequently increasing (compare Figure 4, left). The important impact of contrail costs on environmental costs can be is shown in Figure 4 (right) although emission induced environmental costs are expected to increase with increasing contrail costs, due to longer detours.

With increasing contrail cost weighting long detours around ice-supersaturated regions become more attractive and contrail costs can be significantly reduced, whereas delay costs only slightly increase in this case study. The sum of environmental and direct operating costs will be minimized, if contrail costs are weighted with 40 t CO_2 eq. emissions (Figure 5), which is higher than the reference value of 32 t CO_2 eq. emissions derived from global climate model data in 2005.

Table 4: Mean assessment of each contrail cost weighting scenario (averaged over 128 flights). The last two lines represent scenarios with increased cruising speed by 5 % and up to maximum Mach number in the 56 tons scenario, respectively.

Contrail cost weighing [t CO_2 eq. emissions]	Contrail costs [€]	Delay costs [€]	EC [€]	DOC [€]	Flight time [h]	Ground distance [km]
0	197	90.58	665	22981	2.519	1028.05
6	190	90.69	658	22982	2.519	1028.02
12	184	90.70	653	22985	2.520	1028.12
16	180	90.71	649	22989	2.520	1028.28
24	162	90.70	631	23001	2.521	1028.60
32	112	91.10	581	23034	2.522	1029.96
40	100	91.17	570	23024	2.522	1029.41
48	98	91.19	596	23027	2.522	1029.58
56	93	91.31	563	23056	2.525	1029.92
Speed increased by 5 %	89	77.69	576	22782	2.439	1029.92
Mach max	85	66.33	600	22571	2.361	1029.92



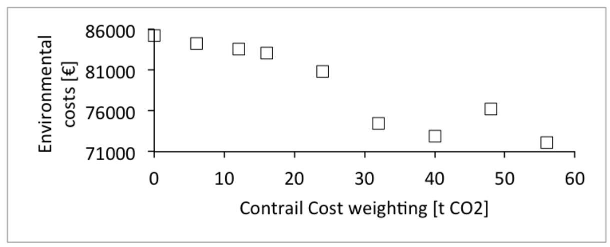


Figure 4: Impact of contrail cost weighting on direct operating costs (left) and environmental costs (right) integrated over all 128 flights of this case study.

4 CONCLUSION

Trajectory optimization under real weather conditions causes temporal shifts (along track uncertainties) and complicates the predictability of the trajectory. Therewith, certain predefined spatial coordinates at certain time stamps as requested for an efficient air traffic flow management in trajectory based operations could not be met, if too much importance is attributed to the optimal trajectory. Specifically, detours around cost sensitive or dangerous areas, such as contrail inducing ice-supersaturated regions or thunderstorm cells cause significant deviations from the target time of arrival. In most cases, those along track uncertainties cause delays, which in turn cause extra costs, because time slots cannot be met at the airport. Furthermore, those delays hamper the predictability of the trajectory. Delay costs, on the other hand, are specific for each aircraft type, crew and passenger category. They depend on the capacity utilization of the airport and on the following calculated take off time. Hence, a substantial air traffic simulation compiling a multi-criteria trajectory optimization should include a coupling with the expected turnaround and delay costs, so that high delay costs may be considered in the estimation of optimum flight paths and speeds.

In this case study, an air traffic assessment of environmental and direct operating costs with special respect to a coupling of contrail costs and delay costs are exemplified in a simulation environment which is able to consider competitive targets in a multi-criteria trajectory optimization. To avoid contrail formation and corresponding high environmental costs, long detours are necessary with impact on additional fuel burn, emissions and flight time. Furthermore, cruising speed could be increased to reduce delay costs accepting increased fuel burn. An optimum between detours and delay costs were found for 128 flights in the United States from and to Boston during three hours. Thereby, 53 % contrail costs could be saved, accepting 0.8 % higher delay costs, compared to a minimum time scenario. When cruising speed is maximized up

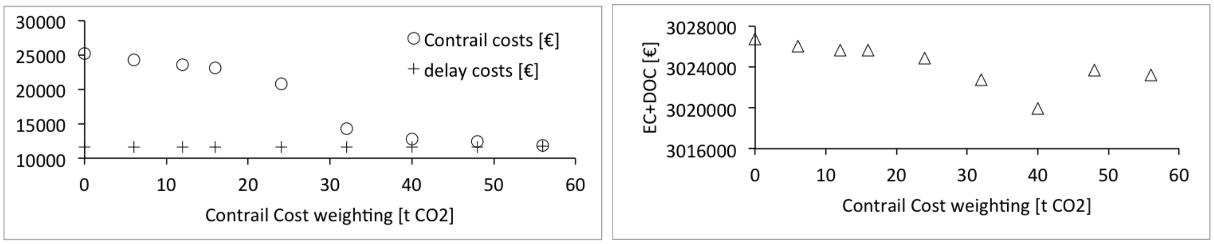


Figure 5: Impact of contrail cost weighting on contrail costs and delay costs (left) and sum of environmental and direct operating costs (right).

to aircraft specific maximum Mach number, 57 % of contrail costs and 27 % delay costs could be saved. Due to the optimized coupling of contrail costs and delay costs, even 2 % of the sum of direct operating costs and contrail costs could be saved.

Although contrails are very expensive, due to a high contribution on global warming, long detours are never profitable because of increased fuel burn and sometimes-significant delay costs. The larger the aircraft and the shorter the planned flight specific turnaround time, the more significant the delay costs will be. On the other hand, the higher the airport capacity utilization, the higher will be the probability to slip into a less crowded time window, if long detours (combined with low environmental costs) are taken into account.

However, the results strongly depend on the boundary conditions given by the flight plan, on the definition of different cost functions and of course on the atmospheric conditions (i.e. size and position of ice-supersaturated regions). With this study, we could show the importance of considering the coupling of air procedures and ground effects in the trajectory optimization. Furthermore, the magnitude of the variability of cost functions in a trajectory optimization could be shown which even more complicates the definition of an optimum aircraft 4D trajectory.

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