Hochschule für Angewandte Wissenschaften Hamburg
Hamburg University of Applied Sciences

AIRCRAFT DESIGN AND SYSTEMS GROUP (AERO)

Innovative Aircraft Technologies –

Unconventional Configurations

Electric Propulsion

Manufacturing

Dieter Scholz Hamburg University of Applied Sciences

Presentation at HAW Hamburg for Chinese Delegation, 11.12.2018

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Welcome to HAW Hamburg

Your Affiliation:

Commercial Aircraft Corporation of China, Ltd

China Commercial Flying Company, Civil Aircraft Flight Test Center

Beijing Aeronautical Science & Technology Research Institute

Shanghai Aircraft Design And Research Institute

Shanghai Aviation Industrial (Group) Co., Ltd

Shanghai Aircraft Customer Service Co., Ltd

Shanghai Aircraft Manufacturing Co., Ltd

Welcome

Hamburg University of Applied Sciences

We develop sustainable solutions for the challenges our society is facing today and in the future.

HAW Hamburg – The leading university in the north of Germany when it comes to applied critical thinking.

Welcome

Hamburg University of Applied Sciences

- About 16800 students, the second largest institution of higher education in the Hamburg region and one of the largest of its kind (university of applied sciences) in Germany.
- Founded in 1970, roots go back to the 18th century.
- Our practice orientated teaching.
- Small groups, interdisciplinary projects and close academic support.

Diversity

Engineering & Computer Science, Life Sciences, Design, Media & Information, Business & Social Sciences – Hamburg University of Applied Sciences offers a wide range of undergraduate and postgraduate degree programs within its four faculties leading to the academic qualifications »Bachelor« and »Master«.

Applied Sciences

- Practice orientation is our trademark: Practice in laboratories, study projects, close cooperation with industry.
- In many programs students have to complete one semester-long internship in industry.
- In addition to an academic title, our professors worked for many years in private companies and public institutions before joining the university.

International

Over 2200 international students study at HAW Hamburg (13 % of all students) from over 100 nations. International guest students from our partner universities. Hamburg University of Applied Sciences has co-operations with about 200 European universities and world wide.

My Visits to China

庆安集团有限公司 Qing'an Group Co., Ltd.

董事长兼总经理
丁凯

党委书记兼副董事长
靳武强

庆安集团有限公司（简称庆安公司）创建于1955年10月，是我国"一五"时期的156项重点建设项目之一；集航空机载武器装备、飞行器操纵控制系统（装置）两大专业优势为一体，是中国大型的机载设备研制、生产企业。2007年，荣获由国务院颁发的国家科学技术进步奖特等奖。

庆安公司主要承担航空航天机载设备系列产品的研制和生产。其中防务产品包括机械、液压、气动、电子、电气装置及控制系统；民用航空转包产品有飞机飞控、电源、机轮刹车、起落架收放等系统用零件、组件。非航空领域主要从事各型空调压缩机的研制和生产。 庆安公司建有国家级企业技术中心及2个博士后科研工作站，设有航空产品、制冷设备、检测技术三个研究所；建有国家一级计量中心、国家一级理化试验室、航空系统西北地区环境试验中心,可进行产品的气候环境和机械环境试验；在复杂壳体、精密齿轮、大型框架、各类液压阀、大导程多头螺旋轨道等零件加工、液压密封和特种锻铸造、焊接、热表处理等技术领域都有独特的技术诀窍。 庆安公司具有雄厚的科研、开发、设计、生产能力和健全的质量保证体系。形成以飞行器、武器（发射）操纵控制系统及装置为主导的航空产品体系和以空调压缩机产品为主导的民品制冷产品体系。

庆安公司在西安高新技术产业开发区建立了庆安制冷工业园，具备年产各型空调压缩机500余万台的生产能力，成为国内领先的空调压缩机研制、生产、服务基地之一；在西安经济开发区建设了民用航空液压操纵产品转包生产厂区，先后与GE-AS、GOODRICH、EATON、MOOG等多家世界航空机载设备知名企业建立了合作关系。

企业文化 企业荣誉

My Visits to China

Qing'an Group Co., Ltd. (referred to as Qing'an Company) was **founded in** October **1955**. It is one of the 156 key construction projects in China's "First Five-Year" period; it is the second major company of airborne weaponry and aircraft control systems in China. **It is located in the city of Xi'an, China**.

Qing'an Company is mainly engaged in the research and production of aerospace airborne equipment series products. The defense products include mechanical, hydraulic, pneumatic, electronic, electrical devices and control systems. **The civil aviation subcontracting products include aircraft flight control [with high-lift systems], power supply, wheel brakes, landing gear retracting and other system parts and components.** The non-aviation field is mainly engaged in the development and production of various types of air conditioning compressors. It has an annual production capacity of more than 5 million air-conditioner compressors and has become one of the leading research, production and service bases for air-conditioning compressors in China.

Qing'an Company has a state-level enterprise technology center and two post-doctoral research stations. It has three research institutes: aviation products, refrigeration equipment and testing technology. The regional environmental testing center can test the climatic environment and mechanical environment of products; processing parts, hydraulic seals and special forging and welding of complex shells, precision gears, large frames, various hydraulic valves, etc. Qing'an has a strong research, development, design, production capacity and sound quality assurance system.

Qing'an Company is also located in the Xi'an Economic Development Zone, where **a civil aviation subcontracting production plant has been built**. It has established **cooperative relationships with many world-class airborne equipment companies** such as GE-AS, GOODRICH, EATON and MOOG.

HAW HAMBURG

My Visits to China

A special Short Course "**Design of High Lift Systems (1)**" was given from 13.07. to 22.07.2016 at AVIC Qingan Group (QAG), Xi'an, Shaanxi, China. This short course discussed the needs for high lift together with high lift aerodynamics based on the Short Course "Aircraft Design". It was further based on material from my lectures "Aircraft Systems", "Development of Aircraft Systems" and the Short Course "Evaluation of Aircraft Systems". The material was complemented with special design techniques for high lift systems as well as many examples of high lift systems and components of passenger aircraft.

My Visits to China

The Course held in Xi'an was extended with a Short Course "**Design of High Lift Systems (2)**", given from 28.11. to 01.12.2016 at TechSAT in Germany for 14 participants who where for the most part already among the participants in Xi'an. The topics this time: 1.) Slat/Flap Actuation, 2.) Mechanisms and Gear Trains, 3.) Slat/Flap Support Mechanisms, 4.) Slat/Flap Aerodynamic Load Estimation, 5.) Software: Direct Operating Costs for Aircraft Systems (DOCsys), 6.) Presentation of High Lift Systems from Selected Aircraft.

My Visits to China

Aircraft Design = 飞行器设计

The **Short Course "Aircraft Design"** was given in Nanjing, China at Nanjing University of Aeronautics and Astronautics (NUAA) in the frame of the Summer Lecture Program 2018 from 09th to 20th July 2018. Lecturers from all over the world applied with their 200 course offers. 61 courses were selected by NUAA, inviting lecturers from 22 countries and 5 continents.

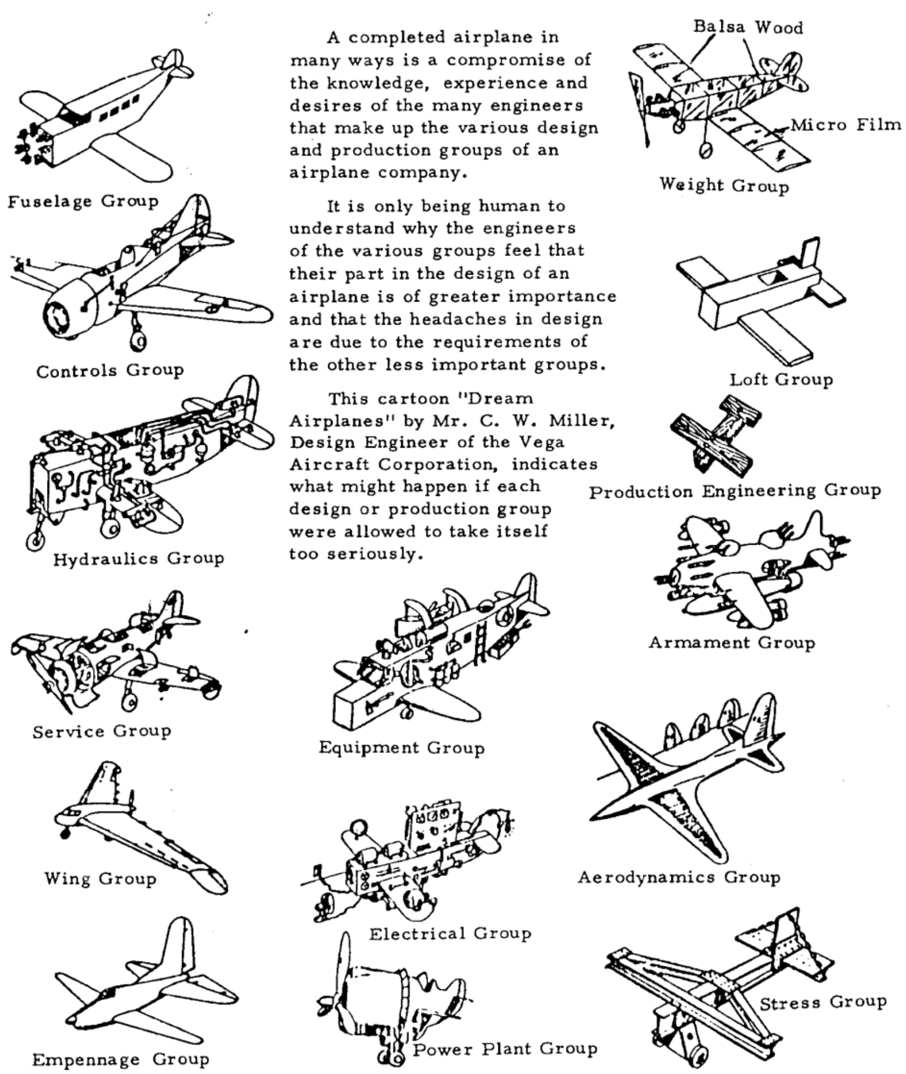
Nanjing University of Aeronautics and Astronautics

Scientific Research Publishing, Wuhan

Aircraft Design Basics

Aircraft Design Wisdom

- **No discipline should dominate** in Aircraft Design. Do not design your aircraft around the engine, the aerodynamics, ... (see consequences in picture to the right!)
- Start from **Top Level Aircraft Requirements** (TLAR) that are based on market needs. Do not trim the TLARs such to make your design ideas shine.
- Start with a **wide variety of design principles** and narrow down based on trade studies / **evaluation**. Do not get locked in by one design idea (e.g. electric propulsion).
- **Engine (and landing gear) integration** are important parts of Overall Aircraft Design (OAD) and effect many disciplines. Do not put your engines somewhere on the aircraft based just on one (good) idea.



First Law of Aircraft Design

Maximum Take-Off mass is a combination of PayLoad and Fuel mass (to reach maximum useful load) plus the Operating Empty mass of the aircraft:

$$m_{MTO} = m_{PL} + m_F + m_{OE}$$

$$m_{MTO} - m_F - m_{OE} = m_{PL}$$

$$m_{MTO} \cdot \left(1 - \frac{m_F}{m_{MTO}} - \frac{m_{OE}}{m_{MTO}} \right) = m_{PL}$$

$$\boxed{m_{MTO} = \frac{m_{PL}}{1 - \frac{m_F}{m_{MTO}} - \frac{m_{OE}}{m_{MTO}}}}$$

m_{MTO} : Maximum Take-Off mass

m_F : Fuel mass

m_{OE} : Operating Empty mass

m_{PL} : PayLoad

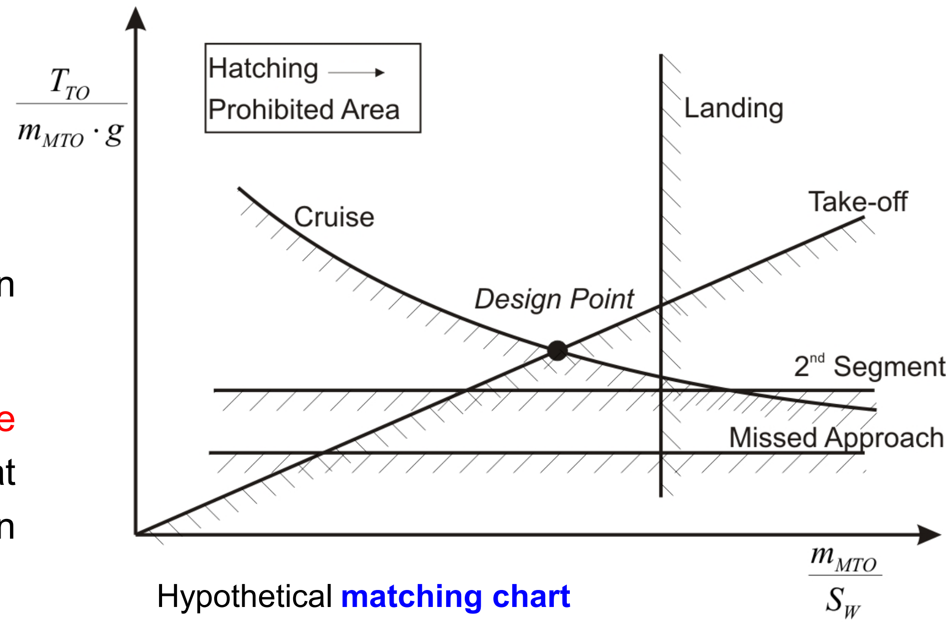
In case of electric propulsion fuel mass is meant to be battery mass.

Maximum Take-Off mass is a surrogate parameter for cost !

Several Design Requirements Considered Simultaneously with the Matching Chart

- Requirements:
  - **Take-off** (engine failure)
  - **2nd Segment Climb** (engine failure)
  - (Time to Initial Cruise Altitude, not shown in chart)
  - **Cruise**
  - **Missed Approach** (engine failure)
  - **Landing**
- Thrust-to-Weight versus Wing Loading.
- Graphical Optimization to find the Design Point.
- Note: Some design features may not have an effect, if they influence a flight phase that has (in one particular design) no effect on the Design Point.

- Heuristic for an optimum aircraft:
  - Lines from Take-Off, Landing and Cruise meet in one point
  - Move Cruise Line by selecting $1 \leq x_{opt} \leq 1.31$ for $V_{opt} = x_{opt} \cdot V_{md}$



Hypothetical matching chart

Find detailed information on

Aircraft Design

at

Hamburg Open Online University (HOOU)

http://hoou.ProfScholz.de

Scholz 2015

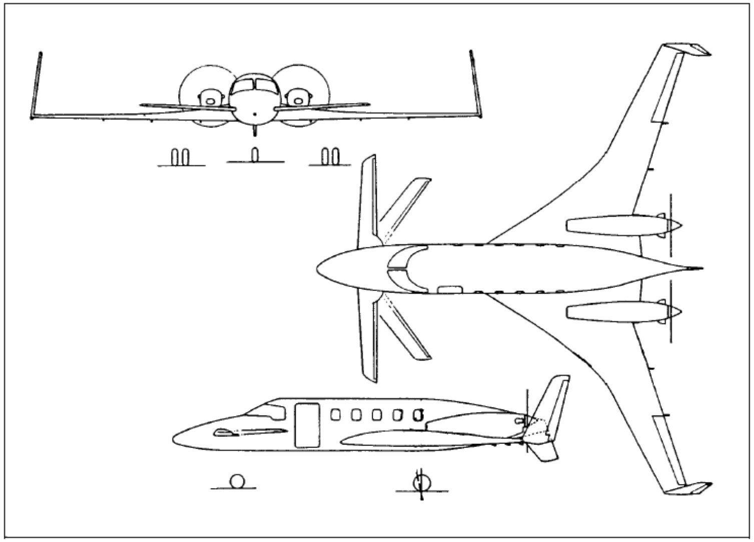
Unconventional and Innovative Configurations

Unconventional and Innovative Configurations

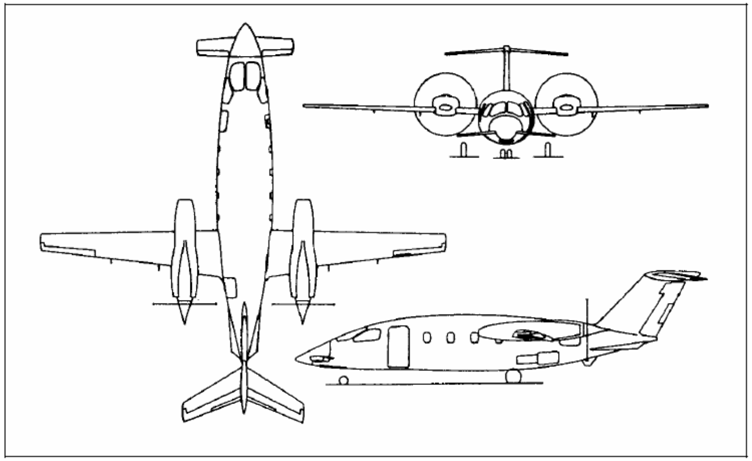
Conventional aircraft configurations differ in many aspects, but they all have a fuselage, wings and an empennage at their *rear end.* This configuration is called *tail aft aircraft*.

Unconventional aircraft configurations differ in at least one attribute from these main attributes of a conventional configuration.

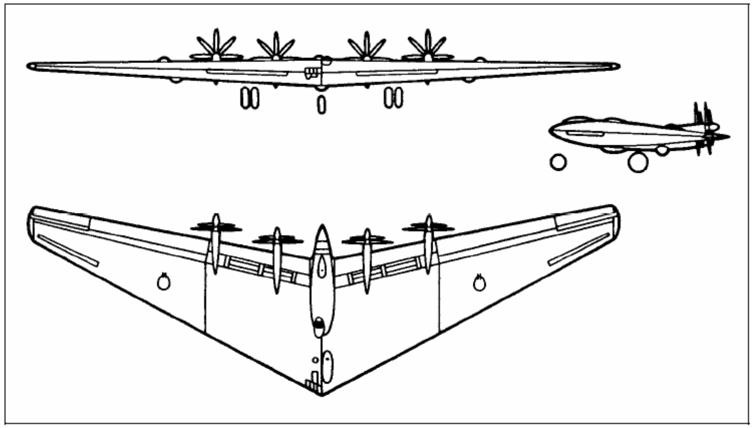
Examples of unconventional configurations:



Canard:
Beech Starship

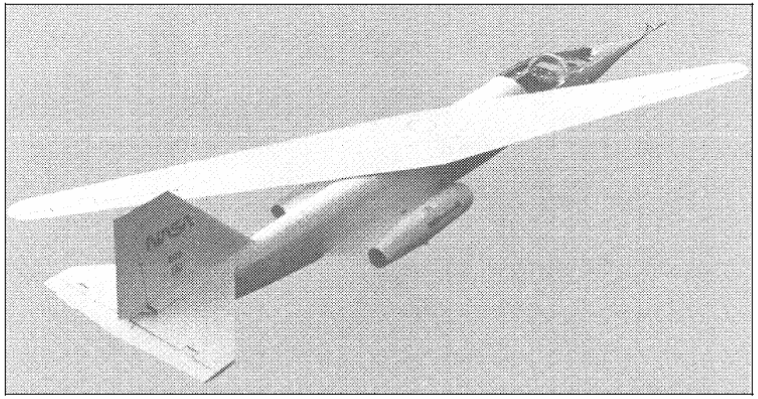


Three-surface aircraft:
Gates Piaggio GP-180

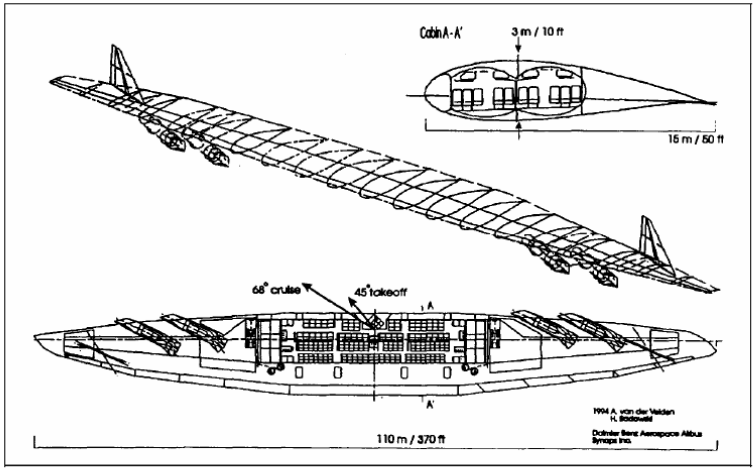


Flying wing:
Northrop XB-35

Unconventional and Innovative Configurations



Pivoting oblique wing aircraft:
NASA AD-1 Experimental aircraft.
Sweep is adjustable from 0° to 60°.



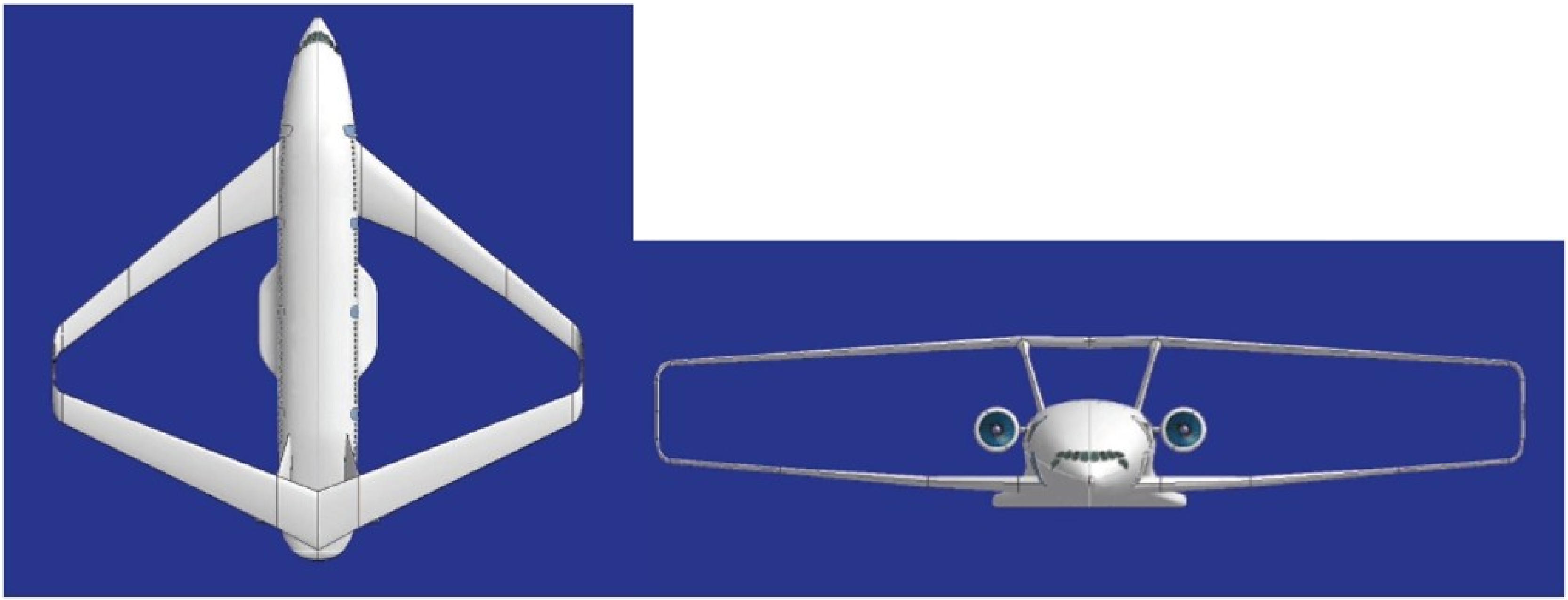
Oblique flying wing aircraft, OFW:
Study: DaimlerChrysler Aerospace Airbus.
Pax: 250, M_{CR} : 1.6, Sweep: 45° ... 68° .

BWB Definition

1) Conventional Configuration: "Tube and Wing" or "Tail Aft" (Drachenflugzeug)
2) Blended Wing Body (BWB)
3) Hybrid Flying Wing
4) Flying Wing

The Blended Wing Body aircraft is a blend of the tail aft and the flying wing configurations: A wide lift producing centre body housing the payload blends into conventional outer wings.

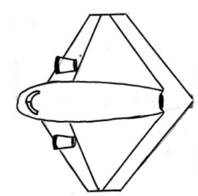
Box Wing Definition

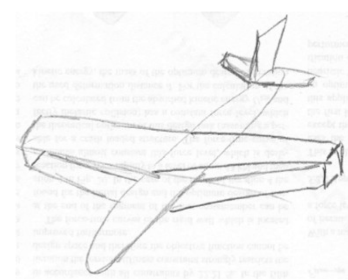


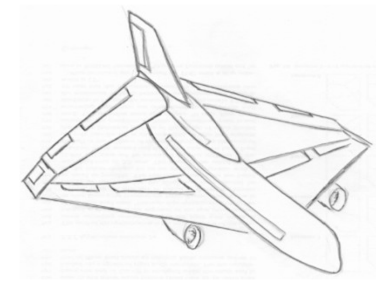
The Box Wing aircraft is a biplane with a conventional fuselage.
The two nonplanar wings are connected with a vertical fin at their tips.
If wings are swept, one wing is swept forward while the other is swept back.

Box Wing Systematic

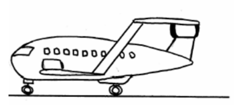
- **Hand Sketches**







- **Creative Methods**
- **Brainstorming**
- **Gallery Method**



VERHEIRE, E.: Systematic Evaluation of Alternative Box Wing Aircraft Configurations. Bachelor Thesis, HAW Hamburg, 2013

- **Modified 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

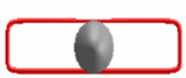
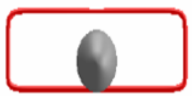
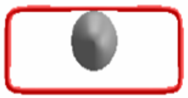
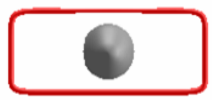
Number of Combinations: $3 \cdot 3 \cdot 2 \cdot 3 \cdot 1 \cdot 3 = 162$

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

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

Box Wing Systematic

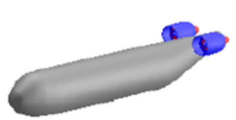
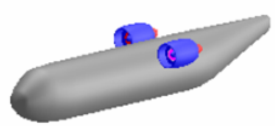
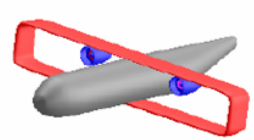
Box wing with different wing vertical position

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

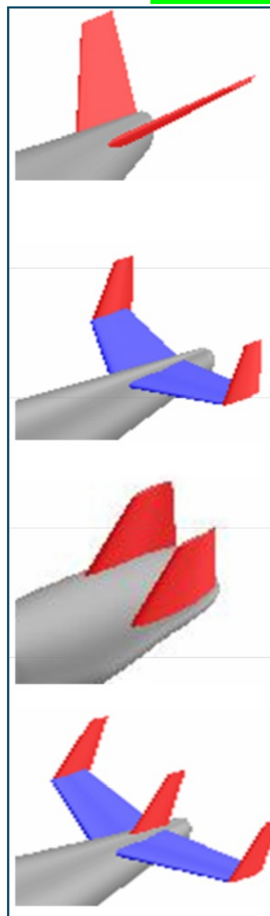
Horizontal tail surface position along the fuselage length

	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			

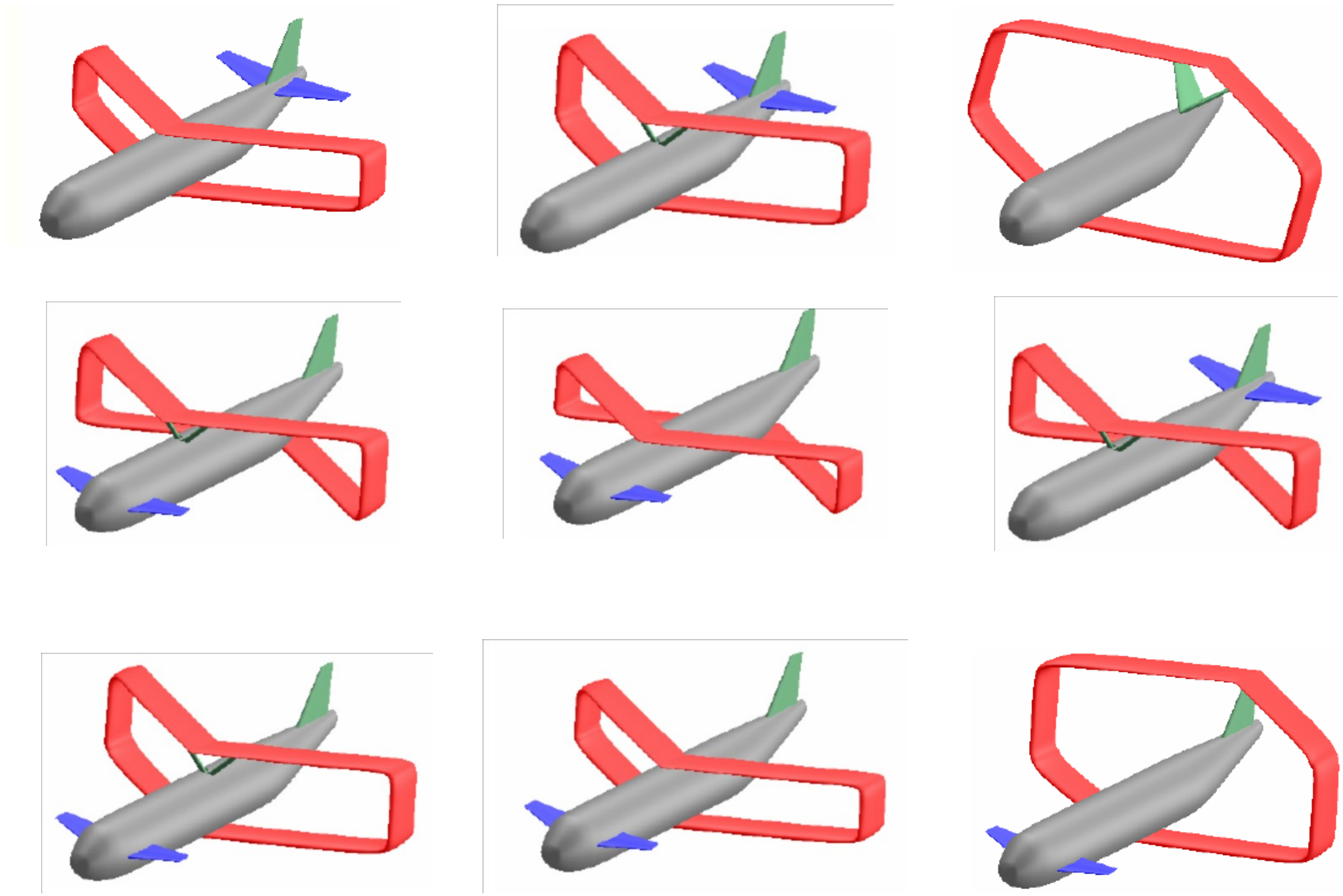
Example of possible vertical tails



All possible variations together would lead to 31 104 000 combinations (from Bachelor thesis)

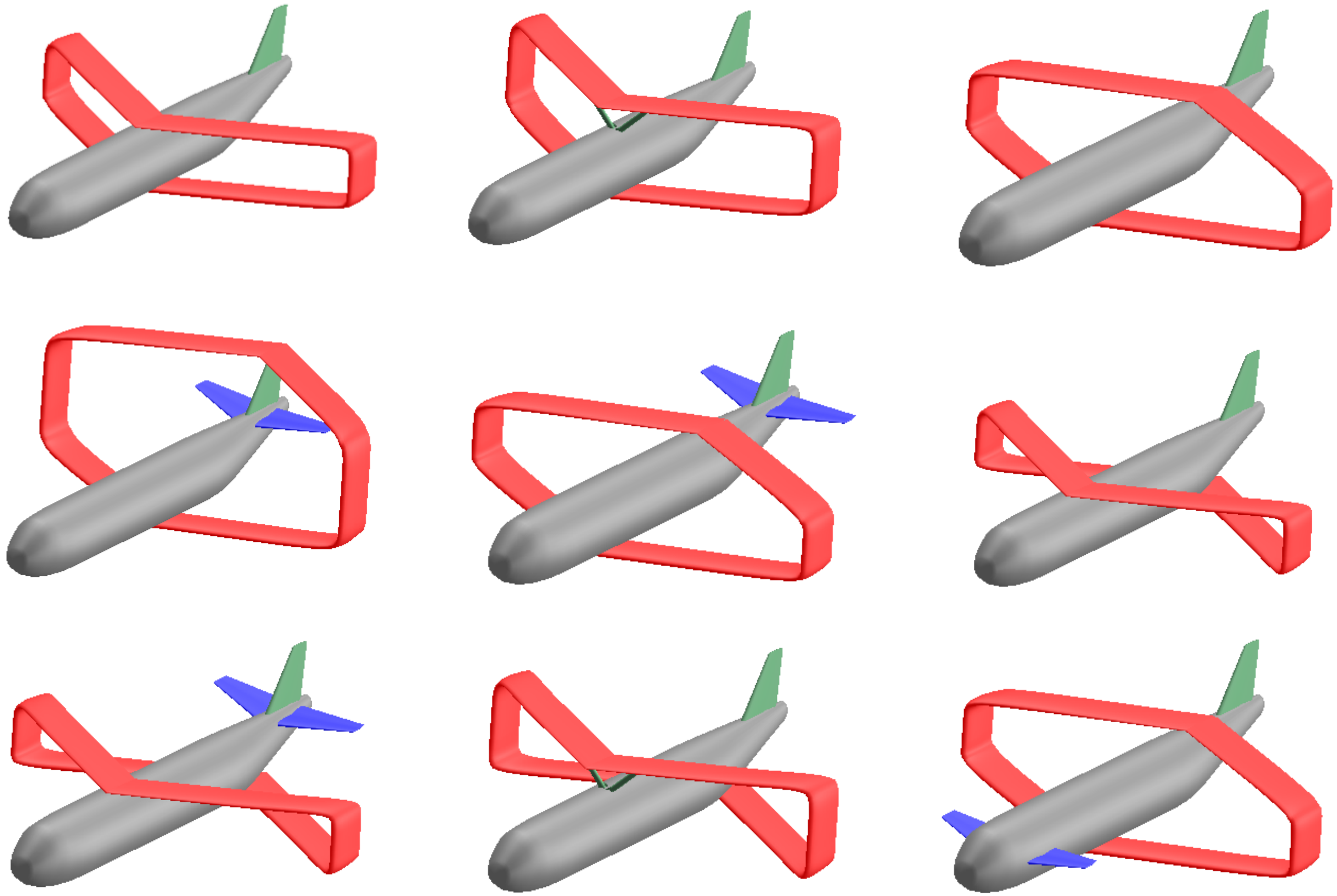
Unconventional and Innovative Configurations

Box Wing Systematic – 18 Finalists



Unconventional and Innovative Configurations

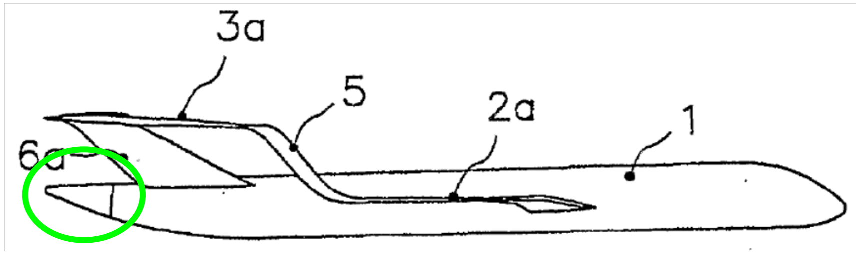
Box Wing Systematic – 18 Finalists

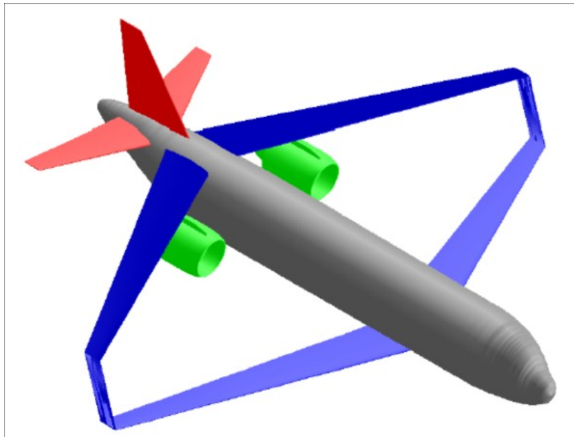


Box Wing Systematic – General Morpholocial Analysis

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

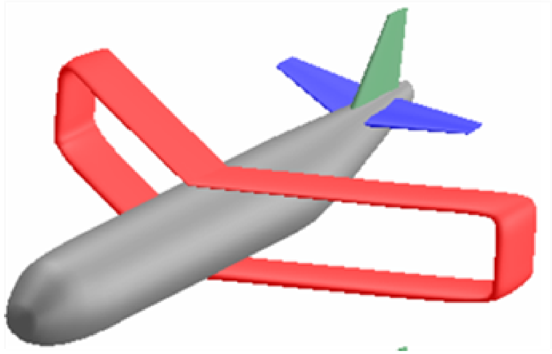
- Configuration
- Force Fighting
- Family Concept
- Drag
- Zero Lift Drag
- Induced Drag
- Weight
- Empty Weight
- Flight Mechanics
- Longitudinal Static Stability and CG Range
- Operation
- Ground Handling
- Development
- Time and Cost
- Risk



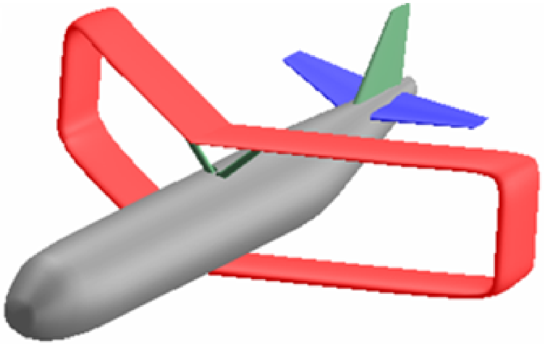


Box Wing Systematic – The Winners

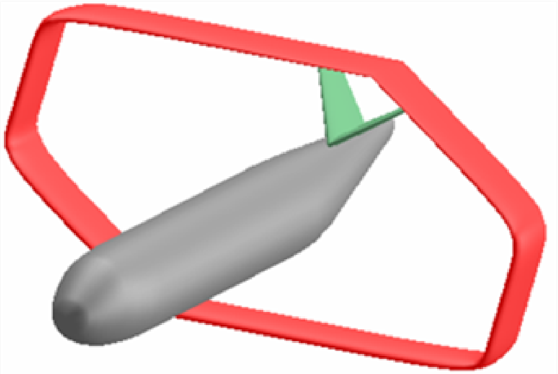
1.



2.



5.



Best unconventional configuration

BWB – L/D from Lecture Notes

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

A : aspect ratio
S_{wet} : wetted area
S_W : reference area of the wing
e : Oswald factor; passenger transports: $e \approx 0.85$

from statistics: $k_E = 15{,}8$

S_{wet} / S_W : conv. aircraft 6.0 ... 6.2
BWB ≈ 2.4

A : conv. aircraft 7.0 ... 10.0
VELA 2 5.2

$E_{max} = 23{,}2$

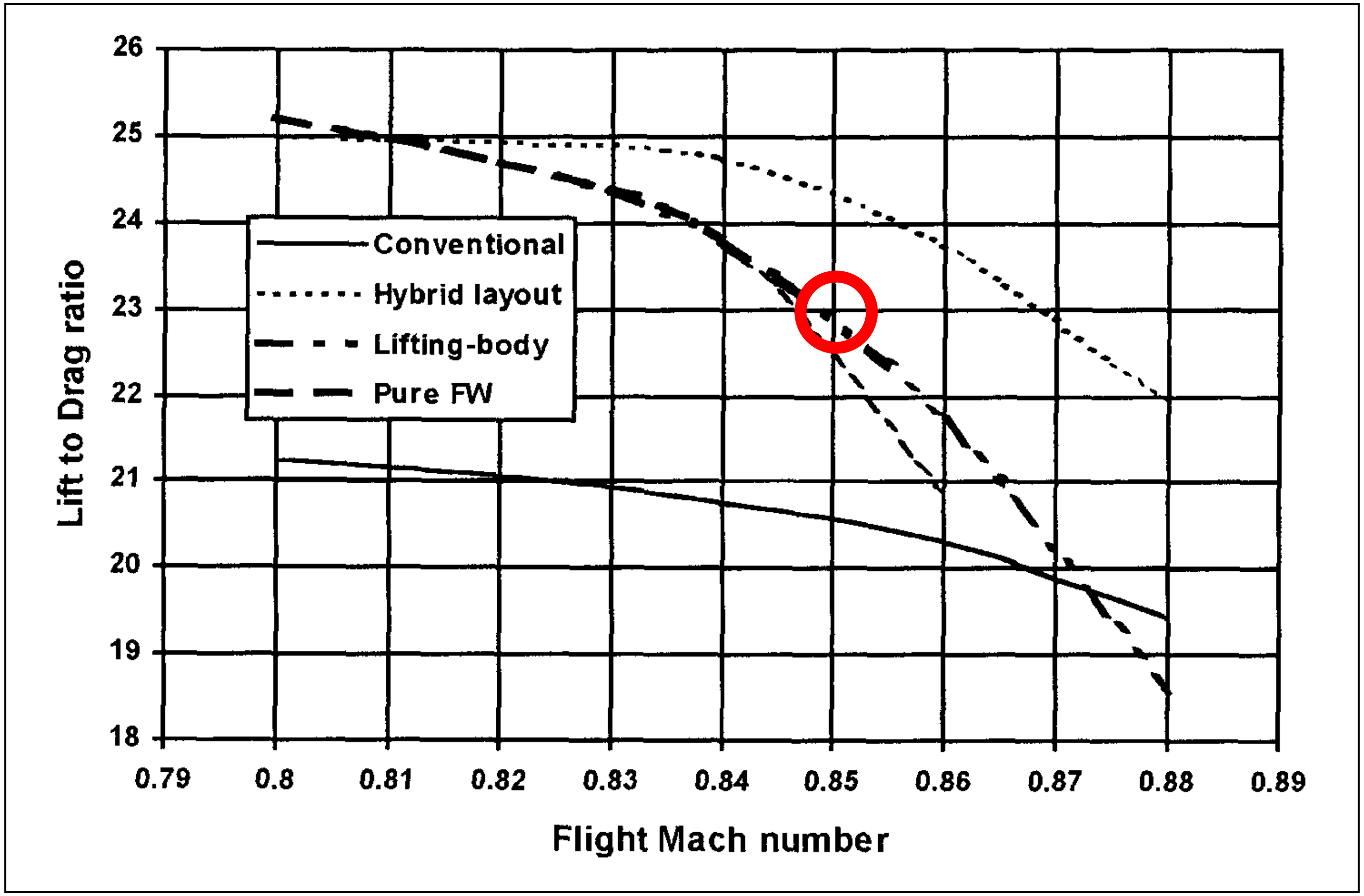
$$E_{max} = k_E \sqrt{\frac{A}{S_{wet} / S_W}}$$

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

$$\overline{c_f} = 0.003$$

BWB – L/D from TsAGI Research

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



Box Wing – Drag Estimation

$$C_{D,i} = \frac{C_L^{\,2}}{\pi \cdot A \cdot e}$$

$$A_{tot} = A_{ref} \qquad \boxed{A_{tot} = 9{,}53}$$

For a single box wing:

$$\boxed{A_{wing} = \frac{b^2}{S_{tot}/2} = 2 \cdot A_{ref} = 19{,}06}$$

Reference aircraft (A320):

$$(C_{D,i})_{ref} = \frac{C_{L,ref}^{\,2}}{\pi \cdot A_{ref} \cdot e}$$

Box wing aircraft (single wing):

$$(C_{D,i})_{wing} = \frac{C_{L,wing}^{\,2}}{\pi \cdot A_{wing} \cdot e}$$

For the wing of the reference aircraft and the single wing of the box wing the same Oswald factor (e) is considered. Both aircraft are assumed to have same mass. Thus:

$C_{L,ref} = C_{L,BW} = C_{L,Wing}$.

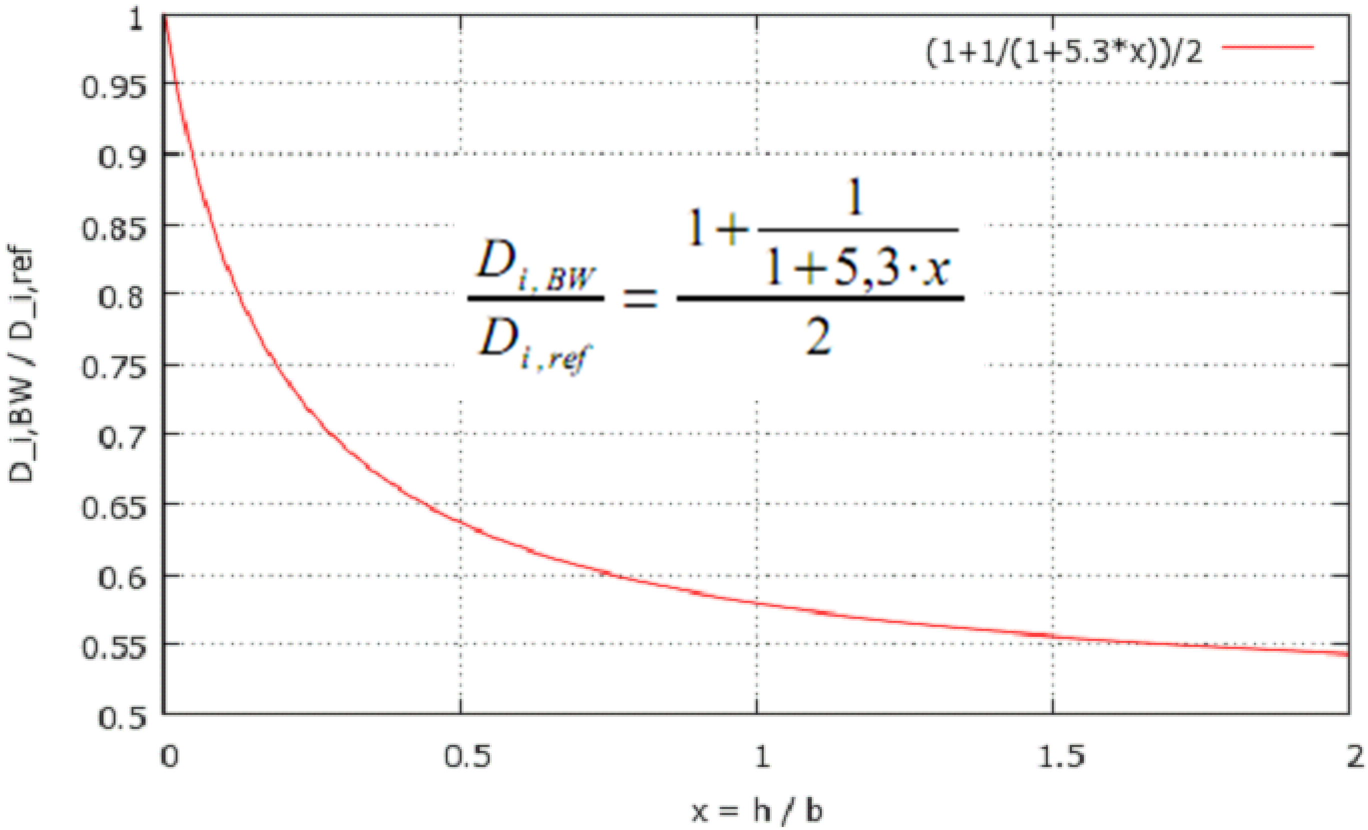
$$(C_{D,i})_{wing} = \frac{(C_{D,i})_{ref}}{2}$$

$$D_{i,ref} = q_\infty \cdot (C_{D,i})_{ref} \cdot S_{tot}$$

$$D_{i,BW} = 2 \cdot q_\infty \cdot \frac{(C_{D,i})_{ref}}{2} \cdot \frac{S_{tot}}{2}$$

$$\boxed{\frac{D_{i,BW}}{D_{i,ref}} = \frac{1}{2}}$$

Box Wing – Drag Estimation



$$\frac{D_{i,BW}}{D_{i,ref}} = \frac{1+\frac{1}{1+5{,}3\cdot x}}{2}$$

Overall Comparison – Tail Aft / BWB / Box Wing

Issue	Tail Aft	BWB	Box Wing
L/D	-	+	+
emissions	-	+	+
stall characteristic	o	+	o
CLmax	+	-	o
OEW / MTOW	+	-	(-)
noise shielding	o	+	o
stat. long. stab.	+	-	o
take-off rotation	+	(SS)	+
L/G integration	+	(SS)	o
tank volume	o	+	-
wake vortex	o	o	+
streching	+	-	(-)
turn around	+	-	o
ditching	o	SS	o

SS :
"Show stopper"

Overall Comparison – Tail Aft / BWB / Box Wing – Final Result

Issue	Tail Aft	BWB	Box Wing
total	+4	-2	+1

Electric Propulsion

Validation – Are we Doing the Right Thing?

Electric (Air) Mobility with/without Grid Connection?

"I am also much in favor of Electric Propulsion in aviation – once the problem with the Aerial Contact Line is solved!"

(one of my engineering friends)

We know:

- Electric propulsion suffers from large battery weight / low specific energy.
- Hybrid electric propulsion makes use of fuel with high specific energy, but leads to rather complicated, heavy and expensive systems.

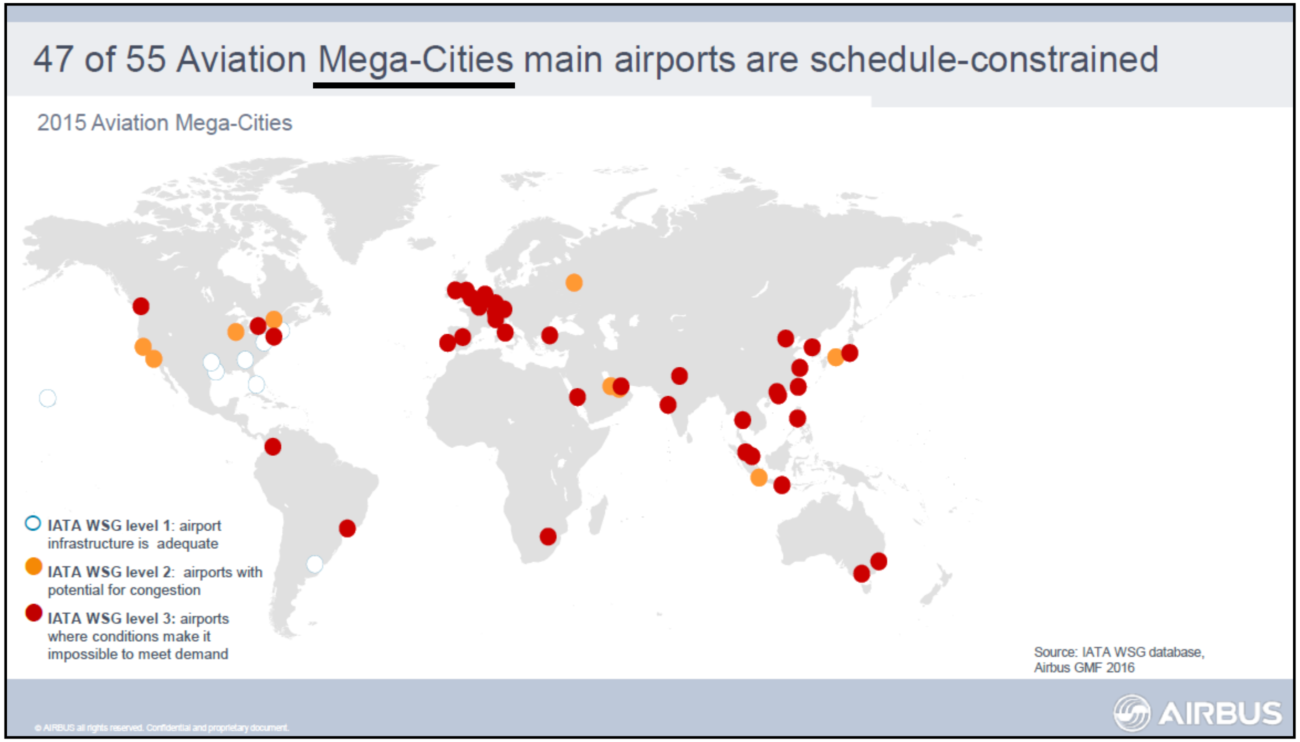
Validation – Are we Doing the Right Thing?

Grid Connected Electric Mobility Operates Successfully on Tracks!

- Aircraft: *Induced drag* is drag due to Lift = Weight. Train: *Rolling Friction* is also drag due to Weight.
- Aircraft: For minimum drag, *induced drag* is 50% of total drag.
- For the same weight, rolling friction of a train is 5% of the induced drag of an aircraft!
- This means: For the same weight, drag of an aircraft is reduced by ≈ 47.5% if put on rails!

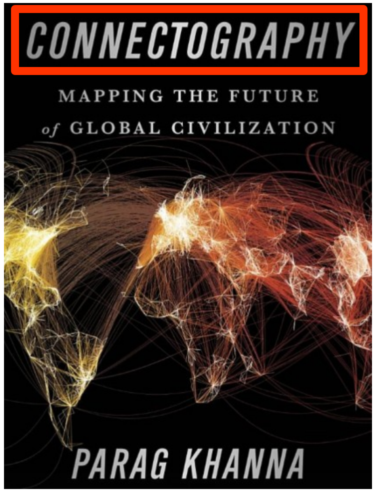
Validation – Are we Doing the Right Thing?

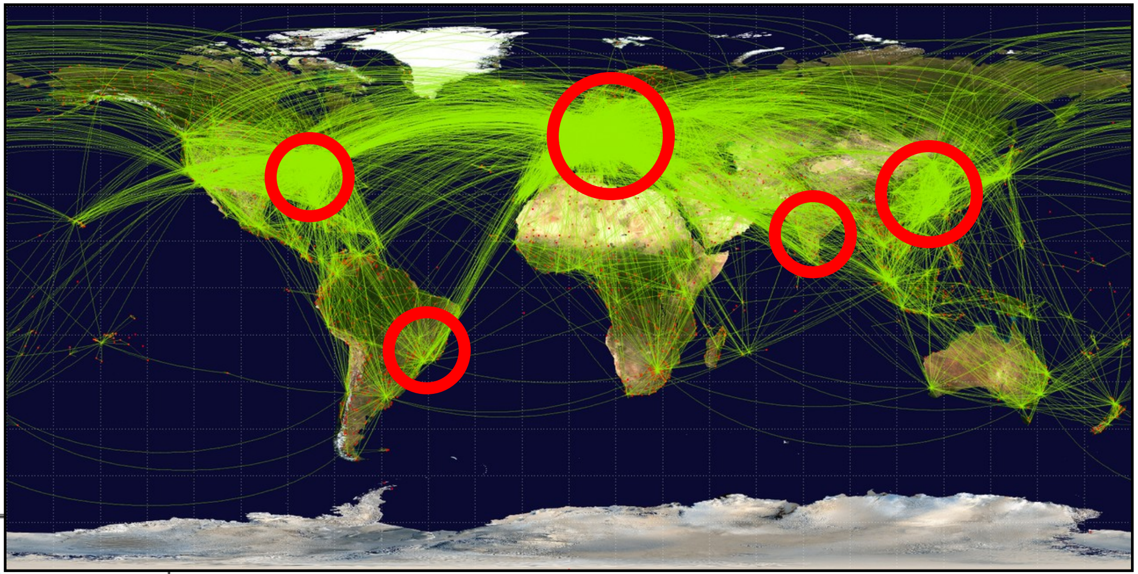
Mobility between Megacities – How?



- The world's population growth takes place in megacities.
- Airports at megacities are schedule-constrained already today – more so in the future.
- Adjacent megacities require mass capacity. Up to medium range => high speed trains needed!
- Megacities connect globally long range mostly over oceans => aircraft needed!

Validation – Are we Doing the Right Thing?





World Airline Routemap (Wikipedia)

Maps of World

Areas with adjacent megacities that will increasingly be *connected* by high speed trains.

Validation – Are we Doing the Right Thing?

Connecting Adjacent Megacities – Beijing & Shanghai – Comparing Aircraft with Train

Time	Location	Mode
08:20	Beijing Capital Times Square	Walk
08:30	Xidan	
08:40		
08:50		Metro Line 4
09:00	Xuanwumen	
09:10		
09:30		Metro Line 2
09:40	Dongzhimen	
09:50		Metro Airport Line
10:00	Beijing Capital International Airport	
10:10		
. . .	. . .	
11:20		
11:30	Beijing Capital International Airport	
11:40		
11:50		
. . .	**Aircraft**	Air China 1557
13:20		
13:30		
13:40	Shanghai Hongqiao	
13:50	Pick-up luggage	

(a) Travel mode: metro + aircraft

Time	Location	Mode
08:20	Beijing Capital Times Square	Walk
08:30	Xidan	
08:40	Beijing South Railway Station	Metro Line 4
08:50		
09:00	Beijing South Railway Station	
09:10		
09:20		
09:30		
09:40		
09:50		
10:00		
. . .	**Train**	
11:20		
11:30		
11:40		
11:50		
13:10		
13:20		
13:30		
13:40		
13:50 **new: 13:28**	Shanghai Hongqiao	

(b) Travel mode: metro + high-speed rail

China High Speed Rail (CHR)
Beijing to Shanghai:

- 1200 passengers per train
- **1200 km distance**
- 350 km/h
- ≈ every 20 min. (an A380 every 10 min.)
- usually fully booked
- 88000 passengers per day (both directions)

Example: Train number G1

Source:
https://doi.org/10.1155/2017/8426926

- Comparison **air transportation versus high-speed rail** for a trip from Beijing Capital Times Square to Shanghai Hongqiao in China.
- Despite the large spatial distance of more than 1200 km, **passengers** using either mode **arrive** approximately **at the same time**. Probability of delays is less on the train.

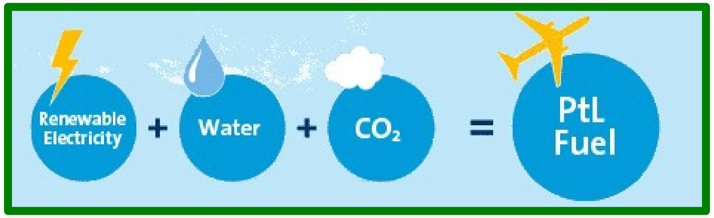
Validation – Are we Doing the Right Thing?

Many Possible Energy Paths for Aviation

1.	fossile fuel	=> jet engine		no future solution
2.	bio fuel (algae, ...)	=> jet engine		not sustainable
3.	regenerative electricity	=> aerial contact line	=> electric engine	not for aviation
4.	regenerative electricity	=> battery	=> electric engine	**electric**: only for short range
5.	regenerative electricity	=> LH2	=> jet engine	new infrastructure & planes
6.	regenerative electricity	=> LH2 => fuel cell	=> electric engine	see 5.; trade-off !
7.	regenerative electricity	=> **PtL** (drop in fuel)	=> jet engine	same infrastructure & planes
8.	regenerative electricity	=> PtL => GT/Gen.	=> electric engine	**hybrid electric**, heavy
9.	regenerative electricity	=> PtL => GT/Pump	=> hydraulic motor	**hybrid hydraulic** , ???

PtL: Power to Liquid

GT: Gasturbine; **Gen.**: Generator



Additional conversions & major aircraft parts: Solutions 6 (one more component) and 8/9 (two more comp.)

Summing up the Considerations for Validation

- Physics favor trains over aircraft (*low drag due to weight*) => less energy, less CO2.
- PtL for jet engines is big competition for any electric flight bringing regenerative energy into aircraft.
- Hybrid propulsion has better applications than aircraft.
- Unpredictable political environment for short range flights.
- Aircraft are the only means of transportation over oceans **long range.**
  Ships are too slow and hence no regular service, bridges and tunnels are limited in length.
- Trains better on **short range** (*less access time to station, less waiting time in station, ...*).
- Trains better to connect adjancent megacities over land up to **medium range** with high volume.
  A380 is too small and unfit, because designed for long range.
- Aircraft over land, if ...
  - **long range**,
  - **short range** and no train available due to low volume traffic
    - aircraft need less investment into infrastructure than (high speed) trains.
      Construction costs for high speed trains: 5 M€/km to 70 M€/km (2005, Campos 2009)
    - alternative: rail replacement bus service
  - over remote areas, if no train is available (mountains, desserts, polar regions).

So, again:

Where is the market niche for short range, small passenger aircraft with (hybrid-) electric propulsion?

Aircraft Design for Electric Propulsion

First Law of Aircraft Design – Consequences for Electric Propulsion

- The "First Law of Aircraft Design" may have no solution.
- No solution, if m_{MTO} is infinity or negative.
- No solution if m_F / m_{MTO} is too large:
  - range is too high,
  - specific energy of fuel or batteries is too low,
  - propulsion is inefficient,
  - aerodynamics are inefficient.
- No solution, if m_{OE} / m_{MTO} is too large (typical value: m_{OE} / m_{MTO} = 0.5):
  - structure is too heavy
  - systems are too heavy
  - propulsion is too heavy

$$\boxed{m_{MTO} = \frac{m_{PL}}{1 - \frac{m_F}{m_{MTO}} - \frac{m_{OE}}{m_{MTO}}}}$$

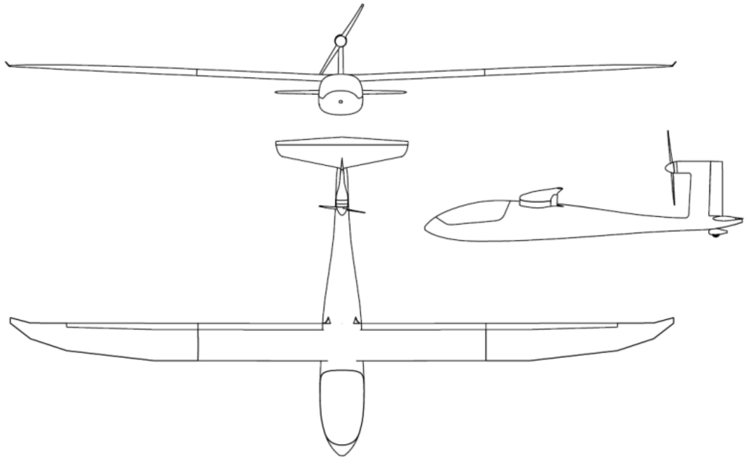
- Maximum take-off mass m_{MTO} is proportional to payload m_{PL} .
- Viability of electrical propulsion is <u>not a matter of aircraft size</u>.
  Very large electrical aircraft would be possible (if technology is ready)!

- Viability of electric propulsion is strongly a matter of
  - range and
  - specific energy.

Engine Integraton – Example

e-Genius
Uni Stuttgart

- **Integration of the engine in the tail.** Particularly electrical motors with their compact configuration are suitable for this. Advantages:
  - Compared to conventional touring motor gliders a substantial larger propeller-diameter can be realized without a high and consequentially heavier undercarriage. This leads to an increased propeller-efficiency.
  - The front body part has the aerodynamic quality of a modern glider (no vorticities and local impact pressure peaks) and thus a very small drag.
  - The propeller is well protected from ground contact.



Maximum Relative Battery Mass

$$m_{MTO} = m_{OE} + m_{bat} + m_{PL}$$

$$\frac{m_{bat}}{m_{MTO}} = 1 - \frac{m_{OE}}{m_{MTO}} - \frac{m_{PL}}{m_{MTO}}$$

$$\frac{m_{OE}}{m_{MTO}} \approx 0.50$$ technology parameter

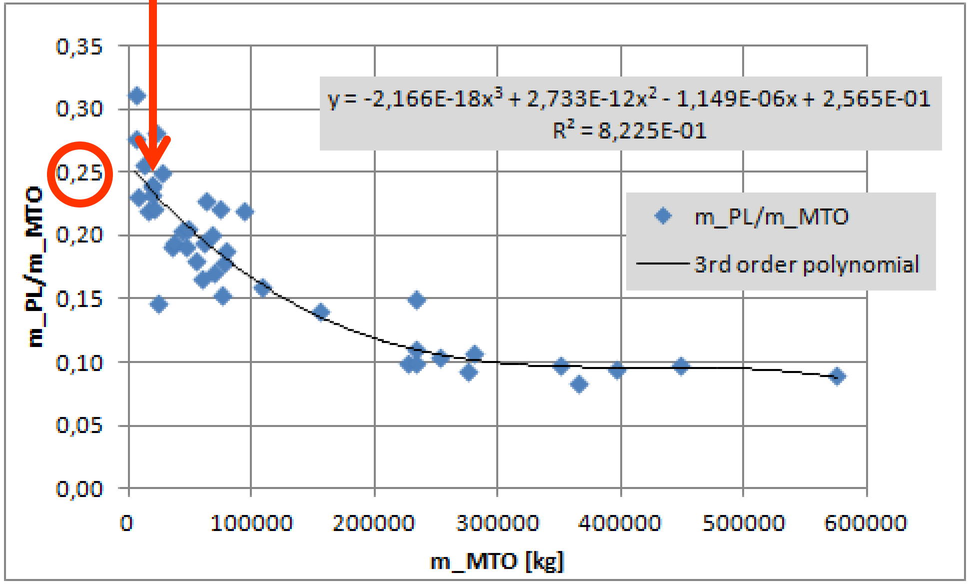
$$\boxed{\frac{m_{PL}}{m_{MTO}} = 0.25 : \frac{m_{bat}}{m_{MTO}} = 0.25 \qquad \frac{m_{PL}}{m_{MTO}} = 0.10 : \frac{m_{bat}}{m_{MTO}} = 0.40}$$

$$\boxed{0.25 \le \frac{m_{bat}}{m_{MTO}} \le 0.40}$$

this is equivalent to **revenue / expenses**

m_{MTO} : Maximum Take–Off mass
m_{bat} : battery mass
m_{OE} : Operating Empty mass
m_{PL} : PayLoad

small A/C; short range



Payload, m_PL calculated from "typical number of seats" from manufacturers seat layout and 93 kg/seat. Data points represent passenger aircraft most frequently in use with 19 seats or more. Note: Although the regression is quite good, physically m_PL/m_MTO is a function of range.

Aircraft Design for Electric Propulsion

Maximum Range for Electrical Propulsion

$$e_{bat} = \frac{E_{bat}}{m_{bat}} \qquad L = W = m_{MTO}\, g \qquad E = \frac{L}{D} \qquad D = \frac{m_{MTO}\, g}{E}$$

$$P_D = D V = \frac{m_{MTO}\, g}{E} V = P_T = P_{bat}\, \eta_{prop}\, \eta_{elec} \qquad V = \frac{R}{t}$$

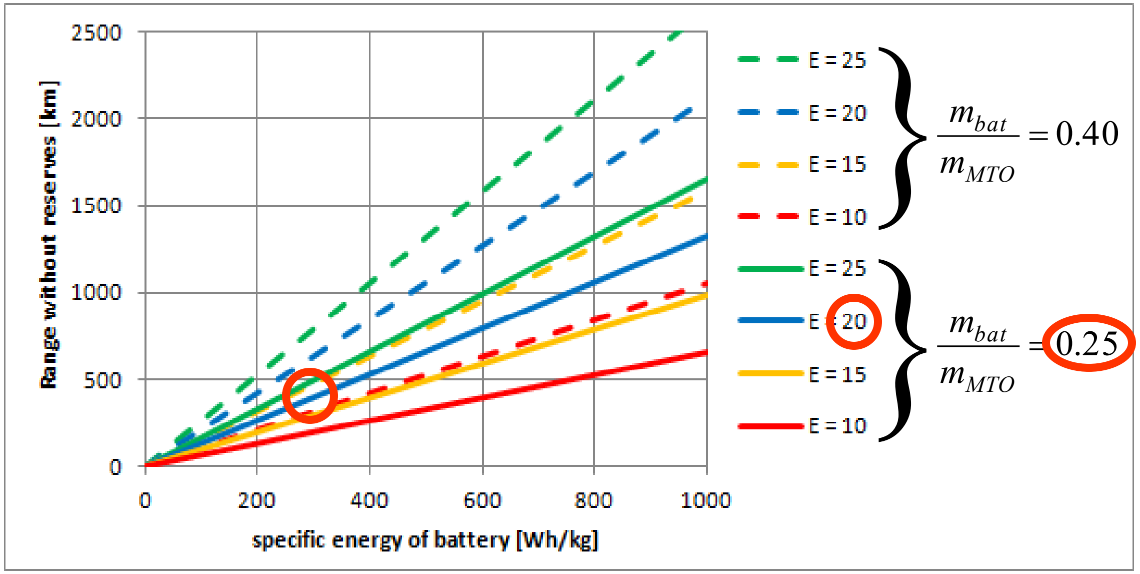
$$P_{bat} = \frac{E_{bat}}{t} = m_{bat}\, e_{bat} \frac{V}{R}$$

$$m_{bat}\, e_{bat} \frac{V}{R} \eta_{elec}\, \eta_{prop} = \frac{m_{MTO}\, g}{E} V$$

$$\boxed{R = \frac{m_{bat}}{m_{MTO}} \frac{1}{g} e_{bat}\, \eta_{elec}\, \eta_{prop}\, E}$$

$$\eta_{elec} = 0.9; \qquad \eta_{prop} = 0.8$$

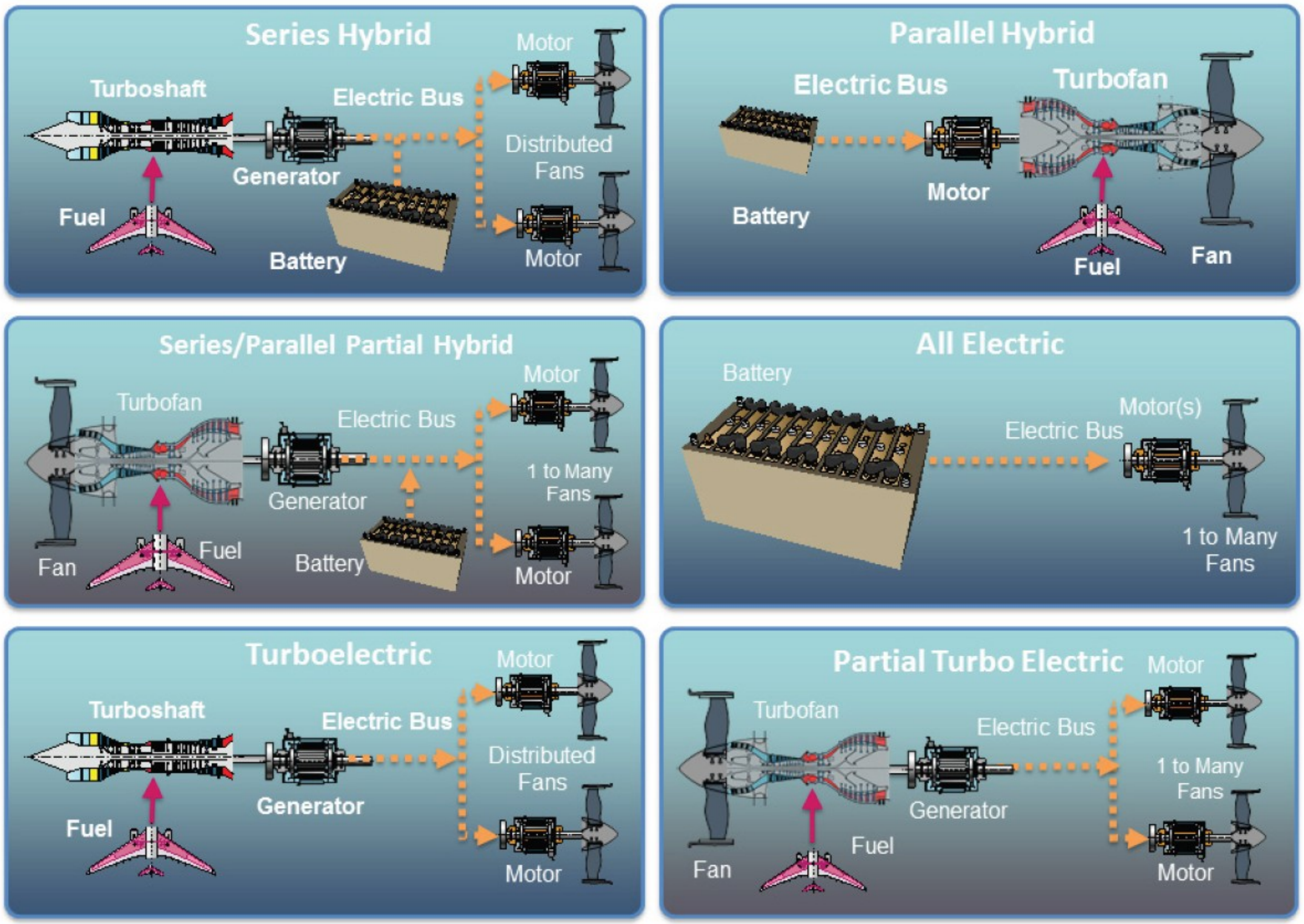
e_{bat} : specific energy
E_{bat} : energy in battery
E : glide ratio (aerodynamic efficiency)
L : lift
D : drag
W : weight
V : flight speed
R : range
t : time
g : earth acceleration
P : power
η : efficiency (prop: propeller)



○ : realistic parameters

Aircraft Design for Electric Propulsion

The Major 6 Turbo / Electric / Hybrid Architectures



http://doi.org/
10.17226/23490

Collecting Aircraft Design Wisdom

- Thrust levels depend on flight phase. Decreasing thrust for: Take-Off $\rightarrow$ Climb $\rightarrow$ Cruise
- Cruise thrust is ≈20% of take-off thrust
- Climb thrust is ≈80% down to ≈20% of take-off thrust (≈50% on average)
- Take-off thrust required for only 5 min. (fuel ratio: 25 min / t_F)
- Operating Empty Mass ≈50% of Maximum Take-Off Mass
- Engine mass is ≈10% of Operating Empty Mass

Derivation of Exergy Density, *b*

$E = A + B$	E: energy
$B = W$	A: anergy
$\eta = W / E = B / E$	B: exergy
$B = \eta E$	W: work
$E = m_F H_L$	η: efficiency
$e = E / m_F = H_L$	m_F: fuel mass
$b = B / m_F = \eta E / m_F$	H_L: lower heating value
$\boxed{b = \eta H_L}$	e: specific energy
	b: specific exergy

	Gas Turbine (GT)	Electric Motor (EM)	**Hydraulic Motor** (HM)
relative component mass, m_x/m_{GT}	1.0	1.0	**0.1**
efficiency, η	0.35	0.9 (with controller)	0.9 (with controller)

	kerosine (k)	battery (b)	accumulator (a)
energy density, e	43 MJ/kg = 11900 Wh/kg	300 Wh/kg	5.0 Wh/kg
specific **exergy**, $b = \eta\ e$	**4165 Wh/kg**	270 Wh/kg	4.5 Wh/kg
relative specific exergy, b_x/b_k	1.0	0.065	0.01

Generic Evaluation of Turbo / Electric / Hydraulic Architectures

- Reference Configuration

  Kerosene feeds Gasturbine (turbofan)
- All Electric

  Component mass: ≈ unchanged

  Battery mass (exergy comparison): 15 times that of kerosene (with snowball effects even more)
- Turbo Electric: Gasturbine + Generator + Electric Motor

  Component mass: 3 times mass of Gasturbine

  Efficiency (from storage to propulsor): $0.9 \cdot 0.9 = 81\%$ that of reference i.e. 28%

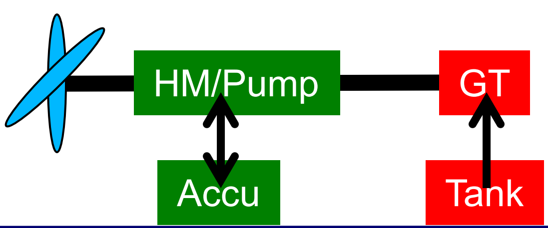
  Fuel mass: $1/0.81 = 1.2$ that of reference
- Turbo Hydraulic: Gasturbine (GT) + Pump + Hydraulic Motor (HM)

  Component mass: now only 1.2 the mass of the gasturbine
- Parallel Hydraulic Hybrid – hydraulic used only during take-off (accumulator filled again for TOGA)

  Component mass: $0.8+0.2 \cdot 0.1$=> only 82% that of reference => OEW reduced by 1.8%

  Assume 5h flight => 5% of energy is in accumulator.

  Storage mass: $0.95 + 0.05/0.01= 5.95$ that of reference => This idea does not work!



Aircraft Design for Electric Propulsion

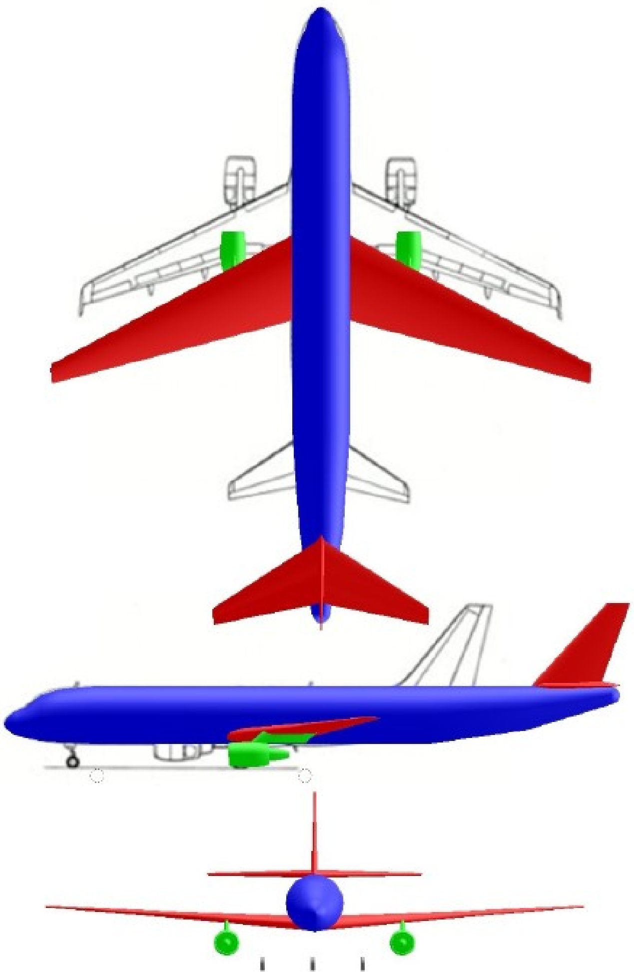
Battery Powered A320

- Only design solution with Range reduced by 50%
  => not a fair trade-off <=

- Specific Energy: 1.87 kWh/kg
- Energy density: 938 kWh/m³
- Batteries in LD3-45 container
- 2 container in cargo compartment
- 13 container forward and aft of cabin
- Fuselage streched by 9 m to house batteries

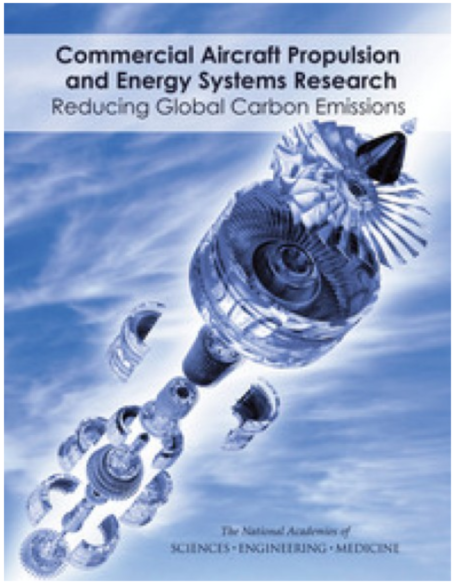
- MTOW plus 38%
- Battery mass plus 79% (compared with fuel mass)
- On study mission (294 NM) environmental burden (Single Score) down by 45% (EU electrical power mix)

Parameter	Value	Deviation from A320
Requirements		
m_{MPL}	19256 kg	0%
R_{MPL}	755 NM	-50%
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%
Main aircraft parameters		
m_{MTO}	95600 kg	30%
m_{OE}	54300 kg	32%
m_F	22100 kg	70%
S_W	159 m²	30%
$b_{W,geo}$	36.0 m	6%
$A_{W,eff}$	9.50	0%
E_{max}	18.20	≈ + 3%
T_TO	200 kN	38%
BPR	6.0	0%
h_{ICA}	41000 ft	4%
s_{TOFL}	1770 m	0%
s_{LFL}	1450 m	0%
Mission requirements		
R_{Mi}	294 NM	-50%
$m_{PL,Mi}$	13057 kg	0%
Results		
$m_{F,trip}$	7800 kg	72%
SS	0.0095	-45%



Summary Compiled from National Academies of Sciences (USA)

- The most important parameters are specific energy (Wh/kg) for energy storage and specific power (kW/kg).
- Jet fuel is an excellent way to store energy, with approximately 13000 Wh/kg.
- State of the art: 200-250 Wh/kg (2016).
- The committee's projection of how far the state of the art will advance during the next 20 years: 400-600 Wh/kg.
- All-electric regional and single-aisle aircraft would be suitable only for short-range operations, and even then they would require a battery system specific energy of 1800 Wh/kg.
- CO_2 emissions from the source of electricity used to charge the batteries.
- Cost of new infrastructure at airports to charge aircraft batteries, new power transmission lines to airports and, potentially, new generating (power plant) capacity.
- **No** electric propulsion concept will mature to the point to meet the needs of **twin-aisle aircraft within the next 30 years**.



The National Academies of
SCIENCES · ENGINEERING · MEDICINE

http://doi.org/10.17226/23490

Manufacturing

Airbus – Future Factory (1/2)

Video:
https://youtu.be/csQHIEggeYQ

Digitally planned and simulated factory

--- Flow principle with feeder lines

--- Further component lines, Mixed line floor grid, Mixed line side shell, Mixed line lower shell, Mixed line upper shell

Aircraft definition based on online catalog

Production control

--- Paperless production

Logistics

--- Lean hangar logistics

Major component standard equipping

--- Just-in-time and Just-in-sequence

--- Integrated riser ducts and fibre-optics

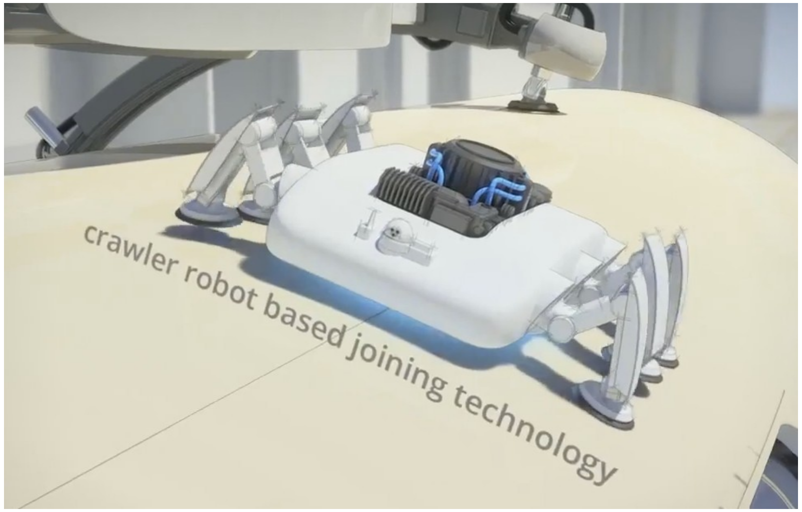
--- Bracket-free system installation:
with integrated raceways, and wireless transmitters for cabin signals

--- Automated ground based logistics

--- Large components delivery in standard containers

--- Flexible handling device

--- RFID identification



Manufacturing

Airbus – Future Factory (2/2)

--- Smart tool for all assemblies
--- Ergonomic position on adaptive jig
--- Equipment protection with shrink foil
--- Laser controlled positioning
--- Crawler robot based joining technology
--- Accurate surface treatment on joins
--- Digital printing of customized electrics
--- Cobot (Co-Operative Robot) for any non-ergonomic areas: controlled by augmented reality
--- Integrated quality checks and documentation
--- Progress tracking for customer
--- Automated fuselage assembly

Digital paint shop

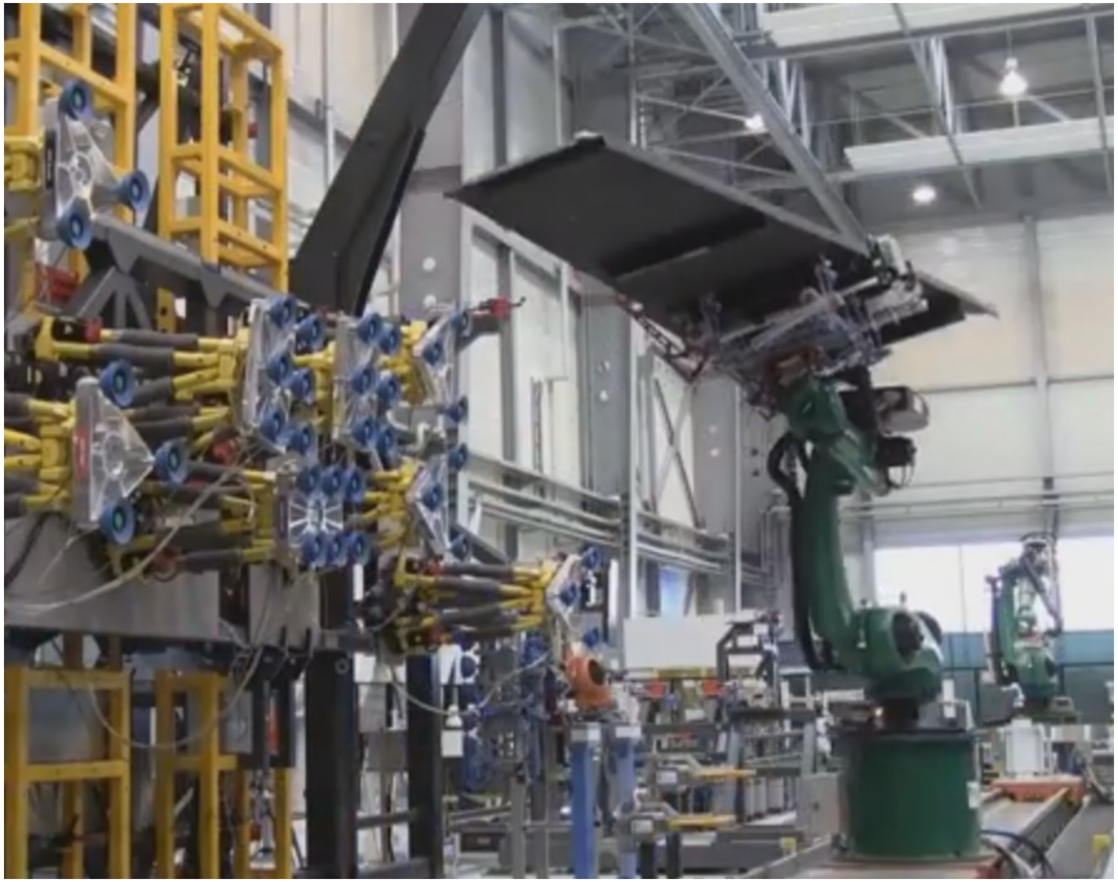
--- Inkjet digital painting without masking
--- Printed radiation shield and structural health monitoring
--- Printed aerodynamic riblets
--- Integrated quality check and documentation

Final assembly line

--- Same technical principles: for large components and in final assembly line

Fraunhofer: Robotics

Fraunhofer IFAM – Video:
Automated Assembly Technology in Aerospace Manufacturing



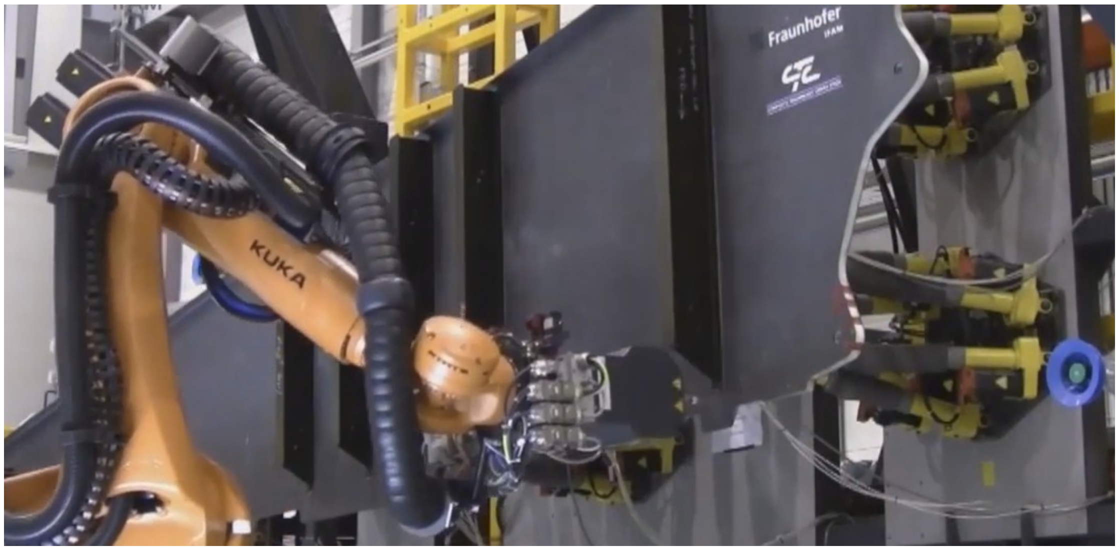
Video:
https://youtu.be/su_6hQOs3jQ

In Aerospace industry machining of major components such as wings, fuselage shells or tail planes is a real challenge. With robotic based machining and mobile robotic systems there are promising opportunities for the manufacturing of the future regarding higher productivity, reduction of lead time and decrease of investment costs. Major enablers for this vision are adaptive automation systems with high accuracy in a continuously changing environment.

Manufacturing

Fraunhofer: Robotics

Fraunhofer IFAM – Video:
Automated Vertical Tail Plane Assembly

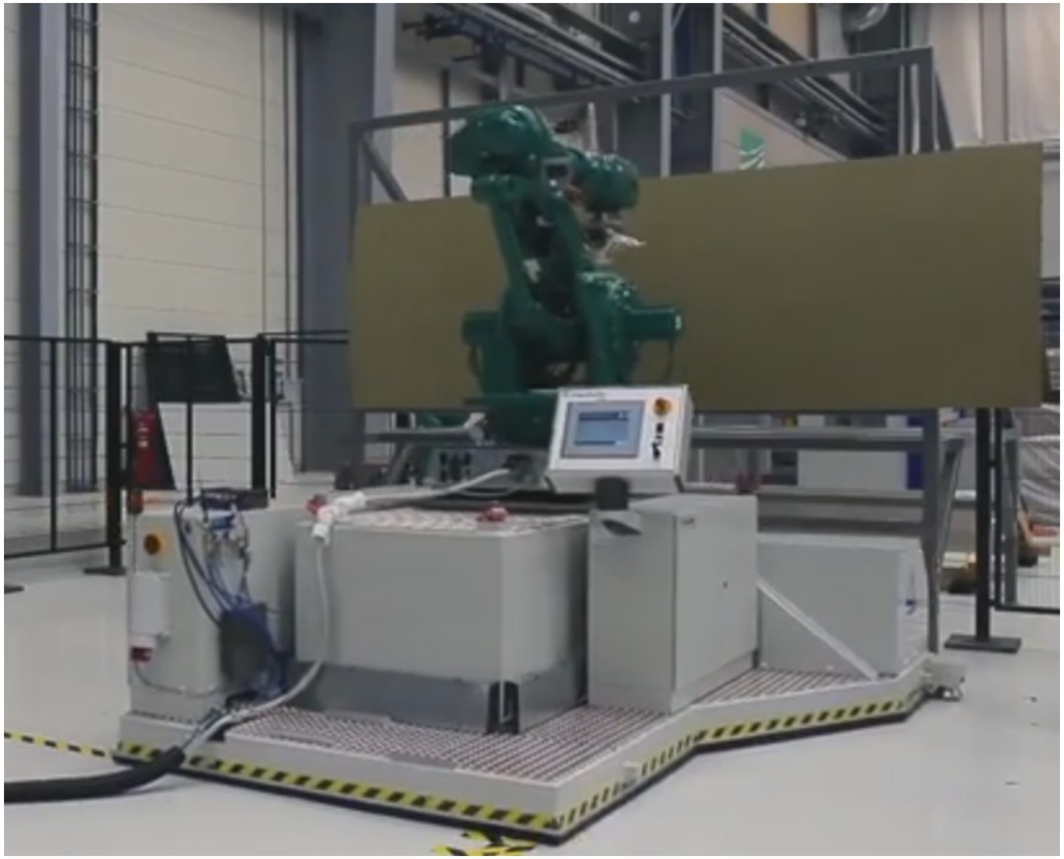


Video:
https://youtu.be/Ugwp4wElyLo

The video shows:
--- Automatic handling of VTP shell
--- Rigging of VTP shell into flexible jig
--- 3D measurement of rib joint area for virtual assembly
--- Plasma surface treatment of rib joining area
--- Tolerance adaptive adhesive application with online quality assurance
--- Flexible rib joining gripper and jig
--- Positioning and joining of rib
--- Fixation of rib on shell (modular gripper)
--- Curing of adhesive
--- **Plasma surface treatment of shell joining area** (picture)
--- 3D measurement of spar joining area for virtual assembly
--- Automated joining

Fraunhofer: Robotics

Fraunhofer IFAM – Video:
Robotic Machining Technology in Aerospace Manufacturing



Video:
https://youtu.be/-IE138uoLV0

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Participants of the Seminar "Innovative Aircraft Technologies"