Innovative Aircraft Design –
Options for a New Medium Range Aircraft

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Abstract

Task was to find an innovative aircraft design for a new medium range aircraft. The aircraft design methodology is based on equations (in contrast to numeric methods) and formal optimization with a genetic algorithm called differential evolution. Airbus has postponed an all-new A320 to 2025 or even 2030. This allows including also unconventional configurations into the search. Economic requirements are extreme: 25 % to 40 % reduction in fuel consumption, 35 % reduction in Cash Operating Costs. To achieve this, all aircraft design parameters have to be open for discussion. An aircraft called "The Rebel" is prepared to go to extreme parameters: low cruise speed, high wing span and long take-off and landing distance. Without new technologies it achieves 36 % reduced fuel consumption. The "Smart Turboprop" stays in conventional limits with its parameters, but makes use of a braced wing with natural laminar flow. It also achieves 36 % reduced fuel consumption plus a 17 % reduction in Direct Operating Costs (DOC). In addition, several Box Wing Aircraft were designed: Diamond Box Wing and Biplane Box Wing as Wide Body and alternatively as Slender Body. The Biplane Box Wing shows overall advantages due to its conventional tail. The details of Box Wing Aircraft design were mastered, but the Direct Operating Costs of the Box Wing Aircraft turned out to be higher than those of the A320 reference. This leaves the "Smart Turboprop" as the proposed configuration for an Airbus A320 replacement. As a short term measure, it is proposed to offer a horizontal wing tip extension as an option for the A320neo instead of the winglets. An extension with the same length as the winglet height offers far greater drag reduction. Airports will tolerate and accommodate some aircraft with a wing span above the ICAO limit in Class C of 36 m.
Content

• Project Background

• Requirements
  • For Economics
  • At Airports

• Range of Investigation for a New A320 (NSR, A30X)
  • Pure Optimization "The Rebel"
  • "Smart Turboprop" (!)
  • "Box Wing Aircraft" (BWA)

• Summary
The research project was part of the
- Leading-Edge Cluster Competition of the Federal Ministry of Education and Research
- Aviation Cluster Hamburg Metropolitan Region
- Lighthouse Project 3: Airport 2030
  - Work Package 4: Aircraft Configurations for Efficient Ground Operations
  - Work Task 4.1: Evolutionary Aircraft Configurations "Possible A320 Successor"

Duration: 1st December 2008 - 31th January 2014 = 5 years and 2 month
Employees and Students

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Daniel Schiktanz

Andreas Johanning
PhD Candidate at TUM

Tahir Sousa

Ricardo Caja Calleja

Priyanka Barua

Mihaela Niță

Liana Urseanu

Students with Thesis or Project

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Sameer Ahmed
Nishant Bhanot
Jonne Bobis
Jeremy Bouten
Leon Dib
Karim Drews
Martin Fekete
Elena García Llorente
Steffen Hausenberg
Fahad Aman Khan
Hoa Ly
Hartwig Ottermann
Veselin Pavlov
Aday Pérez Reyes
Maria Pester
Karunanidhi Ramachandran
Haider Riaz
Luis Salord Losantos
Víctor Julián Sánchez Barreda
Daniel Schiktanz
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Jeroen Verstraete
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Student Assistants

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Alain Chahine
Andreas Johanning
Matthias Koppe
Daniel Marciano
Mahmud Mir
James Murray
Dennis Paape
Maria Pester
Daniel Schiktanz
"Evolutionary" not "Revolutionary"

Estimation of maximum glide ratio $E = L/D$ in normal cruise

<table>
<thead>
<tr>
<th>$A$</th>
<th>aspect ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{\text{wet}}$</td>
<td>wetted area</td>
</tr>
<tr>
<td>$S_W$</td>
<td>reference area of the wing</td>
</tr>
<tr>
<td>$e$</td>
<td>Oswald factor; passenger transports: $e \approx 0.85$</td>
</tr>
</tbody>
</table>

from statistics: $k_E = 15.8$

<table>
<thead>
<tr>
<th>$S_{\text{wet}}/S_W$</th>
<th>conv. aircraft</th>
<th>BWB</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6.0 ... 6.2</td>
<td>$\approx 2.4$</td>
</tr>
</tbody>
</table>

$$E_{\text{max}} = k_E \sqrt{\frac{A}{S_{\text{wet}}/S_W}}$$

$$k_E = \frac{1}{2} \sqrt{\frac{\pi e}{c_f}} = 14.9$$

$$c_f = 0.003$$
"Evolutionary" not "Revolutionary"

Not suitable for a "Possible A320 Successor":

Oblique Flying-Wing (OFW)

\[
t/c = 30\% \quad A \approx 110/15 \approx 7.5
\]
"Evolutionary" not "Revolutionary"

Not suitable for a "Possible A320 Successor": 

![Diagram of an aircraft and interior layout.]
"Evolutionary" not "Revolutionary"

Square-Cube-Law =>

The BWB configuration is favoured for ultra large aircraft. Why does physics demand a BWB?

\[ S_W \propto l^3 \]

A321 scaled to the same size as the A380.

**A321:** \[ \frac{m_{MTO}}{S_W} = 727 \text{ kg/m}^2 \]

**A380-800F:** \[ \frac{m_{MTO}}{S_W} = 698 \text{ kg/m}^2 \]

Aircraft even bigger => BWB

Let's split the wing to double effective aspect ratio, \( A = \frac{b^2}{S} \)

=> a box wing aircraft!
Ideas from the Web …
Ideas from the Web …

2.5 liters/pax/100 Km

ATR aircraft offers the lowest greenhouse gas emissions, best technical solutions, and unique commonality while remaining the most cost efficient technology.

New, say Yes to ATR aircraft and choose the best solution for short haul flights.

Designed for economics, 80% less fuel costs

Reduced ecological footprint 2.5 liters/pax/100 km (at 100 min per gallon per pass)

The only ETOPS 120-min turbo prop
More Ideas from the Web …

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>m_MTO</th>
<th>M_CR</th>
<th>P_eq</th>
<th>Pax</th>
</tr>
</thead>
<tbody>
<tr>
<td>A320</td>
<td>78 t</td>
<td>0.76</td>
<td>xxx</td>
<td>180</td>
</tr>
<tr>
<td>A400M</td>
<td>141 t</td>
<td>0.70</td>
<td>4 x 8250 kW</td>
<td>xxx</td>
</tr>
<tr>
<td>ATR 72</td>
<td>23 t</td>
<td>0.46</td>
<td>2 x 1950 kW</td>
<td>72</td>
</tr>
<tr>
<td>Q400</td>
<td>29 t</td>
<td>0.60</td>
<td>2 x 3780 kW</td>
<td>78</td>
</tr>
<tr>
<td>Smart TP</td>
<td>56 t</td>
<td>0.51</td>
<td>2 x 5000 kW</td>
<td>180</td>
</tr>
</tbody>
</table>
Aircraft Take Shape …
At the end of the project: Something to touch …
... and to fly ...

Watch videos on https://goo.gl/vj2Hq6
... and it gets reported:

RESEARCH DAVID KAMINSKI-MORROW LONDON

Study backs ‘smart turboprop’ design

Researchers looking to increase medium-haul aircraft efficiency favour an advanced turboprop over box-wing concepts.

In co-operation with Airbus, Hamburg University of Applied Sciences embarked on a study to explore a possible successor to the A320, as part of a project known as Airport 2030.

As well as an optimised conventional jet configuration, the study examines various box-wing designs, as well as the option of a turboprop. The team aims to consider high-efficiency aircraft designs which would avoid changing ground infrastructure.

The project involves studying families of single- and twin-aisle box-winged aircraft of 126-218 seats. However, while box-wing concepts offer a reduction in drag, this economic advantage is countered by the increased weight of the wing.

The direct operating costs of box-wing models are calculated to be some 20% higher than those of the A320.

However, the “smart turboprop” design’s economics prove more promising, the study says, with a 17% lower operating cost and a 36% cut in fuel burn.

This is based on a twin-engined aircraft with a high wing braced by struts, and a T-tail configuration featuring technologies including laminar flow.

What else in the News?

**PROPULSION JOHN CROFT WASHINGTON DC**

**05/2011:**

**90-seat turboprop beckons to P&WC**

Engine manufacturer to begin assembling next-generation powerplant to prepare for possible creation of bigger airframes.

**AIRFRAMES MAVIS TON SINGAPORE**

**01/2013:**

**ATR keen to satisfy 90-seat audience**

Turboprop manufacturer yet to convince shareholders despite Asian regional carriers' interest in potential larger aircraft.

**ANALYSIS MURDO MORRISON LONDON**

**01/2013:**

**ATR ascends as Bombardier suffers**

Growing demand from lessors helps Franco-Italian airframer beat Canadian rival in turboprop orders and deliveries race.

**WHO WILL LAUNCH AN ALL-NEW 90-SEAT TURBOPROP?**

The chances are, nobody will – but pressure from airline customers might conjure up a 2013 launch of a product that regional aircraft makers agree will eventually be a necessity.

**DEVELOPMENT DAVID KAMINSKI MORROW TOULOUSE**

**01/2011:**

**Demand for big turboprops will grow, says ATR**

Airframer seeks "convergent" solution with engine manufacturers to develop future 90-seat models.

---

"I'm insisting on one point. The priority is cost-effectiveness, not spending money on speed."

FILIPPO BAGNATO
Chief Executive, ATR
What else in the News?

03/2014:

TURBOPROPS
Airbus Group keen on 90-seat ATR, but in no rush to launch

01/2015:

Can ATR cope with success?
After its best-ever year, French manufacturer faces challenges of ramp-up, maintaining sales and future product direction

05/2015:

Market needs put 90-seater plan at bottom of ATR list
Resistance from Airbus Group contributes to retreat from larger model as production capacity continues to increase
Meanwhile at Airbus internally

What else in the News?

“We’re not redesigning the A320. It’s pretty damn good just the way it is,” John Leahy, Airbus’s chief commercial officer, says in a promotional video touting the A320neo’s fuel efficiency. He says the company doesn’t believe new technologies being researched will be ready before the mid-2020s. That’s when Airbus is likely to contemplate an all-new design to replace the A320 family. [1]

At Airbus any all-new single aisle aircraft is unlikely to be constructed before 2025.

01/2010: Airbus sees lifespan of at least 10 years for re-engined A320
Ground Handling (to be considered in Airport2030)

- **Example: Continuous Cargo Compartment**
  - Time saving: No repositioning of loader
  - Cargo handling is not on critical path for gate positions
  - Slight time advantage only in few cases (e.g. two door oper. on apron)
  - Same costs
Ground Handling (to be considered in Airport2030)

- **Example: Continuous Cargo Compartment**
  - Time saving: No repositioning of loader
  - Cargo handling is not on critical path for gate positions
  - Slight time advantage only in few cases (e.g. two door operation on apron)
  - Same costs

- **Most evaluated technologies with advantages on the ground impair the DOC of the aircraft**
  - Twin-aisle
  - Increase of aisle width
  - Foldable seat (if seat is heavier)

- **Ground handling processes need to be robust to avoid delays!**

Aircraft need to be optimized for cruise!
**Economic Top Level Requirements**

**Airbus/DLR Design Challenge for 2013** (M. Fokken, Airbus):

- **Fuel burn**: minus 25% versus an A320 with 190 instead of 180 pax
- **CoC**: minus 35% versus an A320 with 190 instead of 180 pax

**SNECMA** (Aviation Week & Space Technology, 2014-03-31) [2]:

“Buyers of next-generation short/medium-range airliners will expect big steps in aircraft economics, at least a **40-percent fuel-burn-per-passenger improvement**,“ says Vincent Garnier, Snecma vice president of marketing strategy for civil engines.
### Requirements at Airports …

... are Driving Today’s Aircraft Design! [3]

**Annex 14 — Aerodromes**

**ICAO**

#### Table 1-1. Aerodrome reference code

(see 1.6.2 to 1.6.4)

<table>
<thead>
<tr>
<th>Code element 1</th>
<th>Code element 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Code</strong> number</td>
<td><strong>Aeroplane reference field length</strong></td>
</tr>
<tr>
<td>(1)</td>
<td>(2)</td>
</tr>
<tr>
<td>1</td>
<td>Less than 800 m</td>
</tr>
<tr>
<td>2</td>
<td>800 m up to but not including 1 200 m</td>
</tr>
<tr>
<td>3</td>
<td>1 200 m up to but not including 1 800 m</td>
</tr>
<tr>
<td>4</td>
<td>1 800 m and over</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Distance between the outside edges of the main gear wheels.
Range of Investigation for a New A320

- **Standard Jet Configuration**
  "The Rebel"

- **Standard Prop Configuration**
  "Smart Turboprop"

- **Non-Standard Jet Configuration**
  "Box Wing Aircraft" (BWA)
  - Wide Body / Slender Body
  - Diamond BWA / Biplane BWA

**Genetic algorithm** (Differential Evolution) proposes parameters. Aircraft „designed“ automatically in EXCEL. **Optimization for minimum DOC.** About 2000 feasible designs tested in one run.
Aircraft Design and Systems Group

15 iteration loops
20 optimization variables
about 230 input variables
about 150 geometry parameters
about 1000 parameters

Optimizing Convergence of the Differential Evolution Genetic Algorithm

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>VBA</th>
<th>Optimus®</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>KF=1 F=0.7</td>
<td>KF=1 F=0.25</td>
</tr>
<tr>
<td>Iterations</td>
<td>4200</td>
<td>2100</td>
</tr>
<tr>
<td>Best DOC</td>
<td>1.169894</td>
<td>1.16835</td>
</tr>
</tbody>
</table>

Equivalence-mile direct operating costs [US$ / NM / t of payload]

Number of experiments
Standard Jet Configuration: "The Rebel"

- Conventional Jet Configuration … but …

- Questioning established requirements. This results in:
  - wing span: $b > 36 \text{ m}$
  - take-off and landing distance: $s_{\text{TOFL}} > 1800 \text{ m}$
  - cruise Mach number:
    \[ M_{CR} < 0.76 \]

<table>
<thead>
<tr>
<th>Code number (1)</th>
<th>Code element 1</th>
<th>Code element 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aeroplane reference field length (2)</td>
<td>Code letter (3)</td>
</tr>
<tr>
<td>1</td>
<td>Less than 800 m</td>
<td>A</td>
</tr>
<tr>
<td>2</td>
<td>800 m up to but not including 1,200 m</td>
<td>B</td>
</tr>
<tr>
<td>3</td>
<td>1,200 m up to but not including 1,800 m</td>
<td>C</td>
</tr>
<tr>
<td>4</td>
<td>1,800 m and over</td>
<td>D</td>
</tr>
</tbody>
</table>

- Considering alternative objective function
  - DOC (standard), DOC + Added Values
  - Minimum fuel

### Standard Jet Configuration: "The Rebel"

#### Early conceptual design

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Deviation from A320*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Requirements</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( m_{\text{MPL}} )</td>
<td>19256 kg</td>
<td>0 %</td>
</tr>
<tr>
<td>( R_{\text{MPL}} )</td>
<td>1510 NM</td>
<td>0 %</td>
</tr>
<tr>
<td>( M_{\text{CR}} )</td>
<td>0.55</td>
<td>- 28 %</td>
</tr>
<tr>
<td>( \max(s_{\text{TOFL}}, s_{\text{LFL}}) )</td>
<td>2700 m</td>
<td>+ 53 %</td>
</tr>
<tr>
<td>( n_{\text{PAX}} ) (1-cl HD)</td>
<td>180</td>
<td>0 %</td>
</tr>
<tr>
<td>( m_{\text{PAX}} )</td>
<td>93 kg</td>
<td>0 %</td>
</tr>
<tr>
<td>( SP )</td>
<td>28 in</td>
<td>- 3 %</td>
</tr>
</tbody>
</table>

#### Main aircraft parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Deviation from A320*</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_{\text{MTO}} )</td>
<td>66000 kg</td>
<td>- 10 %</td>
</tr>
<tr>
<td>( m_{\text{OE}} )</td>
<td>39200 kg</td>
<td>- 5 %</td>
</tr>
<tr>
<td>( m_{\text{F}} )</td>
<td>7500 kg</td>
<td>- 42 %</td>
</tr>
<tr>
<td>( S_{\text{W}} )</td>
<td>68 m²</td>
<td>- 45 %</td>
</tr>
<tr>
<td>( b_{\text{W,geo}} )</td>
<td>48.5 m</td>
<td>+ 42 %</td>
</tr>
<tr>
<td>( A_{\text{W,eff}} )</td>
<td>34.8</td>
<td>+ 266 %</td>
</tr>
<tr>
<td>( E_{\text{max}} )</td>
<td>26.1</td>
<td>+ 48 %</td>
</tr>
<tr>
<td>( T_{\text{TO}} )</td>
<td>89100 N</td>
<td>- 20 %</td>
</tr>
<tr>
<td>( BPR )</td>
<td>15.5</td>
<td>+ 158 %</td>
</tr>
<tr>
<td>( SFC )</td>
<td>1.03E-5 kg/N/s</td>
<td>- 37 %</td>
</tr>
<tr>
<td>( h_{\text{ICA}} )</td>
<td>30000 ft</td>
<td>- 23 %</td>
</tr>
<tr>
<td>( S_{\text{TOFL}} )</td>
<td>2490 m</td>
<td>+ 41 %</td>
</tr>
<tr>
<td>( S_{\text{LFL}} )</td>
<td>2110 m</td>
<td>+ 45 %</td>
</tr>
<tr>
<td>( t_{\text{TA}} )</td>
<td>32 min</td>
<td>0 %</td>
</tr>
</tbody>
</table>
**Standard Jet Configuration: "The Rebel"**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Deviation from A320*</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOC mission requirements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_{DOC}$</td>
<td>750 NM</td>
<td>0 %</td>
</tr>
<tr>
<td>$m_{PL,DOC}$</td>
<td>19256 kg</td>
<td>0 %</td>
</tr>
<tr>
<td>EIS</td>
<td>2030</td>
<td>-----</td>
</tr>
<tr>
<td>$c_{fuel}$</td>
<td>1.44 USD/kg</td>
<td>0 %</td>
</tr>
<tr>
<td>Results</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{F,trip}$</td>
<td>3700</td>
<td>- 36 %</td>
</tr>
<tr>
<td>$U_{A}$</td>
<td>3070</td>
<td>+ 6 %</td>
</tr>
<tr>
<td>DOC (AEA)</td>
<td>93 %</td>
<td>- 7 %</td>
</tr>
</tbody>
</table>

**Operating empty mass breakdown**

- Wing: 24%
- Fuselage: 7%
- Horizontal tail: 25%
- Vertical tail: 25%
- Engines: 13%
- Landing gear: 5%
- Systems: 4%
- Operator’s items: 1.0%

**Component drag breakdown**

- Wing: 32%
- Fuselage: 38%
- Horizontal tail: 17%
- Vertical tail: 4%
- Engines: 8%

**Direct operating cost breakdown**

- Depreciation: 23%
- Interest: 17%
- Insurance: 14%
- Fuel: 15%
- Maintenance: 14%
- Crew: 6%
- Fees: 24%
Proposal: **Horizontal Wing Tip Extension on A320neo as Option**

- Wingtip devices: Very **limited efficiency** compared to the same length of material used to horizontally extend the wing [4]

\[
k_{e, WL} = \left(1 + \frac{2}{k_{WL}} \frac{h}{b}\right)^2 = \frac{A_{eff}}{A} = \left(\frac{b_{eff}}{b}\right)^2
\]

- **Results from an additional study** [5] in Airport2030:
  “Airport Compatibility of Medium Range Aircraft with Large Wing Span”

- Consider this option: Extend the wing span and **just deal with consequences** at airports!
- => Airbus should also offer a **horizontal** wing tip extension as option for A320neo.
Proposal: **Horizontal Wing Tip Extension on A320neo as Option**

- Optional horizontal wing tip extension **limits risk and costs compared to a new wing**
- A **slow introduction** of aircraft with larger wing span (Class C => Class D) will force airports to accept this
- **Landing fees** are based on MTOW and are hence **unchanged**
- Study [4] showed: Many **airports still have some capacity** for a limited number of former Class C aircraft now with larger span
- Airports will start to rearrange gate layout initially with **additional markings**
Standard Prop Configuration: "Smart Turboprop"

- **Turboprop** engine advantages:
  - Compared to turbofan engines: **More fuel efficient**
  - Compared to counter-rotating open rotor:
    - Lower development risk
    - No added structural weight (500 kg [1]) to cater for rotor-burst shielding

- Low flying $\rightarrow$ higher speed of sound $\rightarrow$ similar speed at lower Mach number

- Additional future technologies:
  - **Strut braced wing** (30% less wing mass; literature study)
  - **Natural laminar flow**

- All this together:

  „Smart Turboprop“
Open-Rotor Disadvantages

Airbus, Snecma Tackle Open-Rotor Integration

March 31, 2014
Graham Warwick, Aviation Week & Space Technology [2]

... 

Key to economic viability will be the weight penalty incurred to protect the aircraft from damage caused by a rotor burst or blade release. A turbofan can contain a released blade, but an open rotor will require shielding of the airframe and systems. In Airbus's baseline concept, which has pusher open-rotor engines mounted on the aft fuselage and a conventional T tail, shielding of the rear fuselage and tail adds about 500 kg to the aircraft's weight ...

Comments:
- In contrast: Propeller blades are assumed not to release. Nevertheless:
- Mounting engines on the aft fuselage (c.g. shift ...) leads to overall weight penalties.
Low Flying – Similar Speed at Lower Mach Number

![Graph showing the relationship between cruise altitude and speed for different categories of aircraft at two different Mach numbers.]

- Speed of sound
- Cruise speed turbo prop (Mach number = 0.71)
- Cruise speed turbo fan (Mach number = 0.76)
The „Speed Corner“

The altitude of the speed corner:

\[ h_{SC} = \left(1 - \left(\frac{V_E}{M_{MO} \cdot a_0}\right)^{0.3805}\right) \cdot \frac{T_0}{L} \]

The true airspeed allowed in the speed corner:

\[ V = M_{MO} a_0 \sqrt{1 - \frac{L h_{SC}}{T_0}} \]
Propeller Integration

- Minimum propeller clearance from fuselage
- Minimum propeller clearance between propellers
- Propeller may not extend over wing tip

⇒ Landing gear length and weight
Natural Laminar Flow Representation

\[
\frac{Re_T}{10^6} = -0.0112 \phi_{LE}^2 - 0.1107 \phi_{LE} + 22.167
\]

(purple) border between NLF and HLF

\[
Re_T = Re \frac{x_T}{c}
\]

Dieter Scholz
Innovative Aircraft Design

M. Hepperle, DLR [7]
Smart Turboprop: Results

- **Choosing the optimum aircraft configuration:**

  Smart Turboprop optimized for low DOC compared to A320

<table>
<thead>
<tr>
<th>Turboprop w/o NLF/SBW</th>
<th>T-tail</th>
<th>Conventional tail</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 engines</td>
<td>4 engines</td>
</tr>
<tr>
<td>High wing</td>
<td>-13.6%</td>
<td>-11.4%</td>
</tr>
<tr>
<td>Low wing</td>
<td>-12.4%</td>
<td>-11.5%</td>
</tr>
</tbody>
</table>

- **Wisdom from this optimization study:**
  - 2 engines better than 4 engines
  - For 2 engines: **High wing better** than low wing (0.4 ... 1.2 % PT)
  - For 4 engines: Low wing as good as high wing
  - NLF improves DOC by about 2.8 % PT
  - Struts improve DOC by about 0.5 % PT
  - NLF and Struts improve DOC by about 3 % PT
Standard Prop Configuration: "Smart Turboprop"

### Main aircraft parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Deviation from A320*</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_{MTO} )</td>
<td>56000 kg</td>
<td>-24%</td>
</tr>
<tr>
<td>( m_{OE} )</td>
<td>28400 kg</td>
<td>-31%</td>
</tr>
<tr>
<td>( m_{F} )</td>
<td>8400 kg</td>
<td>-36%</td>
</tr>
<tr>
<td>( S_W )</td>
<td>95 m²</td>
<td>-23%</td>
</tr>
<tr>
<td>( b_{W,geo} )</td>
<td>36.0 m</td>
<td>+6%</td>
</tr>
<tr>
<td>( A_{W,eff} )</td>
<td>14.9</td>
<td>+57%</td>
</tr>
<tr>
<td>( E_{max} )</td>
<td>18.8 ( \approx ) 7%</td>
<td></td>
</tr>
<tr>
<td>( P_{eq,ssl} )</td>
<td>5000 kW</td>
<td>------</td>
</tr>
<tr>
<td>( d_{prop} )</td>
<td>7.0 m</td>
<td>------</td>
</tr>
<tr>
<td>( \eta_{prop} )</td>
<td>89%</td>
<td>------</td>
</tr>
<tr>
<td>( \text{PSFC} )</td>
<td>5.86E-8 kg/W/s</td>
<td>------</td>
</tr>
</tbody>
</table>

### Requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_{MPL} )</td>
<td>19256 kg</td>
<td>0%</td>
</tr>
<tr>
<td>( R_{MPL} )</td>
<td>1510 NM</td>
<td>0%</td>
</tr>
<tr>
<td>( M_{CR} )</td>
<td>0.51</td>
<td>-33%</td>
</tr>
<tr>
<td>( \text{max}(s_{TOFL}, s_{LFL}) )</td>
<td>1770 m</td>
<td>0%</td>
</tr>
<tr>
<td>( n_{PAX} \text{ (1-cl HD)} )</td>
<td>180</td>
<td>0%</td>
</tr>
<tr>
<td>( m_{PAX} )</td>
<td>93 kg</td>
<td>0%</td>
</tr>
<tr>
<td>( SP )</td>
<td>29 in</td>
<td>0%</td>
</tr>
</tbody>
</table>
Standard Prop Configuration: "Smart Turboprop"

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Deviation from A320*</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOC mission requirements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_{DOC}$</td>
<td>755 NM</td>
<td>0 %</td>
</tr>
<tr>
<td>$m_{PL,DOC}$</td>
<td>19256 kg</td>
<td>0 %</td>
</tr>
<tr>
<td>EIS</td>
<td>2030</td>
<td></td>
</tr>
<tr>
<td>$c_{fuel}$</td>
<td>1.44 USD/kg</td>
<td>0 %</td>
</tr>
<tr>
<td>Results</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{F,trip}$</td>
<td>3700 kg</td>
<td>- 36 %</td>
</tr>
<tr>
<td>$U_{a,f}$</td>
<td>3600 h</td>
<td>+ 5 %</td>
</tr>
<tr>
<td>DOC (AEA)</td>
<td>83 %</td>
<td>- 17 %</td>
</tr>
</tbody>
</table>

Operating empty mass breakdown:
- Wing: 13%
- Struts: 1.4%
- Fuselage: 1.4%
- Horizontal tail: 26%
- Vertical tail: 25%
- Engines: 18%
- Landing gear: 6%
- Systems: 6%
- Operator's items: 1.0%
- Soundproofed material: 1.7%

Component drag breakdown:
- Wing: 23%
- Struts: 9%
- Fuselage: 48%
- Horizontal tail: 8%
- Vertical tail: 5%
- Engines: 6%

Direct operating cost breakdown:
- Depreciation: 14%
- Interest: 11%
- Insurance: 6%
- Fuel: 24%
- Maintenance: 16%
- Crew: 27%
- Fees: 1%
Smart Turboprop: Analysis of the Results

- In 1988, we would have preferred a turbofan aircraft as well
Smart Turboprop: Analysis of the Results

- Today, fuel price is four times as high as in 1988 (inflation-adjusted)!
Smart Turboprop: Analysis of the Results

- For an A320 successor, a next generation turboprop engine could be used
Smart Turboprop: Analysis of the Results

- Strut-braced wing slightly improves DOC
Smart Turboprop: Analysis of the Results

- Natural laminar flow slightly improves DOC
Smart Turboprop: Analysis of the Results

- The average stage length of an A320 is quite short (approx. 600 NM)!
### Smart Turboprop and the DLR/Airbus Design Challenge

<table>
<thead>
<tr>
<th>Design Requirements</th>
<th>Smart Turboprop</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PAX</strong></td>
<td>- 5% / - 3%</td>
</tr>
<tr>
<td>190 all economy @ 30° pitch</td>
<td>- 25%</td>
</tr>
<tr>
<td>135 kg/pax pay/load capacity for high density layout @ 28° pitch</td>
<td></td>
</tr>
<tr>
<td><strong>Range</strong></td>
<td>- 25%</td>
</tr>
<tr>
<td>2000 NM (90% of flights within Europe and USA &lt; 500 NM range). Technical means to enable up to 2900 NM range</td>
<td></td>
</tr>
<tr>
<td><strong>TOFL</strong></td>
<td>- 12%</td>
</tr>
<tr>
<td>2000 m, SL, MTOW, ISA +15°C</td>
<td></td>
</tr>
<tr>
<td><strong>LDGFL</strong></td>
<td>- 13%</td>
</tr>
<tr>
<td>1500 m, SL, MLW, ISA +15°C</td>
<td></td>
</tr>
<tr>
<td><strong>Mach</strong></td>
<td>- 35%</td>
</tr>
<tr>
<td>0.79</td>
<td></td>
</tr>
<tr>
<td><strong>Initial Climb/Max. Altitude</strong></td>
<td>- 0%</td>
</tr>
<tr>
<td>FL 350 / FL 410</td>
<td></td>
</tr>
<tr>
<td><strong>Span</strong></td>
<td></td>
</tr>
<tr>
<td>Max. 36m or technical means to achieve ICAO class C</td>
<td></td>
</tr>
<tr>
<td><strong>Noise</strong></td>
<td></td>
</tr>
<tr>
<td>-5 dB cum. vs. Chapter 4</td>
<td></td>
</tr>
<tr>
<td><strong>Fuelburn</strong></td>
<td>- 36%</td>
</tr>
<tr>
<td>-25% versus A320 (CFM) 2009</td>
<td></td>
</tr>
<tr>
<td><strong>Emissions</strong></td>
<td></td>
</tr>
<tr>
<td>Near zero emissions at gate and during taxi</td>
<td></td>
</tr>
<tr>
<td><strong>CoC</strong></td>
<td>≈ - 16%</td>
</tr>
<tr>
<td>-35% versus A320 (CFM) 2009</td>
<td></td>
</tr>
</tbody>
</table>
Non-Standard Jet Configuration: "Box Wing Aircraft" (BWA)

- Unconventional Aircraft Configuration
  - Reduction of Induced Drag
  - Different Types considered
    - Diamond BWA / Biplane BWA
    - Wide body / Slender body
Box Wing Aircraft

- Hand Sketches
- Creative Methods
  - Brainstorming
  - Gallery Method
- Modified Morphological Analysis

<table>
<thead>
<tr>
<th>Stagger</th>
<th>Sweep</th>
<th>Box Wing Vertical Position</th>
<th>Horizontal Stabilizer Position</th>
<th>Vertical Stabilizer Position</th>
<th>Engine Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>=</td>
<td>&lt;&lt;</td>
<td>L – H</td>
<td>Can</td>
<td>Aft</td>
<td>Fuse – aft</td>
</tr>
<tr>
<td>≠</td>
<td>&gt;&gt;</td>
<td>L – SH</td>
<td>No</td>
<td></td>
<td>Fuse – mid</td>
</tr>
<tr>
<td>≠</td>
<td>&lt;&gt;</td>
<td></td>
<td></td>
<td></td>
<td>Wing</td>
</tr>
</tbody>
</table>

Number of Combinations: $3 \cdot 3 \cdot 2 \cdot 3 \cdot 1 \cdot 3 = 162$

Modified Morphological Analysis:
Successive combination (in „best“ order) followed by immediate down selection => 18


BARUA, P; SCHOLZ, D.: Systematic Approach to Analyze, Evaluate and Select Box Wing Aircraft Configurations from Modified Morphological Matrices. TN, HAW Hamburg, 2013
### Box Wing Aircraft

<table>
<thead>
<tr>
<th>Box wing with different wing vertical position</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Low – High Position</strong></td>
<td><strong>Low – Super High Position</strong></td>
</tr>
<tr>
<td><img src="image1" alt="OpenVSP front view figure" /></td>
<td><img src="image2" alt="OpenVSP front view figure" /></td>
</tr>
</tbody>
</table>

### Horizontal tail surface position along the fuselage length

<table>
<thead>
<tr>
<th>Canard</th>
<th>No Horizontal tail</th>
<th>Horizontal surface</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image5" alt="OpenVSP 3-D figure" /></td>
<td><img src="image6" alt="OpenVSP 3-D figure" /></td>
<td><img src="image7" alt="OpenVSP 3-D figure" /></td>
</tr>
</tbody>
</table>

### Engine positions for box wing aircraft

<table>
<thead>
<tr>
<th>Fuselage Aft</th>
<th>Fuselage Middle</th>
<th>On the wing</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image8" alt="OpenVSP 3-D figure" /></td>
<td><img src="image9" alt="OpenVSP 3-D figure" /></td>
<td><img src="image10" alt="OpenVSP 3-D figure" /></td>
</tr>
</tbody>
</table>

All possible variations together would lead to 31104 000 combinations (from Bachelor thesis)
Box Wing Aircraft
Box Wing Aircraft
Box Wing Aircraft: General Morphological Analysis

German: „Nutzwertanalyse“ (ZANGEMEISTER): Weighted Sum of Evaluation Points

- Configuration
  - Force Fighting
  - Family Concept
- Drag
  - Zero Lift Drag
  - Induced Drag
- Weight
  - Empty Weight
- Flight Mechanics
  - Longitudinal Static Stability and CG Range
- Operation
  - Ground Handling
- Development
  - Time and Cost
  - Risk
Box Wing Aircraft: General Morphological Analysis: Results

1.  

2.  

3.  

Best unconventional configuration
Box Wing Aircraft: Aerodynamics

Measurements of induced drag of different box wings in the wind tunnel of HAW Hamburg

The reference wing

Box Wing Aircraft: Aerodynamics

\[
\frac{D_{i,\text{box}}}{D_{i,\text{ref}}} = \frac{e_{\text{ref}}}{e_{\text{box}}} = k
\]

**Box Wing Aircraft: Glide Ratio**

For $E_{\text{max}}$: $C_{D0} = C_{Di}$

Considering a ratio $h/b = 1$, it yields to $C_{Di,BW}/C_{Di,\text{ref}} \approx 0.5$:

- Box Wing flies at reference Aircraft Altitude
  \[
  \frac{E_{\text{max}, BW}}{E_{\text{max}, \text{ref}}} = \frac{4}{3} = 1.33
  \]

- Reference Aircraft flies at Box Wing Altitude
  \[
  \frac{E_{\text{max}, BW}}{E_{\text{max}, \text{ref}}} = \frac{3}{2} = 1.5
  \]

- "Fair" comparison:
  \[
  \frac{E_{\text{max}, BW}}{E_{\text{max}, \text{ref}}} = \sqrt{2} = 1.41
  \]

Considering a realistic ratio $h/b = 0.25$, it yields to $C_{Di,BW}/C_{Di,\text{ref}} \approx 0.75$:

\[
\frac{E_{\text{max}, BW}}{E_{\text{max}, \text{ref}}} = 1.15
\]

---

**Glide ratio of a Box Wing Aircraft is 15 % higher than that of the reference aircraft**

---

Box Wing Aircraft: Longitudinal Static Stability

Stability Limit

\[ h < h_0 + \frac{dC_{L,2}}{dC_L} \cdot \frac{V'}{c_c} \]

h: C/G position as multiple of the length of MAC1, measured from the leading edge of MAC1

Control Limit

\[ C_{L,2} \text{ needs to be low. Thus for a given } C_L \]
\[ C_{L,1} \text{ needs to be increased} \]

Trim Condition

\[ C_{L,2} \text{ needs to be lower than } C_{L,1} \Rightarrow \frac{C_{L,1}}{C_{L,2}} > 1 \]

Forward wing needs higher lift coefficient than aft wing

Munk: drag independent of stagger

Box Wing Aircraft: Aerodynamics

Prandtl (for h/b = infinity):

\[
\frac{C_{D,i}}{C_{D,i,\text{min}}} = \frac{2 \left( x^2 + 1 \right)}{(x + 1)^2} \quad \text{with} \quad x = \frac{C_{L,1}}{C_{L,2}}
\]

**Induced drag increases if lift coefficients are different**

LOCKHEED: Transonic Biplane Concepts. NACA CR 132462, 1974

Box Wing Aircraft: Aerodynamics

Sensitivity of induced drag to non-optimum lift distributions (Tornado)

If the low wing is in front => No induced drag increase!
**Box Wing Aircraft: Cabin and Fuselage Layout (Wide Body)**


Box Wing Aircraft: Design Evolution (Wide Body)

- Ideally: $\frac{E_{\text{max, BW}}}{E_{\text{max, ref}}} = 1.5$
- Fair comparison: $\frac{E_{\text{max, BW}}}{E_{\text{max, ref}}} = 1.41$
- Limited h/b ratio: $\frac{E_{\text{max, BW}}}{E_{\text{max, ref}}} = 1.15$
- Disadvantages outweigh advantages: $\frac{m_{\text{OE, BW}}}{m_{\text{OE, ref}}} = 1.4$
- Thin wings: $\frac{m_{\text{W, BW}}}{m_{\text{W, ref}}} = 2.2$
- Snowball effects: $\frac{m_{\text{OE, BW}}}{m_{\text{OE, ref}}} = 1.4$
- Calibration: $\frac{m_{\text{OE, ref}}}{m_{\text{OE, handbook}}} = 1.16$
- DOC $\frac{m_{\text{D, BW}}}{m_{\text{D, ref}}} = 1.1$
- DOC $\frac{DOC_{\text{BW}}}{DOC_{\text{ref}}} = 1.19$

### Box Wing Aircraft: Results (Wide Body)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Deviation from A320*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main aircraft parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{MTO}$</td>
<td>89600 kg</td>
<td>+22 %</td>
</tr>
<tr>
<td>$m_{DE}$</td>
<td>55800 kg</td>
<td>+35 %</td>
</tr>
<tr>
<td>$m_{F}$</td>
<td>14500 kg</td>
<td>+12 %</td>
</tr>
<tr>
<td>$S_W$</td>
<td>155 m²</td>
<td>+27 %</td>
</tr>
<tr>
<td>$b_{W,geo}$</td>
<td>35.9 m</td>
<td>+5 %</td>
</tr>
<tr>
<td>$A_{W,eff}$</td>
<td>18.9</td>
<td>+99 %</td>
</tr>
<tr>
<td>$E_{max}$</td>
<td>19.5</td>
<td>≈+11 %</td>
</tr>
<tr>
<td>$T_{TO}$</td>
<td>134 kN</td>
<td>+21 %</td>
</tr>
<tr>
<td>BPR</td>
<td>6</td>
<td>+0 %</td>
</tr>
<tr>
<td>SFC</td>
<td>1.62E-5 kg/N/s</td>
<td>-2 %</td>
</tr>
<tr>
<td>$h_{ICA}$</td>
<td>40700 ft</td>
<td>+5 %</td>
</tr>
<tr>
<td>$s_{TOFL}$</td>
<td>1770 m</td>
<td>0 %</td>
</tr>
<tr>
<td>$s_{LFL}$</td>
<td>1450 m</td>
<td>0 %</td>
</tr>
<tr>
<td>$t_{TA}$</td>
<td>25 min</td>
<td>0 %</td>
</tr>
</tbody>
</table>

**Requirements**

- $m_{MPL}$: 19256 kg, 0 %
- $R_{MPL}$: 1510 NM, 0 %
- $M_{CR}$: 0.76, 0 %
- $max(s_{TOFL}, s_{LFL})$: 1770 m, 0 %
- $n_{PAX}$ (1-cl HD): 180, 0 %
- $m_{PAX}$: 93 kg, 0 %
- $SP$: 29 in, 0 %
Box Wing Aircraft: Results (Wide Body)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Deviation from A320*</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOC mission requirements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_{DOC}$</td>
<td>755 NM</td>
<td>0 %</td>
</tr>
<tr>
<td>$m_{PL,DOC}$</td>
<td>19256 kg</td>
<td>0 %</td>
</tr>
<tr>
<td>EIS</td>
<td>2030</td>
<td>--</td>
</tr>
<tr>
<td>$c_{fuel}$</td>
<td>1.44 USD/kg</td>
<td>0 %</td>
</tr>
<tr>
<td>Results</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{F,trip}$</td>
<td>6425 kg</td>
<td>+ 10 %</td>
</tr>
<tr>
<td>$U_{af}$</td>
<td>2617 h</td>
<td>- 10 %</td>
</tr>
<tr>
<td>DOC (AEA)</td>
<td>119 %</td>
<td>+ 19 %</td>
</tr>
</tbody>
</table>

Operating empty mass breakdown:
- Fwd wing: 13%
- Aft wing: 15%
- Winglets: 6%
- Fuselage: 23%
- V-Tail: 1%
- Engines: 18%
- Landing gear: 5%
- Systems: 5%
- Operator’s items: 6%

Component drag breakdown:
- Fwd wing: 47%
- Aft wing: 11%
- Winglets: 9%
- Fuselage: 13%
- V-Tail: 16%
- Engines: 4%

Direct operating cost breakdown:
- Depreciation: 27%
- Interest: 1%
- Insurance: 15%
- Fuel: 6%
- Maintenance: 1%
- Crew: 9%
- Fees: 29%
### Box Wing Aircraft: Results (Slender Body)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Deviation from A320*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Requirements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{\text{MPL}}$</td>
<td>19256 kg</td>
<td>0 %</td>
</tr>
<tr>
<td>$R_{\text{MPL}}$</td>
<td>1510 NM</td>
<td>0 %</td>
</tr>
<tr>
<td>$M_{\text{CR}}$</td>
<td>0.76</td>
<td>0 %</td>
</tr>
<tr>
<td>$\max(s_{\text{TOFL}}, s_{\text{LFL}})$</td>
<td>1770 m</td>
<td>0 %</td>
</tr>
<tr>
<td>$n_{\text{PAX}}$ (1-cl HD)</td>
<td>180</td>
<td>0 %</td>
</tr>
<tr>
<td>$m_{\text{PAX}}$</td>
<td>93 kg</td>
<td>0 %</td>
</tr>
<tr>
<td>$\text{SP}$</td>
<td>29 in</td>
<td>0 %</td>
</tr>
</tbody>
</table>

### Main aircraft parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Deviation from A320*</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{\text{MTO}}$</td>
<td>90900 kg</td>
<td>+ 24 %</td>
</tr>
<tr>
<td>$m_{\text{DE}}$</td>
<td>57700 kg</td>
<td>+ 40 %</td>
</tr>
<tr>
<td>$m_{\text{F}}$</td>
<td>14000 kg</td>
<td>+ 7 %</td>
</tr>
<tr>
<td>$S_{\text{W}}$</td>
<td>153 m$^2$</td>
<td>+ 26 %</td>
</tr>
<tr>
<td>$b_{\text{W,geo}}$</td>
<td>36.0 m</td>
<td>+ 5 %</td>
</tr>
<tr>
<td>$A_{\text{W,eff}}$</td>
<td>17.0</td>
<td>+ 79 %</td>
</tr>
<tr>
<td>$E_{\text{max}}$</td>
<td>21.4</td>
<td>$\approx$ + 21 %</td>
</tr>
<tr>
<td>$T_{\text{TO}}$</td>
<td>136 kN</td>
<td>+ 22 %</td>
</tr>
<tr>
<td>$BPR$</td>
<td>6</td>
<td>+ 0 %</td>
</tr>
<tr>
<td>$SFC$</td>
<td>1.62E-5 kg/N/s</td>
<td>- 2 %</td>
</tr>
<tr>
<td>$h_{\text{ICA}}$</td>
<td>41900 ft</td>
<td>+ 8 %</td>
</tr>
<tr>
<td>$s_{\text{TOFL}}$</td>
<td>1770 m</td>
<td>0 %</td>
</tr>
<tr>
<td>$s_{\text{LFL}}$</td>
<td>1450 m</td>
<td>0 %</td>
</tr>
<tr>
<td>$t_{\text{TA}}$</td>
<td>32 min</td>
<td>0 %</td>
</tr>
</tbody>
</table>

**Add. tank:** 14 m$^3$
### Box Wing Aircraft: Results (Slender Body)

#### Parameter | Value | Deviation from A320* |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DOC mission requirements</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_{DOC}$</td>
<td>755 NM</td>
<td>0 %</td>
</tr>
<tr>
<td>$m_{PL,DOC}$</td>
<td>19256 kg</td>
<td>0 %</td>
</tr>
<tr>
<td><strong>EIS</strong></td>
<td>2030</td>
<td>----</td>
</tr>
<tr>
<td>$c_{fuel}$</td>
<td>1.44 USD/kg</td>
<td>0 %</td>
</tr>
<tr>
<td><strong>Results</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{E,trip}$</td>
<td>6242 kg</td>
<td>+ 7 %</td>
</tr>
<tr>
<td>$U_{A_f}$</td>
<td>2617 h</td>
<td>- 10 %</td>
</tr>
<tr>
<td>DOC (AEA)</td>
<td>120 %</td>
<td>+ 20 %</td>
</tr>
</tbody>
</table>

#### Operating empty mass breakdown
- Fuel wing: 23%
- Alt wing: 14%
- Winglets: 6%
- Finsage: 1%
- V Tail: 5%
- Engines: 18%
- Landing gear: 5%
- Systems: 15%
- Operator’s items: 4%

#### Component drag breakdown
- Fuel wing: 11%
- Alt wing: 12%
- Winglets: 17%
- Finsage: 29%
- V Tail: 35%
- Engines: 6%

#### Direct operating cost breakdown
- Depreciation: 16%
- Interest: 13%
- Insurance: 11%
- Fuel: 6%
- Maintenance: 5%
- Crew: 9%
- Fees: 28%
Box Wing Aircraft: Family Concept (Wide Body)

**Box Wing**
*General Familiarization*

**Twin Aisle Family Highlights**

Two-class seating

<table>
<thead>
<tr>
<th></th>
<th>218</th>
<th>V200 +6 frames</th>
<th></th>
<th>V100</th>
<th>V200</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>base</td>
<td>33.1 m</td>
<td>37.21 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Underfloor Volume</td>
<td>34.17 m$^3$</td>
<td>38.42 m$^3$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Longitudinal distance from AC1 to AC2 (F)</td>
<td>12.50 m</td>
<td>15.50 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Winglets Sweep (at 25% chord)</td>
<td>28.67$^\circ$</td>
<td>43.44$^\circ$</td>
</tr>
</tbody>
</table>

Box Wing Aircraft: Family Concept (Slender Body)

**Box Wing**
*General Familiarization*

**Single Aisle Family Highlights**

**Two-class seating**

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
<th>S2</th>
<th>+8 frames</th>
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<tr>
<td>178</td>
<td>178</td>
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<td></td>
</tr>
<tr>
<td>150</td>
<td>base</td>
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<td></td>
</tr>
<tr>
<td>126</td>
<td>S1</td>
<td></td>
<td>~4 frames</td>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>base</th>
<th>S100</th>
<th>S200</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuselage Length</strong></td>
<td>37.44 m</td>
<td>34.09 m</td>
<td>41.51 m</td>
</tr>
<tr>
<td><strong>Underfloor Volume</strong></td>
<td>38.66 m³</td>
<td>35.20 m³</td>
<td>42.86 m³</td>
</tr>
<tr>
<td><strong>Longitudinal distance from AC1 to AC2 (1')</strong></td>
<td>14 m</td>
<td>12.9 m</td>
<td>16 m</td>
</tr>
<tr>
<td><strong>Winglets Sweep</strong> (at 25% chord)</td>
<td>36.76°</td>
<td>30.87°</td>
<td>45.38°</td>
</tr>
</tbody>
</table>
Box Wing Aircraft: Ground Handling

Box Wing Aircraft: Flying Qualities Calculation, Flight Simulation

Dutch Roll Mode:
Damping versus Frequency

$h = 0 \text{ km} \ldots 13 \text{ km}$,  
$V = 100 \text{ m/s} \ldots 240 \text{ m/s}$


Summary

• Ground handling needs to be robust – it is NOT a financial game changer

• 36 m requirement for max. wing span in Class C drives the design today!

• Standard Jet Configuration, "The Rebel":
  • Challenges only requirements (wing span, take-off distance, cruise Mach number), no new technology!
  • Optimized for minimum fuel: => 36 % less fuel consumption, 7% less DOC.

• "Smart Turboprop":
  • Efficient engine combined with braced wing and natural laminar flow on wing.
  • Meeting all standard requirements! Optimized for (lower) cruise Mach number.
  • Optimized for minimum DOC: => 36 % less fuel consumption, 17 % less DOC.

• "Box Wing Aircraft":
  • This may be the best Box Wing configuration:
  • But nevertheless: No advantage in DOC or fuel burn compared to baseline.
Outlook

Integration of Life Cycle Assessment into Conceptual Aircraft Design
→ Optimization for minimum environmental impact

Contribution of different in- and outputs to the environmental impact of an Airbus A320-200

Contribution of the endpoint categories to the environmental impact of an Airbus A320-200

Cooperative PhD Thesis in progress:
Life-cycle based Multidisciplinary Aircraft Design Optimization for Future Scenarios

More information:

http://Airport2030.ProfScholz.de

info@ProfScholz.de
References

This presentation is based on AERO's extensive publications and student's contributions as mentioned on the slides. Please see also at http://Airport2030.ProfScholz.de and http://library.ProfScholz.de


The method for aircraft optimization is described in Chapter 6 of:


The "Smart Turboprop" is optimized with an extension to OPerA, called PrOPerA by Andreas Johanning.


## Appendix

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Explanation</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Requirements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{\text{MPL}}$</td>
<td>Maximum payload [kg]</td>
<td>---</td>
</tr>
<tr>
<td>$R_{\text{MPL}}$</td>
<td>Maximum range [kg] (with maximum payload)</td>
<td>---</td>
</tr>
<tr>
<td>$M_{\text{CR}}$</td>
<td>Cruise Mach number</td>
<td>---</td>
</tr>
<tr>
<td>max($s_{\text{TOFL}}$, $s_{\text{LFL}}$)</td>
<td>Maximum take-off and landing field length [m]</td>
<td>Requirement for the maximum allowable take-off and landing field length</td>
</tr>
<tr>
<td>$n_{\text{PAX}}$ (1-cl HD)</td>
<td>Number of passengers</td>
<td>one class, high density layout</td>
</tr>
<tr>
<td>$m_{\text{PAX}}$</td>
<td>Passenger mass [kg]</td>
<td>Mass of person, carry on baggage, and checked in baggage</td>
</tr>
<tr>
<td>$SP$</td>
<td>Seat pitch [in]</td>
<td>Seat pitch for the one class high-density layout</td>
</tr>
</tbody>
</table>

- Most of the given values are rounded
- The given deviation refers to the real values and not to the rounded values
## Appendix

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Explanation</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_{\text{MTO}} )</td>
<td>Maximum take-off mass [kg]</td>
<td>---</td>
</tr>
<tr>
<td>( m_{\text{OE}} )</td>
<td>Operating empty mass [kg]</td>
<td>---</td>
</tr>
<tr>
<td>( m_F )</td>
<td>Fuel mass [kg]</td>
<td>For required payload and range combination</td>
</tr>
<tr>
<td>( S_W )</td>
<td>Wing area [m²]</td>
<td>---</td>
</tr>
<tr>
<td>( b_{W,\text{geo}} )</td>
<td>Geometrical span [m]</td>
<td>---</td>
</tr>
<tr>
<td>( A_{W,\text{eff}} )</td>
<td>Effective aspect ratio [-]</td>
<td>---</td>
</tr>
<tr>
<td>( E_{\text{max}} )</td>
<td>Maximum glide ratio [-]</td>
<td>---</td>
</tr>
<tr>
<td>( T_{\text{TO}} )</td>
<td>Take-off thrust for each engine [N]</td>
<td>---</td>
</tr>
<tr>
<td>( P_{\text{eq,ssl}} )</td>
<td>Equivalent take-off power at static sea level [kW]</td>
<td>---</td>
</tr>
<tr>
<td>( BPR )</td>
<td>Bypass-Ratio [-]</td>
<td>---</td>
</tr>
<tr>
<td>( d_{\text{prop}} )</td>
<td>Propeller diameter [m]</td>
<td>---</td>
</tr>
<tr>
<td>( \eta_{\text{prop}} )</td>
<td>Propeller efficiency [%]</td>
<td>---</td>
</tr>
<tr>
<td>( SFC )</td>
<td>Thrust specific fuel consumption [kg/N/s]</td>
<td>---</td>
</tr>
<tr>
<td>( PSFC )</td>
<td>Power specific fuel consumption [kg/W/s]</td>
<td>---</td>
</tr>
<tr>
<td>( h_{\text{ICA}} )</td>
<td>Initial cruise altitude [m]</td>
<td>---</td>
</tr>
<tr>
<td>( s_{\text{TOFL}} )</td>
<td>Take-off field length [m]</td>
<td>---</td>
</tr>
<tr>
<td>( s_{\text{LFL}} )</td>
<td>Landing field length [m]</td>
<td>---</td>
</tr>
<tr>
<td>( t_{\text{TA}} )</td>
<td>Turnaround time [min]</td>
<td>---</td>
</tr>
</tbody>
</table>
## Appendix

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<thead>
<tr>
<th>Parameter</th>
<th>Explanation</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOC mission requirements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_{\text{DOC}}$</td>
<td>Range for the DOC calculation [NM]</td>
<td>---</td>
</tr>
<tr>
<td>$m_{\text{PL,DOC}}$</td>
<td>Payload mass for the DOC calculation [kg]</td>
<td>---</td>
</tr>
<tr>
<td>EIS</td>
<td>Entry into Service</td>
<td>---</td>
</tr>
<tr>
<td>$c_{\text{fuel}}$</td>
<td>Fuel cost [USD/kg]</td>
<td>Fuel costs are estimated for the entry into service</td>
</tr>
<tr>
<td>Results</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{\text{F,trip}}$</td>
<td>Fuel mass (for the DOC range) [kg]</td>
<td>----</td>
</tr>
<tr>
<td>$U_{\text{a,f}}$</td>
<td>Utilization [h]</td>
<td>Product of the number of flights per year and the duration of the flight on the DOC-range</td>
</tr>
<tr>
<td>DOC (AEA)</td>
<td>Direct Operating Costs</td>
<td>DOC calculated using the method of the Association of European Airlines</td>
</tr>
</tbody>
</table>
Appendix

Additional Parameters – Standard Jet Configuration: "The Rebel"

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Explanation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cabin</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( w_{\text{aisle}} )</td>
<td>Aisle width</td>
<td>8 in</td>
</tr>
<tr>
<td>( w_{\text{seat}} )</td>
<td>Seat width</td>
<td>17 in</td>
</tr>
<tr>
<td>( w_{\text{armrest}} )</td>
<td>Armrest width</td>
<td>1.6 in</td>
</tr>
<tr>
<td>( s_{\text{clearance}} )</td>
<td>Sidewall clearance</td>
<td>0.5 in</td>
</tr>
<tr>
<td>Wing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \varphi_{25} )</td>
<td>Wing sweep at 25 % chord</td>
<td>10°</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>Wing taper ratio</td>
<td>0.25</td>
</tr>
<tr>
<td>Vertical tail</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( S_V )</td>
<td>Vertical tail area</td>
<td>15.8 m²</td>
</tr>
<tr>
<td>( \varphi_{25,V} )</td>
<td>Vertical tail sweep at 25 % chord</td>
<td>30°</td>
</tr>
<tr>
<td>( \lambda_V )</td>
<td>Vertical tail taper ratio</td>
<td>0.34</td>
</tr>
<tr>
<td>Horizontal tail</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( S_H )</td>
<td>Horizontal tail area</td>
<td>5.7 m²</td>
</tr>
<tr>
<td>( \varphi_{25,H} )</td>
<td>Horizontal tail sweep at 25 % chord</td>
<td>13°</td>
</tr>
<tr>
<td>( \lambda_H )</td>
<td>Horizontal tail taper ratio</td>
<td>0.32</td>
</tr>
<tr>
<td>DOC</td>
<td></td>
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<tr>
<td>( k_{\text{delivery,OE}} )</td>
<td>Delivery price per kg m_{OE}</td>
<td>1602 USD/kg</td>
</tr>
</tbody>
</table>
Appendix
Additional Parameters – Standard Jet Configuration: "The Rebel"

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Explanation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero lift &amp; wave drag</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_{D,0}$</td>
<td>Zero lift drag</td>
<td>221 drag counts</td>
</tr>
<tr>
<td>$C_{D,W}$</td>
<td>Wave drag</td>
<td>10 drag counts</td>
</tr>
<tr>
<td>Induced drag</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a_e$</td>
<td></td>
<td>-0.00152</td>
</tr>
<tr>
<td>$b_e$</td>
<td></td>
<td>10.82</td>
</tr>
<tr>
<td>$c_e$</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>$M_{comp}$</td>
<td>Highest Mach number without compressibility effects</td>
<td>0.3</td>
</tr>
<tr>
<td>$Q$</td>
<td></td>
<td>1.08</td>
</tr>
<tr>
<td>$P$</td>
<td></td>
<td>0.0088</td>
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<tr>
<td>$A_{W,eff}$</td>
<td>Effective aspect ratio of the wing</td>
<td>34.8</td>
</tr>
<tr>
<td>$c_{f_e}$</td>
<td>Correction factor for Oswald factor</td>
<td>1.17</td>
</tr>
</tbody>
</table>

$$e = \frac{k_{e,M}}{Q + P \cdot \pi \cdot A_{W,eff}}$$

$$k_{e,M} = a_e \left( \frac{M}{M_{comp}} - 1 \right)^{b_e} + c_e$$

### Appendix

#### Additional Parameters – Smart Turboprop

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Explanation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cabin</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$w_{\text{aisle}}$</td>
<td>Aisle width</td>
<td>20 in</td>
</tr>
<tr>
<td>$w_{\text{seat}}$</td>
<td>Seat width</td>
<td>20 in</td>
</tr>
<tr>
<td>$w_{\text{armrest}}$</td>
<td>Armrest width</td>
<td>2 in</td>
</tr>
<tr>
<td>$s_{\text{clearance}}$</td>
<td>Sidewall clearance</td>
<td>0.6 in</td>
</tr>
<tr>
<td><strong>Wing</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\varphi_{25}$</td>
<td>Wing sweep at 25% chord</td>
<td>6°</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Wing taper ratio</td>
<td>0.20</td>
</tr>
<tr>
<td><strong>Vertical tail</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_V$</td>
<td>Vertical tail area</td>
<td>19.3 m²</td>
</tr>
<tr>
<td>$\varphi_{25,V}$</td>
<td>Vertical tail sweep at 25% chord</td>
<td>28°</td>
</tr>
<tr>
<td>$\lambda_V$</td>
<td>Vertical tail taper ratio</td>
<td>0.69</td>
</tr>
<tr>
<td><strong>Horizontal tail</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_H$</td>
<td>Horizontal tail area</td>
<td>12.4 m²</td>
</tr>
<tr>
<td>$\varphi_{25,H}$</td>
<td>Horizontal tail sweep at 25% chord</td>
<td>9°</td>
</tr>
<tr>
<td>$\lambda_H$</td>
<td>Horizontal tail taper ratio</td>
<td>0.25</td>
</tr>
<tr>
<td><strong>DOC</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$k_{\text{delivery,OE}}$</td>
<td>Delivery price per kg mOE</td>
<td>1602 USD/kg</td>
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## Appendix
### Additional Parameters – Smart Turboprop

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Explanation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero lift &amp; wave drag</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_{D,0}$</td>
<td>Zero lift drag</td>
<td>314 drag counts</td>
</tr>
<tr>
<td>$C_{D,W}$</td>
<td>Wave drag</td>
<td>0 drag counts</td>
</tr>
<tr>
<td>Induced drag</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a_e$</td>
<td>---</td>
<td>-0.00152</td>
</tr>
<tr>
<td>$b_e$</td>
<td>---</td>
<td>10.82</td>
</tr>
<tr>
<td>$c_e$</td>
<td>---</td>
<td>1</td>
</tr>
<tr>
<td>$M_{comp}$</td>
<td>Highest Mach number without compressibility effects</td>
<td>0.3</td>
</tr>
<tr>
<td>$Q$</td>
<td>---</td>
<td>1.08</td>
</tr>
<tr>
<td>$p$</td>
<td>---</td>
<td>0.0119</td>
</tr>
<tr>
<td>$A_{W,eff}$</td>
<td>Effective aspect ratio of the wing</td>
<td>14.9</td>
</tr>
<tr>
<td>$c_{f_e}$</td>
<td>Correction factor for Oswald factor</td>
<td>1.56</td>
</tr>
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</table>

$$e = \frac{k_{e,M}}{Q + P \cdot \pi \cdot A_{W,eff}}$$

$$k_{e,M} = a_e \left( \frac{M}{M_{comp}} - 1 \right)^{b_e} + c_e$$

Appendix
Additional Parameters – Box Wing Aircraft (Wide Body)

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<tr>
<th>Parameter</th>
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<tbody>
<tr>
<td>Cabin</td>
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<tr>
<td>$w_{\text{aisle}}$</td>
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</tr>
<tr>
<td>$w_{\text{seat}}$</td>
<td>Seat width</td>
<td>20 in</td>
</tr>
<tr>
<td>$w_{\text{armrest}}$</td>
<td>Armrest width</td>
<td>2 in</td>
</tr>
<tr>
<td>$s_{\text{clearance}}$</td>
<td>Sidewall clearance</td>
<td>0.6 in</td>
</tr>
<tr>
<td>Wing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\phi_{25,\text{FW}}$</td>
<td>Forward wing sweep at 25 % chord</td>
<td>29°</td>
</tr>
<tr>
<td>$\lambda_{\text{FW}}$</td>
<td>Forward wing taper ratio</td>
<td>0.24</td>
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<tr>
<td>$\phi_{25,\text{AW}}$</td>
<td>Aft wing sweep at 25 % chord</td>
<td>-28°</td>
</tr>
<tr>
<td>$\lambda_{\text{AW}}$</td>
<td>Aft wing taper ratio</td>
<td>0.80</td>
</tr>
<tr>
<td>V-tail</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_{V}$</td>
<td>V-tail area</td>
<td>25 m²</td>
</tr>
<tr>
<td>$\phi_{25,V}$</td>
<td>V-tail sweep at 25 % chord</td>
<td>-30°</td>
</tr>
<tr>
<td>$\lambda_{V}$</td>
<td>V-tail taper ratio</td>
<td>0.50</td>
</tr>
<tr>
<td>DOC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$k_{\text{delivery,OE}}$</td>
<td>Delivery price per kg m$^{\text{OE}}$</td>
<td>1602 USD/kg</td>
</tr>
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<tr>
<th>Parameter</th>
<th>Explanation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero lift &amp; wave drag</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( C_{D,0} )</td>
<td>Zero lift drag</td>
<td>179 drag counts</td>
</tr>
<tr>
<td>( C_{D,W} )</td>
<td>Wave drag</td>
<td>10 drag counts</td>
</tr>
<tr>
<td>Induced drag</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( e_{\text{ref}} )</td>
<td>---</td>
<td>0.85</td>
</tr>
<tr>
<td>( k_1 )</td>
<td>---</td>
<td>1.04</td>
</tr>
<tr>
<td>( k_2 )</td>
<td>---</td>
<td>0.57</td>
</tr>
<tr>
<td>( k_3 )</td>
<td>---</td>
<td>1.04</td>
</tr>
<tr>
<td>( k_4 )</td>
<td>---</td>
<td>2.13</td>
</tr>
<tr>
<td>( h/b )</td>
<td>---</td>
<td>0.22</td>
</tr>
</tbody>
</table>

\[
e_{\text{box}} = e_{\text{ref}} \cdot \frac{e_{NP}}{e}
\]

\[
e_{NP} = \frac{k_3 + k_4 \cdot \frac{h}{b}}{k_1 + k_2 \cdot \frac{h}{b}}
\]

### Appendix

**Additional Parameters – Box Wing Aircraft (Slender Body)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Explanation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cabin</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$w_{\text{aisle}}$</td>
<td>Aisle width</td>
<td>20 in</td>
</tr>
<tr>
<td>$w_{\text{seat}}$</td>
<td>Seat width</td>
<td>20 in</td>
</tr>
<tr>
<td>$w_{\text{armrest}}$</td>
<td>Armrest width</td>
<td>2 in</td>
</tr>
<tr>
<td>$s_{\text{clearance}}$</td>
<td>Sidewall clearance</td>
<td>0.6 in</td>
</tr>
<tr>
<td><strong>Wing</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\varphi_{25,\text{FW}}$</td>
<td>Forward wing sweep at 25 % chord</td>
<td>35°</td>
</tr>
<tr>
<td>$\lambda_{\text{FW}}$</td>
<td>Forward wing taper ratio</td>
<td>0.9</td>
</tr>
<tr>
<td>$\varphi_{25,\text{AW}}$</td>
<td>Aft wing sweep at 25 % chord</td>
<td>-15°</td>
</tr>
<tr>
<td>$\lambda_{\text{AW}}$</td>
<td>Aft wing taper ratio</td>
<td>0.9</td>
</tr>
<tr>
<td><strong>V-tail</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_{\text{V}}$</td>
<td>V-tail area</td>
<td>36 m²</td>
</tr>
<tr>
<td>$\varphi_{25,\text{V}}$</td>
<td>V-tail sweep at 25 % chord</td>
<td>-37°</td>
</tr>
<tr>
<td>$\lambda_{\text{V}}$</td>
<td>V-tail taper ratio</td>
<td>0.41</td>
</tr>
<tr>
<td><strong>DOC</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$k_{\text{delivery,OE}}$</td>
<td>Delivery price per kg $m_{\text{OE}}$</td>
<td>1602 USD/kg</td>
</tr>
</tbody>
</table>
Appendix
Additional Parameters – Box Wing Aircraft (Slender Body)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Explanation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero lift &amp; wave drag</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_{D,0}$</td>
<td>Zero lift drag</td>
<td>154 drag counts</td>
</tr>
<tr>
<td>$C_{D,W}$</td>
<td>Wave drag</td>
<td>10 drag counts</td>
</tr>
<tr>
<td>Induced drag</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$e_{ref}$</td>
<td>---</td>
<td>0.85</td>
</tr>
<tr>
<td>$k_1$</td>
<td>---</td>
<td>1.04</td>
</tr>
<tr>
<td>$k_2$</td>
<td>---</td>
<td>0.57</td>
</tr>
<tr>
<td>$k_3$</td>
<td>---</td>
<td>1.04</td>
</tr>
<tr>
<td>$k_4$</td>
<td>---</td>
<td>2.13</td>
</tr>
<tr>
<td>$h/b$</td>
<td>---</td>
<td>0.25</td>
</tr>
</tbody>
</table>

$$e_{box} = e_{ref} \cdot \frac{e_{NP}}{e}$$

$$\frac{e_{NP}}{e} = \frac{k_3 + k_4 \cdot \frac{h}{b}}{k_1 + k_2 \cdot \frac{h}{b}}$$

Appendix

Additional Parameters – Box Wing Aircraft (Biplane)

Elena García Llorente:
Conceptual Design Optimization of Passenger Box Wing Aircraft in Biplane Layout.