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ASSESSMENT OF AIR TRAFFIC NETWORKS CONSIDERING MULTI-CRITERIA TARGETS IN NETWORK AND TRAJECTORY OPTIMIZATION

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Abstract

Today's airline industry is facing a highly competitive market, so network and trajectory optimization is driven by fuel and time costs, constrained by air traffic management capacity. The resulting ecological effects on global warming and on environmental health are reflected in the emission trading system (ETS) certificates. However, the ecological impact of air traffic depends on the locality of the emissions. Hence, even the airline network structure affects the air traffic ecological impact. This paper presents an approach of the back coupling of network and trajectory optimization, aiming to minimize both, ecological effects and costs. First, an optimized air traffic network with respect to minimum fuel consumption and minimum ecological costs due to local effects of nitric oxides is compared with a fuel burn optimized network. Second, a lateral trajectory optimization gives the horizontally shortest flight path with respect to minimum costs due to the local effects of nitric oxides. In a third step, vertical trajectory optimization is applied within the optimized routing structure. The calculated amount of emissions is transferred into carbon dioxide equivalent emissions using the global warming potential. Finally, the emissions are expressed in costs considering the effect of the emissions on global warming and on local air quality with the help of the ETS. These costs are used to evaluate both networks, with and without nitric oxide consideration.

1. INTRODUCTION

Trajectory optimization is an important component of each airline to ensure flight paths at optimal costs. This optimization is limited by boundary conditions characterized by airspace capacity and airspace availability, as well as by atmospheric conditions, wind speed and wind direction. By optimizing the trajectory with respect to minimum fuel consumption, both, the major cost driver and parts of ecological criterions (i.e. carbon dioxide and water vapor emissions) are considered. However, the account for the total ecological consequences of air traffic including emissions effecting humans health and the local air quality (sulfur dioxide SO_2, carbon monoxide CO and unburnt hydrocarbons HC) plus emissions influencing the energy budget of the Earth-atmosphere system (carbon dioxide CO_2, water vapor H_2O, nitric oxides NO_x, sulfates SO_4 and soot) is not given by cost optimized or fuel consumption minimized trajectories [1]. Furthermore, the complex radiative influence of condensation trails (contrails) as consequence of water vapor and soot emissions in a cold and ice supersaturated environment is not considered [2], [3]. Nevertheless, the environmental influence of air traffic is not only reflected in the flight path, but also in the aircraft routing and fleet assignment [1]. For example, the influence of NO_x emissions on global warming depends on latitude of the emission, as well as on altitude and conditions within the combustion chamber of the aircraft engine [4], [5]. Hence, in the optimization of the air traffic network structure, different costs caused by differences in NO_x effects have to be considered.

In Europe, carbon dioxide emissions are of political interest not only because in 2013 the part of air traffic CO_2 emissions to the global anthropogenic CO_2 emissions amounts 2 percent [6]. European targets for reducing the environmental impact of aviation can be found in the introduction of the Emission Trading System (ETS) and in aspirations to a more powerful and a more efficient air transport system under Single European Sky (SES) [7]. Both structures are able to consider the ecological effects of air traffic in a more complex way than only reducing carbon dioxide emissions and are used for both, network and trajectory optimization in the current study. In Germany, climate change political targets are defined by the scientific advisory council as decision support, amongst others [8], [9], [10].

The aim of the current study and of our research project MEFUL (Minimize emissions in the operational flight with guaranteed operational safety as contributing to an environmentally friendly air transport system) is to provide a model for optimizing air transport systems under consideration of ecological and economic boundary conditions and keep safety on a high level under Single European Sky restrictions. These optimizations include aircraft routing, trajectories and air traffic flows.

1.1. State of the art

1.1.1. Airline Network Design

The basic aim of a network modeling is to minimize costs. A further network optimization done by an airline aspire a cost and profit assessment after the network had been used and flights are flown. Thereby, the market situation and the effectively realized profit are considered. The account for minimized ecological target functions within the network modeling is often done by the transfer of the ecological effects of the emissions into additional costs.

The global structure of the worldwide air transportation network has an enormous impact on local, national and international economics and ecologic issues. In the eighties and nineties, O'Kelly [11] and Campbell [12] first designed the air traffic network structures. They developed algorithms for the estimation of a number and location of hubs or routes to serve a given demand. A hub is an important part of an airline network and represents a point, where passengers are first collected and afterwards distributed to their destination with another flight. The basic equations of this research are still in use. Today, the definition of favorable knots and reasonable routes is also tried to be answered. The answer is given by a linear optimization with the help of heuristic solution statements [13]. These models had been enhanced by a cost-benefit analysis and a competition considering varying airline strategies and the effective demand at each connection [13]. Extended network schedule design models with Discrete Choice and Market Share Modelling are presented in [14]. An airline network design as tradeoff between economic and ecologic target functions with minimized airline direct operating costs and penalized emissions due to additional costs is introduced by Bower et al. [15]. Braun et al. [16] used a similar approach during the research project REACT4C for multi-target airline network design with modeled emissions using a climate model.

1.1.2. Emission trading system

The Emission Trading System is a powerful tool to transfer the environmental influence of emissions into cost functions and therewith into objective functions within the network and trajectory optimization. This procedure of an internalization of social costs, which are caused by external effects, is a market-based instrument to reduce emissions of polluting substances, for example CO_2 [9]. It works on the principle of "cap and trade" using a quantitative limit (cap) of which the price is controlled by supply and demand in trade. Allocation schemes throughout Europe share this cap to the individual companies in terms of emission allowances, also called EU Allowance (EUA). One emission allowance corresponds to one ton of emitted CO_2. The limited quantity of emission allowances thus gives the company prior to minimization objectives. The emission allowances are tradable. The price per EUA since its market launch in 2010 declined from about 15 €/ EUA to about 5 €/ EUA in 2013 [17]. In February 2014 the so-called back-loading had been introduced by the amended EU Auctioning Regulation. Hence, the available quantity is reduced to 2016 in steps of 900 million EUA [18]. Since then, the price of EUA is more stable at approximately € 6.5/ EUA [17]. The reduced sale volumes will be returned to market in 2019 and 2020 [18]. However, it is expected to start from a desired price stability, which will be implemented. The strong depreciation of the emission allowances suggests a high potential for savings in CO_2 emissions in each company. It is assumed that this potential will be saturated in 2050, where the research findings of the project MEFUL are expected to be applied. A continuous reduction in the emission allowance per company (due to an assumed increasing environmental awareness) would result in an increased value of the certificates. This is enhanced by an assumed growing demand for air transport. To use this instrument in the air traffic optimization, a sensibility study of the price of an EU Allowance had been performed to estimate the required value in the cost-based optimization.

1.1.3. Trajectory optimization

Trajectory optimization is one of the most important research topics in air traffic due to its potential to a more efficient and more powerful air traffic system. Especially the targets defined by SESAR [7] regarding free airspace structures consisting of aircrafts, each flying its optimized trajectory, require efficient trajectory optimization tools, which are able to consider boundary conditions given by other traffic participants. In general, a single target function (e.g. minimum fuel flow) is used for the optimization. This can be done by using the Base of Aircraft Data (BADA) by the European Organization for the Safety of Air Navigation (EUROCONTROL) [19], which provides specific aircraft performance parameters and allows a performance modelling for a wide range of aircraft types. Some missing dependencies like compressibility effects in the calculation of the drag coefficient had been considered by [20] resulting in a more precise modeling of the aircraft performance, the Enhanced Jet Performance Model (EJPM). This model had been used and applied for several problems, for example for estimations of the energy share of kinetic and potential energy during continuous descent operations [21], for considerations of flight profiles without contrail formation [22], for the influence of aircraft performance properties on the contrail life cycle [3], for automated trajectories [23], [24] and for synchronization of automated arrivals [25]. The target functions for optimization and most of the aerodynamic equations of the EJPM are used in the current trajectory optimization.

Multi-criteria optimization of trajectories had also been done by Patrón et al. [26] by using multi-level optimizations in 3-D grid models. Anyhow, this approach only considers the reduction of fuel consumption. Important local differences in the effect of emissions on global warming are not considered. The research project REACT4C of the German national aeronautics and space research centre (DLR) published interesting findings regarding ecological trajectory optimization [1], [27], [4] and [5]. However, all these approaches can not be generalised due to the major impact of the assumed atmospheric conditions.

2. MODEL DESCRIPTION

In this study, optimized trajectories of the aircraft type Airbus A320 with minimum fuel consumption are serving connections within an optimized air traffic network considering minimum fuel consumption and minimum latitude and longitude dependent effects of NO_x emissions on global warming as shown by Skowron et al. [4]. This network can be used by an example airline serving parts of the air traffic demand projected for the year 2033. This airline has to overcome additional costs due to the internalization of ecological costs.

2.1. Airline network optimization considering local induced NO_x emissions

The definition of the network follows a linear programming and enhances the network model of Barzinpour et al. [28]. This bi-objective non-strict model finds regular line connections of synchronous traffic flows and serves the demand. Thereby, Barzinpour et al. [28] minimizes the costs defined by the distance for each connection. Local hubs are detected and connections are added, involving hub-destination connections, as well as point-to-point links. In the current study, the model is enhanced by the possibility of a limited number of hubs, to satisfy an organizational structure. Furthermore, the current model allows a preselection of potential hubs, which are suited for the airline. Point-to-point connections are possible if at least one of the destinations is directly connected with a hub via a further flight. The current model uses a long term demand forecast to ensure long term cost effectiveness. Connections may be banned, which is used for links with high ecological impact due to NO_x emissions. Thus, regional effects of NO_x are applicable. Because the model is allowed to choose between the knots to be served, only the cost optimal routes are selected during optimization and connections with high costs will be neglected. The aircraft range is considered as a boundary condition by a maximum distance per connection. Long haul and short haul distances are separated by a defined minimum distance. Restrictions of the capacity are not involved, because the optimization is designed for a single airline. A typical solved network with hub locations and connections is shown in Figure 1. The NO_x and fuel consumption optimized network 'B' is compared to a reference network 'A', optimized with respect to fuel consumption.

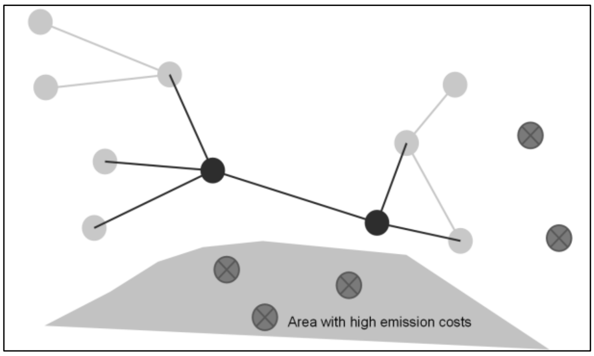

Figure 1: Example network design with hubs (dark grey) and connected nodes (light grey circles), crossed nodes are not connected in the current network. Flight-connections are marked with dark grey lines for hub-to-hub and hub-to-point-connections, point-to-point-connections are enhanced with light grey lines.

2.2. Trajectory optimization

Optimized trajectories consider both, lateral and vertical optimized flight paths. Besides local effects like NO_x effects on global warming, the main ecological effect of air traffic is determined by trajectories. In the current study, these flight paths have been optimized with respect to minimum fuel flow considering both, lateral impacts (like wind speed and wind direction), and vertical leverage (like climb, cruise altitude, and descent). For lateral optimization a pathfinding algorithm is used, the vertical optimization is done by a flight performance model build on the findings of Kaiser [20]. An iterative connection of both strategies allows the definition of the optimal flight path.

2.2.1. Lateral trajectory optimization

In this study an implemented free flight concept is assumed and the routing is not restricted to AIP-waypoints. For routing, map tiles are defined as spatial resolution between departure and destination. These map tiles can be transferred into vertices and edges and path finding can be done by connecting tiles with minimum effort for the aircraft. In Figure 2, a grid is shown to create map tiles and two possible trajectories from Frankfurt (FRA) to Dubai (DXB) are pointed out.

Generated edges describe connections within the vertices of the grid and are weighted by costs depending on their direction. Basically, the costs are defined by fuel burn to overcome a correlation between distance and aircraft performance. High level wind direction and wind speed result in a decrease or an increase in flight time, reflected in fuel burn. Here, wind direction and speed is generated randomly and interpolated between defined central points. Hence, for each vertex a decreasing or increasing in fuel burn depending on flight direction is calculated.

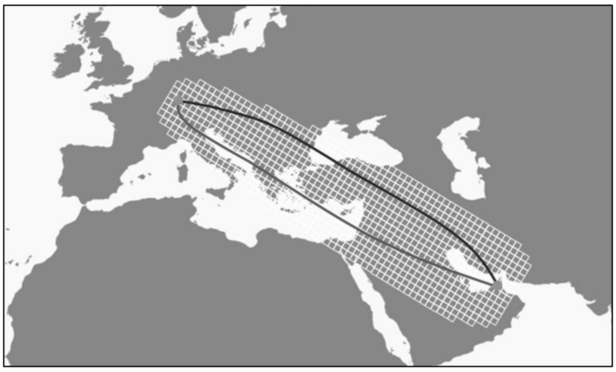

Figure 2: Example for a grid representing map tiles as basis for using a shortest path algorithm to find minimum cost track

The total cost of the connection is the sum of all edge corresponding costs. Here, external costs are considered additionally to fuel burn costs. In the same way, costs due to air traffic control can be applied. According to the costs of each edge, the airline can balance the costs for flying through an expensive area or around it. Airspace closures, as well as obstacles, are realized by a nondefinition of edges within these areas. In the same way, ice supersaturated areas can be considered for contrail formation avoidance. The ecological effects of these routes can be quantified and compared with each other.

For a single-source-single-sink-problem the A-star-algorithm as an adaption of the well-known Dijkstra-algorithm is an efficient path finding model for a large vertices-network in a defined network environment [29]. Better performance is reached by using heuristics like the Manhattan distance method to estimate the distance or additionally cost to destination. The advantage of the A-star algorithm is, that it allows three dimensional path finding. An example of combined lateral and vertical path finding can be found in [26]. To extend the problem to the third dimension, the same lateral nodes are copied in useful flight levels with unique IDs and connections are established, only if the aircraft performance is able to reach the node. In that way, we have the possibility to react on obstacles or wind changes and are tolerable to high cost areas in airspace.

2.2.2. Vertical trajectory optimization

The vertical trajectory optimization is done by an aircraft performance model for an Airbus A320 aircraft with two CFM56-5A3 engines (111.2 kN, each) based on the integration of the dynamic equation as a result of flight mechanics under consideration of the loss of aircraft mass due to fuel flow with a temporal discretization of $\boldsymbol{dt} = \mathbf{1}$ s. Continuous climb operations (cco) are used with a maximum climb gradient $\boldsymbol{\gamma}$ up to 10000 feet altitude (first climb phase) and a maximum climb rate $\boldsymbol{w}$ above 10000 feet up to optimum altitude for cruise (second climb phase). Hence, the first climb phase satisfies a cost index $\boldsymbol{CI} = \mathbf{0}$ yielding a maximum gain in altitude, whereas the second climb phase accounts for a maximum $\boldsymbol{CI}$ and a maximum increase in flight distance. The kinetic energy required for an increasing true air speed after the safety level of 10000 ft altitude is taken from the potential energy resulting in a lower climb angle in the second climb phase.

Take-off is realized with 100 percent thrust, after three minutes, thrust is reduced to 85 percent by one percent per second. The target true air speed for a maximum climb angle corresponds to the target speed for best glide angle during descent and depends on aircraft specific parameters like aircraft mass and wing area, as well as on lift and drag coefficient, which are derived precisely according to Kaiser [20] considering compressibility effects.

The climb rate is defined by

$$\boldsymbol{w} = \sin\gamma \ \boldsymbol{v_{TAS}} \tag{1}$$

where $\boldsymbol{v_{TAS}}$ denotes the true air speed [m s^{-1}]. An extremum estimation of the climb rate results in a target true air speed for a maximum climb rate, depending on the available thrust, the lift and drag coefficients and aircraft specific parameters like aircraft mass and wing area and altitude [20]. The cruising altitude is derived as an extremum problem of the specific range $\boldsymbol{R_{spec}}$ with

$$\boldsymbol{R_{spec}} = \frac{\boldsymbol{v_{TAS}}}{\boldsymbol{m_f}} \tag{2}$$

where $\boldsymbol{m_f}$ defines the fuel flow [kg s^{-1}]. For the extremum estimation $\boldsymbol{v_{TAS}}$ is calculated using the aircraft specific maximum operating mach number [20] and the temperature and density gradient of the standard atmosphere mid latitude winter by Anderson et al. [30]. The target true air speed at a cruising altitude different from optimum altitude with respect to maximum specific range is derived by an extremum estimation of the specific range under consideration of the different boundary conditions (i.e. differences in temperature and density gradient).

For descent, continuous descent operations (cdo) with idle thrust and true air speed for maximum lift/drag angle during gliding flight are calculated. All criterions are proposed by Kaiser [20] and Scheiderer [31]. The target functions of true air speed for the different flight phases are used as controlled variable and are controlled by using a proportional plus integral plus derivative controller (PID controller). Density controlled maximum thrust at flight level and fuel flow are calculated using BADA by EUROCONTROL [19] as also used by [20]. An optimization of the cruising altitude and cruising true air speed with respect to fuel flow is considered as a function of distance between take-off and destination. The trajectories correspond to recommended flight profiles (compared with ICAO [32]) with a climb angle around 18 percent or 1000 feet per nautical mile and an angle of descent in the range of 6 percent. Unsteady flight attitudes are considered during take-off and climb and are optimized with respect to minimum forces of acceleration in the vertical and horizontal direction.

3. APPLICATION

For the demonstration of the back coupling of network optimization and trajectory optimization, the emission of nitric oxides and the corresponding effect on global warming is considered in both models. First, latitude dependent costs due to NO_x effects are considered in the network optimization resulting in a different route structure for a single example airline. Second, latitude dependent NO_x effects are included into the lateral trajectory optimization yielding different routes (and distances) for connections along the boundary of two NO_x regions. To overcome computational effort, the distances are discretized into 10 classes. Third, the vertical trajectory optimization applied to the routes, estimated in the lateral trajectory optimization, gives precise quantities of emitted NO_x masses and fuel flows for each distance class.

3.1. ETS assumptions

The latitude and longitude dependent effect of NO_x emissions by air traffic on global warming is given by Skowron et al. [4] and summarized in Table 1 for areas used in this study. Regions between the estimated areas (Europe and Southeast Asia) are interpolated linearly.

Table 1: Global warming potential over 20 years for latitude and longitude dependent air traffic NO_x emissions according to Skowron et al. [4]

Region	Latiude	Longitude	GWP NOx 20 years
Europe	40 °N - 60 N	10 °W - 40 °E	164
Interpolated Region	61 °N – 4 ° S	43 °E - 83 ° W	246
Southeast Asia	20 °S - 45 °N	90 °E - 150 °E	329
North Atlantic	30 °N - 60 °N	120 °O - 65 °O	478

For the transfer of CO_2 equivalent NO_x emissions into costs, the internalization of external costs performed by the ETS is used. Hereby, a price of 65 € per EUA causes an influence of external costs on airline direct operating costs and is chosen for this work. Furthermore, according to the Institute for Advanced Sustainability Studies, a price of 65 € per EUA is necessary to restrict global warming to a limit of $\boldsymbol{dT} = \boldsymbol{2}$ °C [33].

3.2. Network

An optimized network gives the boundary conditions for the subsequent trajectory optimization. The basic settings of this network are 40 nodes with a predicted demand for each connection between these nodes according to market outlooks by Airbus and Boenig for the year 2033 considering a growth in gross domestic product (GDP) [34] [35].

Expected ecological costs due flight through defined NO_x areas are added to the fuel burn costs assuming an averaged NO_x emission index of $\boldsymbol{EI_{NO_x}} = 0.017$ kg per kg fuel according to Lee et al. [2] and an averaged fuel consumption of 377 kg fuel per 100 km distance. This value corresponds to averaged A320 fuel consumption and has been calculated within the vertical trajectory optimization. Fuel costs are assumed with a value of 0.9 € per kg fuel. Furthermore, ecological costs due to other emissions like SO_2, CO, HC, CO_2, H_2O, SO_4 and soot are considered in total ecological costs using emission indices and global warming potentials for 20 years as published by Lee et al. [2]. The airport representing the demand at a dedicated node is assigned to the NO_x area according to its lateral and longitudinal position.

Therewith, estimated fuel burn costs can be compared and added to ecological costs and NO_x costs, all depending on distance (Table 2). Precise fuel burn costs and emission costs are calculated referring to the vertical trajectory optimization and can be used for a second, more precise network optimization.

For comparison, two network optimizations are simulated, once considering additionally latitude and longitude dependent NO_x effects on global warming and global averaged ecological costs as function of distance (Figure 3) and once accounting only fuel burn costs (Figure 4). All other parameters are equal in both models.

Table 2: Total ecological costs per 100 km distance considering latitude and longitude dependent air traffic NOx costs and other emissions

Region	total ecological costs [€/100 km]	Total costs [€/100km]
Europe	177.1	516.5
Interpolated region	196.8	536.2
Southeast Asia	221.8	561.2
North Pacific	286.8	626.2

At least 30 percent of the given demand has to be served by the networks by aircrafts with a capacity of 300 passengers. Hence, the routing structure is coupled with a required operating frequency.

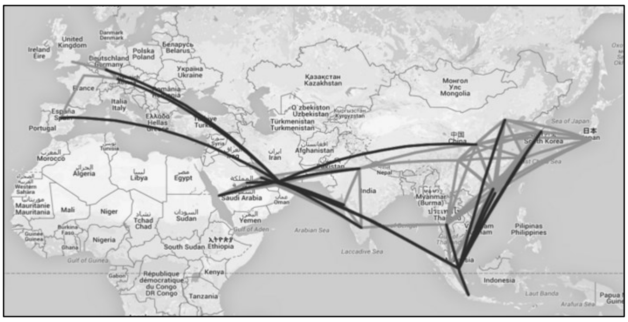

Figure 3: Cost optimized network structure 'A' for the given number of nodes and demand only considering fuel burn costs as function of distance (map plot: Google Maps)

In Figure 3 a map plot shows the optimized network structure without concerning local NO_x effects. It is a pure minimization of fuel burn specific costs as function of distance. Following the demand forecast, a growth of the demand especially in Southeast Asia and in Middle East causes two hubs in Dubai and Singapore (black lines). Light grey lines illustrate the point-to-point connections and are concentrated in Asia as well. Here, an example airline has the possibility to serve a high demand with relatively few offered connections. Fix costs can be reduced by the intense operation of connections with a high demand. However, selected routes to Western Europe are further considered. High demand of short distances to and from Western Europe had been developed during the network optimization.

Figure 4 shows the ecologically optimized network. The NO_x areas are enhanced by colored polygons. The costs per NO_x area can be taken from section 3.1 and Table 2. The North Pacific (polygon in top right corner) region is not flown through and can be moved out of the analysis. This optimization passage can be interpreted as the response of an airline to potentially expected costs due to the internalization of NO_x costs. Southeast Asia is still served, although flights through this area are expensive. Reason is here the need for serving much demand. Anyhow, changes in the network structure are detectable. One hub had been moved out of the expensive area to Europe (Germany, Frankfurt). Therewith, the high serving frequency in Southeast Asia had been reduced, the demand, however, is still served, primarily by point-to-point connections.

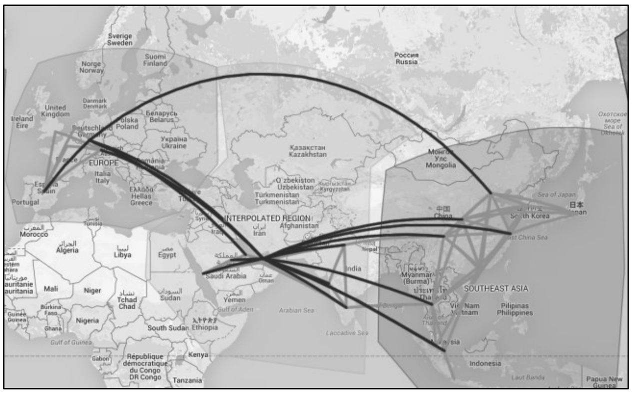

Figure 4: Cost optimized network structure 'B' for the given number of nodes and demand, considering global averaged ecological impact and local differences in the effect of NO_x emissions on global warming. Colored polygons denote the NO_x area (dark grey: Southeast Asia: most expensive, mid polygon: interpolated region, left polygon: Europe: cheapest, black: North Pacific). map plot: Google Maps

Now, the airline enhances its network to Europe and tries to serve other markets, where external costs are reduced. With these approach it could be shown, that the introduction of external costs can change the airline network structure significantly. For further analysis and comparison of both networks, the distances are classified into 10 distance clusters. Table 3 defines the upper and lower values of the cluster and shows the number of flights within each cluster for both networks. Figure 5 and Figure 6 further describe the composition of each network. Here, the NO_x categories 1, 2 and 3 correspond to the following NO_x regions: 1: interpolated region, 2: Europe, 3: Southeast Asia. Due to the displacement of one hub to Europe, longer distances are required in the NO_x considering network ‘B’. In Figure 5, the change of flights per distance cluster and per NO_x category due to environmental network optimization is shown. Longer distances have been added and flights in NO_x category 3 (Southeast Asia) with high external costs have been reduced.

Figure 6 illustrates the relative change in distance cluster and NO_x category due to network optimization. Considering induced traffic on a global scale, a back coupling between higher ticket prices due to external costs and demand has to be considered.

Table 3: Defined clusters of distances derived in the network optimization and number of flights per distance cluster with and without NOx area consideration.

Cluster	Low [km]	High [km]	Number of flights in network 'A'	Number of flights in network 'B'
1	621	1337	49	52
2	1338	2054	36	40
3	2055	2771	32	26
4	2772	3488	10	2
5	3489	4205	2	0
6	4206	4922	8	26
7	4923	5639	2	4
8	5640	6356	16	2
9	6357	7073	0	2
10	7074	7790	0	2
		Total	155	156

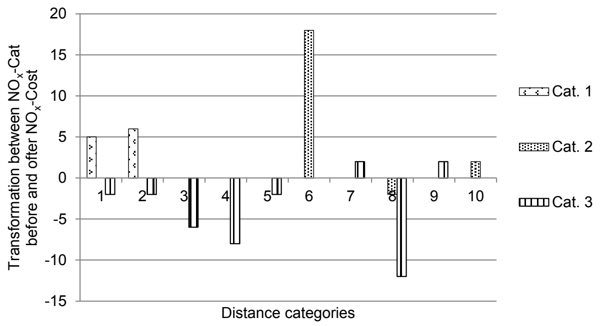

Figure 5: Change of number of flights per NO_x category and per distance cluster due to network optimization with enhanced external costs.

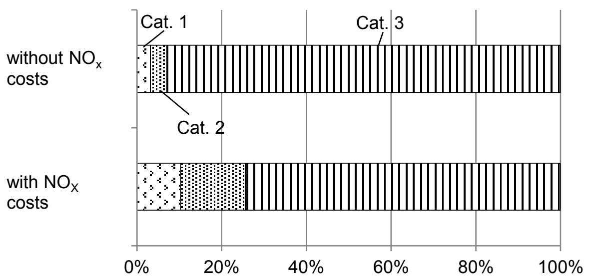

Figure 6: Changes in network connections in due to consideration of NO_x cost categories in network optimization

Furthermore, the demand not served by the example airline will be operated by a competing airline.

Both facts are important market based mechanisms with significant consequences on the cost-benefit ratio, which are not yet considered in the optimization.

A comparison of all costs due to fuel burn, other emissions and NO_x emissions will be drawn after the precise estimation of trajectories for the distance clusters defined according to the network optimization.

3.3. Trajectory optimization

3.3.1. Lateral trajectory optimization

After the network structure is optimized, a pathfinding algorithm for lateral trajectory optimizing is used to consider local restrictions or expensive areas. In Figure 7 an optimized lateral route from Frankfurt (FRA) to Dubai (DXB) is shown. A cell based simulation environment with a map tile depth of 20 kilometers is calculated using seven randomly generated wind fields. In the rendered picture of the cell based simulation (Figure 7) colored polygons indicate cheaper (light grey) and expensive (dark) areas, depending on wind speed and wind direction. Depending on head wind or tail wind, a fuel saving or fuel penalty is added to fuel consumption. This is realized by using wind speed and wind direction compared to heading to calculate the ground speed and the real amount of fuel which is used to fly to the next map tile. During cruise, a fuel burn of 54.8 kg had been estimated to fly the distance of 20 kilometers between two map tiles. During cruise, the speed is approximately 222 meters per second. An example tailwind with 8.3 meters per second yields a fuel saving of 2 kg between two map tiles. Additionally, a randomly located ice supersaturated area with high potential of contrail formation is implemented. This zone is visualized as dark grey polygon in the upper area of Figure 7. The algorithm circumvents the critical zone and searches for the minimum cost track. Transforming the emissions in ecological costs and adding these to operating costs of an airline, it is possible to optimize these trajectories considering multi-criteria target functions. Additional costs, like air traffic control driven en-route charges are neglected assuming an implemented Single European Sky. Caused by the diversion, higher costs are expected for the airline by flying around the sensitive area.

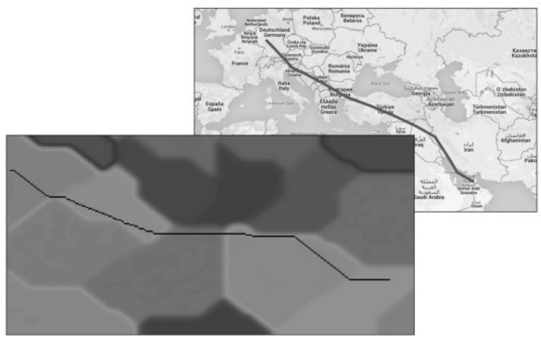

Figure 7: Flight Path from FRA to DXB considering fuel and ecological emissions costs minimizing

In contrary to en-route segments, lateral trajectory optimization in the vicinity of airports is characterized by emitted noise and emissions with high effectiveness on air quality. Especially noise sensitive areas near urban sectors should be spared by low altitude traffic or should be completely restricted for aviation. In the current study, for flight segments near airports, a map tiles depth of 500 meters is implemented and cells are connected with external costs for noise, other emissions and fuel burn. Additionally, some crucial areas are restricted.

Figure 8 shows the terminal maneuvering area of Frankfurt and a climb and flight path (white line) in the direction of Dubai DXB (compare Figure 7). The airport is located in the western area and the outbound flight path ends seamless in the en-route path in the south east.

While the lateral trajectory optimization gives the flight path with minimum fuel flow, airlines can also be animated to bypass a sensitive sector of airspace (black path, Figure 8). This provides the opportunity to limit the effect of locally effective emissions. Unlike a fixed flight ban in the restricted area, there is also the possibility to introduce a flyover charge. This charge should be in the range of the additional costs, caused by flying around the restricted area. Note, currently, the lateral trajectory model does not distinguish between different fuel flows for different flight segments. Hence, a more complex coupling between the lateral and the vertical trajectory optimization is expected to result in both, more precise lateral and vertical trajectories.

A detour increases the flight distance and beside extra fuel burn costs, it leads to higher emissions during the route. These emissions have been internalized by using the emission trading system. These costs are applied to the airline.

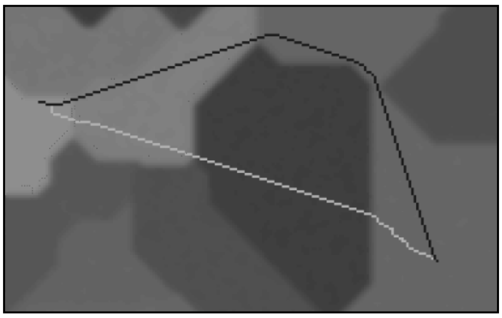

Figure 8: Flightpath in vicinity of the airport FRA and trajectories avoiding and crossing a high cost area as an example for protection against emissions

In Figure 8 the diversion amounts 23 kilometers after take-off (difference between white and black line). Both flight paths are calculated with the flight performance model resulting in an extra fuel burn of 97.1 kilograms. Assuming a fuel price of 0.9 € per kilogram, the extra costs for additional fuel burn for the detour are 87.3 €. However, not only costs for fuel burn, but also external costs for the effects of emissions on global warming have to be considered. Using the emission indices and global warming potentials of Lee et al. [2], and assuming a price of 65 € per EUA within the emission trading system, additional external costs for the diversion of 23 kilometers are in the range of 29.1 €. Hence, the flyover charges for this example area (Figure 8) have to amount 116.4 €.

3.3.2. Vertical trajectory optimization

The flight performance model gives fuel burn and time of flight for trajectories with optimized cruising altitude depending on the distance required according to the network structure. Therefore, the optimized cruising altitude has to be determined respecting the target function of the airline. In Figure 9, the fuel burn during flight is plotted for two distinguishing cruising altitudes, 11.7 and 5 km, showing, that flying at higher altitudes yields less fuel burn, although initially, more fuel is consumed during climb.

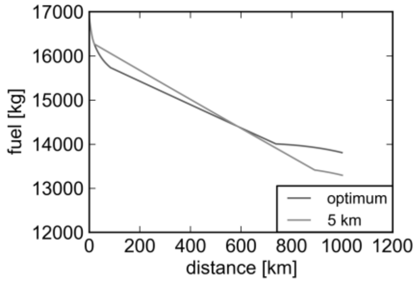

Figure 9: Fuel burn over a 1000 km flight distance for two different cruising altitudes. Black: cruising altitude is at 11.7 km yielding maximum specific range, light grey: the aircraft cruises at 5 km.

Aiming a maximum specific range, the aircraft flies a few meters higher, than for minimum fuel consumption. Figure 10 and Figure 11 show the total fuel burn and time of flight for a 5998 km distance flight as function of cruising altitude, respectively. Note cruising beneath 6.7 km yields more fuel burn than fueled (17 t) and does not satisfy boundary conditions of the flight performance model.

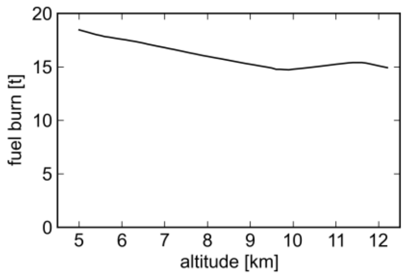

Figure 10: Total fuel burn for a distance of 5998 km (mean distance of cluster 8, Table 3) as function of cruising altitude.

Minimum fuel burn is reached at 9.9 km cruising altitude. But in 11.7 km the maximum specific range is reached. For a little bit more fuel, a significantly higher true air speed and therewith shorter time of flight are reached (compare Figure 9).

In the current study, the cruising altitude satisfies the target function of an economically and ecologically operating airline. Table 4 shows the total fuel burn and the number of flights with mean distances according to the defined clusters in Table 3. Note, cluster 9 and 10 cannot be served by an A320, because the distances are greater than the maximum range of an A320 (>6000 km). Hence, for serving the NO_x effect friendlier network, the aircraft fleet should be extended, causing other costs.

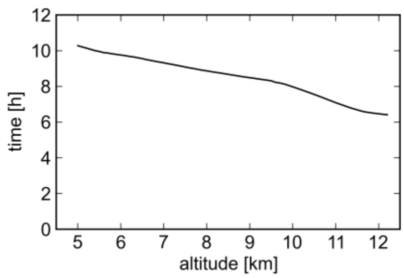

Figure 11: Time of flight for the same flights as plotted in Figure 8 as function of cruising altitude.

Table 4: Time of flight and total fuel burn for defined distances

Cluster	Low [km]	High [km]	Number of flights in network 'A'
1	621	1337	49
2	1338	2054	36
3	2055	2771	32
4	2772	3488	10
5	3489	4205	2
6	4206	4922	8
7	4923	5639	2
8	5640	6356	16
9	6357	7073	0
10	7074	7790	0
		Total	155

With the precise information of total fuel burn as function of distance, the network optimization can be applied again to check on any changes in routing structure. Furthermore, the networks can be compared with each other and the influence of ecological costs on the network can be estimated. Figure 12 shows the sum of all ecological and economical costs considered in this study of an example airline operating in each network. Here, local NO_x effects are assumed in both networks and the number of flights per distance cluster and per NO_x category is considered. Although the NO_x considering network 'B' contains longer distances, the total distance required to serve the network is shorter, than for network 'A'. This can be seen in differences of the fuel costs (black dotted). Maybe this effect is only caused by the discretization of flight distances into 10 distance cluster. Otherwise, results of the network optimization without consideration of NO_x effects would have been different, because the fuel burn is the only cost, considered in network 'A'. However, ecological costs (small crossed) are reduced in network 'B', mainly because the airline is operating in cheaper areas regarding local NO_x effects. A small reduction of ecological costs is caused by the reduction other emission due to shorter distances.

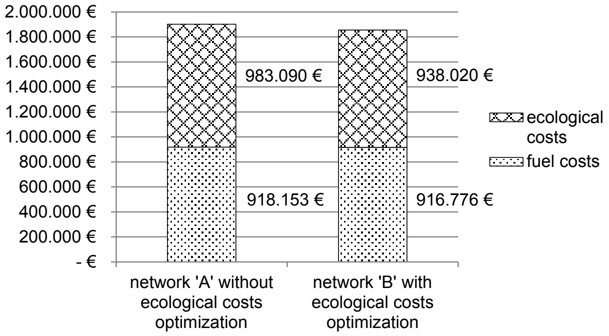

Figure 12: Total ecological and economical costs of an example airline serving both networks.

4. DISCUSSION AND CONLUSION

In this study, a coupled optimization of ecological and economic effects of a network structure and of the flight performance is shown. External costs due to latitude and longitude dependent NO_x effects on global warming are used to optimize an airline network with respect to minimum NO_x effects. Thereby, indirect operating costs are not considered. Different NO_x effects had been considered by transferring the NO_x effects into carbon dioxide equivalent emissions. For this calculation a global warming potential considering the effects of emissions for 20 years after emission is used. The carbon dioxide equivalent emissions are transferred into costs using the emission trading system and assuming a price of 65 € per ton emitted carbon dioxide (EUA). Using a flight performance model, the total amount of emissions could be reduced by optimizing the cruising altitude with respect to maximum specific range. Therewith, economic airline issues are also respected. Furthermore, the flight performance model had been used to calculate precise values of fuel burn. A lateral trajectory optimization is implemented providing the possibility of the shortest path to consider wind direction and wind speed, restricted areas, contrail or noise sensitive areas or even local NO_x effects. In this study, the NO_x areas are too large for finding connections at the boundary of two different NO_x regions, where the pathfinding could have been used for the cost-benefit-decision, weather a diversion through the neighbored cheaper NO_x area would be better or not. Hence, the lateral trajectory optimization could not be applied completely.

Considering local NO_x effects in the air traffic network structure, an airline, mostly operating in Southeast Asia, is recommended to shift parts of the connections and even a hub to airports in Europe, where the demand is large, but smaller NO_x effects on global warming are detected. Beside the fact, that this change would result in longer distances which no longer can be served by an A320 aircraft, the airline would save costs in fuel burn and ecological costs in a range of 46 thousand Euros (compare Figure 12). Thereby, a similar number of passengers were transported, because the same ratio of the demand had to be served.

With this study, the effect of the internalization of ecological costs on an airline routing structure could be shown and possibilities for enhancing the airline benefit are developed. Considering other costs than costs due to carbon dioxide in the emission trading system, incentives can be offered to the airline to avoid ecological critical connections or to allocate external costs on ticket prices.

The internalization of ecological costs already happens at german airports, where a statutory provision for charging purposes can be seen, among other things for NO_x emissions. However, especially NO_x related charges are usually depending only on engine type and a standardized landing and take-off cycle (LTO). Thus, no incentive can be put on airlines to adjust flight procedures and trajectories to reduce emissions, since a modification would not bring benefits. Furthermore, a significantly higher proportion of environmental charges for approach, departure and en-route is necessary to balance the costs of a flight towards a more ecologically friendlier air traffic system. This risk is detected, among other things, assuming an acceptance of 65 € per ton of CO_2 emission and a share of NO_X costs of 17 percent of the fee for the global warming potential.

5. OUTLOOK, NEXT STEPS

In this study, three models and their connection with each other have been introduced, each representing a different part in air traffic optimization towards a more sustainable air transport. Each of these models will be improved to estimate the ambitious aims of our research project MEFUL. Of particular importance is the enhancement of the models towards a more complex coupling of the models among themselves. However, even with the current state of the models, interesting findings could be drawn regarding the consideration of ecological issues in network and trajectory optimization.

The most important next step is the respect of wind speed and wind direction in the flight performance model. Thereby, a direct coupling of the flight performance model with the lateral trajectory will result in total optimized flight paths. A more complex coupling of lateral and vertical trajectory optimization is aspired to better consider diversions due to lateral conditions for the avoidance of expensive regions because of contrails, NO_x areas or noise sensitive areas. An implementation of a precise combustion module into the flight performance model for correct calculation of emitted quantities is planned to minimize special emissions. Furthermore, the consideration of the aircraft fleet in cost-benefit-calculations is aimed to respect required changes in aircraft type in cost analysis.

An efficient A-Star-algorithm is expected to give a possibility for dynamic routing in live simulations of the air traffic flow as a response to unexpected obstacles like thunder cells, ice supersaturated regions with a high potential of contrail formation, changed wind fields or routing under traffic constraints.

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