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A TOOLCHAIN FOR OPTIMIZING TRAJECTORIES UNDER REAL WEATHER CONDITIONS AND REALISTIC FLIGHT PERFORMANCE

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ABSTRACT:

Reducing emissions is a very prevailing topic also in aviation industry. Besides technological improvements it is necessary to also adjust procedures and operations. We present a tool that is able to optimize flight trajectories not only regarding economical factors but also ecological ones. Due to the utilization of a flight performance model and a detailed engine model, it is possible to determine an aircraft's emission quantities during all phases of a flight. Besides those like CO_2, NO_x, CO, Black Carbon, etc. we are also considering contrail formation and their influence on the global warming. By transforming emissions into monetary values we can find a trade off between multiple criteria. After describing the employed models and software architecture we present some use cases where we successfully applied our toolchain.

1. INTRODUCTION

Today's aviation industry draws responsible for around 2 % of all anthropologically induced emissions, regarding CO_2 only [1]. The need for reducing those emissions is no point of contention anymore. One goal of the Single European Sky (SES) program is a reduction of 75 % of carbon dioxide and 90 % of nitrogen oxides per passenger kilometer until 2050, compared to the amount of emissions in 2000 [2].

To account for the need of improved, climate friendly aircraft operations, we present a software tool chain, that is capable of optimizing a trajectory regarding multiple criteria. Besides considering direct operating costs only, we took a great effort on modeling a trajectory's influence on global warming. A multi criteria cost function allows to find trade offs between ecological and economical optimal trajectories.

Especially airlines have to be induced to consider an aircraft's ecological footprint during flight planning and execution, because today, emissions don't get much attention from those stakeholders in the aviation sector. They try to operate in a cost optimal way, which often contradicts the request for a more eco-friendly air traffic. By using the prices of Emission Trading Scheme (ETS) certificates, it is possible to monetarily quantify emissions. In the same way we can also consider the ecological and economical impact of condensation trails which have a fairly underestimated influence on climate and therefore on optimal trajectories, as well [3].

Based on these costs additionally to the direct operating costs, we developed a set of so called Key Performance Indicators (KPIs) that can be used to assess and optimize trajectories. With Toolchain for Multicriteria Aircraft Trajectory Optimization (TOMATO) we present a set of software tools for optimizing trajectories considering all the different costs. This paper will describe the technical background like implemented algorithms and the methodologies used to optimize aircraft trajectories from departure to arrival airport including start, climb, cruise, and descent phases.

The flight performance model Compromised Aircraft performance model with Limited Accuracy (COALA) [4] allows us to account a number of different aircraft types and their individual behaviors and performance. With its build in engine model, it can be utilized to determine the amount of different emissions during flight. By using a real atmosphere in conjunction with the engine model, it is possible to calculate criteria for contrail formation. Like for other emissions, we are able to determine their influence on climate and transfer it into a monetary value that can be considered during trajectory optimization.

1.1. State of the art

Optimizing an aircraft's flight trajectory has been of great interest since decades. While economical aspects were the main drivers first, in recent years the ecological impact has become of more interest not at least because of increasing social pressure. There has been a lot of research in this area previously. Especially wind optimized trajectories gained much attention [5, 6]. Some of these researches even considered emissions produced by the aircrafts [7].

A multi criteria approach that ponders the ecological impact and economical interests, i.e. direct operating costs, seems to be not available at the time. There is some basic work in this area [8], but a detailed investigation of trade offs between those factors did get not much attention, yet. Besides traditional emissions like CO_2, in recent years, condensation trail formations get increased attention [6, 7, 9]. The impact of contrails on the global warming has been proven to be up to a magnitude worse than this of CO_2 emissions produced by aircrafts [10].

When performing trajectory optimizations, most approaches focus on cruise phase only [5–9, 11]. Albeit some work utilizes the BADA model [6, 7, 12], a realistic flight performance is often neglected, and some static parameters are assumed, like constant speed and altitude, etc. Even if a 3D or 4D optimization approach is proposed, most work consider the ability of instant step climbs during cruise only [7, 9, 11], but there is no detailed investigation of climb and descent phases when optimizing a full trajectory.

To force an airline to consider a trajectory's ecological impact, there need to be some monetary incentives that influence the overall cost balance. Previous studies came to the conclusion that the prices of ETS certificates, which we need to transform emissions into costs, need to raise a lot. While it currently lays around 4.00€ [1], it needs to be a magnitude higher than today's values [13].

For solving trajectory optimization problems there are primarily two popular approaches around. On the one hand, the path finding algorithm A* as well as the more general Dijkstra algorithm for searching shortest paths in a graph are employed [11, 12]. Otherwise, the optimization is implemented as an optimal control problem [6–8].

Besides all these ongoing researches, that focus on single aspects, we do not know of any approach, that performs a full lateral and vertical trajectory assessment and optimization while considering direct operating costs and emissions as detailed as we will propose in this paper, and which also includes 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 to improve the ecological impact of aviation.

1.2. Outline

The next section will present the software architecture of our tool and employed algorithms, as well as the single modules. Next some use cases will be shown that are representative for the applicability of TOMATO. Afterwards we will discuss shortcomings, give an outlook for further development and draw a conclusion of our work.

2. TOOL ARCHITECTURE

The architecture of our simulation tool is very modular which makes it easily extendible. There are three main processing modules around which the Input / Output (I/O) components are arranged. Everything is glued together by the TOMATO framework which coordinates data transfer from input over processing to output components. Fig. 1 presents the overall architecture and illustrates the single modules as well as the data flow between.

Input data can be divided in three categories:

Natural environmental data provide information about circumstances like weather including wind speed and direction, relative humidity but also atmospheric conditions, e.g. temperature and pressure. Besides providing real weather information in GRIB2 (Gridded Binary 2) data format, it is possible to perform calculations under International Standard Atmosphere (ISA) conditions. For our research, we use historical data provided for free by the National Weather Service NOAA [2].

Artificial environmental data on the other hand comprises information about men-made conditions like airspace structure, restricted areas, cost charges (air traffic controller (ATC), airports, crew, etc.) and other parameters.

Scenario data gives all the information that are dedicated to a single run configuration. This comprises city pairs for which trajectories should be calculated, the aircrafts to serve these routes, including individual performance and emission data, as well as service specific parameters like amount of payload, fuel, passenger (PAX), and so on. Additionally the scenario data set includes general simulation parameters like step size, output directory, etc.

After processing, output data can be saved in different ways like into database and/or on filesystem.

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[1] https://www.eex.com (accessed 09/12/2016)

[2] http://nomads.ncep.noaa.gov

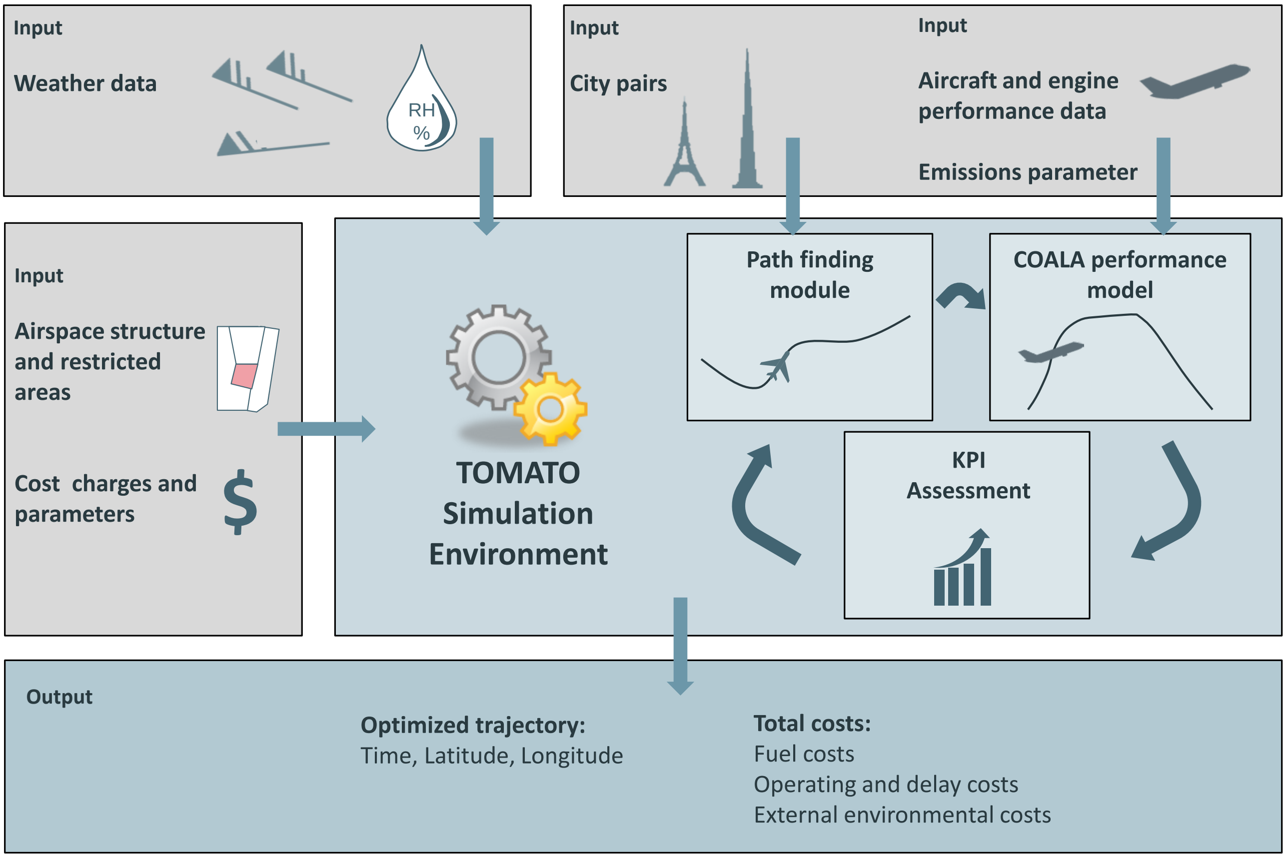

Figure 1: Architecture of TOMATO

Albeit being configurable, those data will contain trajectory information like latitude, longitude and altitude along the route but also the aircraft's state at each step, emitted pollutions and numerous cost values, as well as an overall rating of the trajectory. Besides plain data output, some gnuplot[3] scripts are getting generated, which allows to conveniently plot the lateral path and vertical profile as well as some environmental data of the generated trajectories.

In the following subsections, the main components for generating and assessing trajectories will be discussed in detail. A fully integrated 3D trajectory optimization is a very complex task, which we decided to split into separate lateral and vertical components, which allows to iteratively converge to an optimum.

2.1. Lateral Path Finding

The first step of our iterative trajectory optimization process is to find a lateral flight path. For this step neither detailed performance data nor the exact vertical profile is available, wherefore some assumptions will be made especially regarding parameters like average cruising speed, altitude and costs per time unit. In each iteration those values may be refined after assessing the resulting trajectory.

The lateral path finding module employs the A* algorithm which is an optimal path finding solution [14]. It requires a graph to work on, which is achieved by overlaying the world with a virtual grid where cells can be seen as nodes that are connected via a neighborhood relation. These relations represent the edges of the graph. There are several grids available, from a simple square grid over a real-world lat/lon one up to complex hexagonal geodesic grids. Via configuration parameters it is possible to control the grid's resolution and thus find a trade off between accuracy and runtime.

Determining which path is the best one requires to assess the costs of movement between nodes. The A* algorithm necessitates that the edges which connect nodes carry some positive costs. As outlined, the actual costs of traveling from one point in space

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[3] http://gnuplot.info

to another one are mostly unknown at this time. Only those dependent on distance or determined from fixed parameters, can be calculated yet, e.g. ATC en-route charges. Other factors, especially flight performance related ones like fuel burn and travel time, will be computed afterwards when creating the vertical profile and assessing the trajectory.

To be very flexible regarding considered cost factors, TOMATO allows to stack multiple layers representing different costs. A basic price for movement is calculated by using the distance between nodes, an average cruising speed and some cost factor per time unit. These assumptions are necessary because a detailed evaluation of flight performance and trajectory assessment can be made in steps two and three. Our iterative process allows to use these results as input for a refined optimization. Nevertheless, there are some influences on the trajectory that can be considered in detail even at the first step. A rather obvious one is the effect of winds, which has a direct impact on the aircraft's ground speed and thus on travel time.

Another cost factor, that is independent of actual flight performance and travel time are ATC charges which are related to distance. Especially in European air space, where these costs are very heterogeneous, it is appealing especially to lateral optimization to avoid expensive areas in favor of cheaper ones, even if wind conditions are not optimal on this track anymore. The calculation of costs for ATC services is depicted in section 2.3. Furthermore it is possible to define areas of prohibited airspace, where no aircraft shall be operated. The appropriate layer will account an infinite cost value for those areas to ensure the path finding algorithm will never choose a way through these ones.

When it comes to ecological optimization, contrails can have an appreciable influence on trajectories, because such formations have a rather large effect on climate, compared to emissions which are traditionally considered. Whether contrails occur or not depends on two criteria that need to be greater than or equal to 1, namely the Schmidt-Appleman-Criterion and the relative humidity over ice [15].

While the first one is tightly coupled to actual flight performance (cf. section 2.2), the latter is purely dependent on environmental conditions, i.e. temperature and relative humidity. Therefore it can be consulted to estimate which areas are in favor of contrail formation and should be avoided during lateral path finding. According to Schumann [15], the relative humidity over ice ϕ_{ice} can be derived from the one over water (ϕ_{water}) as well as the current temperature, as shown in eq. (1).

$$\phi_{ice} = \phi_{water} * \frac{e^*_{water}}{e^*_{ice}} \tag{1}$$

$$e^*_x = e^{\sum_{i=0}^{3}\left(K_i * T^{i-1}\right) + K_4 \ln(T)} \tag{2}$$

Here e^*_x designates the saturated vapor pressure over water (e^*_{water}) and ice (e^*_{ice}), respectively, as presented by Sonntag in [16]. The coefficients necessary for each calculation are specified in table 1.

Table 1: Coefficients of vapor pressure formula [16]

Coeff.	e^*_{water}	e^*_{ice}
K_0	-6.0969385×10^3	-6.0245282×10^3
K_1	16.635794	24.721994
K_2	-2.711193×10^{-2}	1.0613868×10^{-2}
K_3	1.673952×10^{-5}	$-1.3198825 \times 10^{-5}$
K_4	2.433502	-0.49382577

Besides lateral avoidance of areas with high likelihood for contrails, our tool can use maneuvers, which we call steps, to dive underneath those regions. An application for this is presented in section 3.2.

2.2. Vertical Flight Profile

After a lateral path is found, a vertical profile needs to be generated in step 2. This adds another dimension to our optimization process. Now we can also vary parameters like speed, altitude, climb gradient, etc. with a direct influence on the profile and therefore on the aircraft's emissions and the costs.

To allow a high quality optimization and assessment of trajectories, it is crucial to employ a precise flight performance model, as well as an emission model that is able to determine an aircraft's climate effective emissions. In TOMATO we therefore utilize the Compromised Aircraft performance model with Limited Accuracy (COALA), developed by Rosenow et al. [4]. An aircraft is simulated to fly along the path calculated beforehand. To achieve a realistic flight performance, COALA utilized the Base of Aircraft Data (BADA) database Family 4 [17] or falls back to version 3.6 [18] if an aircraft is not available in the first case. The constrained precision of BADA [19] is responsible for the also limited accuracy of COALA. Additionally the trajectory is optimized in discrete time. As a trade off between accuracy and performance, a simulation step width of 1 second showed to be an acceptable choice.

The calculation of a trajectory is divided into various phases: start, climb, cruise, descent, whereof the second one is split into an initial part width maximum climb angle and a second one with maximum climb gradient. There is currently no landing implemented, because there is no potential for optimizing this phase and safety is very critical in this stage of flight. For every time step, a target speed is calculated which the aircraft converges to by employing a PID controller that in turn uses the aircraft's lift coefficient as regulating variable.

During start phase the maximum available thrust MTO is derived from maximum climb thrust MCL using eq. (3), according to [19]. Actually, the full thrust is required in very rare cases. Therefore it will be scaled with respect to actual takeoff mass. After lift off, the thrust setting will be maintained until minute 3 of flight after which it is reduced to climb thrust.

$$MTO = 1.33 * MCL \tag{3}$$

The climb phase depicts a continuous climb operation (CCO) [20] and comprises two stages [21]. In the first, a maximum climb angle is maintained until the aircraft reaches an altitude of 10.000 ft. This correlates to the maximum gain in altitude per distance over ground. Above 10.000 ft, climb rate is maximized which accords to a maximum gain in altitude per time unit. This behavior can be influenced by a factor that determines what portion of thrust energy will be invested in kinetic and potential energy, respectively.

In cruise, the target speed is derived from maximum specific range R_{Spec} using eq. (4) [22]. The specific range gives the distance that can be gained out of a certain amount of fuel. It depends on the aircraft's speed v_{TAS} and the fuel flow $\dot{m}_f$.

$$\begin{aligned} R_{Spec} &= \frac{v_{TAS}}{\dot{m}_f} \\ &= \left[\frac{\frac{m}{s}}{\frac{kg}{s}}\right] = \left[\frac{m}{kg}\right] \end{aligned} \tag{4}$$

The last segment of a flight is implemented as continuous descent operation (CDO) [23]. The top of descent (TOD) is estimated by a simulation of the descent phase at every step during cruise. At this point, thrust is reduced to zero and an idle fuel flow is taken from BADA data. A high lift-to-drag ratio is aspired to maximize glide ratio and therefore also maximize the descent distance which in turn leads to a long phase of idle thrust and minimum fuel burn.

Together with COALA there comes an engine model that allows to calculate the aircraft's emissions during flight. These are determined for every single step of a simulation run, because their climate effect is dependent on the region where they are emitted (cf. section 2.3.2 and table 2) and cannot be integrated over the whole trajectory. For products of complete combustion (i.e. CO_2, H_2O, SO_2, H_2SO_4), a proportional relation to fuel flow is assumed, according to Lee et al. [24]. Products of incomplete combustion (i.e. NO_x, CO, Hydrocarbons) are determined by use of the Boeing-2 Fuel Flow method [25].

Another advantage of the engine model is the possibility to test the Schmidt-Appleman-Criterion, that is required to determine if contrail formations occur. It's based on environmental conditions like temperature, pressure, and relative humidity, as well as current performance data, i.e. thrust, speed, and fuel flow. A critical threshold temperature is calculated, as presented in detail by Schumann in [15].

If, at the aircraft's current location, the ambient temperature is below this threshold temperature and additionally the relative humidity over ice is above 1 (cf. section 2.1) at the same time, condensation trails will arise.

2.3. Trajectory Assessment

Assessing a trajectory means to calculate various properties that can then be used to compare it with other trajectories. This gives the possibility to tell which one is better than another one and thus find the optimal trajectory. Because these properties are of very different kind – from flight time, over fuel burn and emissions, up to contrail formation – there is an urgent need to transform those into a common unit to make them comparable and be able to find a trade off between.

Besides following the law and regulations, money is the most influencing factor in an airline's decision-making process. By translating a trajectory's properties into a monetary value, it is possible to calculate the overall costs and find an optimal solution by minimizing those. Weighting properties differently allows to change their individual influence on the global assessment. Single costs can be categorized into two main groups, which allows to differentiate economical and ecological costs and thus find a trade off between environmentally beneficial and cost optimal trajectories.

2.3.1. Direct operating costs

The main cost driver in today's planning processes of airlines are direct operating costs and great effort is spent to minimize those. First of all, these are mainly time dependent costs like crew's salaries, maintenance costs, deprecation rates, and direct or indirect compensations for delays. Using eqs. (5) to (7), those costs can be calculated by multiplying flight time with a factor, which we call *cost rate* $R\left[\frac{€}{s}\right]$. The linear equations were parameterized by statistical analyzes of long term data.

$$\begin{aligned} C_{Time} = t_{Flight} * (&n_{Pilot} * R_{Pilot} + \\ &n_{Steward} * R_{Steward} + \\ &R_{Deprecation} + \\ &R_{Maintenance}) \end{aligned} \tag{5}$$

with

$$R_{Deprecation} = 8.1 * n_{PAX} - 96 \tag{6}$$

$$R_{Maintenance} = 2.3 * n_{PAX} + 309 \tag{7}$$

Delay costs are calculated using eqs. (8) and (9). Those become relevant if trajectories, that are ecological optimized, lead to delay in flight schedule compared to a primarily cost optimized trajectory.

$$C_{Delay} = t_{Delay} * R_{Delay} \tag{8}$$

$$R_{Delay} = 0.35285 * n_{PAX} - 6.874 \tag{9}$$

Besides those time dependent costs, insurance rates, for example, are hooked on the distance traveled. In TOMATO we use eq. (10) to determine these costs.

$$C_{Insurance} = 0.03 * n_{PAX} * d \tag{10}$$

Fuel consumption is another rather large position that goes into the category of direct operating costs. Its influence is tightly coupled with the current fuel price compared to time dependent costs. This will also influence the optimization strategy. If fuel price is high, the trajectory will be designed to minimize fuel burn, the other way around it will be optimized to minimize flight time. The fuel costs of a trajectory can be calculated using eq. (11) and inserting the total amount $m_{fuel}\,[kg]$ of fuel burnt during flight as well as the current price $R_{fuel}\left[\frac{€}{kg}\right]$. Additionally handling costs of around 20 % are incurred.

$$C_{Fuel} = 1.2 * m_{fuel} * R_{fuel} \tag{11}$$

Charges demanded by ATC providers for their services are another big cost factor. For the European airspace unit rates are published by EUROCONTROL [26]. These rates are very heterogeneous as every state has its own individual one and which therefore have an noticeable influence on trajectories [27]. Inserting the published charges R together with the total distance $d\,[km]$ traveled over a certain area into eq. (12), ATC en-route costs for this part of the trajectory can be calculated [28].

$$C_{ATC_{Enr}} = \sqrt{\frac{MTOM}{50}} * \frac{d}{100} * R_{Enr} \tag{12}$$

Besides these en-route charges, there are also fees for using airports and airport services. These costs do not account for trajectory optimization because start and destination are fixed. However, to ensure a comprehensive assessment, using eq. (13) our tool will calculate those, too [29].

$$C_{ATC_{Airport}} = \left(\frac{MTOM}{50}\right)^{0.7} * R_{Airport} \tag{13}$$

Summing up eqs. (5), (8) and (10) to (13) results in the total direct operating costs. We also call those the *Cost Performance Indicators (CPIs)*.

2.3.2. Ecological costs

Translating the amount of emissions into monetary values is achieved by employing a two step process. First we convert every emission into an equivalent amount of CO_2 using their individual global warming potentials (GWPs). This value expresses the proportion of climate effectiveness between a specific emission and the same amount of CO_2 [30]. Tab. 2 presents the values used in TOMATO to transform all the emissions (represented as mass $m_e\,[kg]$ of emission e) into a single amount of equivalent CO_2 (m_{eqCO_2}) using eq. (14).

Table 2: GWP for different emissions

Emission		GWP (100)
CO_2		1
NO_x (*)	[31]	25 – 110
CO (*)	[3]	1.6 – 1.8
H_2O (*)	[32]	0.023 – 7.0
Black Carbon (*)	[32]	480 – 510
H_2SO_4	[24]	-40

(*)values are location dependent

$$m_{eqCO_2} = \sum_{Emission} (GWP_e * m_e) \tag{14}$$

Assessing the influence of contrail formation by a monetary value is more complex because they are not measurable in terms of weight rather than time. Lee et al. identified the CO_2 equivalent amount of contrail formation to be 135×10^{12} Tg in 2005 [24]. Given an amount of 42 million flight hours in the same year [33], whereof 10 % lead to contrail formation [34], one can determine a GWP for contrails of nearly 32 CO_2-equivalent tons per flight hour as depicted in eq. (15).

$$GWP_{Contrail} = \frac{135 * 10^{12} \frac{g}{a}}{0.1 * 42 * 10^{6} \frac{h}{a}} = 32.14 \frac{t}{h} \tag{15}$$

After calculating a total amount of (equivalent) CO_2 emissions, those can be transferred into a cost value via the European Emission Trading Scheme (ETS). An ETS certificate gives the price per ton of CO_2 in Euros (C_{ETS}). Summing up all the emission's prices by applying eq. (16) gives the total ecological cost of a trajectory. In dependence on the CPIs, environmental costs are called *Ecological Performance Indicators (EPIs)*.

$$C_{EPI} = C_{ETS} * (m_{eqCO_2} + GWP_{Contrail} * t_{Contrail}) \tag{16}$$

3. APPLICATION

TOMATO is a very comprehensive toolchain that can be used in various scenarios to investigate different approaches of improvement regarding a more ecological operation of aircrafts. It's applicability reaches from optimization of single trajectories up to the assessment and optimization of full airline networks. In the following section we briefly present some use cases for which we employed our software successfully. Some of those scenarios could even be validated in conjunction with a group of external experts from a German airline.

3.1. Rising ETS costs

As stated previously, todays prices for ETS certificates are very low. The direct operating costs overshoot emission costs by orders of magnitude. Fig. 2 visualizes the proportion between EPIs and CPIs. In the top diagram, plain CO_2 emissions are regarded only. The bottom one shows the effect if all emissions get considered using their GWP values. Therefore we need to raise the influence of ecological factors on the costs and thus the optimal trajectory. This is achieved by assuming a price of 65 € per ETS certificate [21], which raises the impact of ecological costs to ca. one third of direct operating costs.

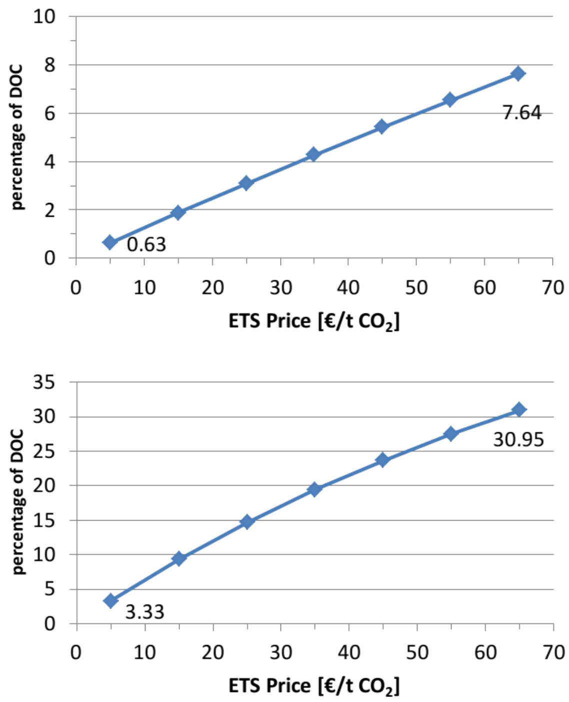

Figure 2: Share of emission costs compared to direct operating cost. Top: regard CO_2 only, Bottom: consider all emissions

3.2. Contrails

Using these figures, we are able to investigate the effect of contrails on trajectories, as well. Fig. 3 presents four different levels of optimization. In the base scenario, there is no avoidance behavior, which only minimizes direct operating costs. The blue areas visualize regions of high relative humidity over ice (cf. eq. (1)) and therefore high likelihood for contrail formation. While at lower altitudes the temperature is too high for actual formations, at cruise altitude contrails occur, as the costs for this kind of emission denotes. Therefore, the first iteration of optimization is going to avoid the area around the top of climb, which leads to slight increase of direct operating costs and general emission costs, but at the same time, safes much more costs concerning contrails. The same effect can be seen if also avoiding the mid-cruise area of contrail formation. We could show, that it is even worth to climb after this segment, than flying on a non-optimal altitude until the TOD.

As presented in detail in [35], we could furthermore show that laterally avoiding condensation trails lead to much more costs than performing those steps and diving underneath affected areas.

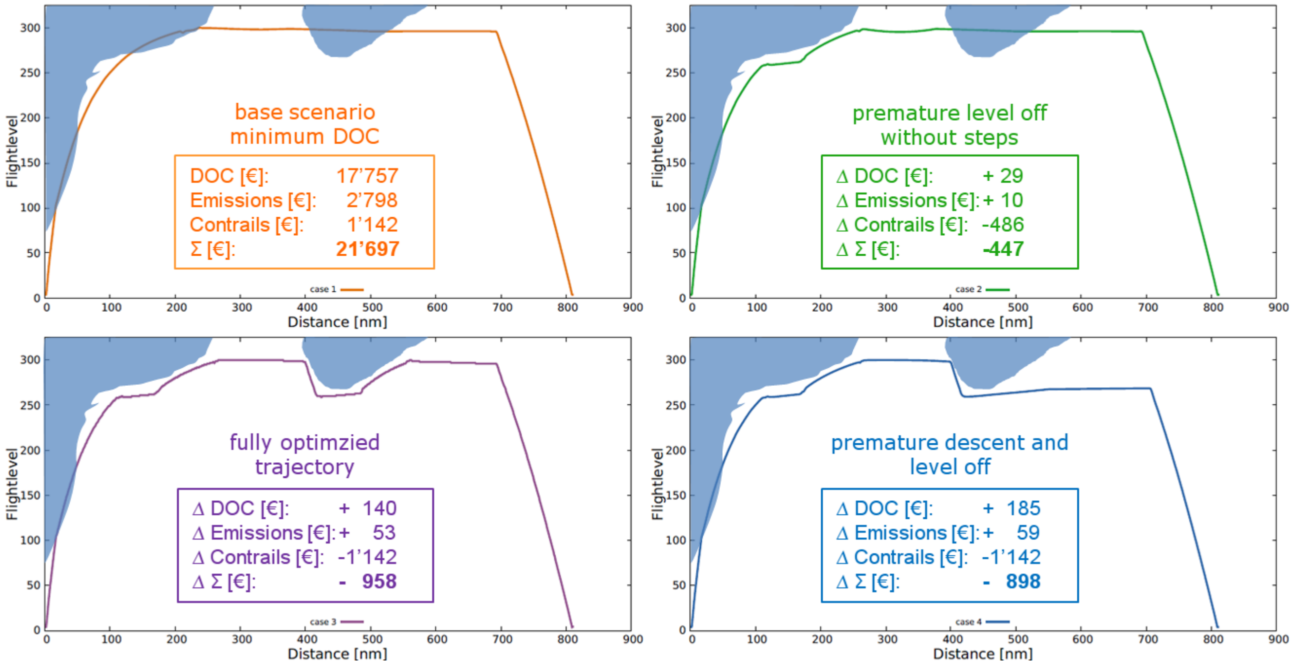

Figure 3: Different trajectories and cost values during optimization of contrail avoidance. Blue areas are regions of high ice saturation with favor for contrail formation.

We examined a lot more scenarios, like optimization of airline networks and flight schedules [21] and the influence of ATC en-route charges on trajectories [27]. Using the capabilities of our flight performance module COALA, we could investigated the effect of variations in climb gradients in favor of a better aircraft configuration at the top of climb and the transition into cruise [36].

4. CONCLUSION AND OUTLOOK

We can conclude that our tool can do real 3D trajectory optimization (lateral and vertical) of multiple criteria under consideration of many different influences. It is very flexible because of the modular architecture which allows to easily exchange modules or add new ones. The ability to modify lots of parameters like weather, contrails, fees, cost rates, etc. gives us the possibility to investigate a great amount of different scenarios and cover lots of use cases, which can contribute to a much more environmentally friendly operation of aircrafts.

In the list of considered emissions, a quite important one, especially in regions around the airport, is missing: noise. Because we are looking at whole trajectories, even from the start on, the affected area is of rather small significance compared to a whole flight. We suggest that approach and departure procedures should instead be investigated separately.

Our effort will flow into the improvement of the toolchain. To retrieve more accurate results, the resolution of the grid has to be increased, which raises the requirements on processing power a lot. Methods need to be investigated that allow to speed up especially the lateral path finding module. Another direction would be to do a real integration of lateral and vertical optimization into a single step by using continuous methods like optimum control, instead of the grid based one we employ currently.

An additional result of trajectory optimization that has not been considered yet, is the influence on safety aspects. In a free flight environment there is much more space available for every single entity, which in turn should lead to increased separation and therefore also in higher safety values. On the other hand, there may be regions of high interest for an optimized trajectory. Such an area could be the jetstream which will surely retain its desirability that it has today. Another procedure may become of interest if ETS prices increase and even contrails account for emissions covered by those certificates: diving underneath areas that are in great favor of contrail formation. Vertical separation infringements may be a direct result of this. To account such issues, we will add models to our toolchain that are able to assess the safety of trajectories, especially their interaction with each other.

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