AN AIRLINE NETWORK DESIGN APPROACH CONSIDERING ENVIRONMENTAL AND ECONOMICAL TARGETS

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Abstract

The integration of near-surface temperature change (dT) as climate target in airline network design for a single airline is proposed in this work, in addition to economical targets. Near surface temperature change is induced by emissions along the flight trajectories of all operated flights in the airline network. The approach allows for investigating the climatological benefits achievable for a single airline through changes in network structure, i.e., the change of origin-destination markets, flight connections and passenger routings. Potential benefits can be achieved for a single airline due to network operation in less climate sensitive regions. These benefits may lead to a competitive advantage in comparison to other airlines of the air transport system, assumed that reductions in network induced climate impact are credited by policy makers in the future. However, the global environmental impact of the air transport system is not reduced with this approach. The proposed methodology is implemented and demonstrated for a single use case covering global transportation flows that shows preliminary results. The use case includes 21 airports, 150 potential OD-markets and a single aircraft configuration available to a single airline for network design. First results encourage further research in this area.

1 Introduction

Airline network design is a key challenge in airline operations, and a basic requirement for subsequent tasks such rotation-, maintenance and crew-planning [2]. Mainly driven by market demand and direct operating costs (DOC), network design aims to create a minimum-cost flight plan from an economic perspective. Tasks in network design include the selection of flights to be operated in the network, determination of respective flight frequencies on origin-destination (OD) pairs, timetable development and passenger routing. Further, network design has to account for system constraints of the operational environment such as airport curfews, and for the cost-efficient use of airline resources such as aircraft fleet and capacity. A survey on airline network design and schedule planning can be found in Gopalan et al. [8]. Network design models in the context of economical targets are proposed in [15] and [6]. Most of the available models build on operations research techniques and optimize for economical targets only, i.e., they focus on monetary aspects such as direct operating costs, expected revenue, and achievable network profit.

Given the challenge of climate change [17], and the need to reduce the aviation induced environmental impact, the question arises whether an individual airline might reduce its impact on climate through structural network changes. Naturally, if the overall demand is unaffected, the remaining routes will be served by other airlines and hence the total climate impact is unaffected. Further, changes in ATM flight operations, e.g., change of flight altitude are not part of this study. However, this methodology can be viewed as a step towards a more climate compatible air transportation. If climate costs were attached to individual routes, the network itself might change and routes with larger climate impact might introduce new

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concepts with respect to aircraft design, technologies and individual flight planning. In any case the identification of the part of the network with lowest climate impact is essential to these questions. In this respect this paper can be viewed as a first step towards a greening of a transport system through structural network changes.

With respect to the inclusion of environmental targets in airline network operation and design, Bower [3] investigated environmental performance for aircraft design on a given fixed airline route network consisting of 4 cities and 8 route segments. Hsu [11] formulated an airline network design model that determines optimal routes, flight frequencies and types of aircraft in response to airport noise charges. Brueckner [4] studied emission charges impact by analysis of effective fuel price increase, and embedded a duopoly airline competition model in a network setting. However, none of these approaches considers near surface temperature change as climate target for the explicit design of single airline networks.

The methodology introduced in this work extends the cost function of a network design model that was developed in the context of this work. A weighting metric is introduced that balances network profit and network induced climate impact in the network design optimization cost function. The metric allows for investigating different network design policies according to different weightings of profit and climate impact in the network optimization process. The chemistry climate response model AirClim [9] of the DLR in combination with a trajectory calculator is used for calculation of climate impact for all potential flight legs available for network design. The climate response model allows for assessing the climate impact of flight emissions on global near surface temperature change. Apart from carbon dioxide emissions, the climate agents H_2O, CH_4 and O_3 as well as contrails are considered by AirClim.

The proposed methodology is implemented, and preliminary results are shown for a single use case covering global transportation flows in climate sensitive regions between Europe, USA, South-America, Africa and Asia. Dependent on the network design policy, changes in network structure and network performance, i.e., network operating costs, fuel consumption, profit and climate impact are investigated. All network responses are evaluated with respect to a reference network optimized for economical targets only.

The paper is organized as follows: Section 2 introduces the network design model that was developed and used in the context of this study. Section 3 outlines the climate model AirClim. Section 4 introduces the cost function, i.e., the weighting metric that is applied in the network optimization for balancing economic and environmental targets. Section 5 introduces the data workflow used for the study. Preliminary results and conclusions are given in Section 6 and Section 7, respectively.

2 Airline Network Design

This section introduces a network design model that we developed in the context of this work, and that is extended to include near surface temperature change dT in the cost function.

The proposed network design model is formulated as a mixed integer program, and generates airline networks “from scratch” based on a given specification of the airline operational environment as shown in Figure 1. The “from scratch” approach ensures that the airline network is built without an existing base schedule but designed from the bottom up. This allows for studying the operational impact of different network design policies independent of a particular airline or legacy network structure. The cost function that balances economical and environmental targets in the network design optimization is introduced in Section 4.

The specification of the operational environment covers the airport infrastructure, fleet mix, and market conditions based on origin-destination pairs, and therefore, defines a scenario of the current or future airline operational environment. That is, the given operational environment determines the operational system constraints and costs to be considered by network design. The airport infrastructure refers to the available airport set and operating hours (restricted by slots and curfews) for each airport. The fleet mix determines the type and number of aircraft available to the airline for network operation. In addition, the fleet mix determines operating costs (DOC) on potential flight legs, and aircraft turn-around times to be observed before the operation of a next flight. The OD-market set defines all potential markets to be entered or dismissed by network design, and associated demand, and fares estimated for each market for the given planning period.

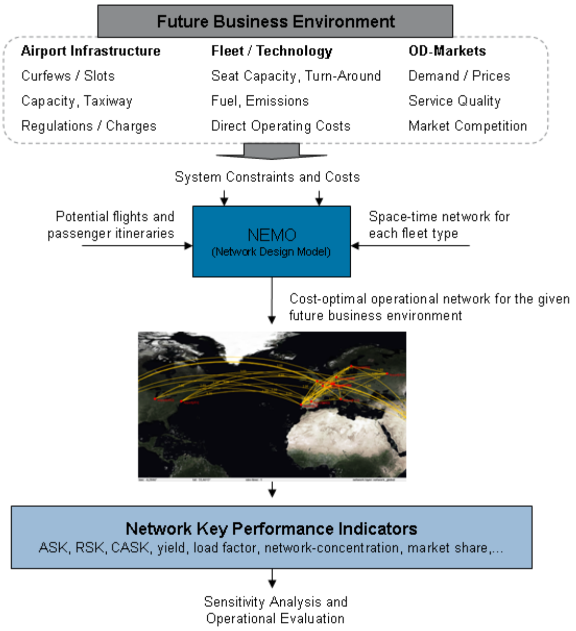

Fig. 1. Network design model.

The DOC method from Liebeck [14] is used for DOC calculations on potential flight legs. This method accounts for fuel, crew, maintenance separated by engine and airframe, airport charges and navigation fees, and for capital costs including interest rates.

Decisions that are to be resolved in the network optimization include the flights to be offered in the airline network, the aircraft types used to operate the offered flights in the network, the total number of aircraft required for network operation, and the passenger flow, i.e., the number of passengers transported on the routes in the transportation network. Potential routes, e.g., non-stop flights available for passengers in the airline transportation network are determined by the flights that are offered in the network. Operational constraints include total passenger demand for each OD-market, aircraft capacity for each operated flight, and aircraft availability and flow balance in the network in order to guarantee fleet assignment [10]. For this study, an additional constraint is set that fixes the network size in terms of available or revenue seat kilometers (ASK/RSK). The constraint ensures that the same network capacity respective traffic output is exposed by all designed networks. This avoids the option of capacity or traffic reduction in order to reduce network climate impact.

3 Assessing Near Surface Temperature Change with AirClim

The climate impact of aviation depends not only on the amount of emissions, but also on the altitude and geographical region of emissions [13]. Therefore it is necessary to use a model, which resolves the atmosphere to at least some extend. We use the chemistry-climate response model, which has a reasonable latitude-height resolution, to calculate the climate impact of an aircraft fleet. The climate model *AirClim* comprises a linearization of atmospheric processes from the emission to radiative forcing, resulting in an estimate in mean near surface temperature change (dT) in the 100 years after the emission took place. Near surface temperature change is presumed to be a reasonable indicator for climate change. AirClim is designed to be applicable for evaluation of numerous air traffic scenarios, routings and technology options. The model accounts for the climate agents CO_2, H_2O, CH_4 and O_3, with the latter two resulting from NO_x emissions. In addition, contrails are taken into account.

AirClim combines a number of precalculated atmospheric data with aircraft emission data to obtain the temporal evolution of atmospheric concentration changes, radiative forcing and temperature changes. Precalculated atmospheric data includes chemical response and chemical perturbations for idealised emission regions, derived from 78 steady-state simulations for the year 2000 by a state-of-the-art climate-chemistry model (E39/CA). A detailed description about functionality of AirClim and validation of the methodology is given in [9]. Here we apply an extended AirClim version with a higher resolution, especially at cruise altitudes [7].

4 Balancing Environmental and Economical Targets

The weighting metric included in the airline network design cost function is introduced in this section. The weighting allows for balancing economical and climatological targets in the network optimization process, and therefore, the study of different network design policies. Balance is controlled by a weighting factor α that is applied to the network profit (determined by passenger fare and DOCs of the airline network), and near surface temperature change (dT) part of the cost function as shown in Equation 1.

$$policy = \alpha \cdot (FARE - DOC) + (1-\alpha) \cdot DT \quad (1)$$

With α a policy factor and *FARE*, *DOC*, *DT* normalized, i.e. dimensionless, variables see below. The "α =1"-network policy corresponds to an airline network design that is designed for economical targets only. All policies are in the range of $0 \leq \alpha \leq 1$.

The inclusion of the weighting metric in the cost function of the network design model introduced (Section 2) is given in Equation 2.

$$\min\left(\sum_i -\alpha \cdot FARE^i x_i + \sum_i \alpha \cdot COC^i y_i + \alpha \cdot CAP^{aircraft} z + \sum_i (1-\alpha) \cdot DT^i y_i \right) \quad (2)$$

The cost function in Equation 2 is shown for a single aircraft type. The index i refers to all potential flights available for network design in the system. Decision variables of the cost function are x_i, y_i and z, with x_i the number of transported passengers on each flight i that is operated in the network. The variable y_i states whether flight i is operated in the network or dismissed, and z is the total number of aircraft required to operate the network. The decision variables x_i and z are integer variables, y_i is binary. The pre-computed cost factors of the optimization function are denoted by $FARE^i$, $CAP^{aircraft}$, COC^i and DT^i. These cost factors are normalized in order to account for the different scales and units of the monetary (usually put in USD per flight or aircraft) and the climate cost factor (expressed, e.g., in Kelvin). That is, the normalized cost factors are dimensionless. In particular, estimated revenue per passenger for each flight i is denoted by $FARE^i$, the cash operating costs for each flight i that is operated is denoted by COC^i, CAP^i are the capital costs for each aircraft in the fleet, and DT^i is the near surface temperature change for each potential flight i. That is, the DOC in Equation 1 is broken down to cash-operating and capital costs, which depend on different decision variables.

As shown in Equation 2, the α factor is applied to the monetary cost factors ($FARE^i$, COC^i, and $CAP^{aircraft}$), and the corresponding weight (1-α) is applied to the near surface temperature change (DT^i) part of the network design cost function. Due to the global network cost minimization target, revenues ($FARE^i$) are included as negative costs in Equation 2, therefore, a negative sign is included ahead of the α-term.

5 Data Workflow

To generate the flight performance and pollutants emission distribution input for the climate response and network design model, all relevant parameters are calculated with the CATS simulation chain [12] on beforehand.

The CATS chain was developed within the DLR project "Climate-compatibel Air Transport System". It uses the commercial design and analysis framework *ModelCenter* based on a client/server architecture, and comprises physics based numeric models for detailed simulation of aircraft design and performance, propulsion and emissions, mission calculation and climate response. As central data interface, the CATS chain uses the DLR standardized *Common Parametric Aircraft Configuration Schema* (*CPACS*), containing detailed parametric description of the aircraft, engine, atmosphere, mission profile, airports and fleet information.

The CATS simulation approach includes 3 phases that are computed in sequence as shown in Fig. 2. First, the aircraft is designed for a given set of design requirements with a detailed physics based aircraft design model and an engine performance database.

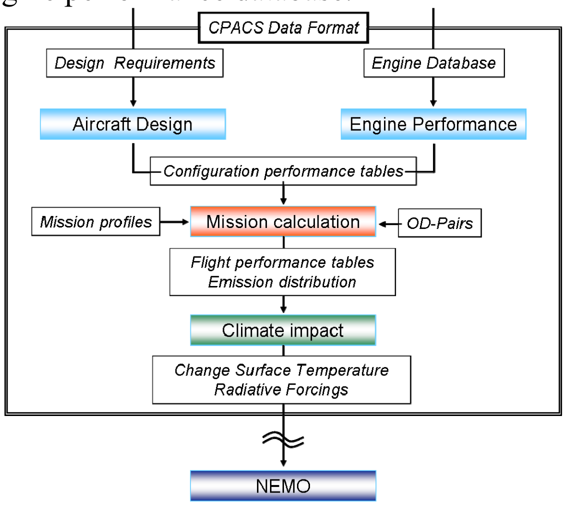

Fig. 2. Data workflow for AirClim and the network design model.

The aerodynamic and engine performance tables, the geometry and weight breakdown for the resulting aircraft are stored in the *CPACS* format and used together with a given mission profile as input for the mission calculation module. For all aircraft configurations and routes in the network, the mission module calculates the 4D trajectory with distribution of pollutants, mission fuel, mission time, etc. The computed trajectories and emission distributions are used as inputs for the assessment of climate impact and on following calculation of DOC.

The network design model is not integrated in the CATS simulation chain, but is able to process the resulting CPACS files to generate the airline network from scratch for a given weighting policy. The resulting DOC and dT values for each flight in the data set are weighted using the metric defined in Section 4. The weighted costs form the base input for the network design model's cost function, along with the set of potential OD-markets, airports, passenger itineraries, expected fares and fleet mix. CPLEX [5] is used as an LP-solver for the network optimization process.

Analysis of the resulting networks and network changes with respect to a reference network optimized for economical targets reveal the system dynamics of network design considering environmental and economical targets. Key figures include, e.g., costs per available seat kilometer, yield, aircraft utilization or flight frequencies on specific markets.

6 Implementation and First Results

This section introduces a global transportation flow scenario that is used to demonstrate the proposed methodology. Transportation flows are characterized by air transport demand between city-pairs. Section 6.1 introduces the assumptions defined for network modeling for a calculation of a first parameter set. Section 6.2 discusses first results of this parameter set.

6.1 Global Transportation Flow Scenario

The scenario covers 21 airports distributed over five geographic regions as listed in Table 1. The selection of regions and airports ensures that all relevant climate-sensitive zones are included in the network optimization.

Table 1. Geographic regions and selected airports.

Geographic region	Airports
Europe + Middle East	FRA, LHR, ARN, MAD, DXB, KEF, ANC
North-America	JFK, ORD, YUL, YYZ, LAX, SEA, LOS
South-America + Mexico	BSB, MEX, GRU
Africa	JNB, CPT
Asia	NRT, SIN

Airport selection focuses on main airports, e.g., international hubs in order to cover global transportation flows with sufficient air travel demand. For the selected airport infrastructure, 150 city-pair (OD) markets are considered for network design. Air travel demand for each of the markets is determined by evaluation of the "Official Airline Guide" (OAG) flight database [16]. The offered airline seat capacity contained in the OAG data is used as an approximation for the overall travel demand structure for each OD-market. The demand retrieved from the data is corrected by an assumed average airline seat load-factor of 70%. The planning period for network design is set to a single day.

A long-haul aircraft configuration (Table 2) is used as fleet mix available for network design, including a maximum fleet size of 100 aircraft and an overall turn-around time of 60 minutes. In addition, it is assumed that the airline is able to operate “open skies” [18] flights between the given airport set. These assumptions allow for serving a large set of long-haul routes required to capture all climate sensitive regions in a single network, and to clarify the potential to reduce the environmental impact through structural network changes. Details on the aircraft configuration are listed in Table 4.

Table 2. Long-haul aircraft configuration.

Aircraft configuration	Value
OEW/MTOW	175t / 365t
Engine thrust	4x 249kN
Cruise speed	0.83Ma
Flight level	10.000m
Max range	14.000km
Turn-around	60min
Seat capacity (3-class layout)	380

Fuel consumption and near surface temperature change cost factors for each potential flight mission in the network are obtained from trajectory and AirClim calculations (Section 5). Ticket fare is set to a constant value of 0.13 USD per revenue seat kilometer (RSK), which is an approximate average of economy fares evaluated over a wide range of route distances and airlines. Airports are assumed to operate 6-22h local time.

Experiments cover the design of a reference network optimized for economical targets only (Section 4). For the reference network, network size in terms of ASK is constrained by market demand and fleet size. Further, networks generated with different weighting policies considering economical and environmental targets are evaluated with respect to the reference network. For all networks, network size is allowed to vary within a 1% bound of the reference network capacity in terms of ASK. This guarantees nearly constant network sizes for all designed networks but exposes sufficient flexibility for the network optimization model to allow for structural network changes, e.g., in the form of changed OD-markets and passenger routes.

6.2 First Results

This section provides a first parameter set that is computed with the given assumptions introduced in the previous section. In this parameter set, flight altitude is fixed to a single altitude of 10.000m for all flights in the networks. Normalization values applied in the cost function (see Section 4) are obtained from the reference network that is optimized for economical targets (network profit) only. The network profit value is applied for normalization of all monetary cost factors, and the network induced climate impact of the reference network is applied for normalization of the dT part of the cost function.

Fig. 3 shows the overall system behavior, i.e., development of network fuel, profit, unit costs (cask) and network load dependent on a reduction of near surface temperature change (dT). The reduction is achieved by variation of the weighting of climate and economical targets in the network optimization process, i.e., each sample in Fig. 3 represents a single network optimized with a different network design policy as controlled by the α-term (Section 4). In Fig. 3, all networks expose the same network size in terms of ASK (within 1% bound of the reference network ASK output). The reduction of 0% corresponds to the network optimized for economical targets only. The maximum dT reduction of approximately 20% in Fig. 3 is achieved by applying a network design policy that optimizes for environmental targets only, i.e., economical targets are neglected. The dT curve in Fig. 3 is displayed in a linear way in order to clarify the development of the other network performance indicators such as fuel and profit with respect to the climate target. The vertical axis of the chart shows the development of the respective network performance indicator with respect to the reference network optimized for economical targets only.

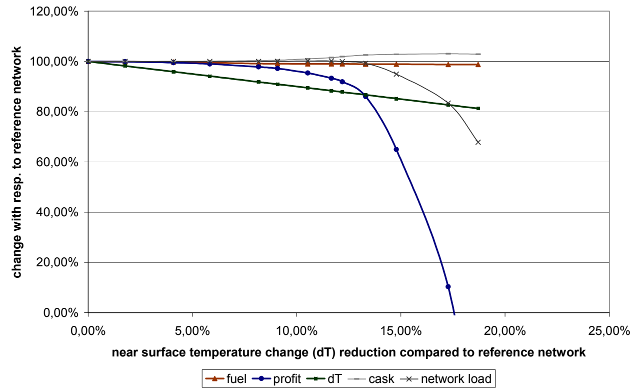

Fig. 3. Development of profit, fuel, unit costs and network load dependent on near surface temperature change (dT) reduction for a single airline.

First, Fig. 3 reveals that fuel consumption in the networks stays nearly constant since the network output in terms of ASK of each designed network is forced to be constant (within a 1% bound). This proves that dT savings are a direct result of structural network changes, e.g., changed routes and markets in contrast to a reduction of fuel burn. Second, Fig. 3 shows that dT savings are proportionally higher than profit losses resulting from optimizing for economical *and* environmental targets in the range of 0-14%. This principle changes for a dT reduction above 14%. Here, profit losses are proportionally higher than the achievable dT reduction, and profit starts to crash. In this extreme range (above 14%), total demand in less climate sensitive areas is already satisfied by the networks. In addition, economical targets exhibit a low priority in the network optimization, e.g., in terms of network load and profit achievement compared to the climate target. The low priority for economical targets in this extreme range allows the system for reducing network load in order to further reduce climate impact through structural changes. This is also indicated by the network load curve that comes down as expected, and an increase of unit costs (cask). A network load below the break-even load factor of an airline network leads to an unprofitable network, i.e., network profit is negative. An airline would not operate in this extreme range.

In contrast to Fig. 3 that shows the overall system behavior (including profitable and unprofitable networks), Fig. 4 focuses on profitable networks only, i.e., networks that expose approximately the same network load and revenue gained from passenger traffic as the reference network optimized for economical targets only. This would be the range of interest for a single airline with respect to climate targets since profit losses are below savings in climate impact as shown in Fig. 4. For the results shown in Fig. 4, traffic output of all networks in terms of RSK is fixed (again within a 1% bound) during the optimization. Due to the assumed fixed fare price per RSK in the network, the same RSK output generates the same revenue. The resulting networks cover approximately the range of a dT reduction corresponding to the range of 0-14% in Fig. 3.

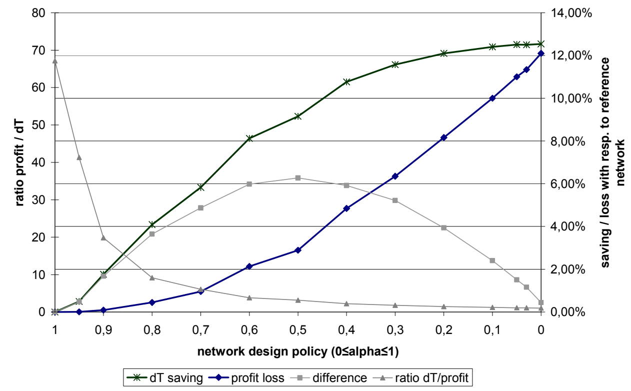

Fig. 4. Development of network profit loss and dT saving for a single airline with fixed traffic output.

Fig. 4 reveals the results in terms of development of profit loss and dT saving for varying α-policies. The α value of 1 corresponds to a network optimized for economical targets only. The α value of 0 corresponds to a network optimized for environmental targets only, i.e., costs and revenues are completely neglected. Again, each sample in the chart refers to a network optimized with the network policy (α) shown on the horizontal axis. The right vertical scale in Fig. 3 shows the dT savings and profit losses with respect to the reference network. The “difference” curve reveals the difference (in percent) of the dT saving and the profit loss curve. The highest difference (approximately 6%) is achieved with a network design policy with α=0.5. The left vertical scale is dimensionless and refers to the ratio between dT savings and respective profit losses. That is, with α=0.9, savings in climate impact (dT) for this single airline would be 20 times as high as the respective profit loss for this policy compared to the reference network. The ratio is high (nearly 70) for an α value close to 1, and declines exponentially as alpha decreases. The ratio converges to 1 for network policies optimizing primarily for climate targets. This behavior suggests that potential reductions in dT can be achieved, at least for the given assumptions, at the cost of very low profit losses. However, further dT reductions become harder and lead to networks with increased unit costs, e.g., due to suboptimal network layouts in terms of aircraft routing or fleet assignment. Therefore, the figures and system behavior discussed in this section encourage further research on potential dT savings for single airlines through structural network changes.

In this study, we analyze first results of a network optimization for a single airline. Some parameters were chose beforehand, e.g. aircraft type, flight altitude, prices, etc. In a future work, we will further investigate the sensitivity of the results to these parameters, and focus on the stability of our results.

Network visualizations[1] are given in Fig. 5 to Fig. 7. The dT normalized to ASK distribution with respect to the routes considered for network design are shown in Fig. 5. The climate impact in this region is enhanced primarily through higher ozone and contrail forcing in the flown altitude of 10.000m. Fig. 6 and Fig. 7 show network layouts generated with different network design policies. Network design policies with low α-values, i.e., high priority for environmental targets, results in a network structure that shifts to the northern zone, i.e., into less climate sensitive areas (Fig. 7), although network size in terms of ASK stays constant.

7 Conclusions and Future Work

A methodology for balancing economical and environmental targets in airline network design for a single airline is proposed in this work.

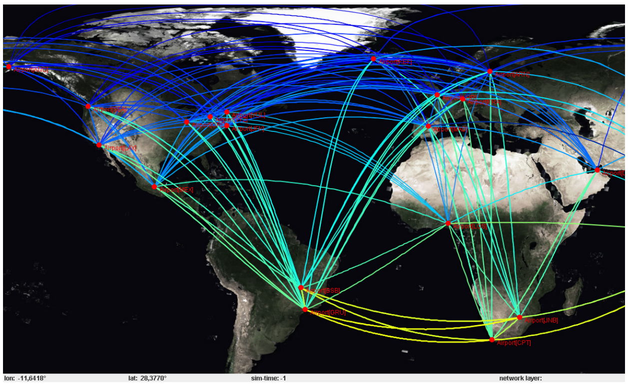

Fig. 5. dT distribution (normalized to ASK) with respect to the routes considered for network design. Color scale ranges from dark blue to yellow (low to high values).

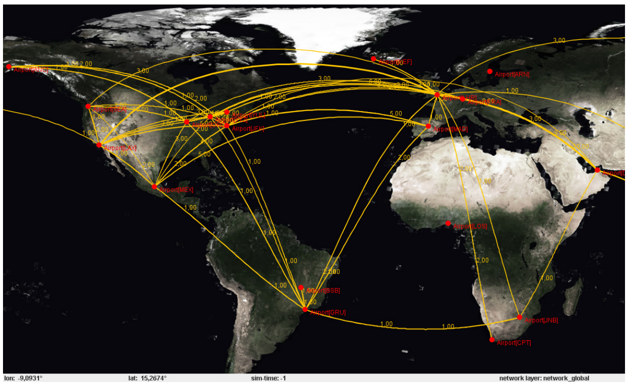

Fig. 6. Network layout for economical targets.

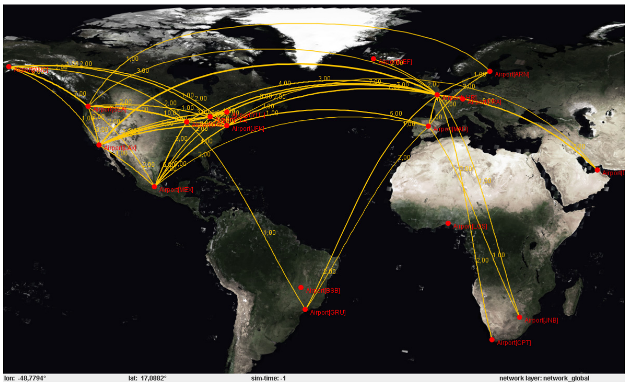

Fig. 7. Extreme network layout for one single airline acc. to environmental targets.

[1] Geodata for map illustrations in this paper is provided by © Unearthed Outdoors, LLC.

In contrast to focus on CO_2 emission reduction as a single climate target only, this work considers near surface temperature change (dT) as a climate target for network optimization. Near surface temperature change is an indicator for the climate impact of induced CO_2 and other greenhouse gas emissions, in dependency of the latitude and altitude where the pollutants are emitted. By change of network structure, i.e., change of markets, offered flights, and flight frequencies but constant network capacity in terms of ASK, environmental benefits for a particular airline in comparison with other airlines can be achieved that may lead to a competitive advantage if these environmental benefits are credited. The climatological benefits are possible through network operation in less climate sensitive areas of the air transport system. However, the change of flight operations, e.g., a change of flight altitude or changes in the trajectory of a particular flight, is not part of this study. Further, the global environmental impact of the complete air transport system is not reduced by including temperature change in the network design cost function. This is due to the fact that transport demand in high climate sensitive regions still needs to be satisfied, and is further expected to increase. However, structural network changes for reducing climate impact, and the design of respective networks may be a potential option towards a more climate compatible air transport system.

First preliminary results prove the methodology to work. For a single use case covering global transportation flows, savings in dT about 10% for a single airline are achieved at the cost of a substantially lower profit loss of 5% with the given assumptions for network modeling and parameter variations (Section 6.1). These results encourage further research in this area. In particular, structural network changes may become an issue if network induced temperature change will be charged by policy makers in the future in contrast to focus on CO_2 emissions only.

Future research will address environmental benefits in terms of temperature change by changing flight level operations in a fixed transportation network. Related activities within the DLR, e.g. the Project *"CATS – Climate Compatible Air Transportation System"* [12], focuses on the assessment of the operational and technological options to reduce the climate impact of air transportation.

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