Hochschule für Angewandte Wissenschaften Hamburg
Hamburg University of Applied Sciences

AIRCRAFT DESIGN AND SYSTEMS GROUP (AERO)

Smart Turboprop – A Possible A320 Successor

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Abstract

Economic Top Level Requirements (TLR) for the next generation of aircraft in the class of the B737 and A320 demand a minimum of 25% fuel burn reduction. These aircraft are built to ICAO airport requirements: Wing span of less than 36 m and field length less than 1800 m. An investigation was undertaken looking at 1.) an optimized standard jet configuration violating given ICAO airport requirements, 2.) a box wing configuration respecting ICAO airport requirements, and 3.) a "Smart Turboprop" flying lower/slower, including a Strut Braced Wing (SBW), and Natural Laminar Flow (NLF). All aircraft are optimized with Differential Evolution (DE) – a Genetic Algorithm (GA). The aircraft are modeled with a spread sheet. For the "Smart Turboprop" the best configuration was found to be one with T-Tail and two engines. It minimized the Direct Operating Costs (DOC) by almost 14 % (without SBW and without NLF). The DOC reduced by 17 % if SBW and NLF were also applied. Take-off mass reduced by 24 % and cruise Mach number (not a requirement) is down to 0.51. Fuel burn benefits could also be obtained even without a new aircraft: Proposed is a gentle violation of ICAO wing span limitations. Manufacturers offering aircraft that are wing span limited and equipped with winglets should offer (as option) also a wing span increase on both tips (by about the same amount as winglet height). Benefits come, because horizontal wing growth (wing span increase) is more efficient than vertical wing growth (winglets).

Airport2030

http://Airport2030.ProfScholz.de

↑ „Smart Turboprop“

FLIGHT INTERNATIONAL

Flightglobal
AVIATION CONNECTED

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. ■

Hamburg University of Applied Sciences

The project aims to explore a possible successor to the A320

14 | **Flight International** | 2-8 September 2014 flightglobal.com

Contents

Economic Top Level Requirements

Requirements at Airports

Range of Investigation

- **Standard Jet Configuration: A320 "Optimized"**
  - **Proposal: Horizontal Wing Tip Extension on A320 as Option**
- **Non-Standard Jet Configuration: Box Wing Aircraft**
- **Proposal: Standard Prop Configuration: Smart Turboprop**

Smart Turboprop: Results

Economic Top Level Requirements

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

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

SNECMA (Aviation Week & Space Technology, 2014-03-31) [1]:

"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! [2]

Annex 14 — Aerodromes *Volume I*

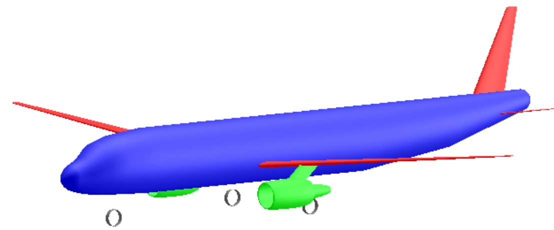
Table 1-1. Aerodrome reference code
(see 1.6.2 to 1.6.4)

Code element 1		Code element 2		
Code number (1)	Aeroplane reference field length (2)	Code letter (3)	Wing span (4)	Outer main gear wheel span[a] (5)
1	Less than 800 m	A	Up to but not including 15 m	Up to but not including 4.5 m
2	800 m up to but not including 1 200 m	B	15 m up to but not including 24 m	4.5 m up to but not including 6 m
3	1 200 m up to but not including 1 800 m	C	24 m up to but not including 36 m	6 m up to but not including 9 m
4	1 800 m and over	D	36 m up to but not including 52 m	9 m up to but not including 14 m
		E	52 m up to but not including 65 m	9 m up to but not including 14 m
		F	65 m up to but not including 80 m	14 m up to but not including 16 m

a. Distance between the outside edges of the main gear wheels.

Range of Investigation

- **Standard Jet Configuration**

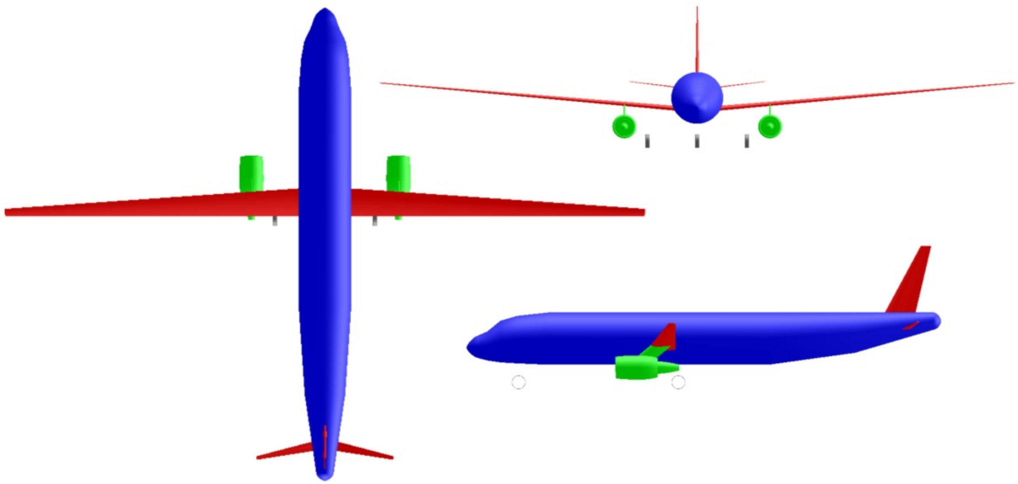


- **Non-Standard Jet Configuration**
  - Wide Body
  - Slender Body
  - Biplane Design, Tail Aft

- **Standard Prop Configuration**

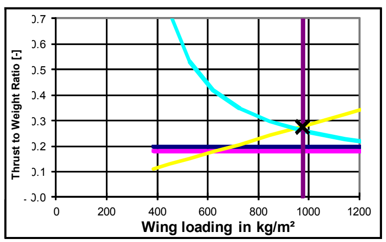
Genetic algorithm proposes parameters
Consistent aircraft „designed“ in EXCEL
Optimization for **minimum DOC**
About 2000 feasible designs tested in one run

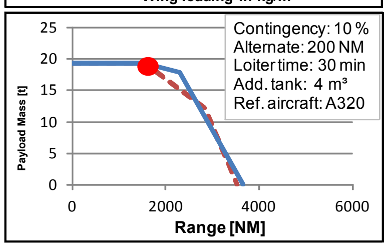
Standard Jet Configuration: A320 "optimized"



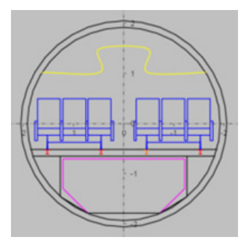
Early conceptual design

Parameter	Value	Deviation from A320*
Requirements		
m_{MPL}	19256 kg	0 %
R_{MPL}	1510 NM	0 %
M_{CR}	0.55	- 28 %
max(s_{TOFL} , s_{LFL})	2700 m	+ 53 %
n_{PAX} (1-cl HD)	180	0 %
m_{PAX}	93 kg	0 %
SP	28 in	- 3 %





Parameter	Value	Deviation from A320*
Main aircraft parameters		
m_{MTO}	66000 kg	- 10 %
m_{OE}	39200 kg	- 5 %
m_F	7500 kg	- 42 %
S_W	68 m²	- 45 %
$b_{W,geo}$	48.5 m	+ 42 %
$A_{W,eff}$	34.8	+ 266 %
E_{max}	26.1	+ 48 %
T_{TO}	89100 N	- 20 %
BPR	15.5	+ 158 %
SFC	1.03E-5 kg/N/s	- 37 %
h_{ICA}	30000 ft	- 23 %
s_{TOFL}	2490 m	+ 41 %
s_{LFL}	2110 m	+ 45 %
t_{TA}	32 min	0 %



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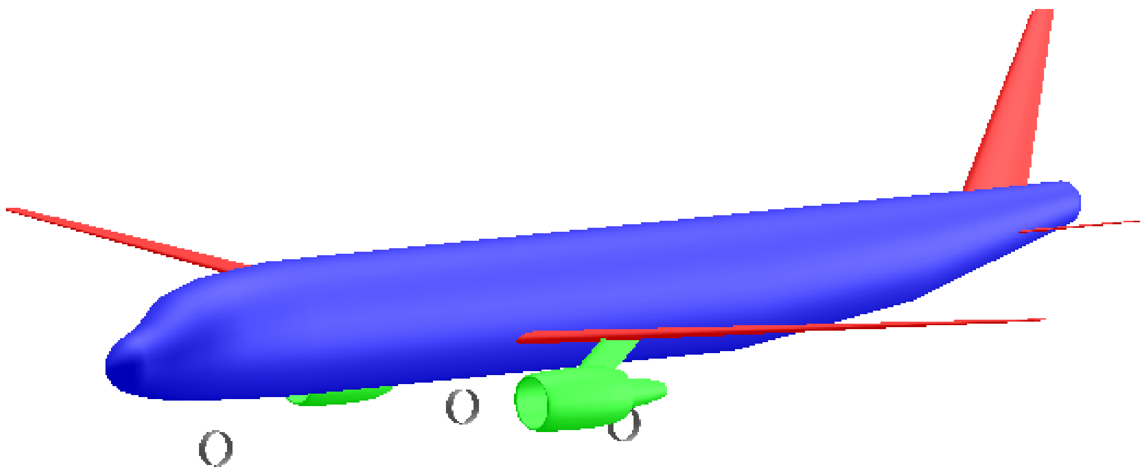
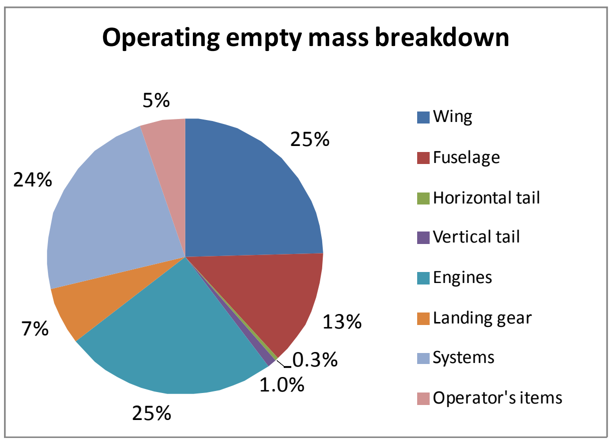
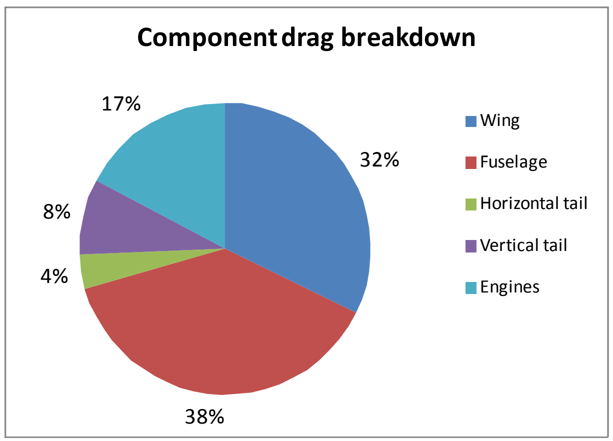
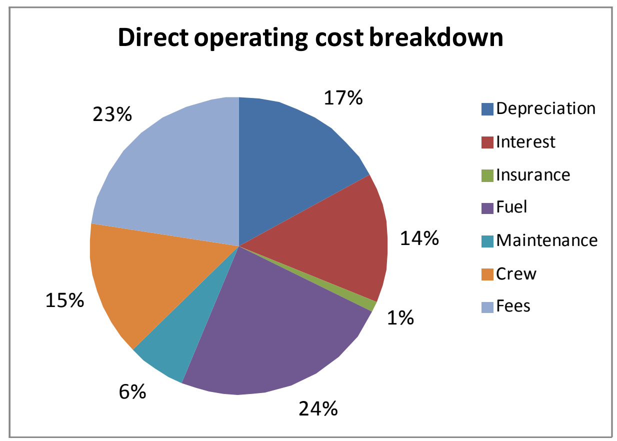
Standard Jet Configuration: A320 "optimized"



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



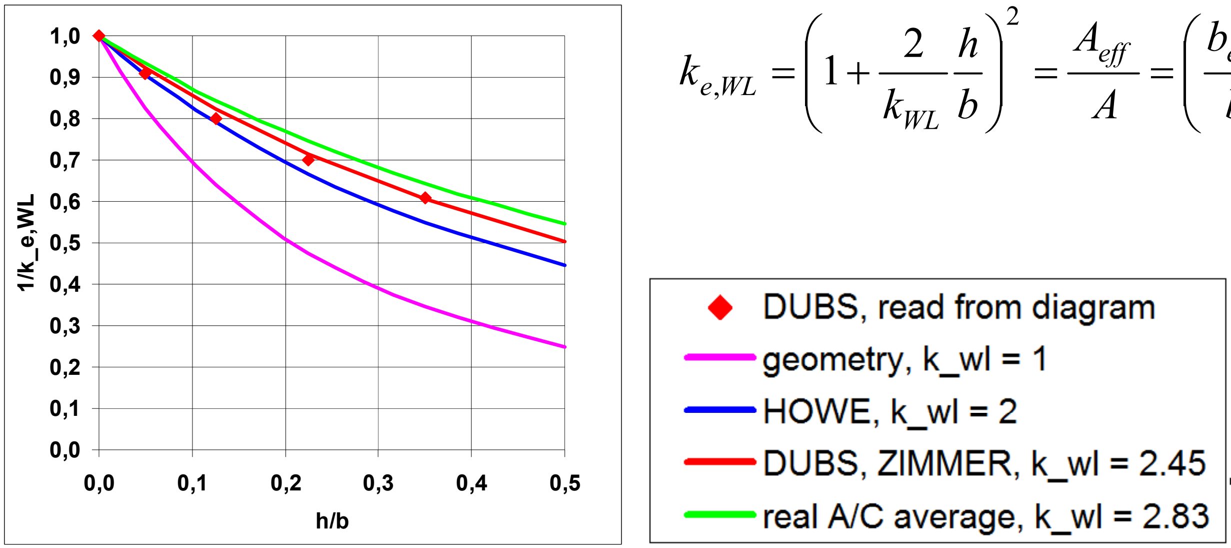




Proposal: Horizontal Wing Tip Extension on A320 as Option

Results from an *additional study* in Airport2030:
"Airport Compatibility of Medium Range Aircraft with Large Wing Span"

- **Wingtip devices: Very limited efficiency compared to the same length of material used to horizontally extend the wing** [3]



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

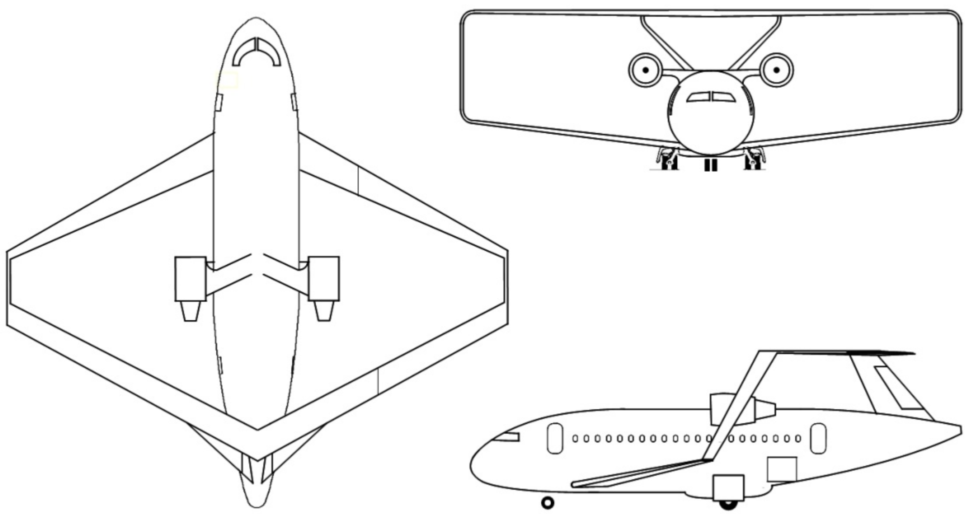
- **Consider this option: Extend the wing span and just deal with consequences at airports**

- **Airbus should also offer a horizontal wing tip extension as option**

Proposal: Horizontal Wing Tip Extension on A320 as Option

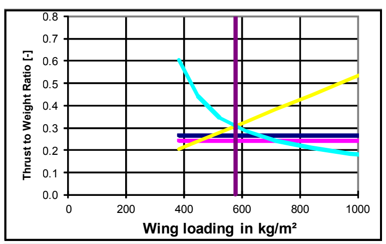
- **Optional horizontal wing tip extension limits risk and costs compared to a new wing**
- **A slow introduction of aircraft with larger wing span (Class C => Class D) will force airports to accept this**
- **Landing fees are based on MTOW and are hence unchanged**
- **Study** [4] **showed: Many airports 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**

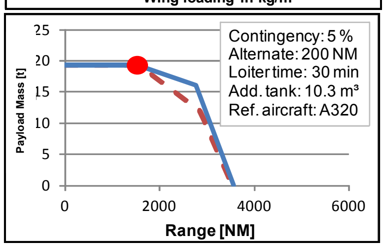
Non-Standard Jet Configuration: Box Wing Aircraft

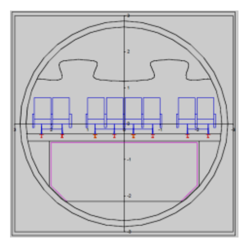


Parameter	Value	Deviation from A320*
Main aircraft parameters		
m_{MTO}	89600 kg	+ 22 %
m_{OE}	55800 kg	+ 35 %
m_F	14500 kg	+ 12 %
S_W	155 m²	+ 27 %
$b_{W,geo}$	35.9 m	+ 5 %
$A_{W,eff}$	18.9	+ 99 %
E_{max}	19.5	≈ + 11 %
T_{TO}	134 kN	+ 21 %
BPR	6	+ 0 %
SFC	1.62E-5 kg/N/s	- 2 %
h_{ICA}	40700 ft	+ 5 %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

Parameter	Value	Deviation from A320*
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 %







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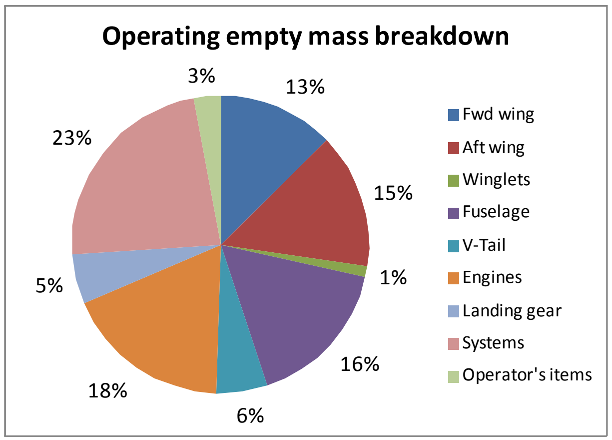
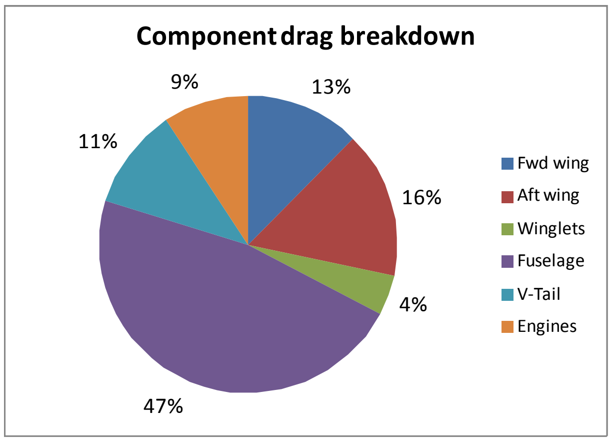
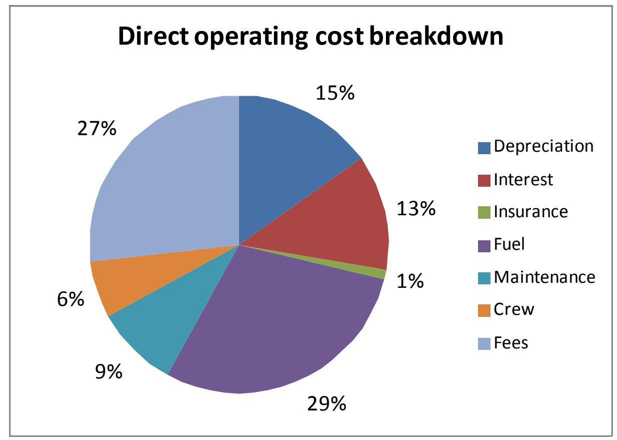
Box Wing Aircraft (Wide Body)

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







Proposals for a new A320: Standard Prop Configuration

- **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 → higher speed of sound → 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

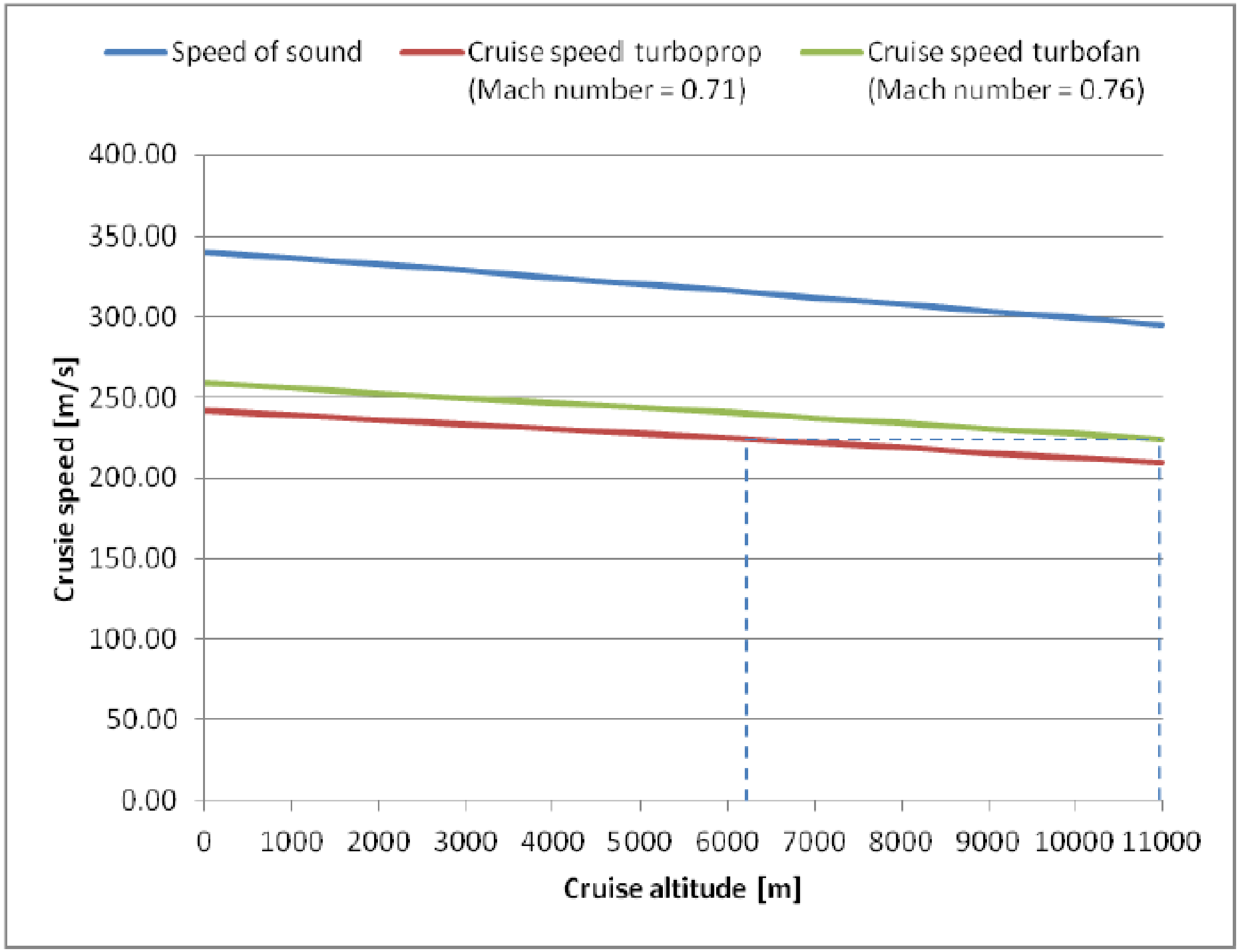
March 31, 2014
Graham Warwick, Aviation Week & Space Technology [1]

…

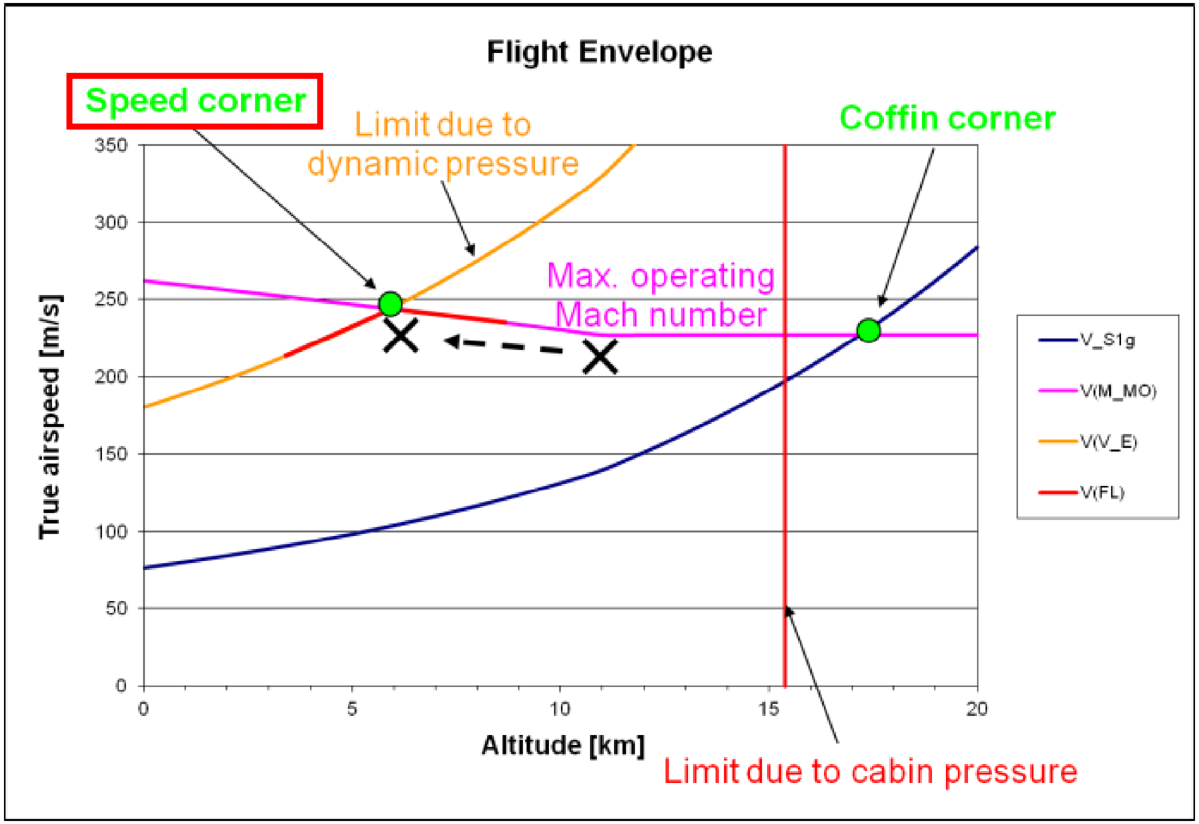
Key to economic viability will be the weight penalty incurred to **protect the aircraft from damage caused by a rotor burst or blade release**. A turbofan can contain a released blade, but an open rotor will require shielding of the airframe and systems. In Airbus's baseline concept, which has pusher 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 be released**.
- Mounting **engines on the aft fuselage** leads to overall **weight penalties** (c.g. shift …)

Low Flying – Similar Speed at Lower Mach Number



The „Speed Corner"



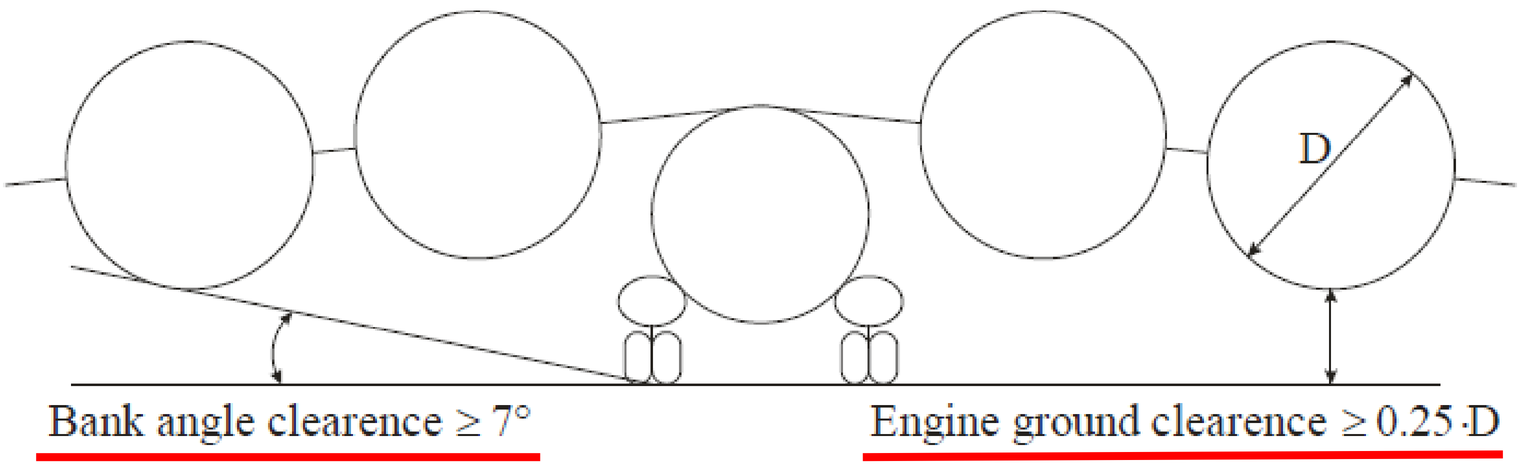
The altitude of the speed corner:

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

The true airspeed allowed in the speed corner:

$$V = M_{MO}\, a_0 \sqrt{1 - \frac{L h_{sc}}{T_0}}$$

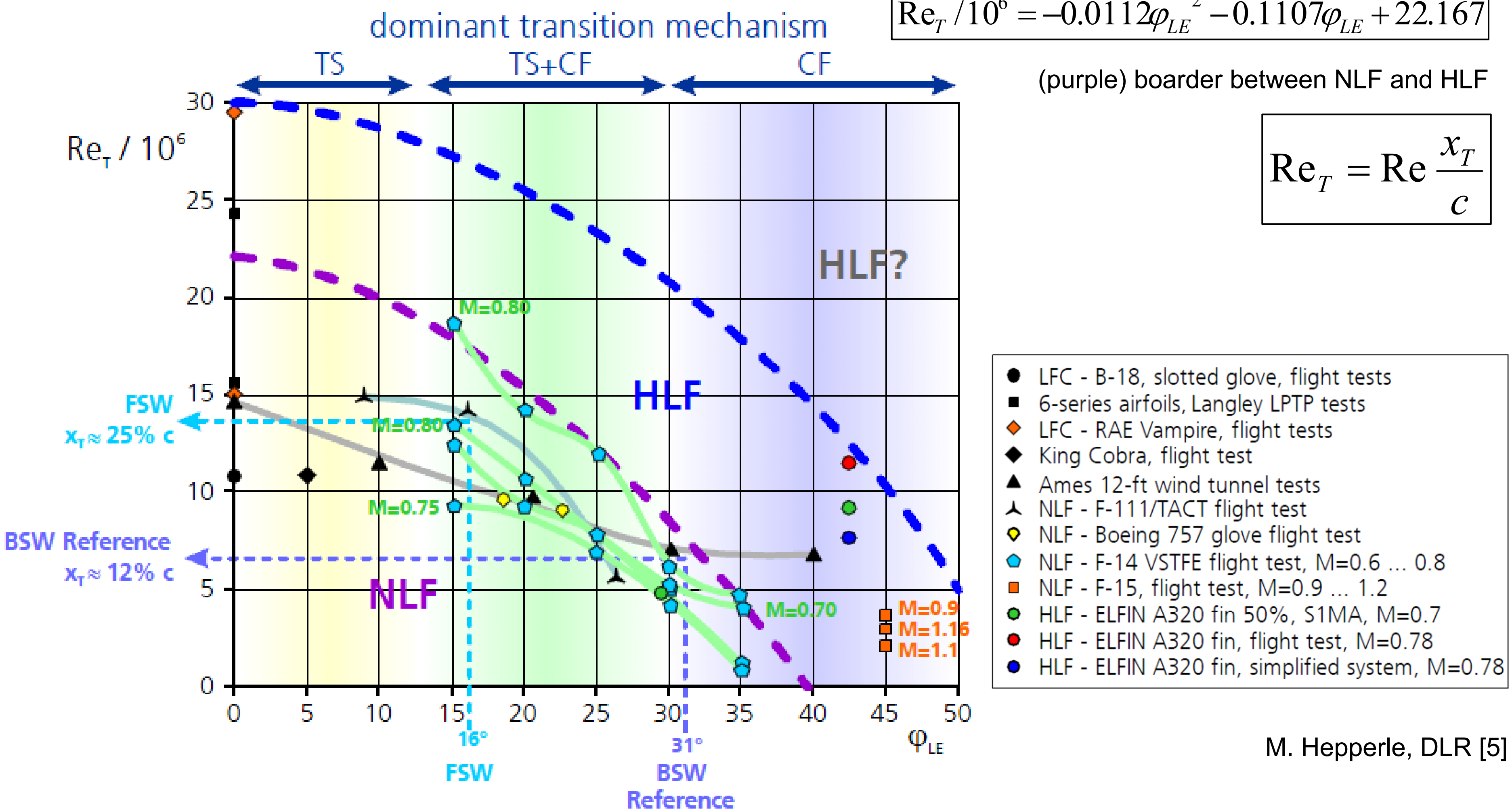
Propeller Integration



- 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



$$Re_T / 10^6 = -0.0112\varphi_{LE}^{\ 2} - 0.1107\varphi_{LE} + 22.167$$

(purple) boarder between NLF and HLF

$$Re_T = Re \frac{x_T}{c}$$

M. Hepperle, DLR [5]

Smart Turboprop: Results

- **Choosing the optimum aircraft configuration:**

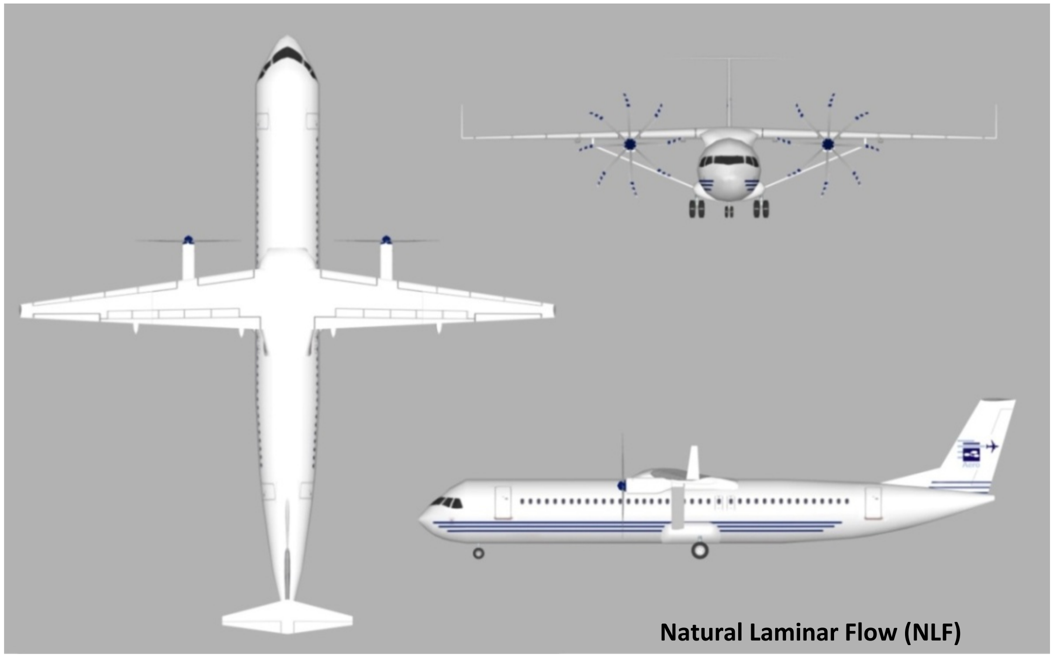
Smart Turboprop **optimized for low DOC** compared to A320

Best config.

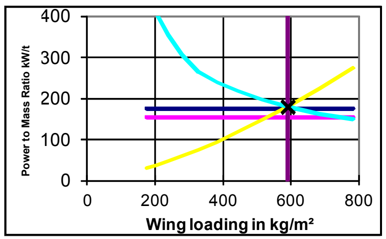
Turboprop w/o NLF/SBW	T-tail		Conventional tail	
	2 engines	4 engines	2 engines	4 engines
High wing	**-13,6%**	**-11,4%**	**-13,3%**	**-11,1%**
Low wing	**-12,4%**	**-11,5%**	**-12,9%**	**-11,1%**

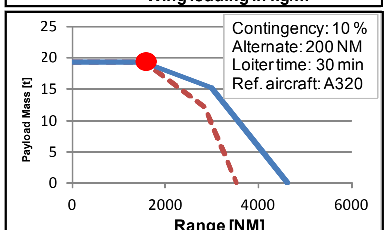
- **Wisdom from this optimization study:**
  - **2 engines better than 4 engines**
  - **For 2 engines: High wing better than low wing (0,4 … 1,2 % PT)**
  - **For 4 engines: Low wing as good as high wing**
  - **NLF improves DOC by about 2,8 % PT**
  - **Struts improve DOC by about 0,5 % PT**
  - **NLF and Struts improve DOC by about 3 % PT**

Smart Turboprop: Results

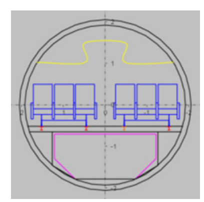


Parameter	Value	Deviation from A320*
Requirements		
m_{MPL}	19256 kg	0 %
R_{MPL}	1510 NM	0 %
M_{CR}	0.51	- 33 %
max(s_{TOFL} , s_{LFL})	1770 m	0 %
n_{PAX} (1-cl HD)	180	0 %
m_{PAX}	93 kg	0 %
SP	29 in	0 %



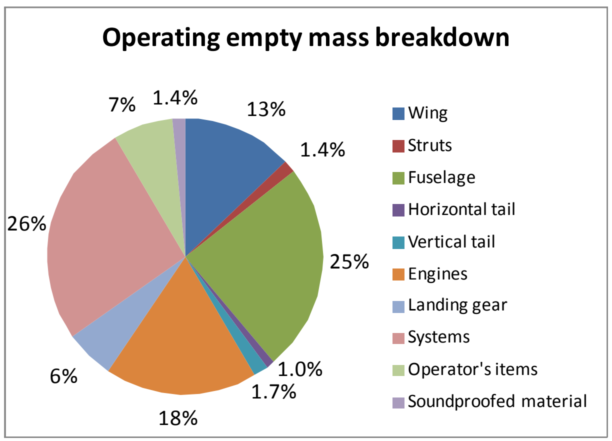


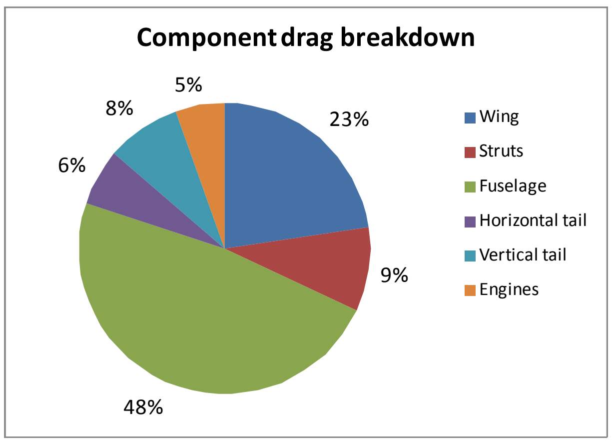
Parameter	Value	Deviation from A320*
Main aircraft parameters		
m_{MTO}	56000 kg	- 24 %
m_{OE}	28400 kg	- 31 %
m_F	8400 kg	- 36 %
S_W	95 m²	- 23 %
$b_{W,geo}$	36.0 m	+ 6 %
$A_{W,eff}$	14.9	+ 57 %
E_{max}	18.8	≈ + 7 %
$P_{eq,ssl}$	5000 kW	------
d_{prop}	7.0 m	------
η_{prop}	89 %	------
$PSFC$	5.86E-8 kg/W/s	------
h_{ICA}	23000 ft	- 40 %
s_{TOFL}	1770 m	0 %
s_{LFL}	1300 m	- 10 %
t_{TA}	32 min	0 %

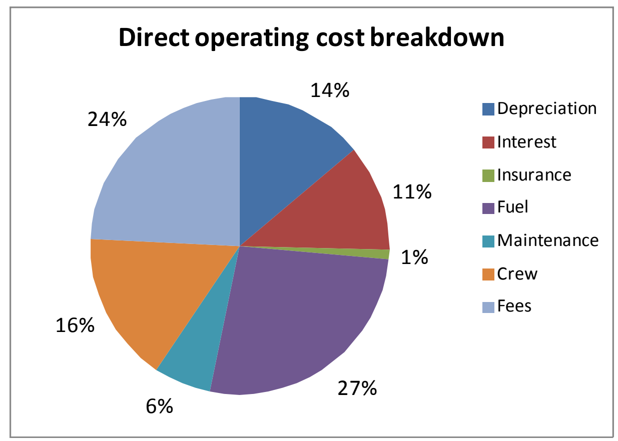


Smart Turboprop: Results

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







Smart Turboprop: Additional Parameters

Parameter	Explanation	Value
Cabin		
w_{aisle}	Aisle width	20 in
w_{seat}	Seat width	20 in
$w_{armrest}$	Armrest width	2 in
$s_{clearence}$	Sidewall clearence	0.6 in
Wing		
φ_{25}	Wing sweep at 25 % chord	6°
λ	Wing taper ratio	0.20
Vertical tail		
S_V	Vertical tail area	19.3 m²
$\varphi_{25,V}$	Vertical tail sweep at 25 % chord	28°
λ_V	Vertical tail taper ratio	0.69
Horizontal tail		
S_H	Horizontal tail area	12.4 m²
$\varphi_{25,H}$	Horizontal tail sweep at 25 % chord	9°
λ_H	Horizontal tail taper ratio	0.25
DOC		
$k_{delivery,OE}$	Delivery price per kg m_{OE}	1602 USD/kg

Smart Turboprop: Additional Parameters

Parameter	Explanation	Value
Zero lift & wave drag		
$C_{D,0}$	Zero lift drag	314 drag counts
$C_{D,W}$	Wave drag	0 drag counts
Induced drag		
a_e	---	-0.00152
b_e	---	10.82
c_e	---	1
M_{comp}	Highest Mach number without compressibility effects	0.3
Q	---	1.08
P	---	0.0119
$A_{W,eff}$	Effective aspect ratio of the wing	14.9
cf_e	Correction factor for Oswald factor	1.56

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

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

NITA, M.; SCHOLZ, D.: Estimating the Oswald Factor from Basic Aircraft Geometrical Parameters. Berlin, DLRK 2012

Acknowledgements

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This presentation is based on work of AERO published extensively. Please see http://Airport2030.ProfScholz.de

The method for aircraft optimization is described in Chapter 6 of:
NIŢĂ, Mihaela Florentina: Contributions to Aircraft Preliminary Design and Optimization. München : Verlag Dr. Hut, 2013. –
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Appendix: Parameters Explained (1)

Parameter	Explanation	Comments
Requirements		
m_{MPL}	Maximum payload mass [kg]	---
R_{MPL}	Maximum range [kg] (with maximum payload)	---
M_{CR}	Cruise Mach number	---
max(s_{TOFL} , s_{LFL})	Maximum take-off and landing field length [m]	Requirement for the maximum allowable take-off and landing field length
n_{PAX} (1-cl HD)	Number of passengers	one class, high density layout
m_{PAX}	Passenger mass [kg]	---
SP	Seat pitch [in]	Seat pitch for the one class high-density layout

- **most of the given values are rounded**
- **the given deviation refers to the real values and not to the rounded values**

Appendix: Parameters Explained (2)

Parameter	Explanation	Comments
Main aircraft parameters		
m_{MTO}	Maximum take-off mass [kg]	---
m_{OE}	Operating empty mass [kg]	---
m_F	Fuel mass [kg]	---
S_W	Wing area [m²]	---
$b_{W,geo}$	Geometrical span [m]	---
$A_{W,eff}$	Effective aspect ratio [-]	---
E_{max}	Maximum glide ratio [-]	---
T_{TO}	Take-off thrust [N]	---
$P_{eq,ssl}$	Equivalent take-off power at static sea level [kW]	---
BPR	Bypass-Ratio [-]	---
d_{prop}	Propeller diameter [m]	---
η_{prop}	Propeller efficiency [%]	---
SFC	Thrust specific fuel consumption [kg/N/s]	---
$PSFC$	Power specific fuel consumption [kg/W/s]	---
h_{ICA}	Initial cruise altitude [m]	---
s_{TOFL}	Take-off field length [m]	---
s_{LFL}	Landing field length [m]	---
t_{TA}	Turnaround time [min]	---

Appendix: Parameters Explained (3)

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

Appendix: Parameters Explained (3)

Parameter	Explanation	Comments
DOC mission requirements		
R_{DOC}	Range for the DOC calculation [NM]	---
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