Hochschule für Angewandte Wissenschaften Hamburg
Hamburg University of Applied Sciences

AIRCRAFT DESIGN AND SYSTEMS GROUP (AERO)

Design Aspects of Passenger Box Wing Aircraft

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Abstract

Future passenger aircraft strive for less fuel consumption, but their design is driven by the requirement at airports of a maximum of e.g. 36 m wing span for short/medium range aircraft. A box wing aircraft staying within the 36 m limit could achieve a drastic reduction in induced drag and hence fuel consumption. Indeed, box wing aircraft have been considered since decades, but so far very little has been done proposing a type that can be certified and is suitable to be used by every day airline operation. This investigation selects the best configuration from a modified morphological analysis, looks at performance, aerodynamic and longitudinal static stability, cabin/fuselage layout, family concepts and ground handling. A model of such proposed aircraft was built with rapid prototyping. With all this, the presented material and facts should serve as a baseline for a realistic discussion about the chances of a box wing configuration to be the next generation short/medium range aircraft.

Content

Requirements at Airports …
… are Driving Todays Aircraft Design!

Annex 14 — Aerodromes *Volume I*

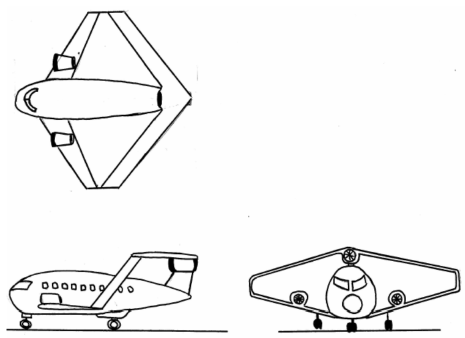
Table 1-1. Aerodrome reference code
(see 1.6.2 to 1.6.4)

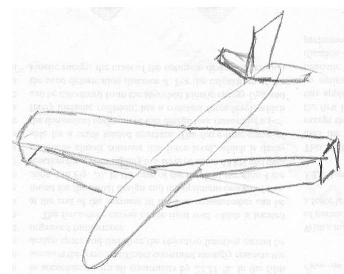
Code element 1		Code element 2		
Code number (1)	Aeroplane reference field length (2)	Code letter (3)	Wing span (4)	Outer main gear wheel span[a] (5)
1	Less than 800 m	A	Up to but not including 15 m	Up to but not including 4.5 m
2	800 m up to but not including 1 200 m	B	15 m up to but not including 24 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

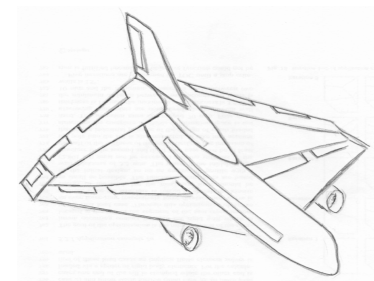
a. Distance between the outside edges of the main gear wheels.

Morphological Analysis

- Hand Sketches



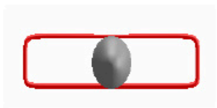
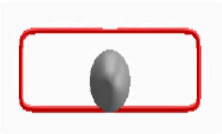
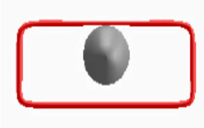
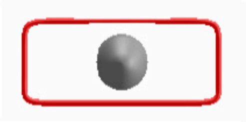




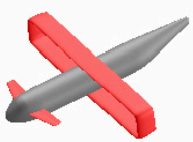
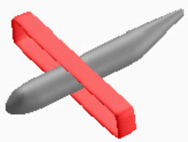
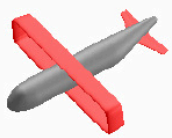
- Creative Methods
    - Brainstorming
    - Gallery Method

Morphological Analysis

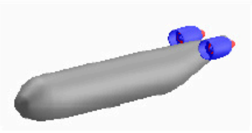
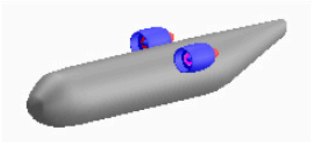
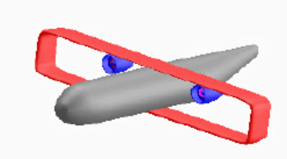
Box wing with different wing vertical position

	Low – High Position	Low – Super High Position	Super Low – High Position	Super Low – Super High Position
OpenVSP front view figure				

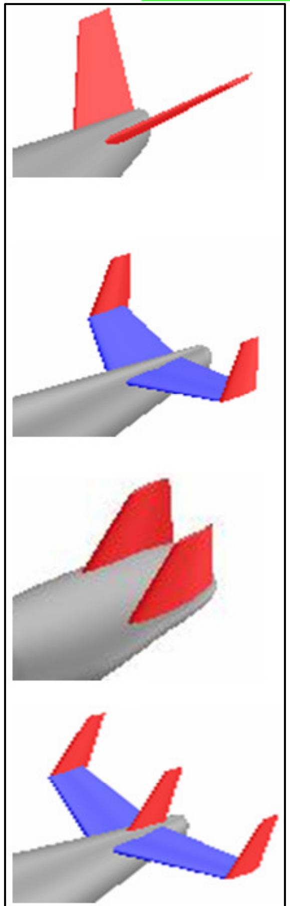
Horizontal tail surface position along the fuselage length

	Canard	No Horizontal tail	Horizontal surface
OpenVSP 3-D figure			

Engine positions for box wing aircraft

	Fuselage Aft	Fuselage Middle	On the wing
OpenVSP 3-D figure			

Example of possible vertical tails



All possible variations together (from Bachelor thesis) would lead to 31104000 combinations

Morphological Analysis

- **Morphological Analysis**

Morphological Analysis Matrix created after down selection

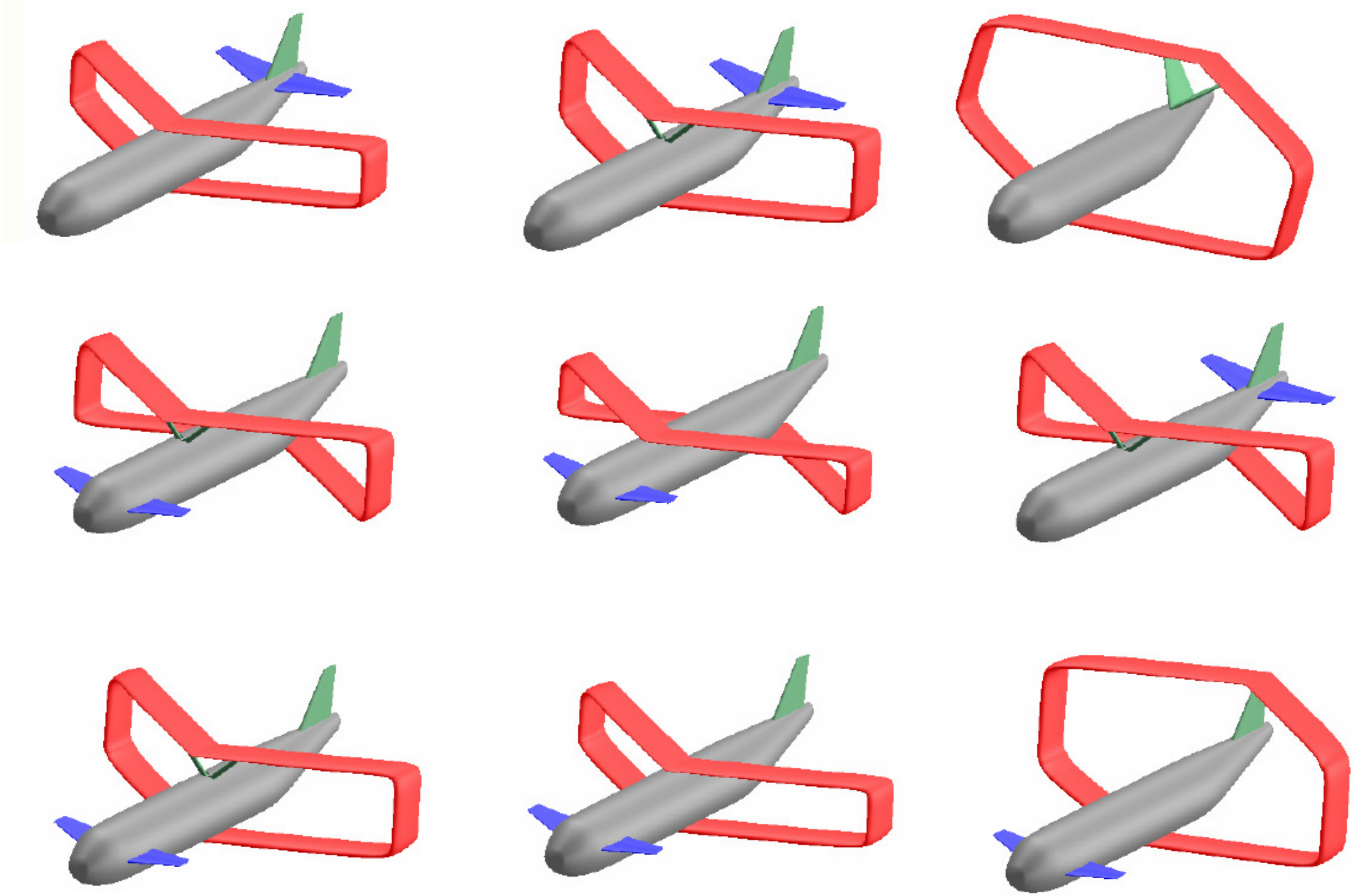
Stagger	Sweep	Box Wing Vertical Position	Horizontal Stabilizer Position	Vertical Stabilizer Position	Engine Position
=	<<	L – H	Can	Aft	Fuse – aft
‾_	>>	L – SH	No		Fuse – mid
_‾	< >		Aft		Wing

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

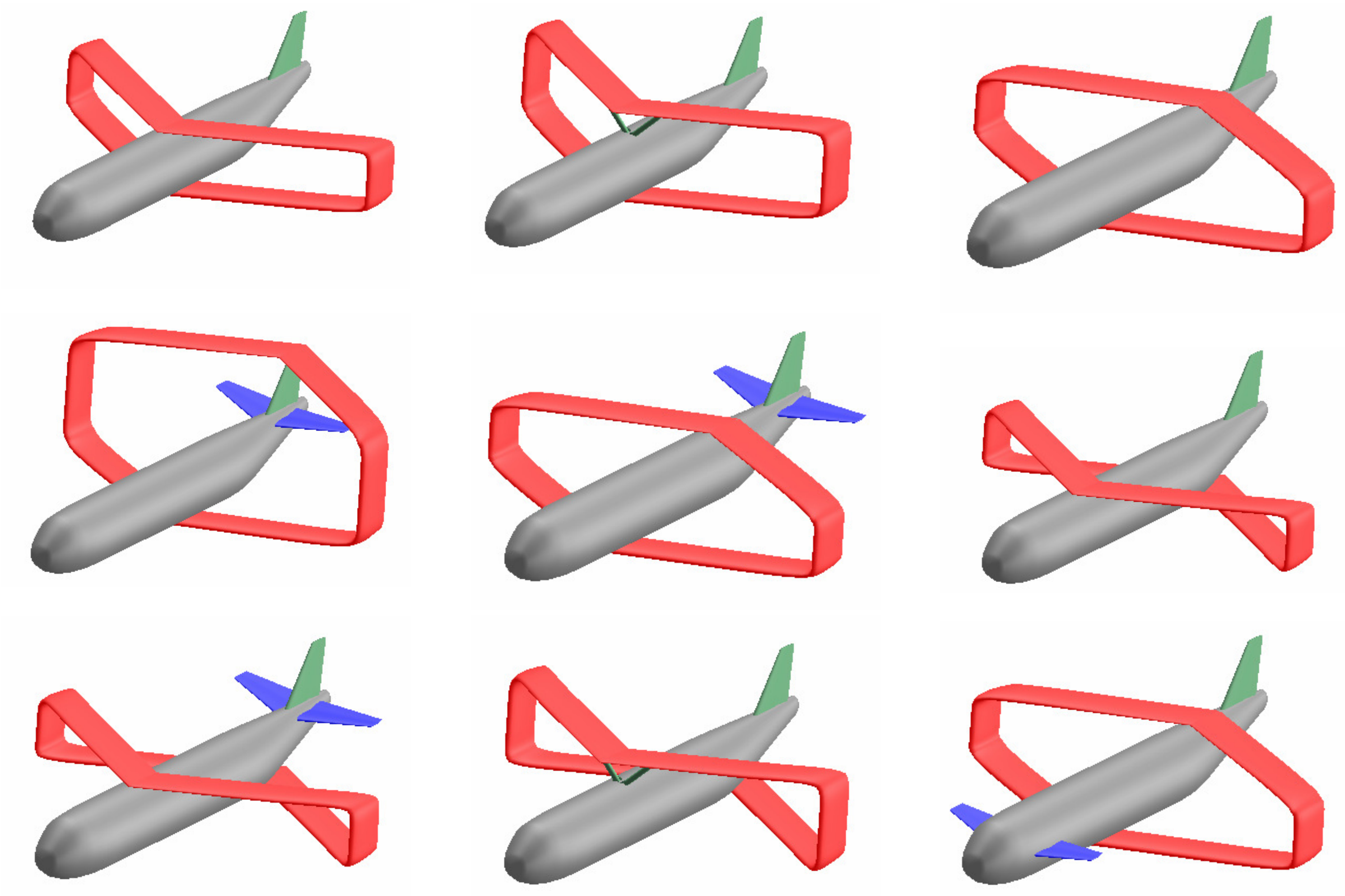
- **Modified Morphological Analysis**

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

18 Candidates from Modified Morphological Analysis ...



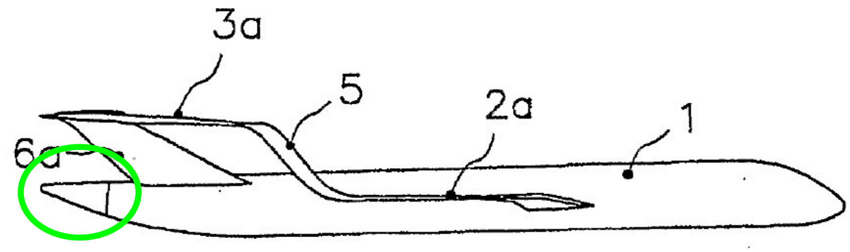
… 18 Candidates from Modified Morphological Analysis

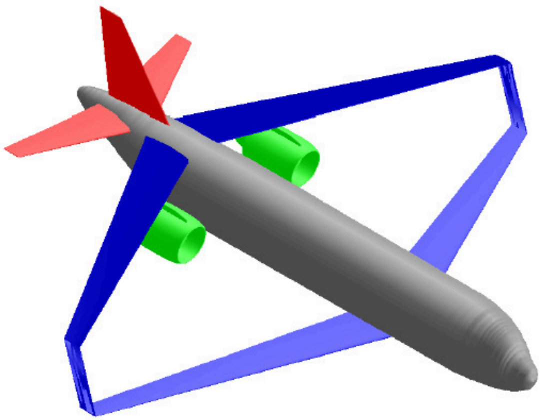


Morphological Analysis – Evaluation

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

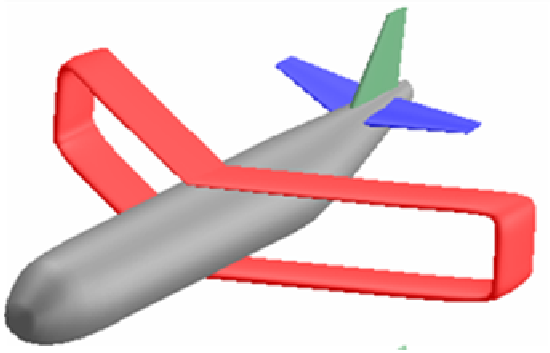
- Configuration
  - Force Fighting
  - Family Concept
- Drag
  - Zero Lift Drag
  - Induced Drag
- Weight
  - Empty Weight
- Flight Mechanics
  - Longitudinal Static Stability and CG Range
- Operation
  - Ground Handling
- Development
  - Time and Cost
  - Risk



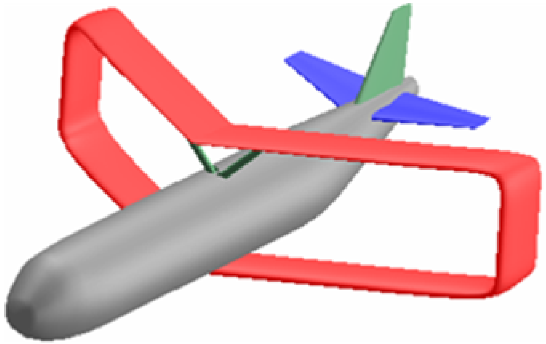


Morphological Analysis – Results

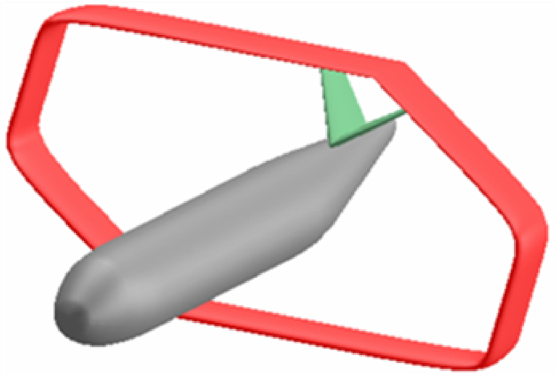
1.



2.



3.



Best unconventional configuration

General Box Wing Performance

Box Wing flies at reference Aircraft Altitude

$$\frac{E_{BW}}{E_{ref}} = \frac{4}{3} = 1.33$$

Reference Aircraft flies at Box Wing Altitude

$$\frac{E_{BW}}{E_{ref}} = \frac{3}{2} = 1.5$$

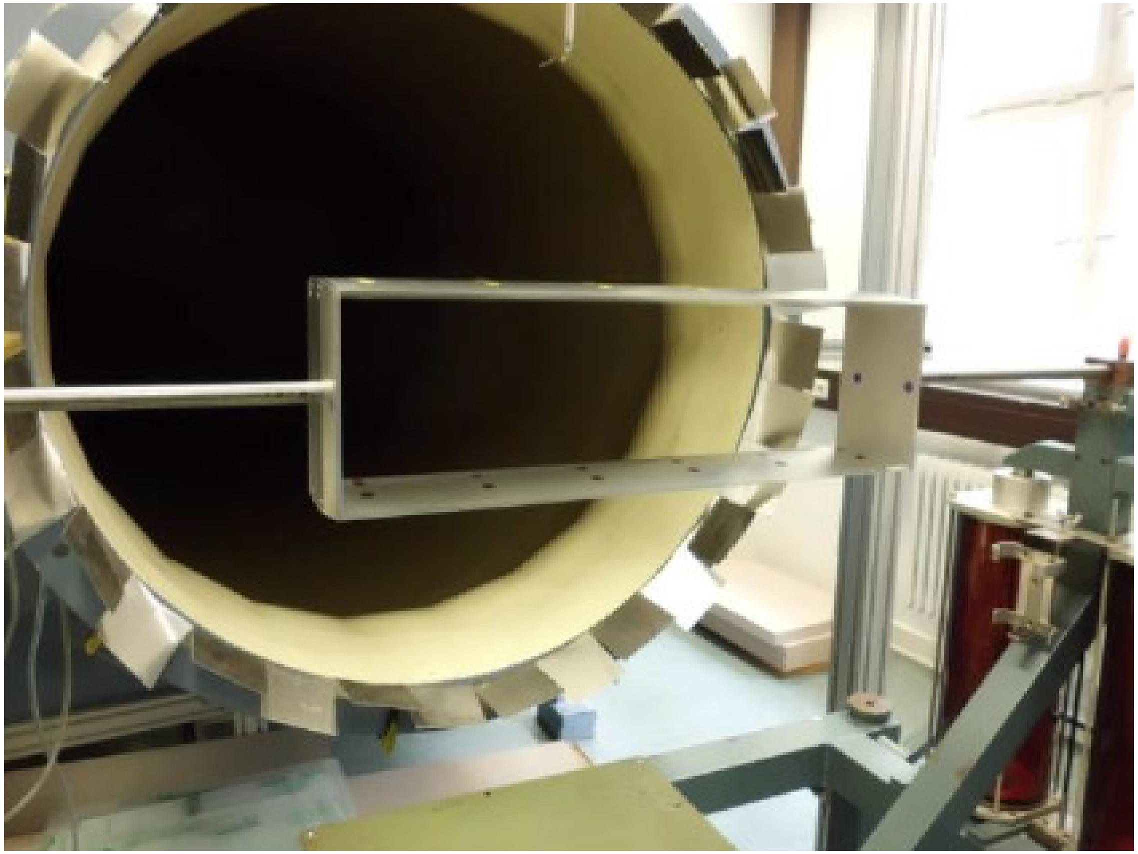
„Fair“ comparison:

$$\frac{E_{max,BW}}{E_{max,ref}} = \sqrt{2} \cdot \sqrt{\frac{A_{BW}}{A_{ref}}} = 1.4142 \cdot \sqrt{\frac{A_{BW}}{A_{ref}}}$$

Considering a realistic ratio $h/b = 0.25$, it yields to $D_{i,ref}/D_{i,BW} = 0.6385$ and:

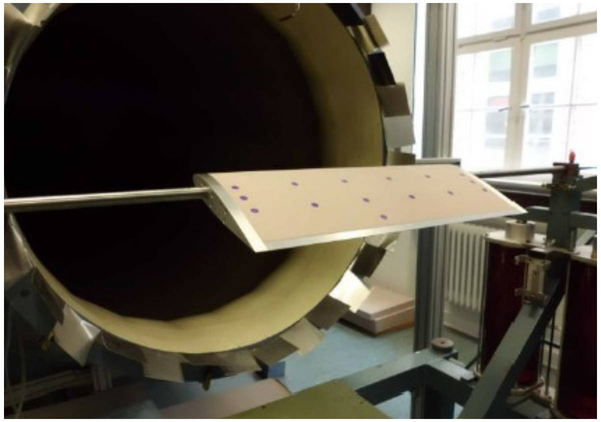
(17) $\frac{E_{max,BW}}{E_{max,ref}} = 1.25$

Box Wing Aerodynamics



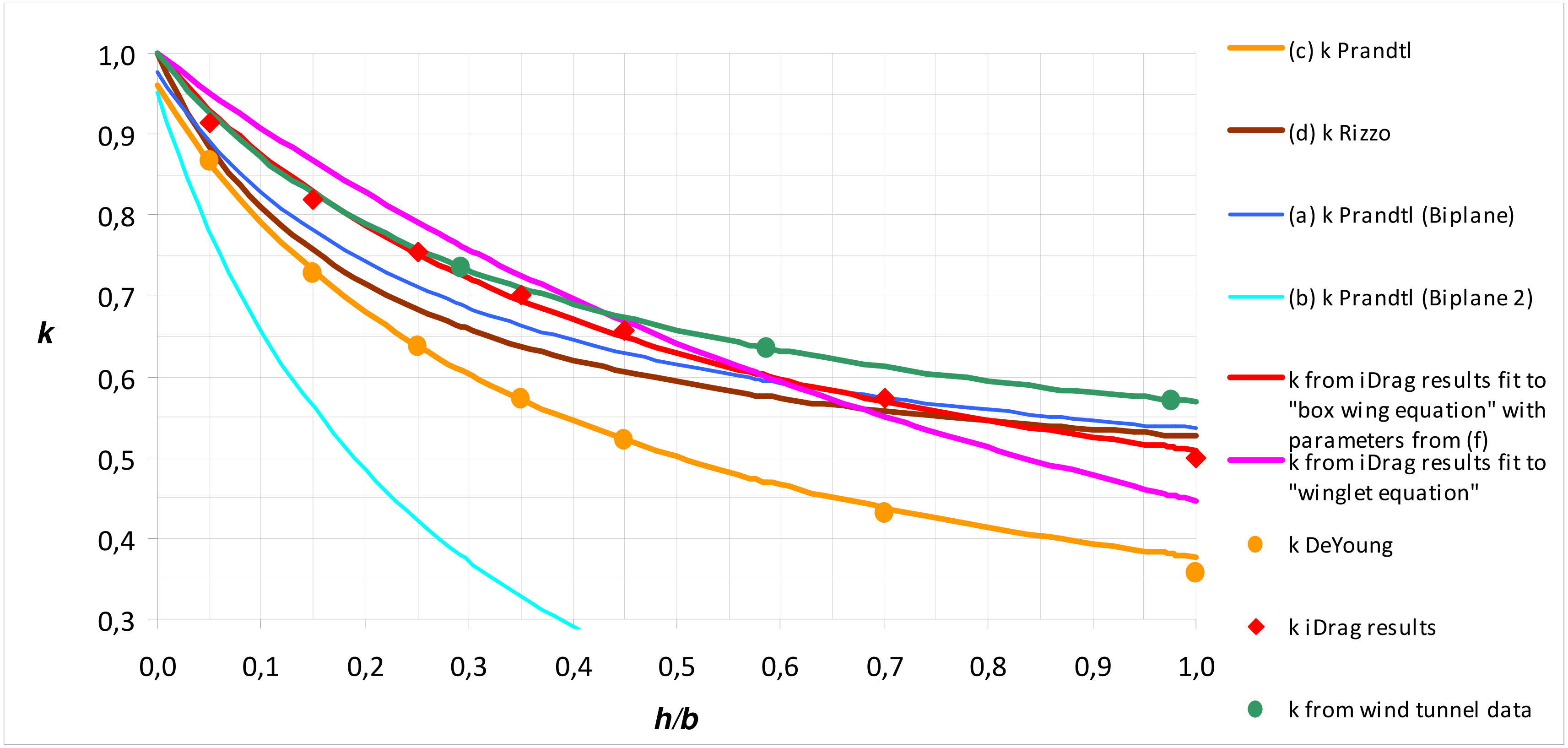
Measurements of induced drag of different box wings in the wind tunnel of HAW Hamburg

The reference wing



Box Wing Aerodynamics – Induced Drag

$$\frac{D_{i,box}}{D_{i,ref}} = \frac{e_{ref}}{e_{box}} = k$$



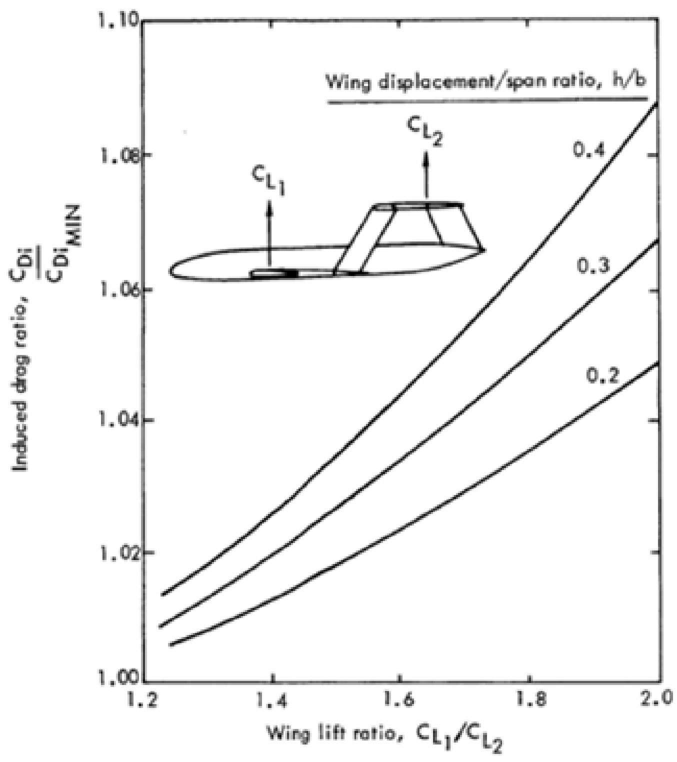
Box Wing Aerodynamics – Induced Drag

$$\frac{D_{i,box}}{D_{i,ref}} = \frac{e_{ref}}{e_{box}} = k \qquad \frac{D_{i,box}}{D_{i,ref}} = k = \frac{k_1 + k_2 \cdot h/b}{k_3 + k_4 \cdot h/b}$$

Case	Configuration	Author	k_1	k_2	k_3	k_4	k for $h/b \to 0$	k for $h/b \to \infty$
(a)	Biplane	Prandtl*	1	-0.66	2.1	7.4	0.976	-0.089
(b)	Biplane (2)	Prandtl	1	-0.66	1.05	3.7	0.952	-0.178
(c)	Box wing	Prandtl	1	0.45	1.04	2.81	0.962	0.160
(d)	Box wing	Rizzo	0.44	0.959	0.44	2.22	1	0.432
(e)	Box wing	iDrag best fit	1.304	0.372	1.353	1.988	0.964	0.187
(f)	Box wing	iDrag $k_1 = k_3$	**1.037**	**0.571**	**1.037**	**2.126**	**1**	**0.269**

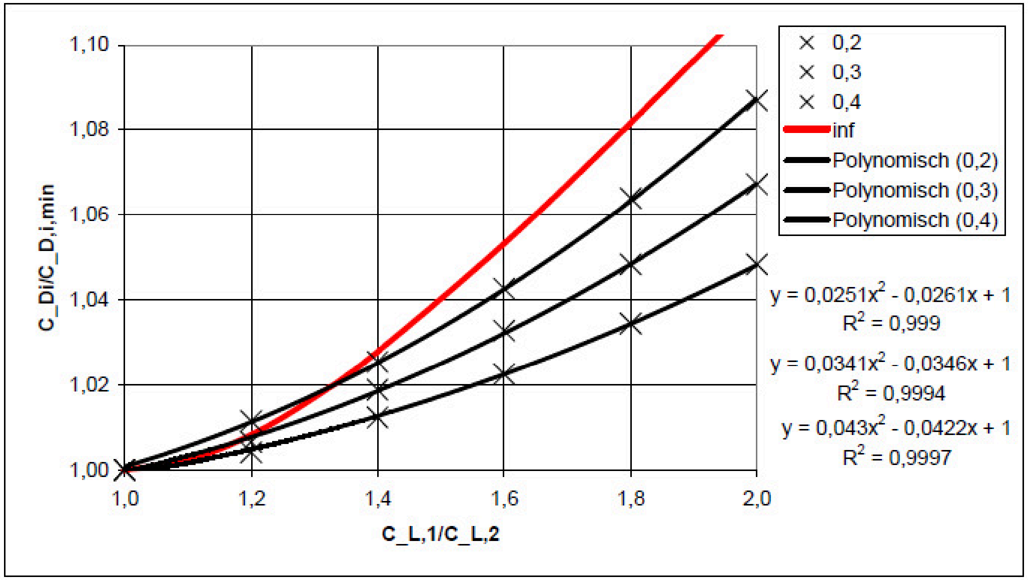
* here, a different equation is used: $k = 0.5 + \frac{k_1 + k_2 \cdot h/b}{k_3 + k_4 \cdot h/b}$.

Box Wing Aerodynamics – Induced Drag and Lift Share

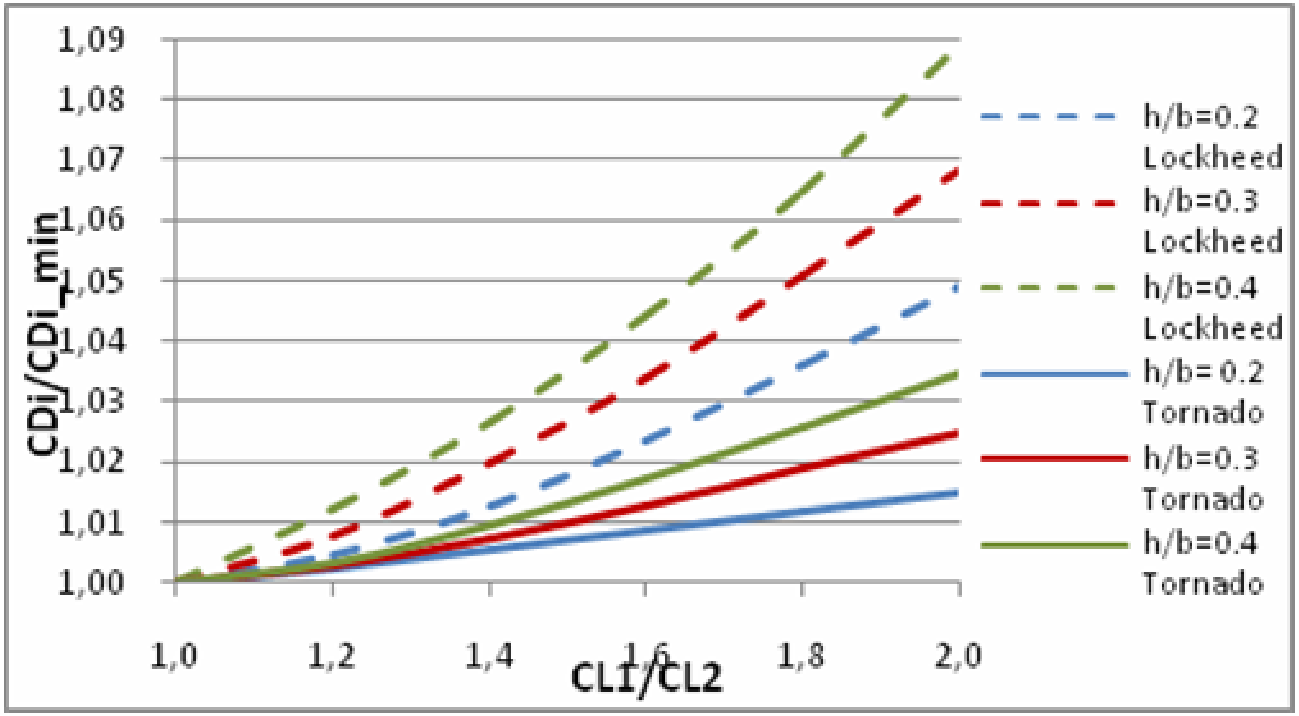


From Lockheed Report

$$\frac{C_{D,i}}{C_{D,i,min}} = \frac{2\,(x^2+1)}{(x+1)^2} \quad with \quad x = \frac{C_{L,1}}{C_{L,2}}$$

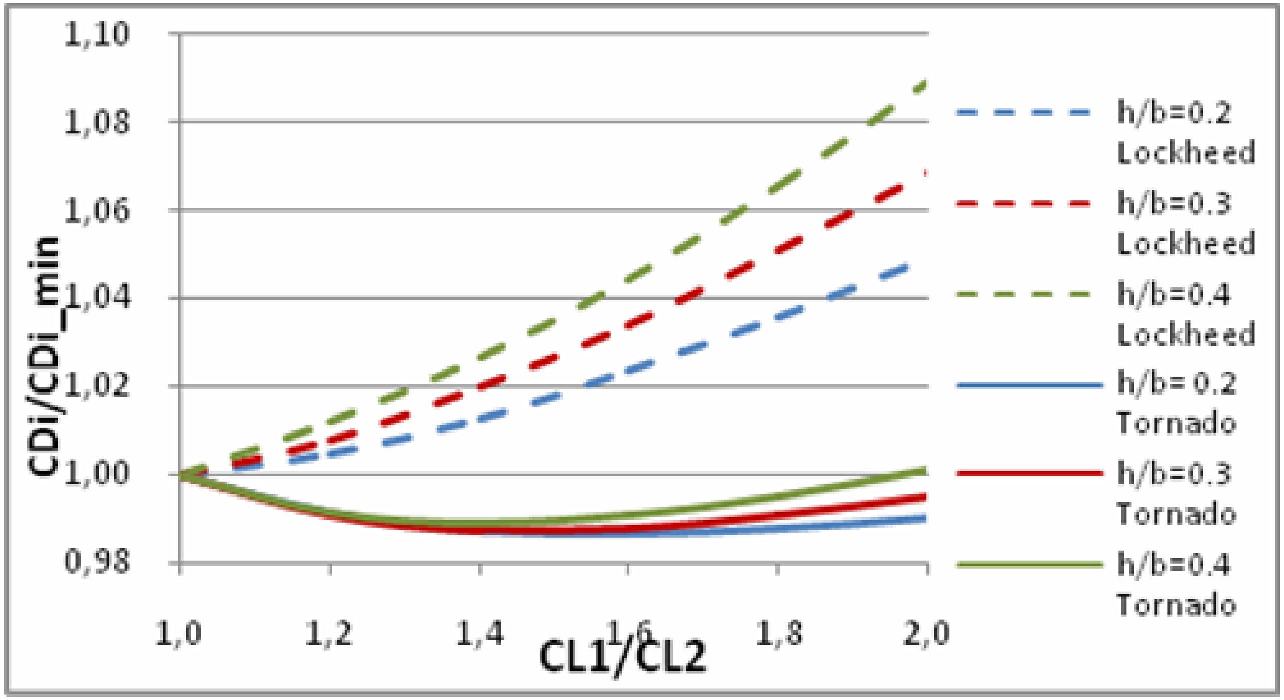


Box Wing Aerodynamics – Lockheed versus Tornado – No Stagger

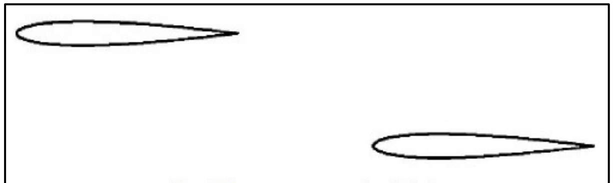


Sensitivity of induced drag to non-optimum lift distributions (Tornado) – Stagger = 0

Box Wing Aerodynamics – Lockheed versus Tornado – Negative Stagger

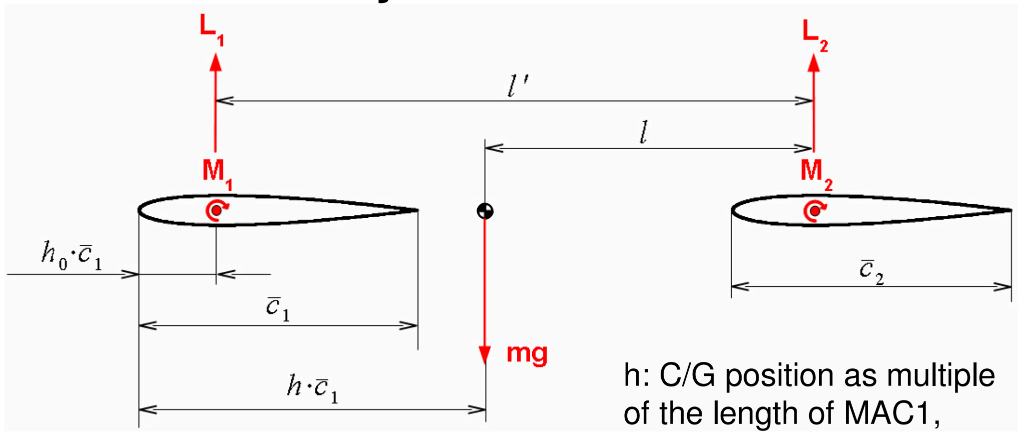


Sensitivity of induced drag to non-optimum
lift distributions (Tornado) – Stagger = -0.5b



Positive stagger of a biplane

Box Wing Longitudinal Static Stability



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

Stability Limit

$$h < h_0 + \frac{\mathrm{d}C_{L,2}}{\mathrm{d}C_L} \cdot \overline{V}' \frac{\bar{c}}{\bar{c}_1}$$

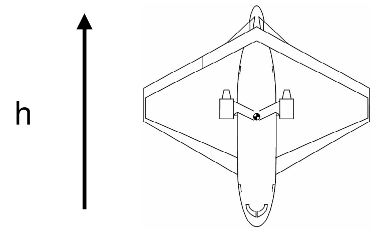
→ needs to be as high as possible

Control Limit → $C_{L,2}$ needs to be low. Thus for a given C_L $C_{L,1}$ needs to be increased

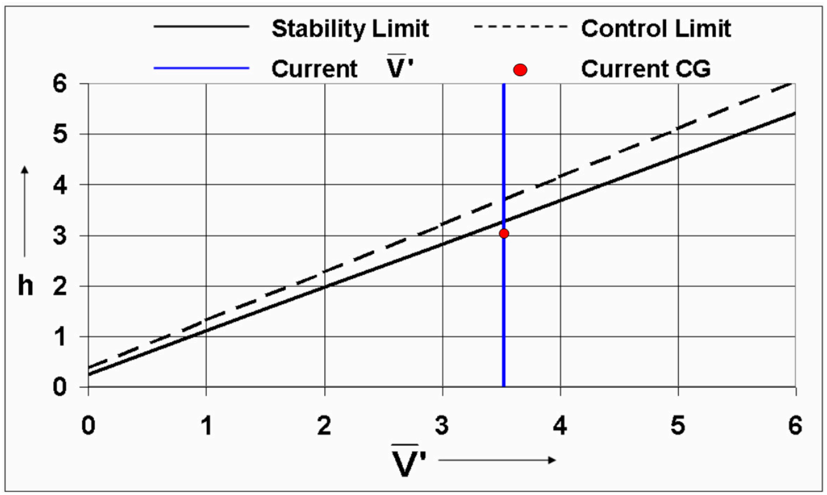
Trim Condition → $C_{L,2}$ needs to be lower than $C_{L,1}$

Box Wing Longitudinal Static Stability

C/G Envelope Diagrams

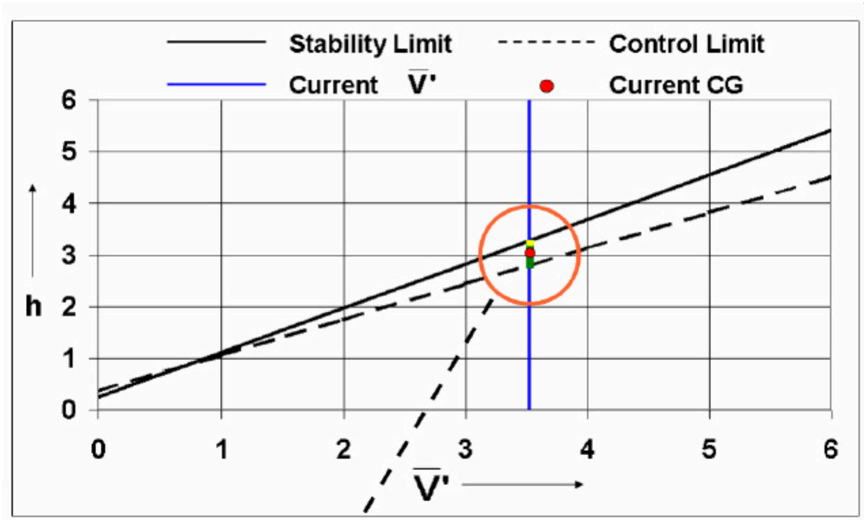


unstable!

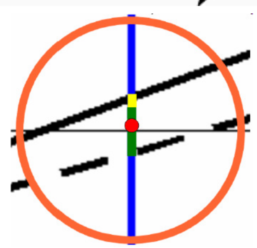


$C_{L,1} = C_{L,2}$

stable!



$C_{L,1}/C_{L,2} = 1,74$



A further increase of the C/G envelope requires a higher $C_{L,1}/C_{L,2}$!

Box Wing Longitudinal Static Stability

Design Measures for Stability

With the help of the spreadsheet it was determined that an increase of the ratio of $C_{L,1}/C_{L,2}$ is the most effective way of expanding the CG envelope. It is important to pay attention to the consequences, e.g. airfoil choice and stall characteristics. Depending on the aircraft geometry, a value of 1,5 to 3 for the $C_{L,1}/C_{L,2}$ ratio is probable.

A general increase of the CG envelope can also be achieved by placing the wings further apart longitudinally. This way the the parameter $\bar{V}$ is increased which makes it also possible to decrease the ratio $C_{L,1}/C_{L,2}$ for a given CG envelope.

An adjustment of the wing sweep can be treated as a supporting measure.

Cabin and Fuselage Layout

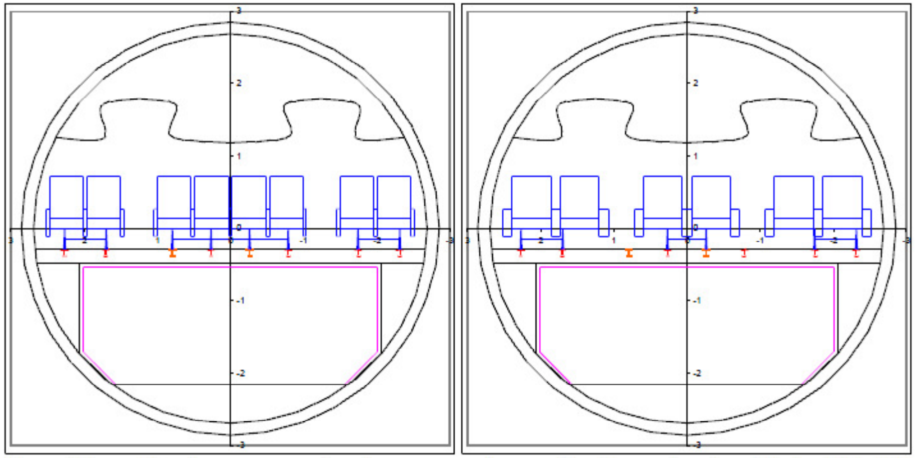


Figure 8.2 Fuselage cross section for economy class and business class (modelled with PreSTo Cabin)

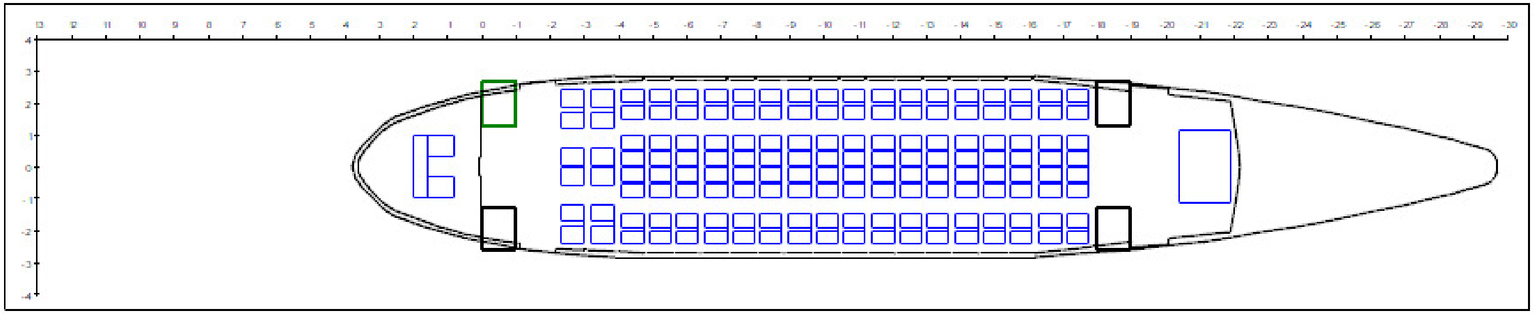
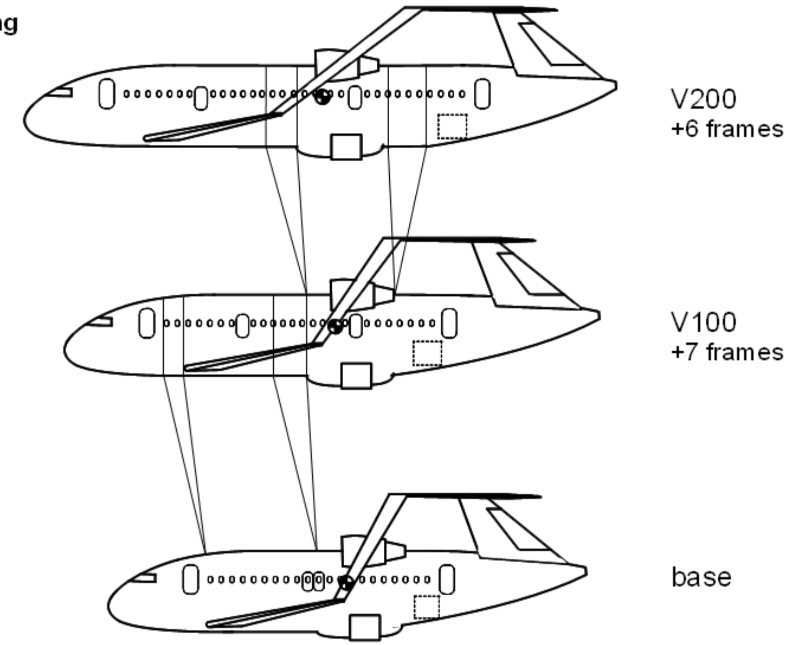


Figure 8.3 Cabin floor plan of the box wing aircraft (modelled with PreSTo Cabin)

Aircraft Family

Box Wing
General Familiarization

Twin Aisle Family Highlights

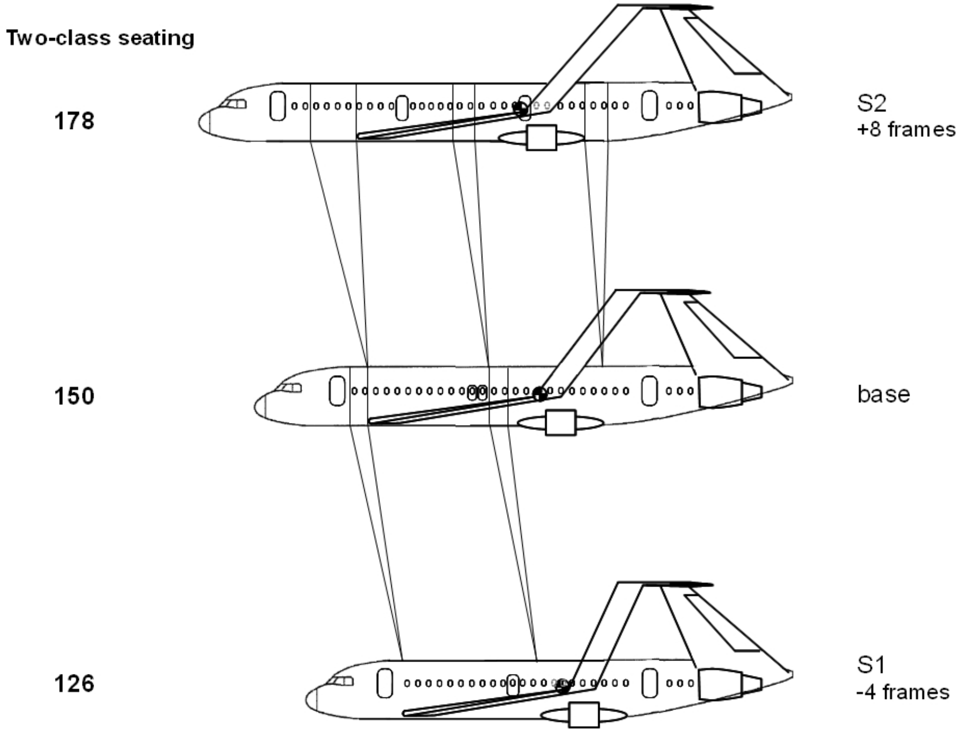


	base	V100	V200
Fuselage Length	33.1 m	37.21 m	41.28 m
Underfloor Volume	34.17 m³	38.42 m³	42.62 m³
Longitudinal distance from AC1 to AC2 (l')	12.50 m	15.50 m	19.57 m
Winglets Sweep (at 25% chord)	28.67°	43.44°	56.12°

Aircraft Family

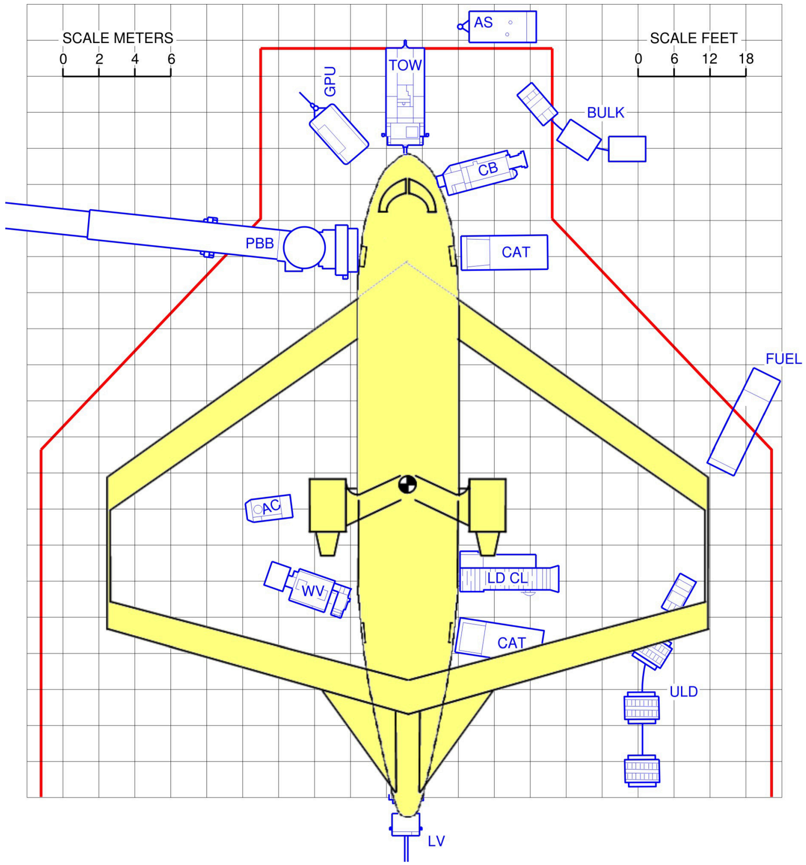
Box Wing
General Familiarization

Single Aisle Family Highlights



	base	S100	S200
Fuselage Length	37.44 m	34.09 m	41.51 m
Underfloor Volume	38.6 6m³	35.20 m³	42.86 m³
Longitudinal distance from AC1 to AC2 (l')	14 m	12.9 m	16 m
Winglets Sweep (at 25% chord)	36.76°	30.97°	45.39°

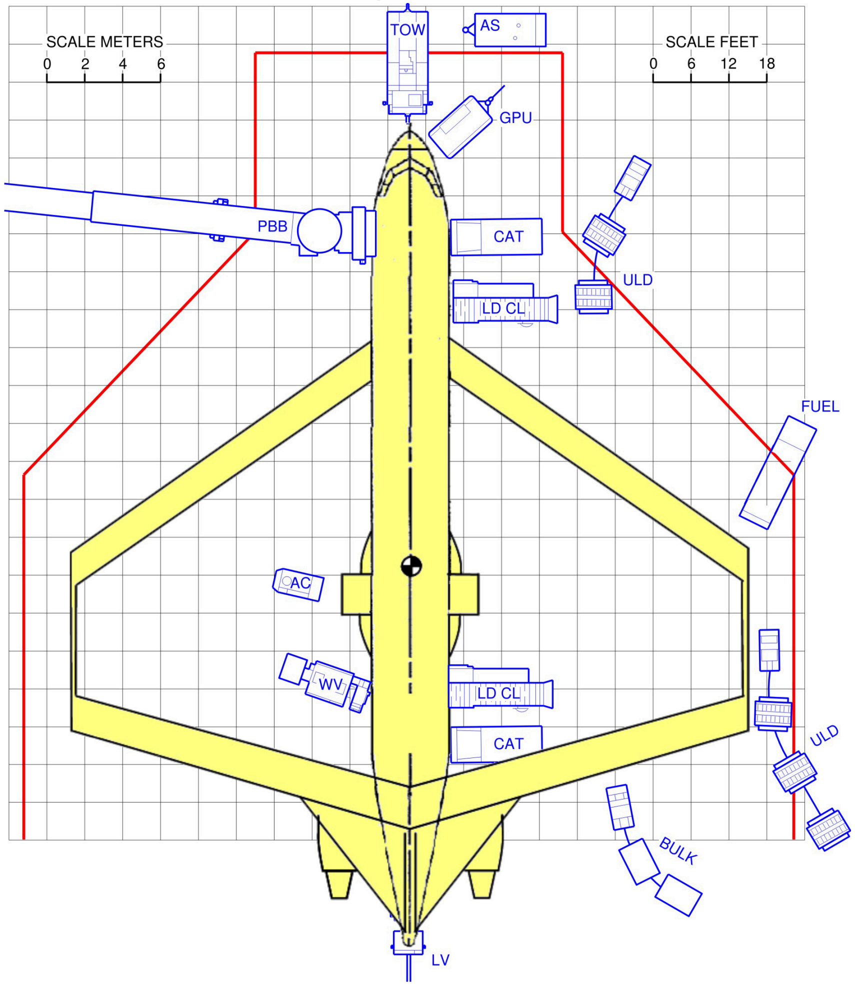
Ground Handling



Ground Support Equipment	
AC	Air Conditioning Unit
AS	Air Starting Unit
BULK	Bulk Train
CAT	Catering Truck
CB	Conveyor Belt
CLEAN	Cleaning Truck
FUEL	Fuel Hydrant Dispenser or Tanker
GPU	Ground Power Unit
LD CL	Lower Deck Cargo Loader
LV	Lavatory Vehicle
PBB	Passenger Boarding Bridge
PS	Passenger Stairs
TOW	Tow Tractor
ULD	ULD Train
WV	Potable Water Vehicle

Summary of Ground handling equipment on V100 and the ramp layout

Ground Handling



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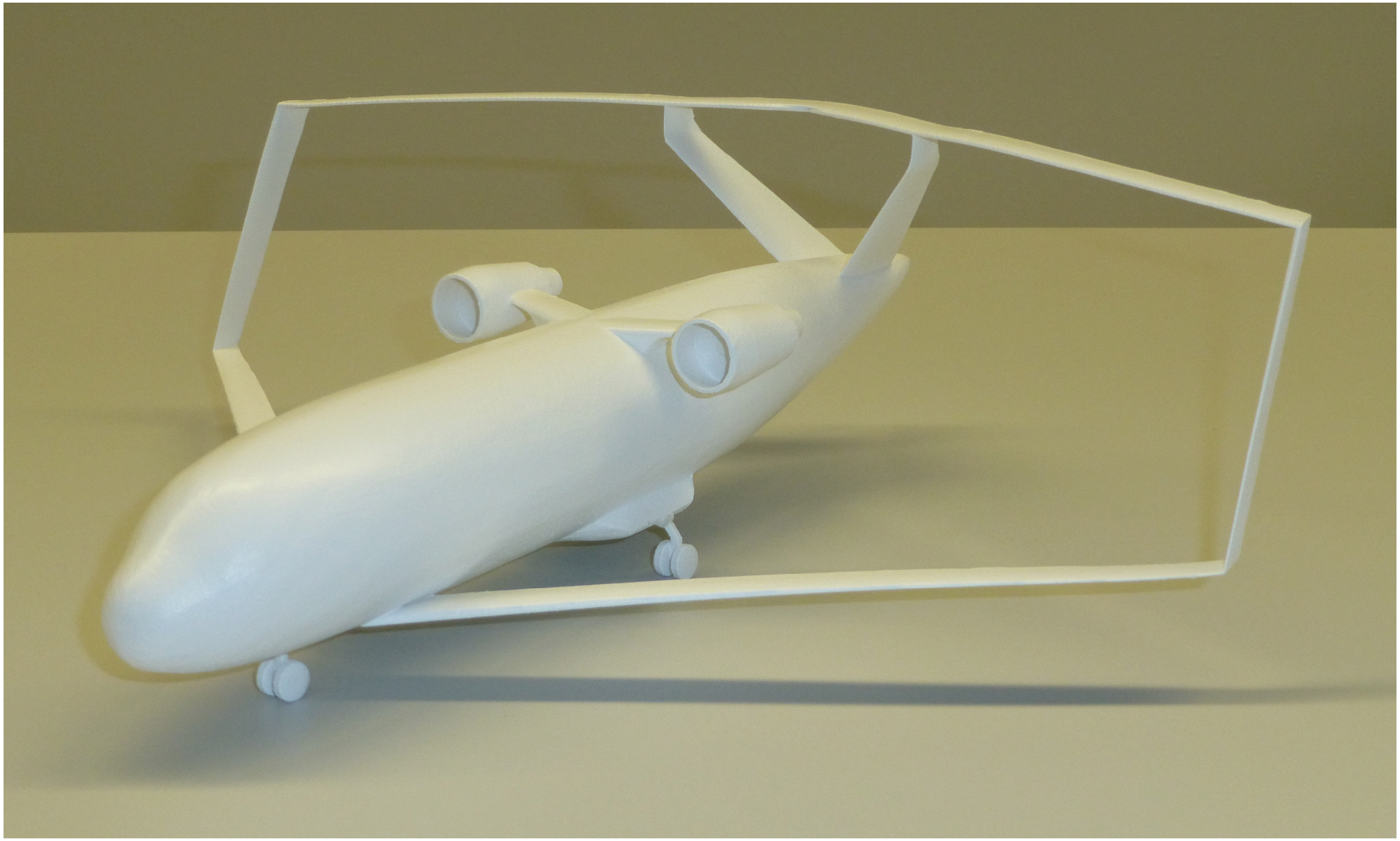
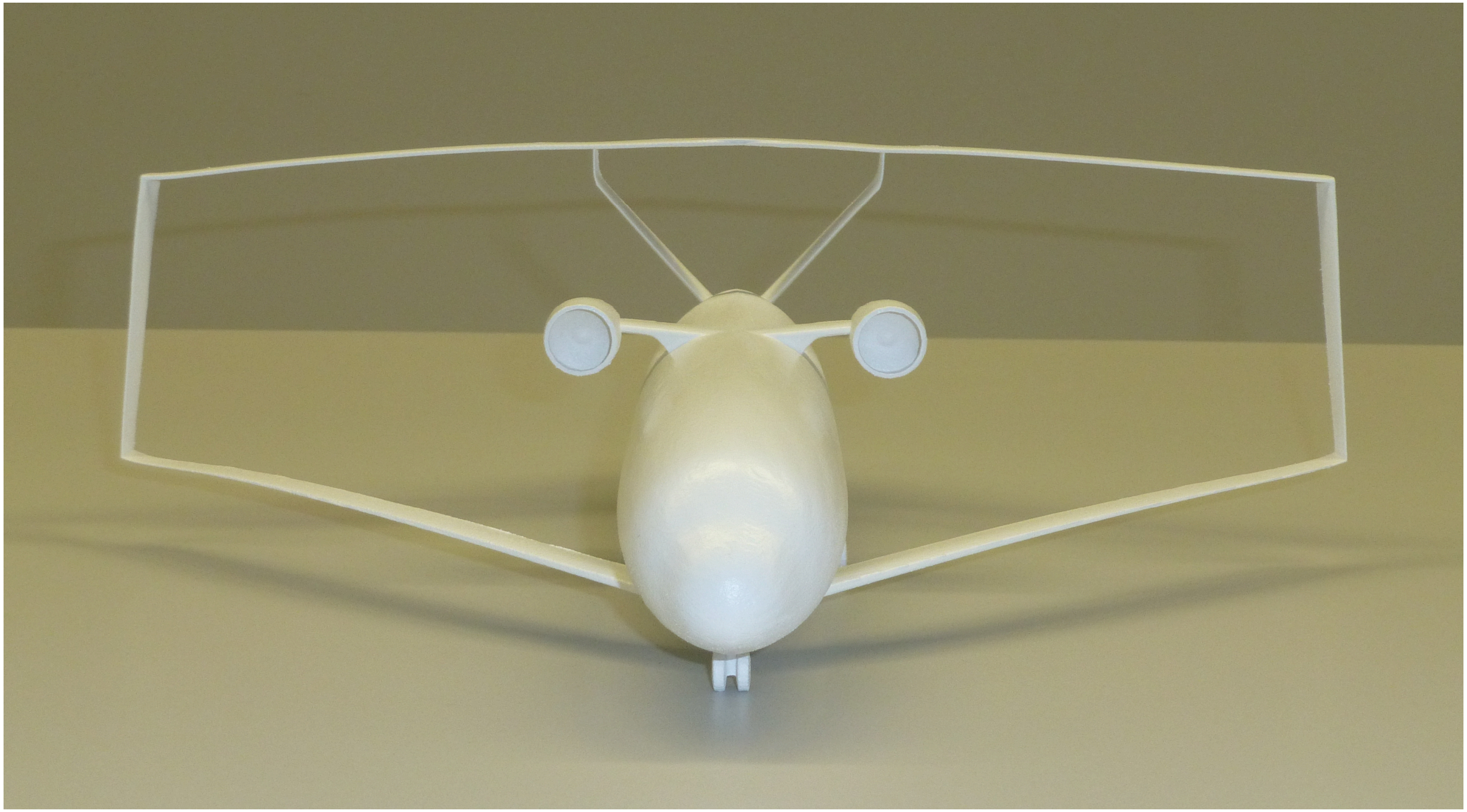
PS	Passenger Stairs
TOW	Tow Tractor
ULD	ULD Train
WV	Potable Water Vehicle

Summary of Ground handling equipment on S200 and the ramp layout

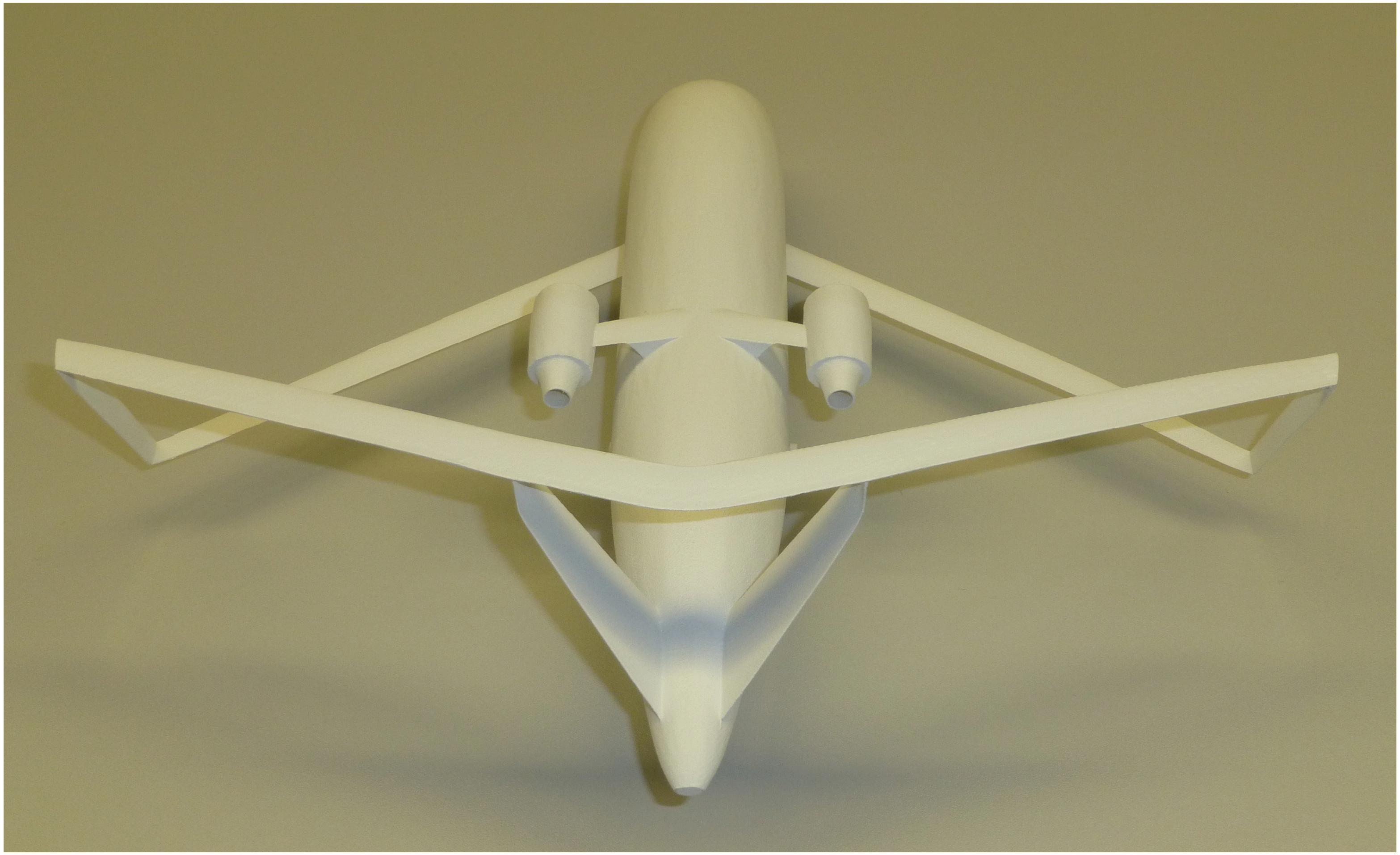
Rapid Prototyping



Rapid Prototyping



Rapid Prototyping



http://Airport2030.ProfScholz.de