AN INTEGRATED MODELLING APPROACH FOR CLIMATE IMPACT ASSESSMENTS IN THE FUTURE AIR TRANSPORTATION SYSTEM – FINDINGS FROM THE WECARE PROJECT

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Abstract. In order to assess the climate impact of technological and operational measures which are introduced to the future air transportation system, the future evolution of the air transportation system must be modelled and analyzed. Within the DLR-project WeCare a modular assessment framework is implemented, which accompanies a 4-layer philosophy for a generic build-up of the passenger air traffic system of the future (Part 1). The four layers consist of the origin-destination passenger demand network, the passenger routes network, the aircraft movements network, and the trajectories network. Due to the global network layer modelling architecture on city pair level, information like how many passengers will travel between certain city-pairs, the (future) routes chosen by the passengers as well as how many aircraft and which size of aircraft will be operated on each route can be provided. Finally, information about the amount, locus and time of emissions can be computed and transferred to climate models for calculating the climate impact. In WeCare, also mitigation strategies by optimizing trajectories are designed and evaluated (Part 2). Mitigation potentials of these less climate-harming trajectories need to be applied on Air Transportation System (ATS) quantity structures and timing to assess cumulative climate impact savable over time.

Keywords: air transportation system, climate impact assessment, evaluation of climate mitigation strategies, scenarios, forecasting, emission inventories

PART 1: SCENARIOS, THE GENERIC BUILD-UP OF THE FUTURE ATS & CLIMATE IMPACT ASSESSMENT

Since the climate impact of aviation highly depends on the amount, species, altitude and latitude of emissions (Koch, 2011) (IPCC, 2013), pure passenger aircraft fleet models with no geo-spatial dimension are not sufficient to assess the global climate impact of aviation. Instead, the spatial distribution of flights is relevant to assess the climate impact of the ATS and the evaluation of potential mitigation strategies and revolutionary new concepts (technological and operational).

A basic research goal of DLR Air Transportation Systems is to explore future evolutions of the global civil ATS. Understanding and modelling the ATS in a comprehensive way is a prerequisite of developing "decision scenarios" (Wack, 1985). To estimate the future realized air passenger demand (APD) on city pair level, not only the assumptions on external socio-economic conditions (e.g. gross domestic product (GDP), population, GDP per capita, …) are relevant. Likewise, the *internal* scenario concerning the ATS, e.g. how the ATS is changing over time with the introduction of new technologies or new operational concepts has a non-neglectable feedback on realized demand. Realized demand is for example a function of airfares which in turn are depended on cost structures. Cost structures might be changed with the introduction of new technologies and operational measures and thus will have an impact on realized demand.

The ATS is abstracted in four main layers to enable a simulation of alterations in any layer. Network-stakeholder-interactions differ layer by layer. Quantitative decision scenarios may be developed by manipulating systematically and pointedly specific scenario factors and parameters within the model environment according to a well-designed scenario narrative. (Schwartz, 2012) A major focus needs to be the fusion of global ATS network forecasting on city pair level, a fleet renewal model and the discipline of aircraft design to enhance the overall quantitative scenario capability on ATS level. (Ghosh et al., 2015b)

THE 4-LAYER PHILOSOPHY AND THE WECARE PROJECT

The DLR-project WeCare made a big progress towards developing and implementing the idea of modelling the future ATS on a network basis. The WeCare project is about assessing climate mitigating effects of operational and technological changes which are also investigated in the context of the future ATS on a global scale with a time horizon until 2050. Therefore, at first, a generic model forecasting future air traffic on network and fleet basis is required. This is implemented in the model chain called AIRCAST (air travel forecast) based on the 4-layer philosophy (Figure 1).

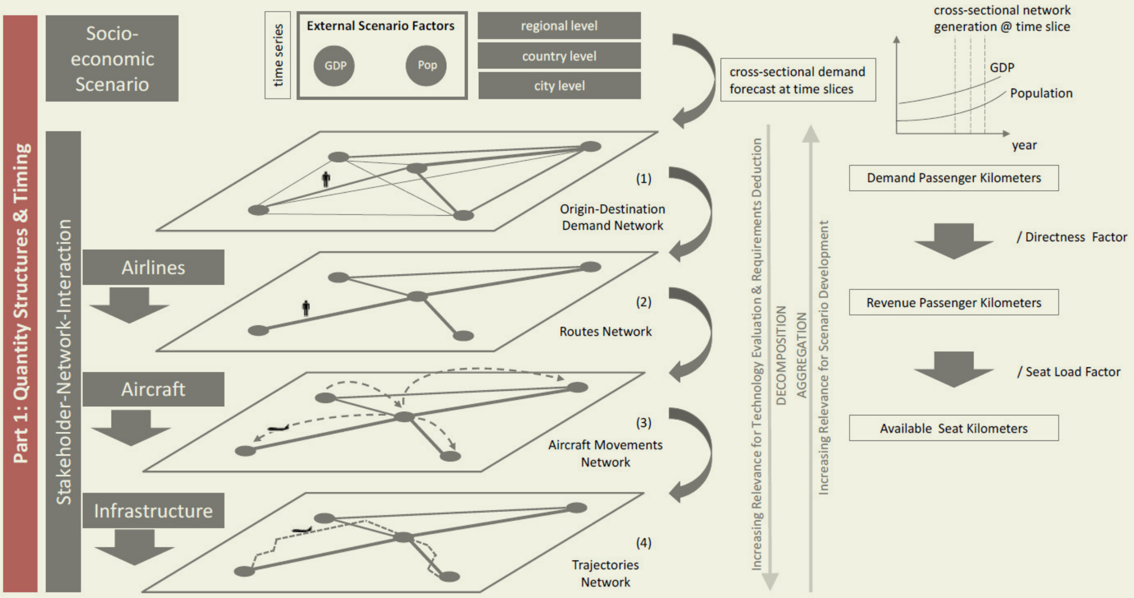

Figure 1. Generic build-up of the future ATS in 4 layers (Ghosh et al. 2015a)

AIRCAST focuses on the structural evolution of global air passenger and aircraft networks abstracted in four main layers. The four layers (see Figure 1) consist of (1) the origin-destination passenger demand network, (2) the passenger routes network, (3) the aircraft movements (ACM) network, and (4) the trajectories network. Each lower layer is derived from the above layer. AIRCAST is used for climate impact assessment and strategy development within the WeCare project. Next, we describe the single layers and the initial starting point of socio-economic scenarios.

EXOGENOUS SOCIO-ECONOMIC SCENARIOS

AIRCAST initializes ATS-networks directly from exogenous socio-economic scenarios. It is designed and planned to use the forecast published by Jorgen Randers "2052" (Randers, 2012) and the five scenarios of the International Futures Global Modeling System (IFs) (Hughes et al., 2006) likewise. In WeCare, the complete run of the modules and experimentation was based on the Randers scenario as a use case. For the time being, it is an alternative aviation scenario which considers worldwide saturation effects of economic growth.

DEMAND NETWORK

Global demand networks are calculated in a two-step approach: (1) topology forecast and (2) forecast of the number of passengers on an edge of the graph. (Terekhov et al., 2015a) (Terekhov et al., 2015b) Elasticities of GDP and airfare on realized air passenger demand are globally analyzed using *Sabre Airport Data Intelligence* (ADI) and *World Bank* data. These are important links between changes of economic wealth (via GDP) and changes through energy cost development and environmental policy measures (via cost and airfare) to demand prediction.

Routes Network

The passenger routes for each demand connection defined in the previous layer are modelled in four steps (Ghosh et al., 2015b):

- Defining plausible passenger routes considering the main transit hubs worldwide and maximum detour factors
- Calculating route probabilities from historical data based on segment probabilities to account for new demand connections
- Allocating the predicted amount of passengers on a demand connection to passenger routes according to the computed probabilities
- Aggregating passengers on the same segment worldwide to get a segment passenger network

The routes network consists of two sublayers: (1) the passenger route network and (2) the passenger segment network. A passenger route from true origin to true destination from a passenger perspective consists of a sequence of flight segments via transfer airports.

AIRCRAFT MOVEMENTS NETWORK

The deduction of aircraft movements is based on the passenger segment network from the previous layer. The frequency-capacity-model FoAM (Forecast of Aircraft Movements) (Kölker et al., 2014) is used to compute aircraft movements on each flight segment worldwide distinguished by seat categories. In a subsequent step, this output is linked to fleet renewal modelling to incorporate the scenario capability of introducing new aircraft concepts into the world fleet. This way, we account for the inertia of the system and transition in technology when creating scenarios as ATS-network evolutions. The aircraft movements network consists of two sublayers: (1) the aircraft movements network by seat categories and (2) the aircraft movements network by aircraft type and aircraft generation.

EMISSION INVENTORIES & TRAJECTORIES NETWORK

The final step in the chain constitutes a simulation of trajectories based on the aircraft movements obtained from the Aircraft Movements Network layer using the Global Air Traffic Emissions Distribution Laboratory (GRIDLAB) developed by DLR. (Linke, 2016) Each mission defined by departure and arrival cities, aircraft type and load factor is simulated under typical operational conditions or by applying new operational strategies, resulting in a network of flight trajectories. For this purpose, DLR's Trajectory Calculation Module (TCM) (Lührs et al., 2014) and Trajectory Optimization Module (TOM) (Lührs et al., 2016) apply simplified equations of motion known as the Total Energy Model in combination with the Base of Aircraft Data (BADA) version 4.1 aircraft performance models by EUROCONTROL (Mouillet, 2013). Based on the aircraft's engine state (e.g. thrust, fuel flow) the engine emission distribution of NO_x, CO and HC species along the trajectory is determined applying the Boeing Fuel Flow Method 2. (DuBois et al., 2006) The amount of CO_2 and H_2O is calculated assuming a linear relationship to the fuel burn. The emission distributions of all flights are mapped into a geographical grid resulting in 3D inventories. These are the essential input for the climate impact assessment tool AirClim (Dahlmann et al., 2016), which determines concentration changes of different radiative forcing agents (CO_2, H_2O, O_3) as well as aviation-induced cloudiness. Based on that, various climate metrics for the given emission scenario can be calculated. This is essential to assess the introduction of new aircraft concepts and operational measures and to simulate the climate impact of a heterogeneous fleet and its evolution over time.

The Trajectories Network can also be used as a basis for models which need that information of energy consumption and flight time on a city pair network level discriminated by aircraft type (specific and generic ones) and aircraft generation (N, N+1, N+2, …) for future time slices, i.e. future scenarios of ATS network evolutions (see Figure 2).

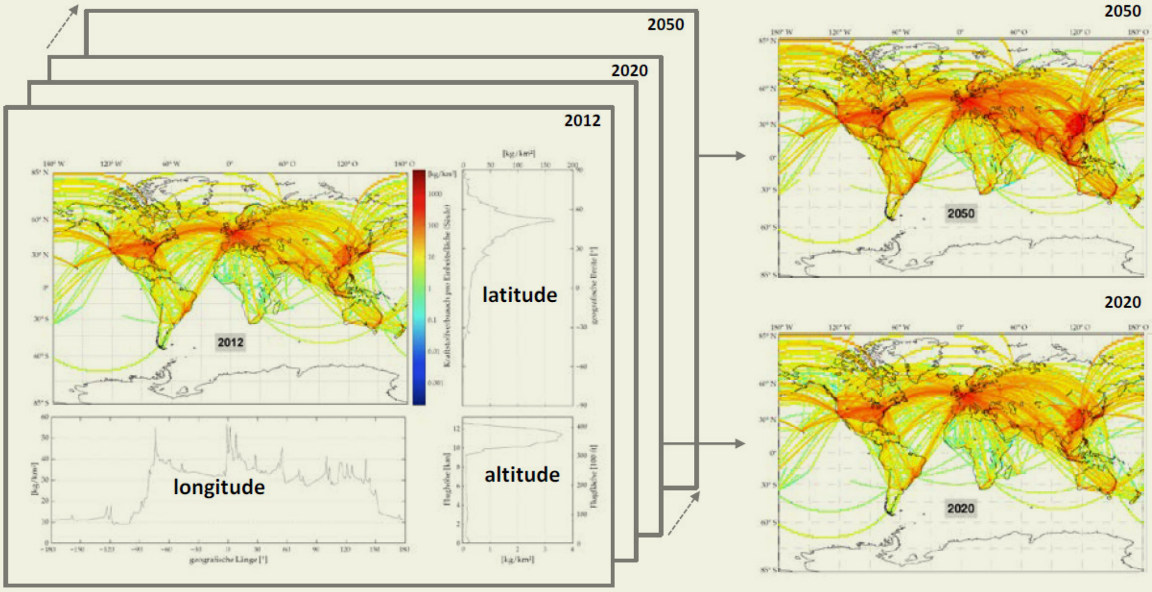

Figure 2. Final result for climate impact assessment as a global scenario capability: spatial distributions of fuel burn and respective 3D emission inventories for future time steps until 2050 according to global developments of the ATS (passenger flows and aircraft movements)

PART 2: FROM POTENTIALS TO SCENARIOS

In other work packages of WeCare various mitigation strategies by optimizing trajectories tactically or strategically have been designed and/or evaluated, e.g. the mitigation potentials of climate-optimized trajectories (Lührs et al., 2016) (see Figure 3) and climate-restricted airspaces (Niklaß et al., 2016).

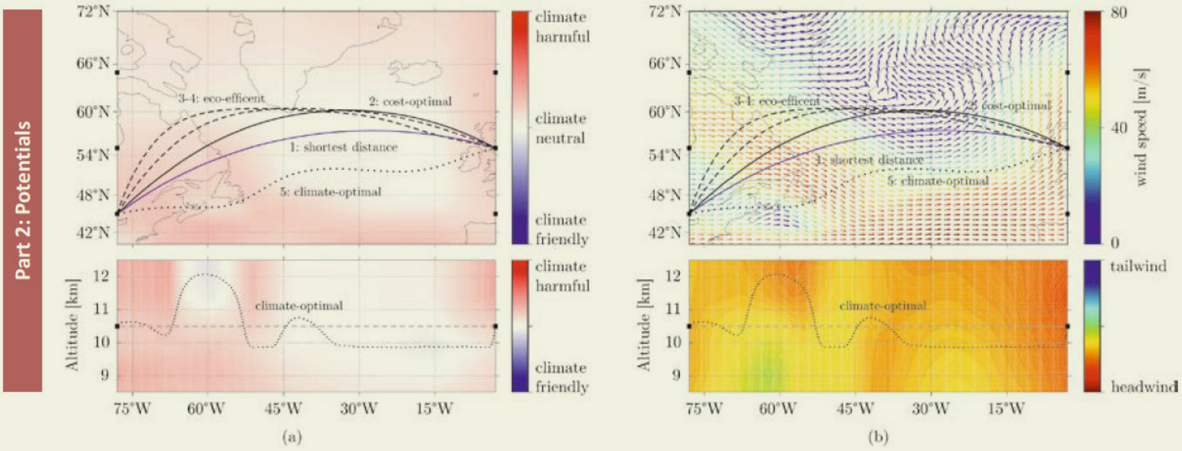

Figure 3. Trajectory optimization: comparison of shortest distance (1), cost-optimal (2), eco-efficient (3-4) and climate-optimal trajectories (5) plotted in (a) total climate change functions and (b) respective wind speeds and directions (Lührs et al., 2016)

Identified potentials of technological and operational mitigation strategies need therefore in a next step to be incorporated into larger scope systems analyses. This can be done with a system like the AIRCAST environment. AIRCAST provides absolute amounts of aircraft movements over time on which a mitigation potential of a specific concept or a set of concepts may be applied with certain times of introduction in the future. Only that way, the *cumulative* climate impact saved compared to a business-as-usual scenario may be quantified and put into perspective to global climate goals.

CONCLUSION

The starting points of modelling the future air transportation system in AIRCAST are exogenous socio-economic scenarios. From those, we develop scenarios of network evolutions. In a first iteration all networks (4 layers) in predefined time steps (in WeCare every five years) until the time horizon are forecasted without applying any future alteration to the system. After that, a scenario of the introduction of new aircraft programs over all seat categories and the introduction of operational measures that should be evaluated needs to be defined until 2050 with all relevant assumptions concerning alterations of cost of operation and quality of travel (Kölker et al., 2015). Especially modelling the feedback of such changes from the supply side of the ATS on the forecast of realized demand and the iterative calculation of all networks is expected to give valuable quantitative insights in the connection between intentional alterations, e.g. to achieve climate targets, and unintended feedbacks of those decisions on the evolution of networks. Modelling future global network evolutions is a means to quantify future shifts in portions of deployed seat categories, shifts of distances flown by seat categories and the geographical shift of aircraft movements induced through heterogeneous air traffic growth by world regions. The scientific value added originates from the consistent modelling of future global ATS networks on city pair level throughout all layers – being global and local at the same time.

Design of mitigation strategies and analyses of their mitigation potentials (Part 2, Figure 3) need to be coupled with modelling of quantity structures and timing of ATS dimensions (Part 1, Figure 1) in order to estimate the absolute cumulative climate impact savable over time.

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