Air Transportation 2050 – A holistic View

Guest Lecture at Royal Melbourne Institute of Technology

Melbourne, September 14th, 2012

Prof. Dr.-Ing. Volker Gollnick, Director
AGENDA

• Introduction of the Institute
  • The Way of Thinking
  • The Way of Working
• Scenarios of Future Air Transportation
• Some Examples of holistic Air Transportation Concepts design and Analysis
  • Climate Optimized Air Transportation
  • Intermediate Stop Operations
  • Laminar Flow Aircraft
• How does the Aircraft look tomorrow?
Institute for Air Transportation Systems

Representation of the main system elements within the institute

Three system related departments provide technical and procedural basic competencies for conceptual technical developments and integration → interfaces to further disciplinary institutes

Covered by a department for system analysis and assessment
Institute for Air Transportation Systems
The Way of Thinking

System hierarchy

- The System – Air Transportation System
- Sub structure – Airport, Aircraft, Airline, ATM
- Subsystem – Terminal, Wing, MRO, Surveillance
- Component – CheckIn, FlightControl, LineMaintenance, Radar
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The Way of Thinking

Integration

„Intellectual Integration“ - Understanding of functional relations and interactions

Modelling - Functional definition and composition of systems on functional level

IT oriented SW-system integration - Integration of calculation and simulation tools

Physical integration of components to systems
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The Way of Thinking

Technology

- A physical principle or technique to realise a function, form concept
- A new rule based procedure like continuous descent approach
- A new process to improve an operation or production like point to point airline network
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The Way of Working

**Air Transport System of the Future**
- Global future scenarios
- Analysis of the entire transportation system
- Business models of airlines
- Development of solutions on system level

**DLR-Air Transportation Systems: System Analysis & Collaborative Design Capabilities**

**Design of System Elements**
- Future aircraft, infrastructures, procedures
- Conceptual design & innovative concepts
- Methods and tools for collaborative design
- Realization of collaborative design

Detailed analysis and design are joint undertakings of the different partners within DLR and beyond

**Innovative solutions and technologies comprehension, reliable predictions**

**Design requirements and targets Evaluation system**

**Innovative solutions and technologies comprehension, reliable predictions**

**DLR Institutes**

**Universities**

**Industrial Partners**
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Virtual Integration Platform (VIP):

A method for integrated air transport concepts development:

Overall Air Transportation Concepts for defined air transportation missions composed of the main subsystems (aircraft, airport, air traffic management, airline operations) including transportation and control processes

Three leading concepts:
- Short range air transport
- Long range air transport
- High speed air transport

How to let them become reality?
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Virtual Integration Platform – How to let them become reality?

Leading Concept Example: Short Range Mission Segment – „Silent and Clean“
Associate Technologies which are of particular but not exclusively interest for this mission

The VIP method and the relying leading concepts **merge different disciplinary research tasks** to a comprehensive **interdisciplinary and integrated research project**
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Three Generations of Multi Disciplinary Optimization

Definition according to Prof. Juan Alonso, Stanford University

- **Optimization assisted design in teams**
- Management of knowledge
- Collaboration of engineers and computers

- Workflow management software
- Networked computing, Interfaces
- Complex problems

- Analysis-based design computations
- Optimization algorithms
- Approximation techniques

1st Gen. 2nd Gen. 3rd Gen.
Institute for Air Transportation Systems
The interdisciplinary way of working

- Distributed computing system -> tools remain on the specialists’ servers.
- Tools of specialists are wrapped -> tools do not need to be adapted.
- Coupling via central data model CPACS (Common Parametric Aircraft Configuration Schema).
CPACS is a hierarchic data model based on an XML schema definition.

- CPACS can hold geometry, analysis results and process data.
- Libraries for handling and geometry processing (TIXI/TIGL).
- Compatible to standards like IGES and STEP.
- Wrappers are stand-alone tools.
- Framework independent implementation.
Different models with different geometric representations can be derived from the global CPACS model using the software libraries.
Different models with different geometric representations can be derived from the global CPACS model using the software libraries.
Institute for Air Transportation Systems
Leading Concept “Comfortable & Clean” – an example for an integrated ATS concept research
Scenarios for future Air Transportation Systems
Scenarios for future Air Transportation Systems
Integration of research of the future into an integrated design process
Despite any disturbancies aviation industry is still expecting **4.8% global annual growth** in terms of growing passenger movements.

*Source: Airbus GMF 2011*
Remarkable growth on long range

Growth on short range is depending on regions

Source: Boeing Market Outlook 2011
Boundaries for Future Developments
Perspectives in Aviation (3/3)

- Short range transport will increase in growing countries with own manufacturing industry
- Long range transport will grow between "Western World, Middle East and Growing Countries"

Source: Airbus GMF 2011
Boundaries for Future Developments

Change of global traffic flow

- Middle East reaches 2/3 of global population within 8 hours flight

- Mega airport turntables provide significant long range transport capacities

- Air transport flows will change resulting in a changing relevance of the actual airport hubs and spokes in Europe

- European Airlines will benefit but also change their business models due to the Middle East and Asian developments
Oil price is constantly growing with increasing gradient, which leads to a highly sensitive and destabilizing development.

Boundaries for Future Developments
Development of oil price 1987 - 2012

Source: EIA
A Paradigm Shift in Aviation
Trade Off between Mobility and Green Transportation

• Mobility is a major pillar of high life style and prosperity

• Increasing energy/oil cost and ecological responsibility argue against quantitative traffic growth

• Ensure mobility with less energy effort, materials, emissions and noise requests for less traffic ➞ less aircraft, less airport, airspace capacity

• Passenger mobility can be achieved with less aircraft movements

• Cost and emissions per flight are to be shared by more people per trip

 ➞ from quantitative to qualitative air transport growth

Source: U. Becker, TU Dresden, V. Gollnick, DLR
The Paradigm Shift of Flying
Changes

Qualitative Growth of Aviation
• Balance of time, cost, emissions, effort
  • Less traffic, less aircraft, consolidated capacities
  • Less noise and emissions
  • More potential for robustness, and reliability in the transportation processes

• Increased level of service
  • More comfort and relaxed travel experience
  • Air transport is more attractive
  • More potential for punctuality (door to door)

• Common Vision
  • Joint targets and common goals

• Integrated ATS
  • Understanding of systems dependencies

Source: U. Becker, TU Dresden, V. Gollnick, DLR
A Paradigm Shift in Aviation
The Blended Wing Body

A potential solution for Mobility and Green Air Transportation:

• It offers potential **benefits**
• Expand the **design space** and possibilities
• It gives **answers** to global developments
• „Known **unconventional‘‘!
• It is **emotional**!
• Still technically **challenging**
The Blended Wing Body
A potential solution for Green Air Transportation

<table>
<thead>
<tr>
<th>Concepts</th>
<th>Payload - Cabin</th>
<th>Range [nm]</th>
<th>Mach</th>
</tr>
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<tbody>
<tr>
<td>BWB 450</td>
<td>468 PAX</td>
<td>7750</td>
<td>0.85</td>
</tr>
<tr>
<td>VELA 3</td>
<td>750 PAX</td>
<td>7650</td>
<td>0.85</td>
</tr>
<tr>
<td>MOB</td>
<td>115 [t]</td>
<td>5087</td>
<td>0.85</td>
</tr>
<tr>
<td>SAX 40</td>
<td>215 PAX</td>
<td>5000</td>
<td>0.8</td>
</tr>
<tr>
<td>DLR BWB</td>
<td>500 PAX</td>
<td>7750</td>
<td>0.85</td>
</tr>
</tbody>
</table>

The Blended Wing Body is a potential solution for Green Air Transportation.
The Blended Wing Body
Design for integrated Air Transportation Systems
The Blended Wing Body
A Coupled

Source: DLR, Institute for Air Transportation Systems
The Blended Wing Body
An Overall ATS Design

Cabin Design
Boarding
Turnaround Operations

Source: DLR, Institute for Air Transportation Systems, Hamburg
The Blended Wing Body
An Overall ATS Design

Block fuel improvements with respect to conventional configurations

Source: DLR, Institute for Air Transportation Systems, Hamburg
Fast Foreward, FFWD
ATS System Analysis of Global Fuel Burn (CO₂) Forecast
# ATS System Analysis of Global Fuel Burn (CO₂) Forecast

## 1 Problem

- **Environmental Impact of Future Air Traffic Growth (CO₂)**
- Difficult to Estimate the Role of:
  - Single Aircraft Families
  - New Technology

## 2 Objectives

- **Estimate Future World Fleet of Airliners and their Fuel Burn (CO₂)**
  - On Basis of Individual Aircraft Models
  - New Technology Penetration
  - Growth & Retirements

## 3 Approach

- **Bottom-Up Fleet and Fuel Burn Forecast**
  - On the Basis of:
    - FESG Forecast Details
    - Individual Aircraft Fleets and Order Books
    - Eurocontrol BADA Performance DB

## 4 Results

- **Flexible Forecast Environment:**
  - Fleet and Fuel Burn of Single Aircraft Types: From **today** up to year **2036**
  - Alternative Growth, Market, Technology & Policy Scenarios
ATS System Analysis of Global Fuel Burn (CO\textsubscript{2}) Forecast

1. Status quo
   - Today's fleet
     - World fleet
     - Sub fleets
   - ASCEND Fleet Data

2. Aircraft Classifications
   - Traffic Shares
   - Retirement curves
   - ICAO FESG Forecast

3. Growth Scenarios
   - Traffic Growth
   - Market Shares
   - Case specific Information

4. Prediction
   - Next years' deliveries

Aircraft specific performance data
Aircraft-specific operation data
New aircraft programs, timelines

Original FESG RPK (Top-Down)
No Biofuel
Biofuel IEA
Biofuel ATAG
ATS System Analysis of Global Fuel Burn (CO$_2$) Forecast

Future Horizons - Short and long term developments

**Development of traffic**
Offered seat capacity of world fleet [Mio]

- Orderbook+Retirements (heutige Flotte)
- Langfristiges Verkehrswachstum
- FFWD Prognose

**Development of technologies**
Operational world fleet aircraft [Tsd]

- 'Offene' Nachfrage (aus Verkehrswachstum)
- Neue Technologie (z.B. A320 Neo)
- Heutige Technologie (z.B. A320)
- Alte Technologie (z.B. A300)
ATS System Analysis of Global Fuel Burn (CO₂) Forecast
Fuel Consumption and CO2 Emissions related to aircraft level and technology scenarios

Operational A/C types
• Fuel flow calculation based on Eurocontrol BADA performance data
• Performance data available for 76 A/C

Future demand
• Technology scenarios based on actual A/C development references, typical production cycles, longterm potentials

Fuel consumption of new A/C
in [litre/Seat/100 km]
seat class 101-150

- Heutige Technologie (z.B. A320)
- Neue Technologie (z.B. A320 Neo)
- Technologieszenario ('Offene' Nachfrage)
- Gesamt (gewichteter Durchschnitt)

![Graph showing fuel consumption trends from 2010 to 2035]
ATS System Analysis of Global Fuel Burn ($\text{CO}_2$) Forecast

Estimation of global effect of A/C families and technologies

Future development of air transport, A/C, fuel consumption/CO2

Average fuel consumption of world A/C fleet
[litre/pax/100 km]
Climate Optimized Air Transportation, CATS
Climate Optimized Air Transportation

Goals

Identify potential for **climate impact reduction** by reducing flight altitude and speed for

- actual aircraft
- re-designed aircraft

using

- a **world fleet** of a representative long range aircraft
- typical **real flight tracks as references** for assessment
- **Average Temperature Response (ATR)** und **Direct Operating Costs (DOC)** as metrics
- Assessment ATR und DOC Änderung **relativ zu heutigen Flugverfahren**
- **Value trade off** ATR vs. DOC
Climate Optimized Air Transportation

Boundary Conditions

Leg network
- **1178 Routes** with annual frequency in **2006** based on OAG data

Vertical profile
- ICA 13-41 kft (step size 1kft)
- Mach 0.4-0.85 (step size 0.001)

Continuous climb cruise

Aircraft
- **A330-200** with CF6-80E1A3 engines calibrated on real data

Cost assessment
- Only **Cash Operating Costs**, Staff and fuel cost basis **2006**

Climate assessment
- 32 years continuous emissions average ATR over 100 years including **CO₂, O₃, CH₄, H₂O, contrails, contrail-cirrus**

\[
ATR_{100} = \frac{1}{100} \int_{2006}^{2106} \Delta T(t) \, dt
\]
Climate Optimized Air Transportation
Design and Analysis Chain based on CPACS and Collaboration

Propulsion
  → engine performance
Aircraft design
  → aerodynamics, weights
Route network
  → mission profile
Atmosphere
  → atmospheric data
Fuel estimation
  → mission fuel
Trajectory calculation
  → 4D trajectories, emission distribution
Flight Envelope
  → feasible trajectories
DOC
  → direct operating costs
Climate impact

Process Control

AirClim
- Linearized response based on DLR E39/CA
- CO₂, CO, O₃, CH₄, H₂O contrails, contrial-cirrus
Climate Optimized Air Transportation
Adaption of A/C Design

Cruise conditions for $\text{DOC}_{\text{rel}} = 1.1$
- ICA (mean) 7947 m
- Ma_{cr} (mean) 0.717

Design steps

Wing optimization
- Wing LE sweep [deg] 32 23 22
- Wing area [m$^2$] 361 366 360
- Wing aspect ratio 9.3 12.6 13
- Wing position (x/LF) 0.341 0.337 0.344

Empenage definition
- HTP LE sweep [deg] 34 24 24
- HTP area [m$^2$] 71 57 55
- VTP LE sweep [deg] 44.4 32 31
- VTP area [m$^2$] 53 60 59
Climate Optimized Air Transportation
Reference: Global leg net of all A330 flight in 2006
Climate Optimized Air Transportation

Reference: Climate impact of actual scenario per route and annualASK
Climate Optimized Air Transportation

Reference: Climate impact of top 112 routes representing 50% of impact of A330 fleet
Climate Optimized Air Transportation

Results: Trade off between DOC and ATR climate impact

- Trade-off for exemplary mission depicted (-> Pareto frontier)
- Mission: DTW-FRA
- Climate impact reduction of 59 % requires 40 % DOC increase wrt. minimum DOC operations!
- Identification of ideal trade-off for whole route network allows for the derivation of a new design point for a more climate-friendly aircraft
Climate Optimized Air Transportation

Value Analysis theory

DOC and ATR change of each individual trajectory relative to reference profile

Relative DOC change

\[ DOC_{rel,i,k} = \frac{DOC_{i,k}}{DOC_{i,ref}} \]

Relative ATR change

\[ ATR_{rel,i,k} = \frac{ATR_{i,k}}{ATR_{i,ref}} \]

Resulting Pareto-frontier

\[ \text{Max}(ATR_{rel,i,k}) = f(DOC_{rel,i,k}) \]
**Climate Optimized Air Transportation**

Deriving new A/C design requirements

Probability distribution of cruise conditions (ICA-Ma) for increasing cost

Lower cruise flight and speed conditions for increasing ΔATR\textsubscript{rel}

request for A/C redesign to recover off design losses

Relative Change in cost

30 \%

Relative change in climate impact

62 \%
Intermediate Stop Operations, ISO

Knowledge for Tomorrow
Intermediate Stop Operations
Generic Single Mission Analysis

1. Problem
   - Long range aircraft often “over-sized” for average mission lengths
   - Payload-Range efficiency (PRE) decreases with very long ranges
   - What would be the ATS-impact of refueling an aircraft during a long-haul flight at an intermediate airport?

2. Objectives
   - Show the fuel saving potential of ISO
     - Single mission
     - Fleet wide
   - Consider given ATS boundary conditions:
     - Routes structure
     - Intermediate airport locations and infrastructure

3. Approach
   - Redesign of A330-200 type of aircraft for shorter ranges
   - Identification of all A330 and 777 routes in 2009
   - Integration of world-airport database

4. Results
   - Ideal mode of operations for each route and ISO airport
   - Single flight fuel saving potential
   - Global fuel saving potential
   - Additional traffic at ISO airports
**Intermediate Stop Operations**

The principle concept

- Long range A/C tend to be oversized in range
- Payload - Range-Efficiency (PRE) decreasing at long range
- Intermediate refueling is an option:
  - In the air: aerial refueling
  - At ground: refueling at airport
- Geographical description of intermediate stop airport (M) w.r.t A and B by:

\[
\begin{align*}
    f_{\text{detour}} &= \frac{AM + MB}{AB} \\
    f_{\text{offset}} &= \frac{\max(AM, MB)}{AM + MB}
\end{align*}
\]
Intermediate Stop Operations
Generic Single Mission Analysis

- A330-200 similar aircraft, re-sized for different design-ranges
- NASA’s Flight Optimization and Performance System (FLOPS) used for conceptual AC-design
- Fuel burn meta-model for off-design mission calculation
- Reference design range 6400 nm
- ISO with original aircraft yields up to 7% block fuel savings on a 6400 nm mission
- A/C resized for 3200 nm design range yields up to ~15.5% block fuel savings on a 6400 nm mission
Intermediate Stop Operations
Fuel Saving Potential

- A330-200 like A/C →
- Design adopted to different ranges
- Reference design for 6400 nm compared to ISO-design for 3200 nm range →
- Theoretical potential for fuel saving is about ~ 15 % für 6400 nm Mission
- About 5% saving possible at given exzentricity $f_{\text{offset}}$ for different ranges (→ PRE-Kurve; ~ 5 %)
**Intermediate Stop Operations**

**Aircraft Fleet Level Analysis - ISO with resized A/C**

- Global fuel saving potential dependent on A/C design range. Resized aircraft is considered at different design ranges (*x-axis*).
- All A330 and 777 routes of the year 2011
- All airports with runways > 3000m and at least ILS or DME are considered
- 4 different operational modes; For each real route the most fuel efficient alternative is selected.

Relative fuel savings on all routes with regards to direct operations

<table>
<thead>
<tr>
<th>Design range [nm]</th>
<th>ISO, resized A/C</th>
<th>Overall savings (sum)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td>2500</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>3000</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>3500</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>4000</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>4500</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>5000</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>5500</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>6000</td>
<td>0.00</td>
<td></td>
</tr>
</tbody>
</table>

**Diagram**

![Diagram showing fuel savings](image-url)
Intermediate Stop Operations
Identification of appropriate intermediate stop airports

- Consideration of
  - typical A330/B777 flight routes (from OAG, 2007)
  - geographical location of real airport

- Typical A330/B777 flight routes (from OAG, 2007)

- Consideration of
  - typical A330/B777 flight routes (from OAG, 2007)
  - geographical location of real airport
Intermediate Stop Operations
Optimal position of appropriate airports depending on design range

- Considering variation of design range changes position of “Hot Spots”
Laminar Flow Aircraft Technologies in Operation, LamAiR
## Laminar Flow Aircraft Technologies in Operation

**Goal:** Advance NLF/HLF TRL, find ATS implications

### Questions

<table>
<thead>
<tr>
<th>1</th>
<th>Questions</th>
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<tbody>
<tr>
<td></td>
<td><strong>Implications of NLF for an airline?</strong></td>
</tr>
<tr>
<td></td>
<td>● Net benefit for network-wide ops. ? Fuel efficiency on actual routes?</td>
</tr>
<tr>
<td></td>
<td>● Economics: Maintenance, utilization, and aircraft price impact ?</td>
</tr>
<tr>
<td></td>
<td>● Under what boundary conditions does N/HLF make sense?</td>
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</tbody>
</table>

### Approach

<table>
<thead>
<tr>
<th>2</th>
<th>Approach</th>
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<tbody>
<tr>
<td></td>
<td><strong>Single flight analysis</strong></td>
</tr>
<tr>
<td></td>
<td>● Based on high-fidelity DLR aero- and structural models</td>
</tr>
<tr>
<td></td>
<td>● Fuel comparison to A320-200 type aircraft</td>
</tr>
<tr>
<td></td>
<td><strong>Real-world route network analysis</strong></td>
</tr>
<tr>
<td></td>
<td>● Based on real flight schedules and route distribution</td>
</tr>
<tr>
<td></td>
<td>● LamAiR A/C gradually substitutes ref. A/C</td>
</tr>
<tr>
<td></td>
<td><strong>Cost-benefit analysis</strong></td>
</tr>
<tr>
<td></td>
<td>● Airline cash-flow modelling <em>(AirTOBS)</em></td>
</tr>
<tr>
<td></td>
<td>● NPV as overall metric for evaluation</td>
</tr>
<tr>
<td></td>
<td>● Parameter variation for maintenance cost, aircraft price and cost of fuel</td>
</tr>
</tbody>
</table>

### Results

<table>
<thead>
<tr>
<th>3</th>
<th>Results</th>
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</thead>
<tbody>
<tr>
<td></td>
<td><strong>Break-even mission range</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Net fuel-efficiency benefit on fleet level</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Break even fuel price</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Definition of targets for e.g. maint. cost</strong></td>
</tr>
</tbody>
</table>
Laminar Flow Aircraft Technologies in Operation

A/C Design

Conceptual Design and Detailed Design performed by Inst. for Aerodynamics

Aerodynamics- and Engine characteristics Constraints for operating laminarity

Detailed Analysis

Single flight analysis

Real route analysis

Network analysis

Economical analysis

Simulation with TCM (LY-LIP)

(LY-SLT)

Simulation with NEMO (LY-LTB)

Simulation with AirTOBS (LY-SLT)

Mission fuel/ time
• Determination of mission fuel and time considering operational constraints and real aero and engine characteristics
  ⇒ Relative change of mission fuel required
Laminar Flow Aircraft Technologies in Operation
Single Mission Operation vs. Fleet Operation

Fuel saving on operational level

-5.5%  -5.7%
-4.0%  -2.0%
-1.9%  -1.0%

Optimum laminar flow
Reduced laminar flow

% of flights substituted with NLF aircraft

Introduction of NLF first on long routes

Available seat kilometer [%]

Share of flights with NLF aircraft [%]

Number of flights [

Fuel change on operational level [%]

Range [km]

Laminar Flow Aircraft Technologies in Operation
Single Mission Operation vs. Fleet Operation

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Number of flights [

Fuel change on operational level [%]

Range [km]
Laminar Flow Aircraft Technologies in Operation
Network Simulation and Analysis

- Netzwerk-Benefit durch Einführung eines NLF Flugzeugs in ein europäisches Routennetz
- Beide Flugzeuge in einem Netz betrieben

Untersuchung des Einflusses:
- Ø-Laminarität
- Turn-Around-Zeit
- Kraftstoffpreis
- Anteil an angebotenen Sitz-km
- Flottenzusammensetzung
- Änderung Kraftstoffbedarf im Netz
- Airline Profit
- Break-even Sitzladefaktor
Laminar Flow Aircraft Technologies in Operation Life Cycle Cost Analysis

• Airline Life Cycle Cost-Benefit Model **AirTOBS**
• Modeling all cost, revenues, and utilization of aircraft operations
• Superior to standard DOC-methods
• **(a)** Cash flow results
  • Main assumptions:
    Fuel price at 80 $/barrel, same aircraft list price and maintenance cost.
• **(b)** Fuel price variation for $\Delta$NPV
  • For design range and representative range distribution
  • Assumptions:
    • **Best case**: +20$/FC maint.; same A/C list price
    • **Worst case**: +500$/FC maint.; +5% A/C list price

![Graph showing NPV vs. Year and NPV vs. Fuel Price](image)
Summary
Value of holistic research on disciplinary technologies

• More realism and reliable results by covering all main interfering effects

• Collaboration in interdisciplinary teams is a research field itself

• Look carefully to global developments as an air transport designer to discover the real needs

• Mobility is more important than capacity and movements in a “green transportation system”

• Paradigm shift from quantitative to qualitative growth

• Blended Wing Body is a potential solution for future green air mobility

⇒ Design requirements and solutions for aircraft and operations
Location

Channel Hamburg (Harburg)

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