DLR student presentations

Introduction to project WeCare

Florian Linke

NASA/DLR Virtual Institute Event

August 21, 2014

IFAR | INTERNATIONAL FORUM FOR AVIATION RESEARCH

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Project WeCare
Overview

Key objectives
- Study of relationships between non-CO2 effects and meteorological processes to realize an eco-efficient air traffic system.
- Understanding the differences between strategic and tactical climate mitigation options

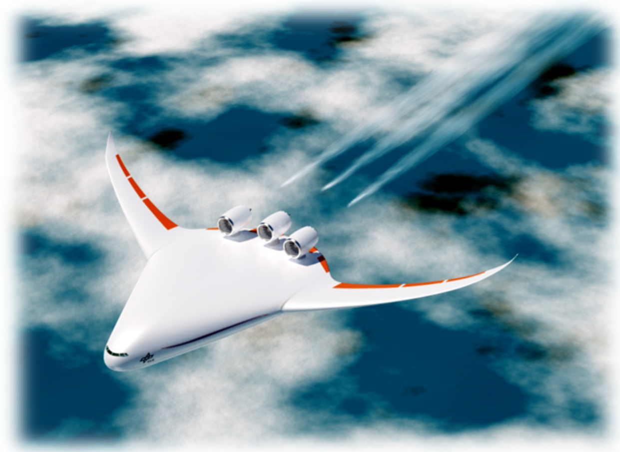
Research
1. Quantification of the climate impact reduction potential of weather-based climate-optimized aircraft operations (-> trajectory optimization)
2. Cost-benefit-analysis of different operational and technological strategies to reduce the climate impact of the global air traffic, today and in the future (-> scenario-based air traffic simulation)
3. Development of new strategies for measuring the influence of air traffic on the atmosphere and experimental proof of certain effects (-> atmospheric physics)

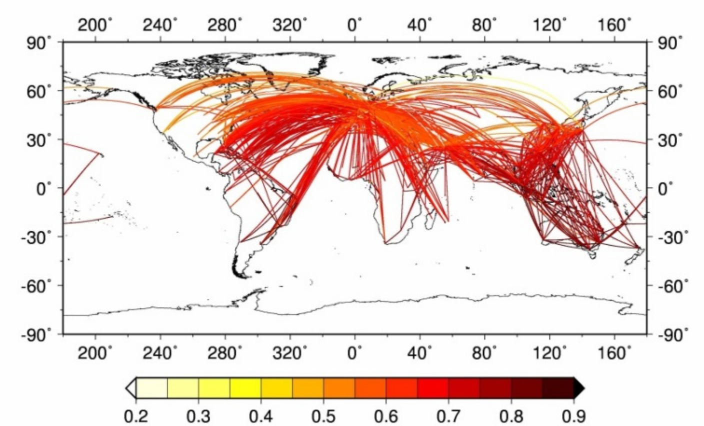
Project WeCare

Future Air Transportation System

Cost-benefit-analysis of different operational and technological strategies to reduce the climate impact of the global air traffic, today and in the future, therefore

- Scenario based description of the global future air transportation system
- Modelling of worldwide demand, flight routes, fleet mix and aircraft operations
- Integration of unconventional aircraft configurations
- Definition of innovative operational strategies
- Performing air traffic simulations considering adapted operations and/or new aircraft types

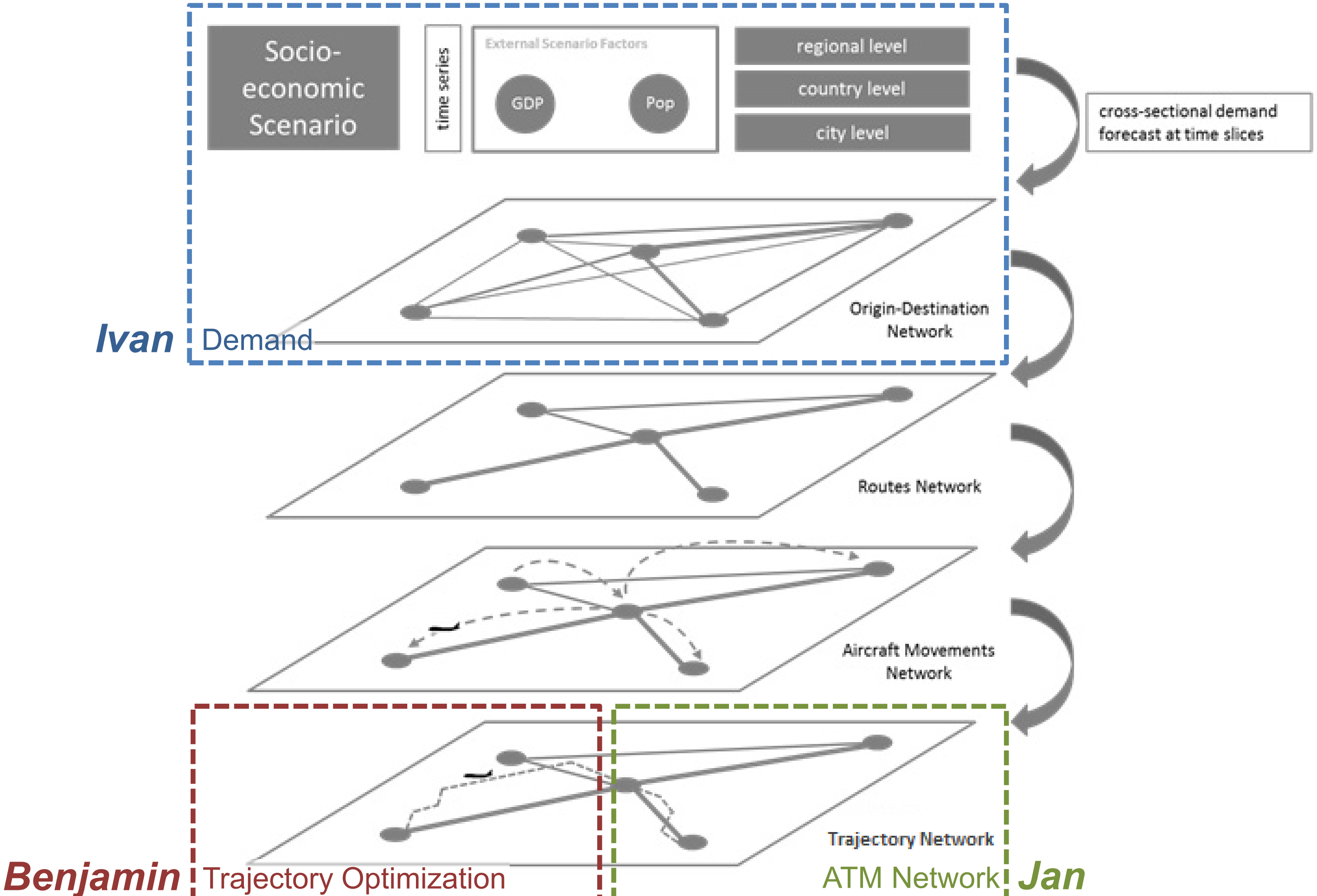




Dahlmann, 2012

Project WeCare

4 layers approach



Ghosh et al, 2014

Forecast of origin-destination air passenger demand between global city pairs using future socio-economic development scenarios

Ivan Terekhov

NASA/DLR Virtual Institute Event

August 21, 2014

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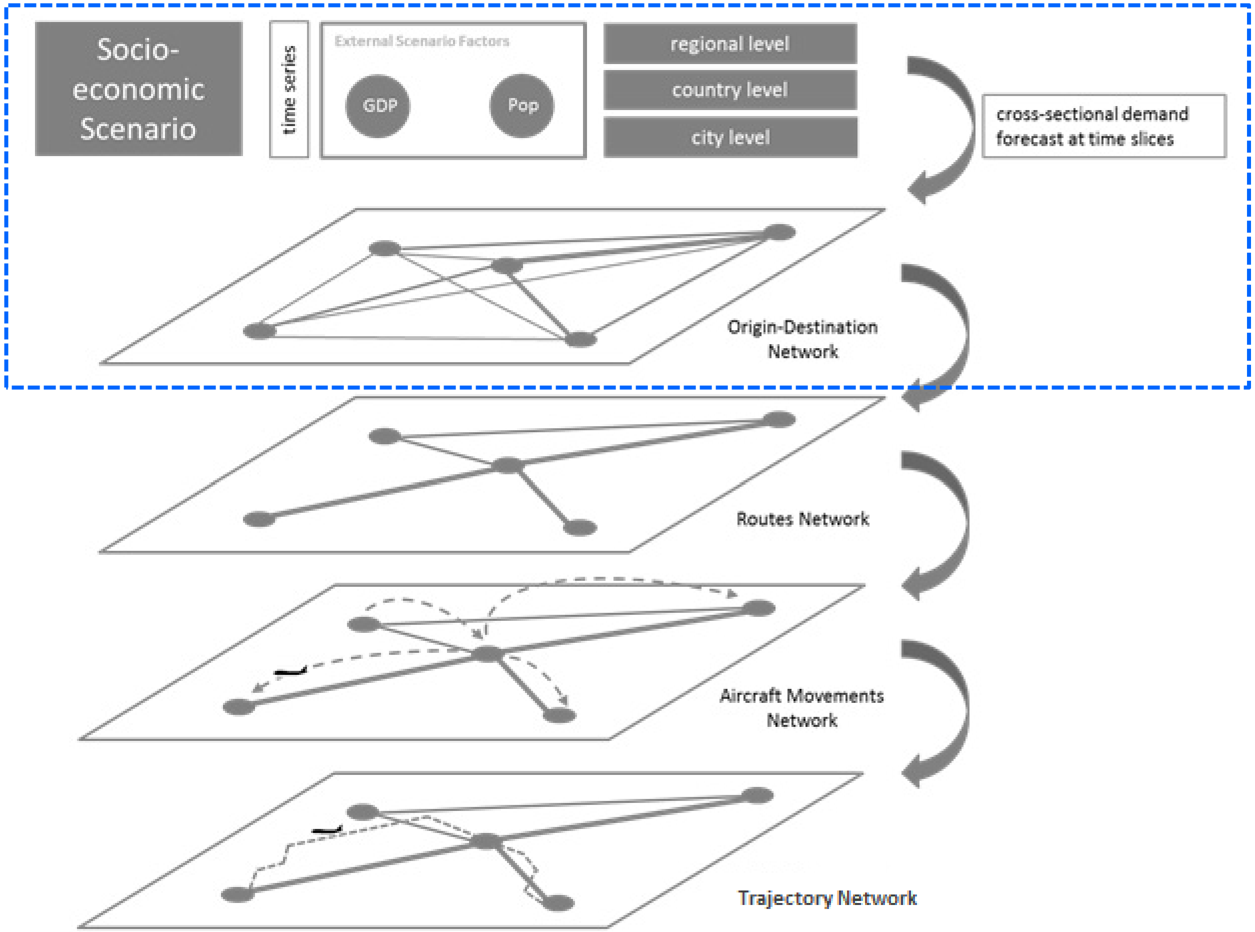
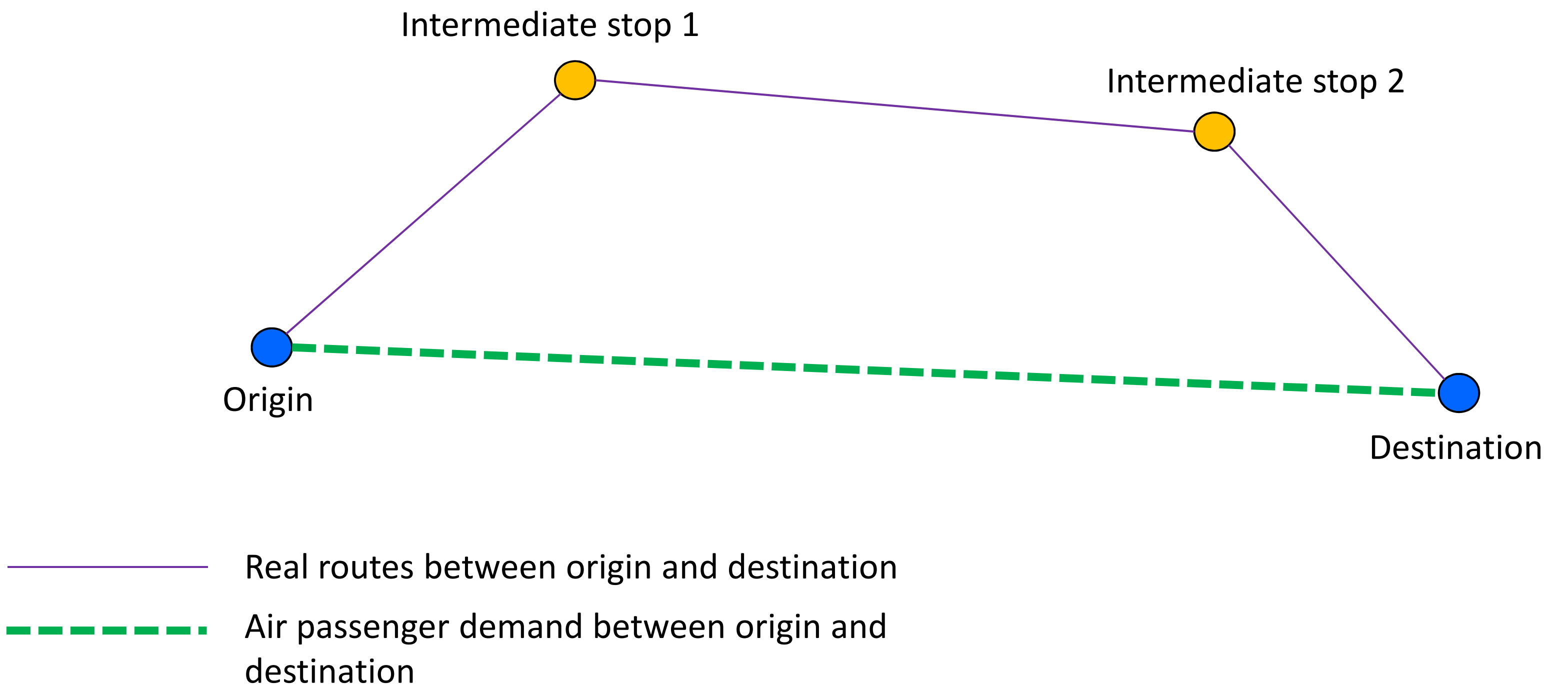
WeCare. 4 layers approach



R.Ghosh et al, 2014

Air passenger demand

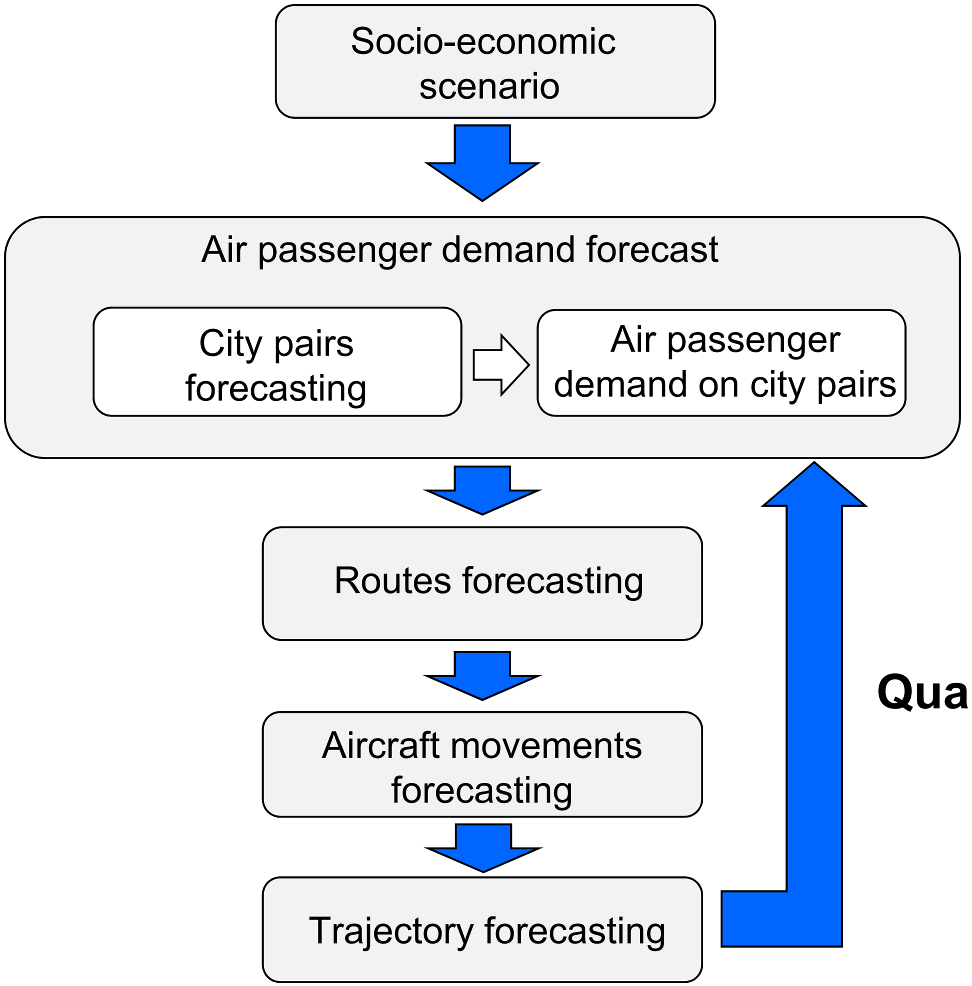
- Air passenger demand is a number of passengers which are traveling between two settlements by air transport regardless of intermediate stops within a year.



Air passenger demand forecast

Aggregation level	*city level*
Number of elements	*as many as possible*
Choosing criteria for elements	*at least one airport*
What is forecasted	*number of passengers, changes in city pairs connections*
Forecasting method:	*Quantitative analogies (passengers), Gravity model (connections)*

Air passenger demand forecast. The method



Quality Travel Index (QTI)

Quality Travel Index (QTI)

$QTI = (QTI_f , QTI_{tt} , QTI_s)$

QTI_f – frequency (frequency↑, QTI_f↑)

QTI_{tt} - travel time (tt↓, QTI_{tt}↑)

QTI_s – segments (segments ↓, QTI_s↑)

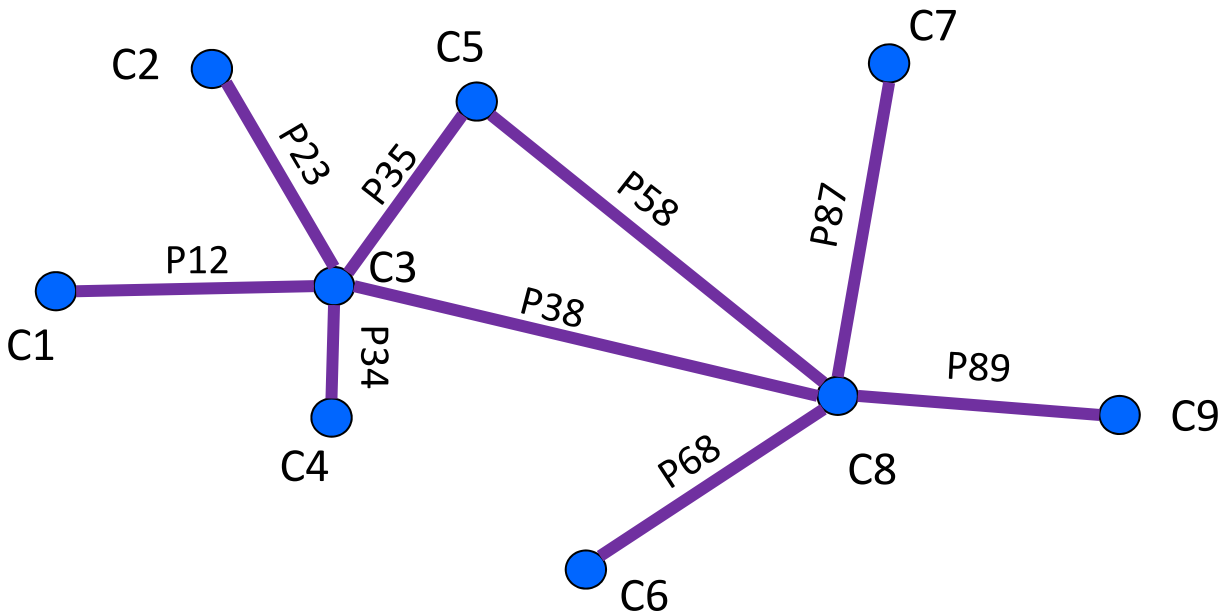
Air passenger demand forecast. The method

- **City pairs definition**

  Gravity model based on cities' socio-economic indicators (GDP, population, airfare)

- **Air passenger demand on city pairs definition**

  Quantitative analogies between forecasted year and the base year

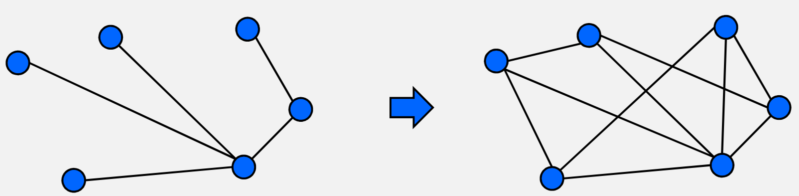


Expected results

Socio-economic scenario

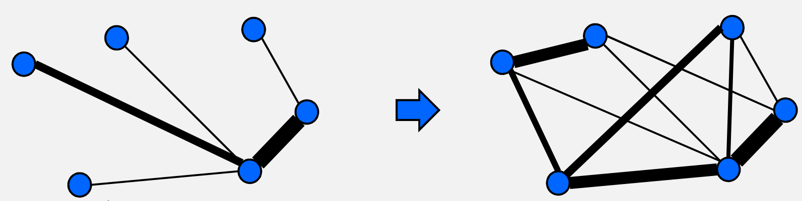
Air passenger demand forecast

Forecast of air passenger demand network within the forecast period



1st year of forecast — Last year of forecast

Forecast of air passenger demand on city-pairs within the forecast period



1st year of forecast — Last year of forecast

Routes forecasting

Quality Travel Index

Current results

What has been done:

- For 2012, data has been collected on the demand and airfare of airport pairs from ADI database;
- 2012 data has been rearranged from the airport to city level;
- Geographical coordinates, city GDP and city population have been found for cities in the database ;
- Clusterization of the cities in 2012 database has been made;
- Gravities between cities for the 2012 base year have been calculated in order to calculate reference gravities for each cluster pair;
- Based on forecast, gravities between cities for years 2015-2050 (5 years step) have been calculated;

Current results. Base year 2012

Origin ADI data (airport level)

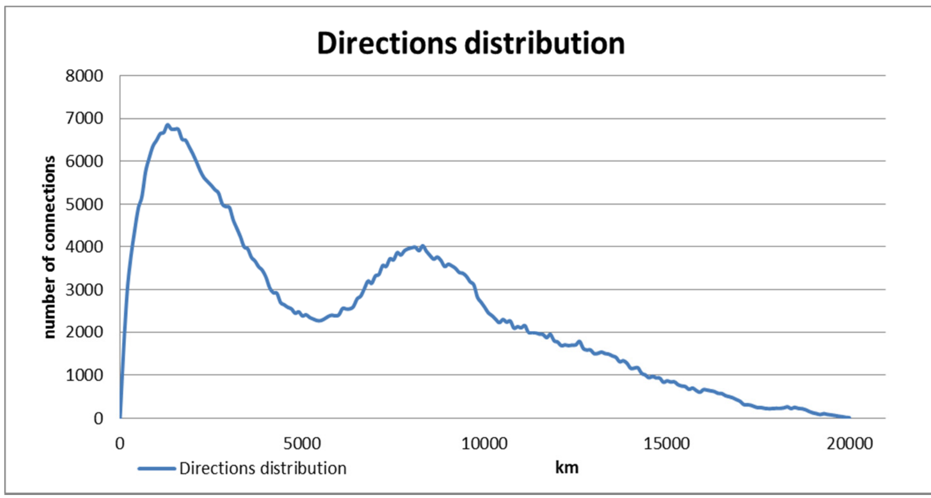
Connections: **759 816**
Passengers: **2 602 804 691**
IATA codes: **6435**

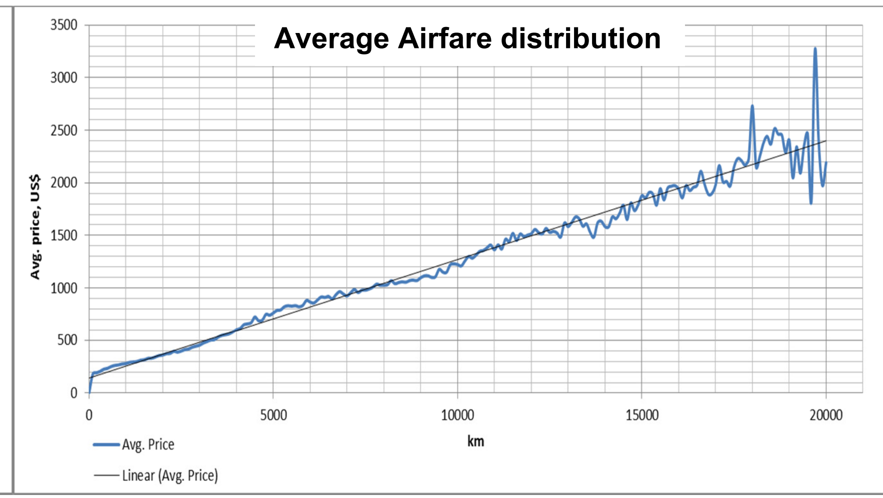
Rearrangement

Connections: **-31,77%**
Passengers: **-2,29%**
IATA codes: **-2,88%**

Rearranged ADI data (city level)

Connections: **518 396**
Passengers: **2 543 211 982**
IATA codes: **4319**





Thank you!

Flight Trajectory Optimization

Considering wind and penalty areas

Benjamin Lührs

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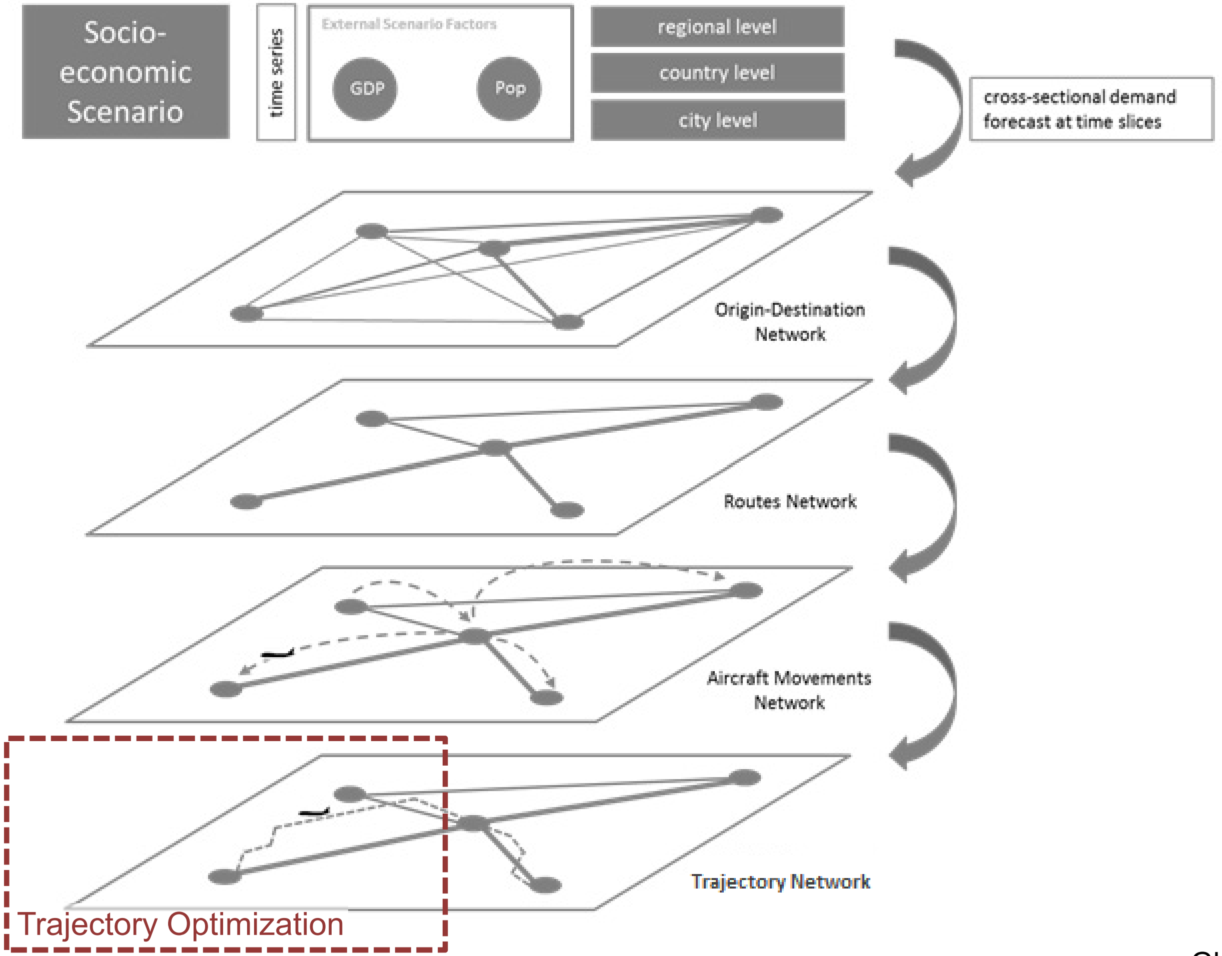
Project WeCare
4 layers approach



Ghosh et al, 2014

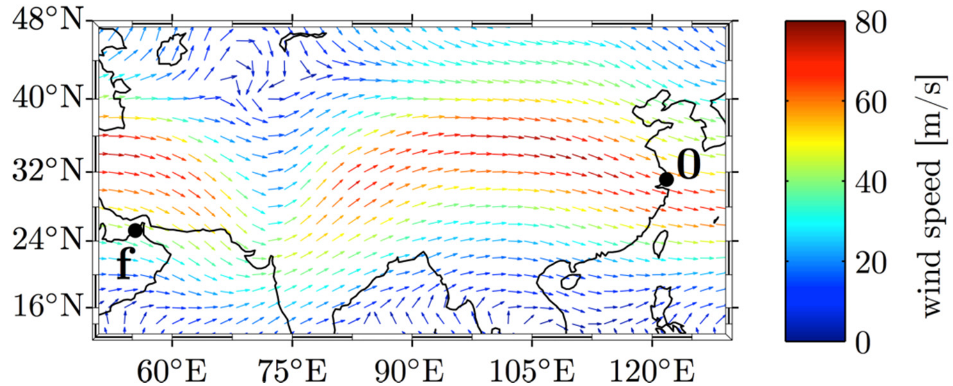
Contents

1. Algorithm
2. Climate optimized trajectories
3. Current work

Definition of the optimization problem

Assumptions

- massless point
- v_{TAS} = const
- H = const or H_p = const
- H << R_E
- flight path angle $\gamma \approx 0$
- stationary windfield
- flight direction controlled by heading angle χ_H

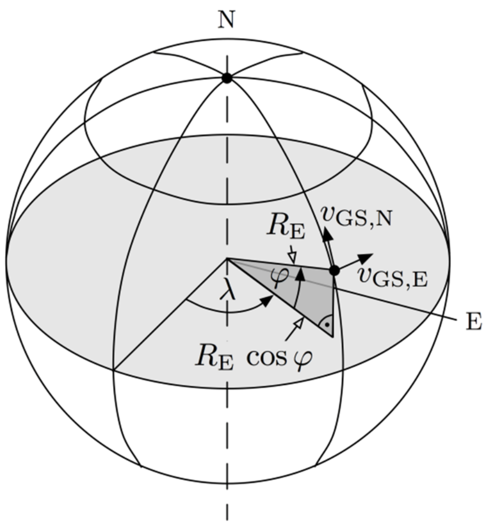


Equations of motion

$$v_{GS,E} = v_{TAS} \sin\chi_H + u_W(\lambda,\varphi)$$
$$v_{GS,N} = v_{TAS} \cos\chi_H + v_W(\lambda,\varphi)$$

$$\dot{\lambda} = \frac{v_{GS,E}}{R_E \cos\varphi} = \frac{v_{TAS} \sin\chi_H + u_W(\lambda,\varphi)}{R_E \cos\varphi}$$

$$\dot{\varphi} = \frac{v_{GS,N}}{R_E} = \frac{v_{TAS} \cos\chi_H + v_W(\lambda,\varphi)}{R_E}$$



Definition of the optimization problem

Optimal control problem

minimize

$$\mathcal{J} = \int_{t_0}^{t_\mathrm{f}} \left[c_t + c_\Psi \cdot \Psi(\lambda, \varphi)\right] \mathrm{d}t$$

$$= c_t \cdot \underbrace{(t_\mathrm{f} - t_0)}_{\text{flight time}} + c_\Psi \cdot \int_{t_0}^{t_\mathrm{f}} \underbrace{\Psi(\lambda, \varphi)}_{\text{penalty function}} \ \mathrm{d}t$$

subject to

$$\dot{\lambda} = \frac{v_\mathrm{GS,E}}{R_\mathrm{E}\ \cos\varphi} = \frac{v_\mathrm{TAS}\ \sin\chi_\mathrm{H} + u_\mathrm{W}(\lambda,\varphi)}{R_\mathrm{E}\ \cos\varphi}$$

$$\dot{\varphi} = \frac{v_\mathrm{GS,N}}{R_\mathrm{E}} = \frac{v_\mathrm{TAS}\ \cos\chi_\mathrm{H} + v_\mathrm{W}(\lambda,\varphi)}{R_\mathrm{E}}$$

and

$$\lambda(t_0) = \lambda_0; \quad \varphi(t_0) = \varphi_0$$
$$\lambda(t_\mathrm{f}) = \lambda_\mathrm{f}; \quad \varphi(t_\mathrm{f}) = \varphi_\mathrm{f}$$

Minimum Principle

(Pontryagin et al., 1967)

Two point boundary value problem

system of 3 differential equations

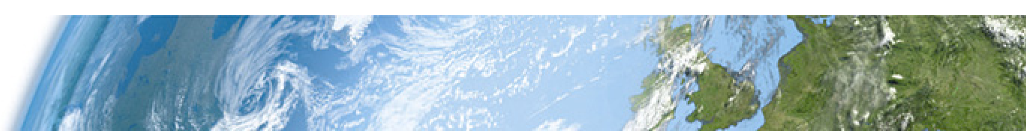
(1)
$$\begin{aligned}\dot{\chi}_\mathrm{H} = {} & \frac{\partial u_\mathrm{W}}{\partial\varphi}\cdot\frac{\sin^2\chi_\mathrm{H}}{R_\mathrm{E}} - \frac{\partial v_\mathrm{W}}{\partial\lambda}\cdot\frac{\cos^2\chi_\mathrm{H}}{R_\mathrm{E}\ \cos\varphi} + \dots \\ & + \left(\frac{\partial v_\mathrm{W}}{\partial\varphi} - \frac{\partial u_\mathrm{W}}{\partial\lambda}\cdot\frac{1}{\cos\varphi}\right)\cdot\frac{\sin\chi_\mathrm{H}\ \cos\chi_\mathrm{H}}{R_\mathrm{E}} + \dots \\ & + \frac{\tan\varphi\ \sin\chi_\mathrm{H}}{R_\mathrm{E}}\cdot\left(v_\mathrm{TAS} + u_\mathrm{W}\ \sin\chi_\mathrm{H} + v_\mathrm{W}\ \cos\chi_\mathrm{H}\right) + \dots \\ & + c_\Psi\left(\frac{\partial\Psi}{\partial\lambda}\cdot\frac{\cos\chi_\mathrm{H}}{\cos\varphi} - \frac{\partial\Psi}{\partial\varphi}\cdot\sin\chi_\mathrm{H}\right)\cdot\dots \\ & \cdot\frac{v_\mathrm{TAS} + u_\mathrm{W}\ \sin\chi_\mathrm{H} + v_\mathrm{W}\ \cos\chi_\mathrm{H}}{R_\mathrm{E}\cdot(c_t + c_\Psi\cdot\Psi)}\end{aligned}$$

(2)
$$\dot{\lambda} = \frac{v_\mathrm{GS,E}}{R_\mathrm{E}\ \cos\varphi} = \frac{v_\mathrm{TAS}\ \sin\chi_\mathrm{H} + u_\mathrm{W}(\lambda,\varphi)}{R_\mathrm{E}\ \cos\varphi}$$

(3)
$$\dot{\varphi} = \frac{v_\mathrm{GS,N}}{R_\mathrm{E}} = \frac{v_\mathrm{TAS}\ \cos\chi_\mathrm{H} + v_\mathrm{W}(\lambda,\varphi)}{R_\mathrm{E}}$$

boundary values

$$\lambda(t_0) = \lambda_0; \quad \varphi(t_0) = \varphi_0$$
$$\lambda(t_\mathrm{f}) = \lambda_\mathrm{f}; \quad \varphi(t_\mathrm{f}) = \varphi_\mathrm{f}$$



Solving the two point boundary value problem

Two point boundary value problem

system of 3 differential equations

$$
\begin{aligned}
(1)\quad \dot{\chi}_{\mathrm{H}} = {} & \frac{\partial u_{\mathrm{W}}}{\partial \varphi} \cdot \frac{\sin^2 \chi_{\mathrm{H}}}{R_{\mathrm{E}}} - \frac{\partial v_{\mathrm{W}}}{\partial \lambda} \cdot \frac{\cos^2 \chi_{\mathrm{H}}}{R_{\mathrm{E}} \cos \varphi} + \dots \\
& + \left(\frac{\partial v_{\mathrm{W}}}{\partial \varphi} - \frac{\partial u_{\mathrm{W}}}{\partial \lambda} \cdot \frac{1}{\cos \varphi} \right) \cdot \frac{\sin \chi_{\mathrm{H}} \cos \chi_{\mathrm{H}}}{R_{\mathrm{E}}} + \dots \\
& + \frac{\tan \varphi \sin \chi_{\mathrm{H}}}{R_{\mathrm{E}}} \cdot (v_{\mathrm{TAS}} + u_{\mathrm{W}} \sin \chi_{\mathrm{H}} + v_{\mathrm{W}} \cos \chi_{\mathrm{H}}) + \dots \\
& + c_{\Psi} \left(\frac{\partial \Psi}{\partial \lambda} \cdot \frac{\cos \chi_{\mathrm{H}}}{\cos \varphi} - \frac{\partial \Psi}{\partial \varphi} \cdot \sin \chi_{\mathrm{H}} \right) \cdot \dots \\
& \cdot \frac{v_{\mathrm{TAS}} + u_{\mathrm{W}} \sin \chi_{\mathrm{H}} + v_{\mathrm{W}} \cos \chi_{\mathrm{H}}}{R_{\mathrm{E}} \cdot (c_t + c_{\Psi} \cdot \Psi)}
\end{aligned}
$$

$$
(2)\quad \dot{\lambda} = \frac{v_{\mathrm{GS,E}}}{R_{\mathrm{E}} \cos \varphi} = \frac{v_{\mathrm{TAS}} \sin \chi_{\mathrm{H}} + u_{\mathrm{W}}(\lambda, \varphi)}{R_{\mathrm{E}} \cos \varphi}
$$

$$
(3)\quad \dot{\varphi} = \frac{v_{\mathrm{GS,N}}}{R_{\mathrm{E}}} = \frac{v_{\mathrm{TAS}} \cos \chi_{\mathrm{H}} + v_{\mathrm{W}}(\lambda, \varphi)}{R_{\mathrm{E}}}
$$

boundary values

$\lambda(t_0) = \lambda_0; \quad \varphi(t_0) = \varphi_0$

$\lambda(t_{\mathrm{f}}) = \lambda_{\mathrm{f}}; \quad \varphi(t_{\mathrm{f}}) = \varphi_{\mathrm{f}}$

Approach: solve a sequence of initial value problems

- Numerical integration of the system of differential equations (Dormand-Prince method)
- Choose initial values for λ and φ according to boundary values at starting point 0

► Free initial value χ_{H0} must be chosen such that boundary conditions at ending point f are satisfied

► Initial heading χ_{H0} is obtained iteratively using the shooting method

Contents

1. Algorithm
2. **Climate optimized trajectories**
3. Current work

Climate optimized trajectories

Factors that contribute to aviation induced climate change

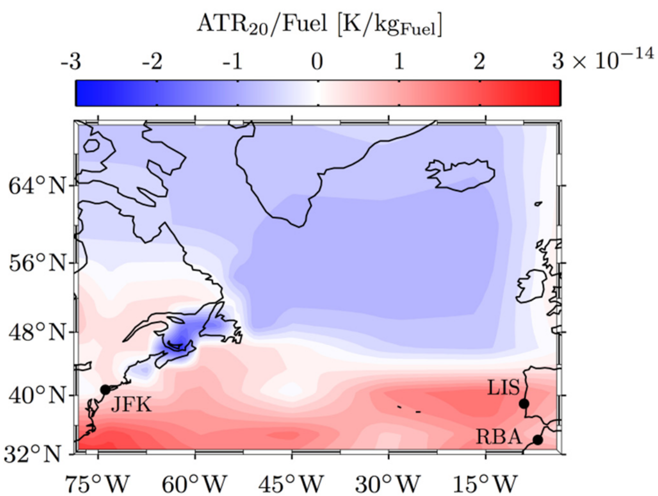
- Volume of emissions } technological/operational improvements
- Location of emissions
- Local weather

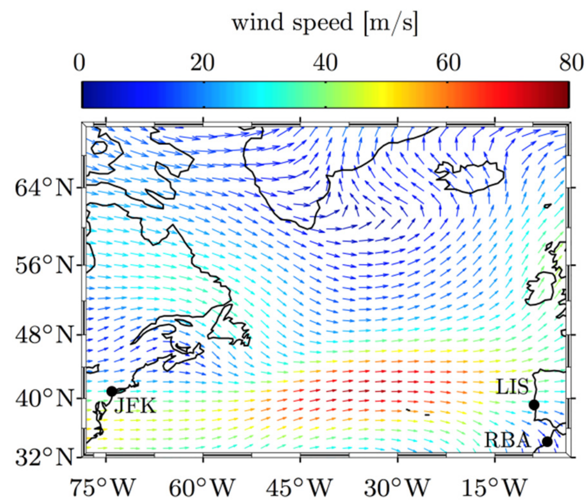
} operational strategies (i.e. avoiding climate sensitive regions)

EU-Project REACT4C (Reducing Emissions from Aviation by Changing Trajectories for the benefit of Climate)

- Identification of typical weather situations (Irvine et al., 2013)
- Determination of climate cost functions for CO_2, O_3, CH_4, H_2O, and aviation induced cirrus cloudiness (Grewe et al., 2014)

▸ Overall climate cost function (summation of all effects)





Climate optimized trajectories

Choice of the costfunction

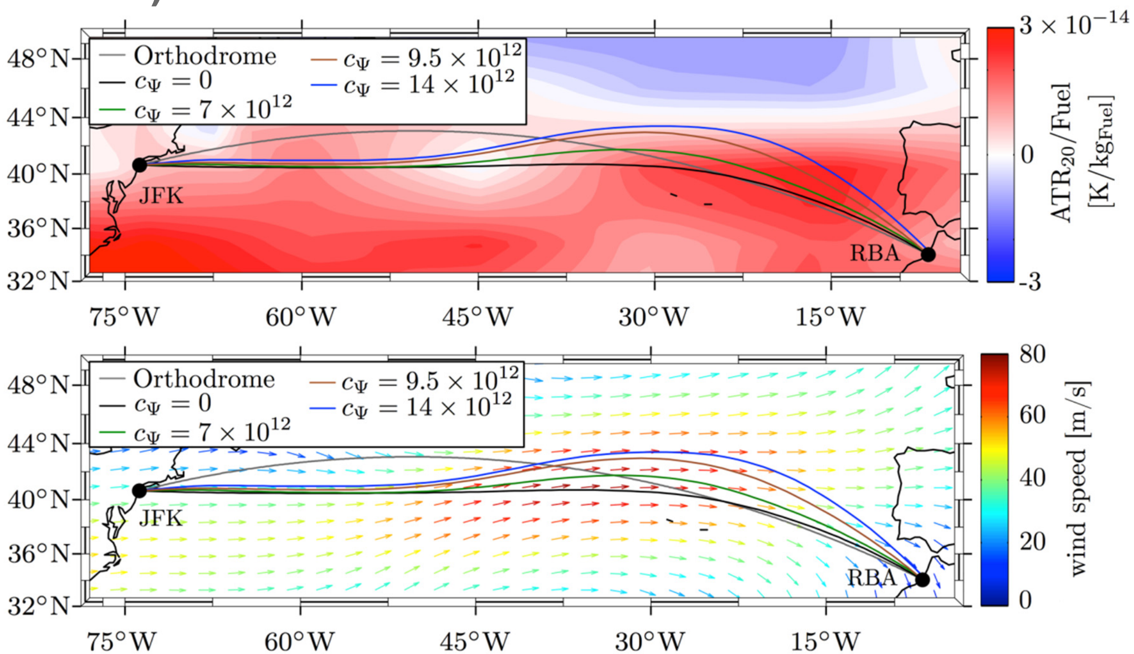
$$\mathcal{J} = \int_{t_0}^{t_\mathrm{f}} [c_t + c_\Psi \cdot \overbrace{\mathrm{FF} \cdot \mathrm{CCF}_\mathrm{tot}(\lambda, \varphi)}^{\mathrm{ATR}_{20}\text{ per time}}]\mathrm{d}t$$

$$= c_t \cdot \underbrace{(t_\mathrm{f} - t_0)}_{\text{flight time}} + c_\Psi \cdot \underbrace{\int_{t_0}^{t_\mathrm{f}} \mathrm{FF} \cdot \mathrm{CCF}_\mathrm{tot}(\lambda, \varphi)\, \mathrm{d}t}_{\mathrm{ATR}_{20}\text{ of flight}}$$

Further assumptions

- v_{TAS} = 247.85 m/s
- H_p = 11278 m
- FF = 1.51 kg/s (A330-200, based on BADA 3.9)
- c_t = 1
- $c_\Psi = 0 \dots 1.4 \cdot 10^{13}$

Results (qualitative)



Climate optimized trajectories

Choice of the costfunction

$$\mathcal{J} = \int_{t_0}^{t_\mathrm{f}} [c_t + c_\Psi \cdot \overbrace{\mathrm{FF} \cdot \mathrm{CCF}_\mathrm{tot}(\lambda, \varphi)}^{\mathrm{ATR}_{20}\text{ per time}}]\mathrm{d}t$$

$$= c_t \cdot \underbrace{(t_\mathrm{f} - t_0)}_{\text{flight time}} + c_\Psi \cdot \underbrace{\int_{t_0}^{t_\mathrm{f}} \mathrm{FF} \cdot \mathrm{CCF}_\mathrm{tot}(\lambda, \varphi)\, \mathrm{d}t}_{\mathrm{ATR}_{20}\text{ of flight}}$$

Further assumptions

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- c_t = 1
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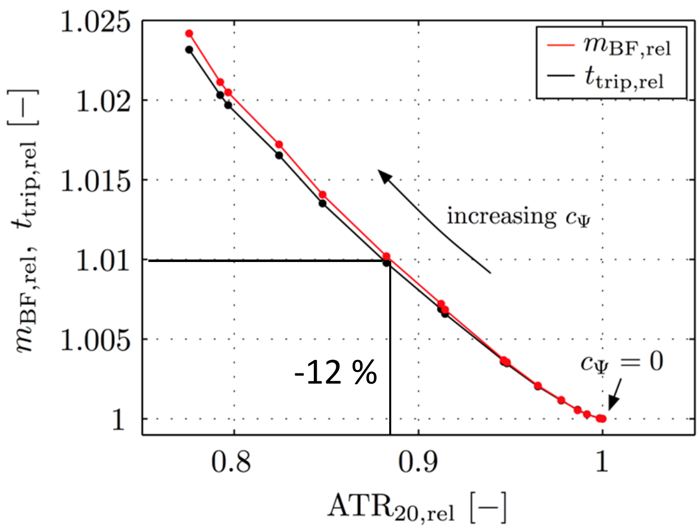
Results (quantitative)



New York - Rabat

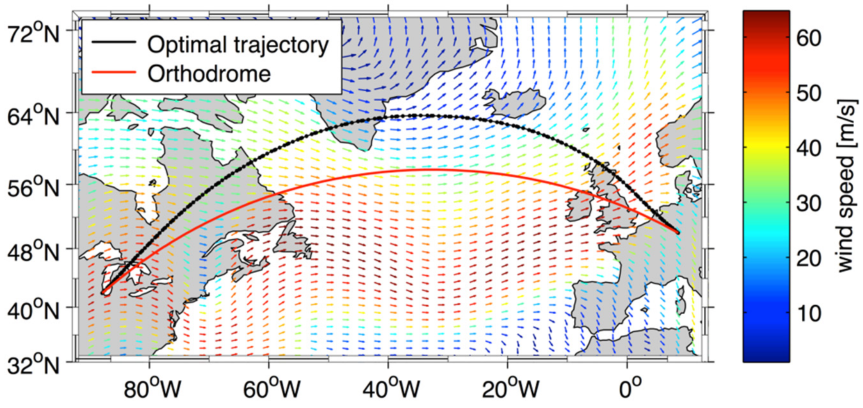
Contents

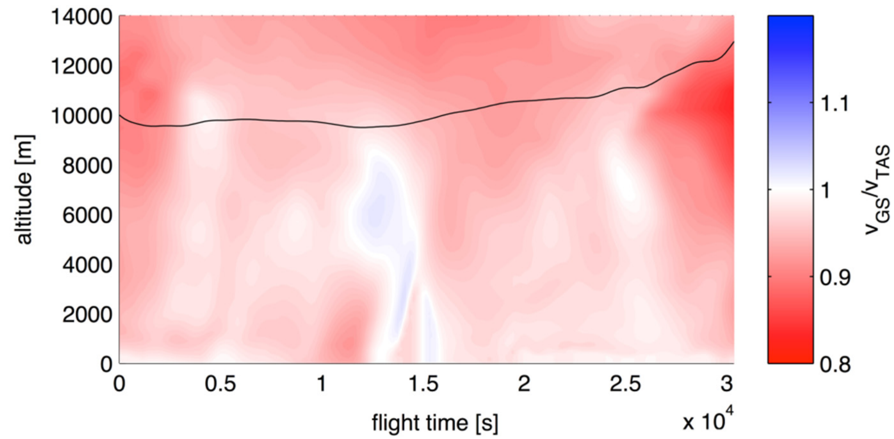
1. Algorithm
2. Climate optimized trajectories
3. Current work

Current work

Improvements

- Integration of performance calculations within the optimization loop
- Modeling of engine emissions
- Control variables: heading and thrust
- Variable altitude (3D-optimization)





Frankfurt – Chicago, minimum fuel trajectory, weather: January 1st, 2012

Thank you very much for your attention

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Application of the Column Generation Method for Large-Scale Air Traffic Flow Management scenarios

Jan Berling

NASA/DLR Virtual Institute Event

August 21, 2014

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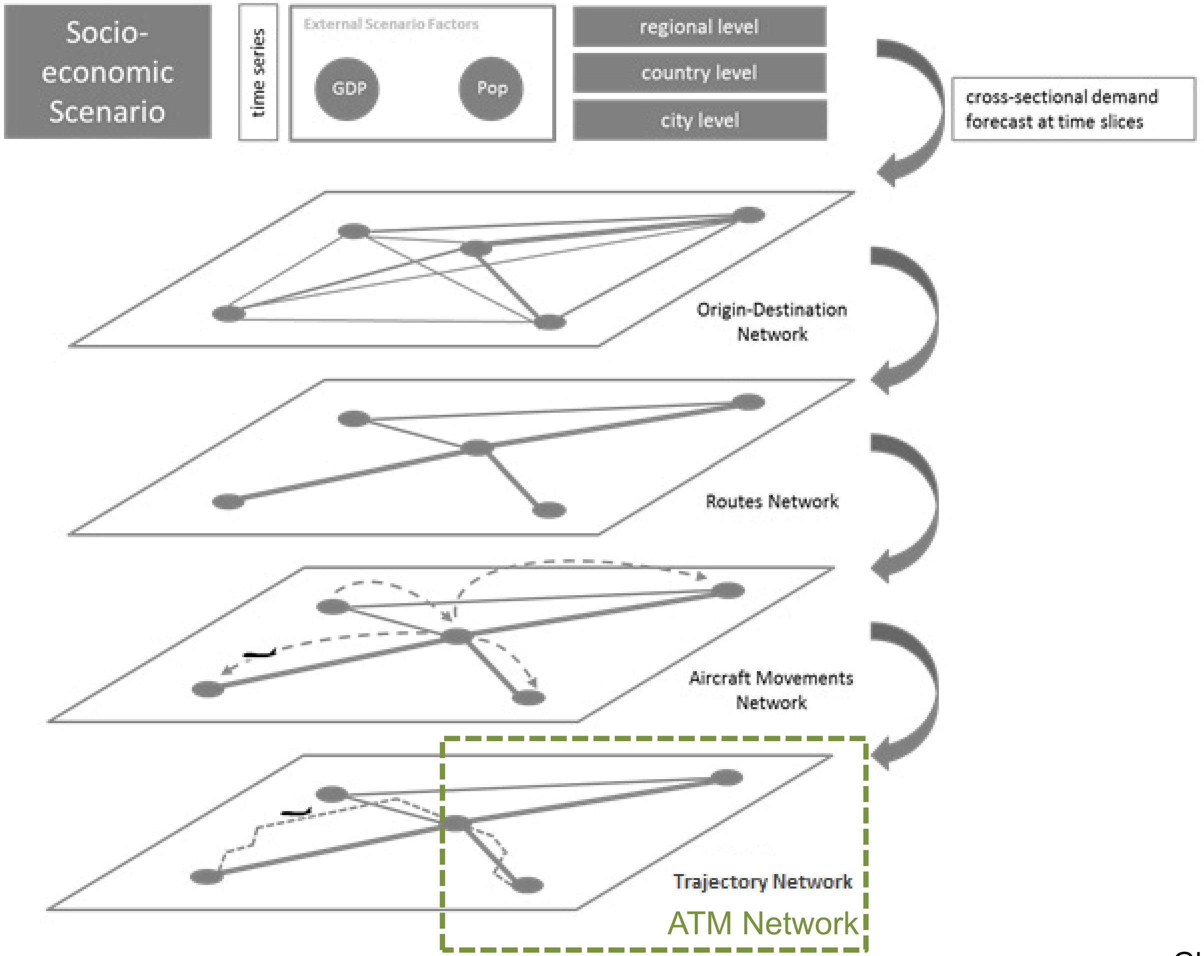
Project WeCare

4 layers approach



Ghosh et al, 2014

Agenda

1. NFE Network Flow Environment
2. Column Generation Approach
3. Exemplary Results
4. Outlook

NFE – Network Flow Environment

What is NFE?

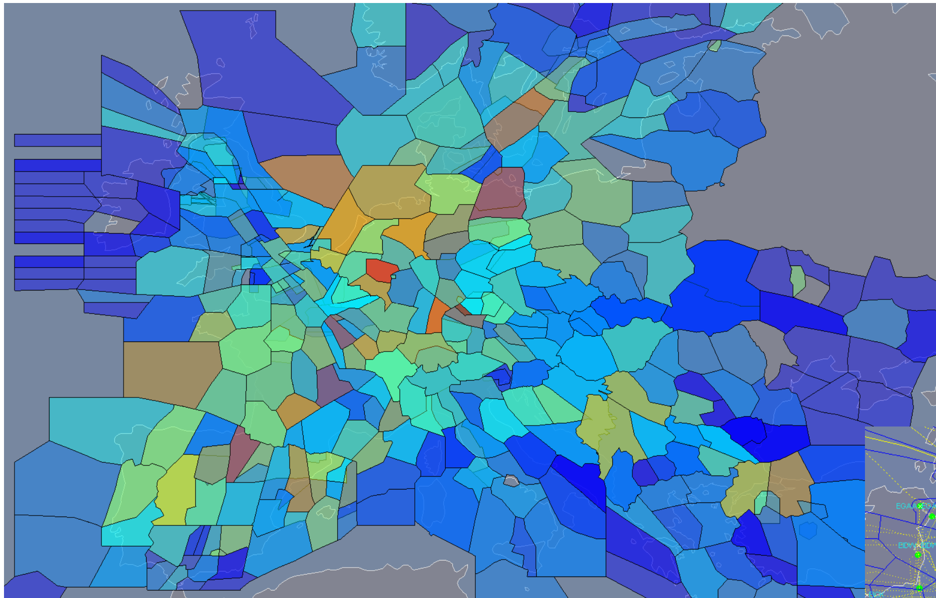
- DLR`s ***tactical*** **Network Management** model developed since 2011
  - 1 Dissertation
  - 4 Diploma theses
  - 2 Publications
- Cooperation with TU Dresden (Traffic Flow Science)
- Model for the allocation of **ATFM departure slots** and **pre-flight re-routings**
- Binary Integer Programing (BIP) optimization algorithm

How is it actually applied?

- **Air Traffic Flow Management (ATFM) delay quantification** due to adverse capacity impact and initiated regulations
- Identification of **weather forecast benefits** within a network model
- Network performance quantification

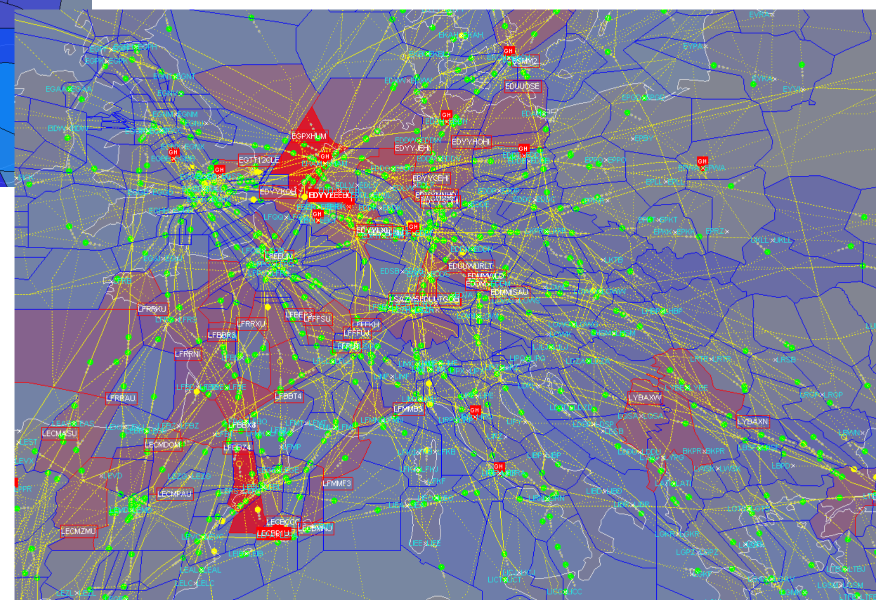
Network Flow Environment

NFE – Network Flow Environment



Air Traffic Management network

- lower and upper airspace
- sector network of ~640 Air Traffic Control (ATC) sectors
- around 20.000 airports
- underlying AIRAC cycle



Demand-Capacity-Balancing

- flight plan data from Network Manager
- network impact data, e.g. weather data
- qualitative mapping of network airport- and sector loads, network performance

Binary integer ATFM optimization problem

Cost Function

$$\min_{x} Z = \sum_{f \in F} \sum_{d \in D} \omega_{fd} x_{fd} \quad x_{fd} \in [0,1]$$

Minimization of total system delay.

Start Constraint

$$\sum_{d \in D} x_{fd} = 1 \quad \forall f$$

Every flight departs exactly one time.

Capacity Constraint

$$\sum_{f \in F} \sum_{d \in D} cto_{st}(f,d) \leq cs_t \quad \forall s,t$$

Demand shall never exceed capacity.

Agenda

1. NFE Network Flow Environment
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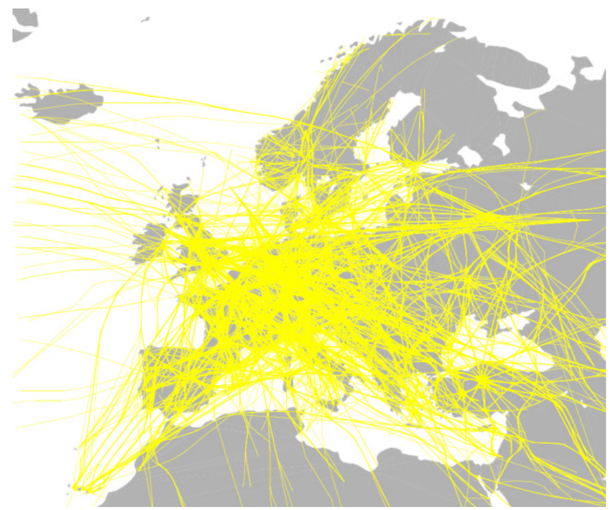
Large-scale ATFM scenario

Motivation for column generation application

- Total 1-day scenario
- Complete European Air Traffic
- Gigabytes of memory usage
- Weather impact data from different sources
- Regulation data for ATC sectors and airports
- First-Planned-First-Served (FPFS) start solution from a heuristic algorithm

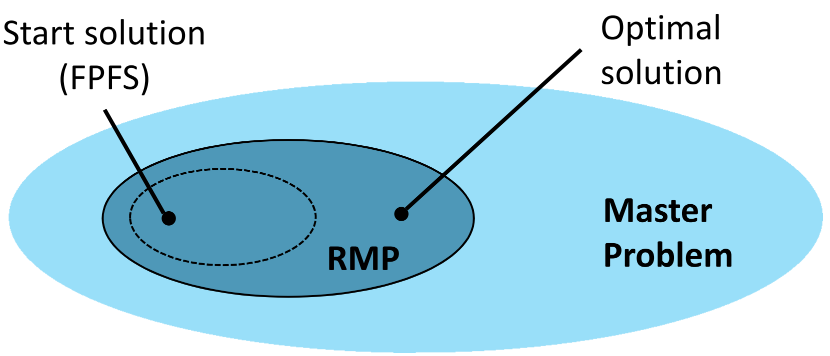
Timeframe	Total [min]	1440
	Granularity (Slot) [min]	15
Movements	Flight Movements [#]	28.784
ATC Sectors	Quantity [#]	638
Airports	Quantity [#]	19.798
Regulations	Sectors	85
	Airports	126

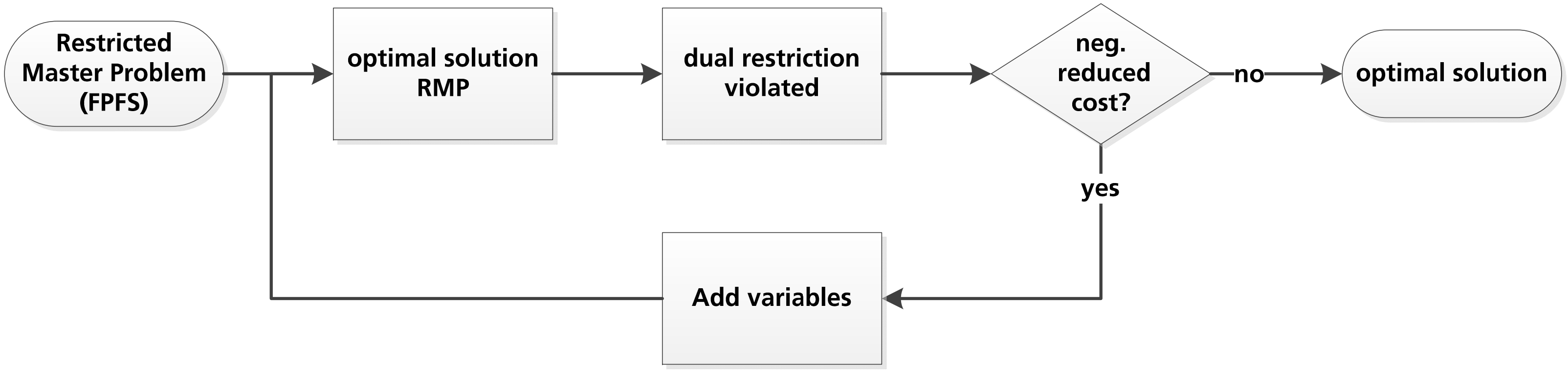
Exemplary 1-Day scenario



Column Generation optimization approach

- Iterative solution process
- Uses a Restricted Master Problem (RMP)
- Starts with a feasible solution (FPFS)
- RMP's are solved by simplex algorithm
- Adds variables with delay saving potential





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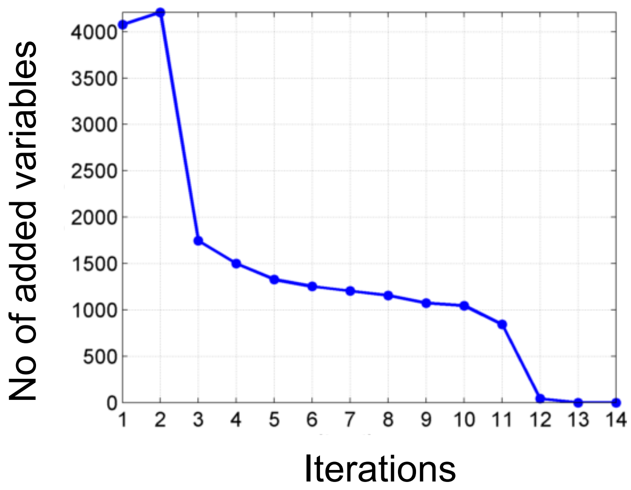
Exemplary Results:

Total delay, calculation time and added variables

Total delay	
FPFS [min]	170.475
Optimum [min]	15.975
Col Gen relative [%]	9,4

Number of variables	
Total [#]	272.624
Column Generation [#]	44.261
Col Gen relative [%]	16,2

Calculation time	
Simplex [s]	1.436
Column Generation [s]	64,4
Col Gen relative [%]	4,5



Agenda

1. NFE Network Flow Environment
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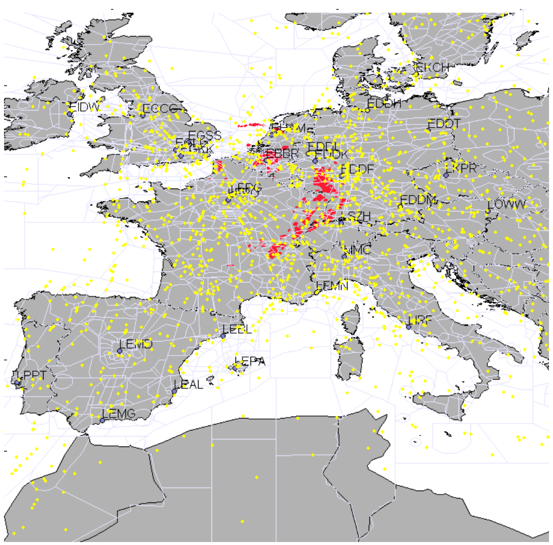
Outlook
NFE model improvements

- Integration of convective radar data within different forcast scenarios
- Application of the model within a *European volcanic ash crisis mitigation concept*
- Application of different routing concepts (free routing concepts)
- Integration of a Dynamic Airspace Management as an ATFM measure



Thank you very much for your attention!

NFE
Network Flow Environment

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