AIRCRAFT DESIGN AND SYSTEMS GROUP (AERO)

Evaluating Aircraft with Electric and Hybrid Propulsion

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Download: http://EHA2018.ProfScholz.de and from https://www.repo.uni-hannover.de
Abstract

Purpose – This presentation takes a critical look at various electric air mobility concepts. With a clear focus on requirements and first principles applied to the technologies in question, it tries to bring inflated expectations down to earth. Economic, ecologic and social (noise) based well accepted evaluation principles are set against wishful thinking.

Design/methodology/approach – Aeronautical teaching basics are complemented with own thoughts and explanations. In addition, the results of past research projects are applied to the topic.

Findings – Electric air mobility may become useful in some areas of aviation. Small short-range general aviation aircraft may benefit from battery-electric or hybrid-electric propulsion. Urban air mobility in large cities will give time advantages to super-rich people, but mass transportation in cities will require a public urban transport system. Battery-electric passenger aircraft are neither economic nor ecologic. How overall advantages can be obtained from turbo-electric distributed propulsion (without batteries) is not clear. Maybe turbo-hydraulic propulsion has some weight advantages over the electric approach.

Research limitations/implications – Research findings are from basic considerations only. A detailed evaluation of system principles on a certain aircraft platform may lead to somewhat different results.

Practical implications – The discussion about electric air mobility concepts may get more factual. Investors may find some of the information provided easy to understand and helpful for their decision making.

Social implications – How to tackle challenges of resource depletion and environment pollution is a social question. Better knowledge of the problem enables the public to take a firm position in the discussion.

Originality/value – Holistic evaluation of electric air mobility has not much been applied yet. This presentation shows how to proceed.

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E-Mail see: http://www.ProfScholz.de
Evaluating Aircraft with Electric and Hybrid Propulsion

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Validation – Are we Doing the Right Thing?
Validation – Are we Doing the Right Thing?

Market Situation

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

Data source: Boeing 2018

(Hybrid-) electric propulsion with small short range passenger aircraft will be in this niche market!

Market value: 1.7% in next 20 years – declining.
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!

Put the aircraft on tracks!
This replaces the Induced Drag by Rolling Friction

• 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 \( \approx 47.5\% \) 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!
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

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<td>13:40</td>
<td>Pick-up Hongqiao</td>
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<tr>
<td>13:50</td>
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</table>

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

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

- 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?

Increasing Political Pressure ...

... to shift short range flights from airports to trains!

Per Jet von Frankfurt nach Köln

Verlagerung der Kurzstreckenflüge auf die Bahn würde Mensch und Umwelt entlasten

Frankfurter Rundschau, 26.10.2018

Kleine Anfragen an die Bundes- und Landesregierungen und die Antworten:

08.10.2018(Q) 19/4784 Potenzial der Verlagerung von Inlandsflügen auf die Bahn am Flughafen Frankfurt
18.09.2017(A) 18/13587 Potenzial der Verlagerung von Flügen auf die Bahn am Flughafen Berliner Flughäfen
06.09.2017(A) 18/13510 Potenzial der Verlagerung von Flügen auf die Bahn am Flughafen München
17.06.2016(A) 19/3263(HE) Potenzial der Verlagerung von Passagierflügen auf die Bahn am Flughafen Frankfurt a.M.
16.06.2016(A) 19/3264(HE) Potenzial der Verlagerung von Frachtflügen auf die Bahn am Flughafen Frankfurt a. M.
28.08.2015(A) 18/5879 Potenzial der Verlagerung von Flügen auf die Bahn am Flughafen München
06.05.2014(A) 18/1324 Potenzial der Verlagerung von Flügen auf die Bahn am Flughafen Frankfurt am Main
05.08.2014(A) 19/542(HE) Verlagerung Kurzstreckenflüge auf die Bahn
07.09.2012(A) 17/10615 Potenzial der Verlagerung von Flügen auf die Bahn am Flughafen Hannover
05.04.2012(A) 17/9274 Potenzial der Verlagerung von Flügen auf die Bahn am Flughafen Frankfurt am Main

http://dipbt.bundestag.de Q: Question; A: Answer; HE: Hessen
Validation – Are we Doing the Right Thing?

Many Possible Energy Paths for Aviation

1. fossil 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

Additional conversions & major aircraft parts: Solutions 6 (one more component) and 8/9 (two more comp.)
Validation – Are we Doing the Right Thing?

**Electric versus Hydraulic Hybrid Propulsion**

<table>
<thead>
<tr>
<th>Electric Hybrid Technology</th>
<th>Hydraulic Hybrid Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Characteristics/ Advantages:</strong></td>
<td><strong>Characteristics/ Advantages:</strong></td>
</tr>
<tr>
<td>• Extension of reach</td>
<td>• Vehicle inertia feeds accumulators</td>
</tr>
<tr>
<td>• Reduction of peak loads</td>
<td>• Acceleration supported by stored hydraulic energy</td>
</tr>
<tr>
<td>• Power peaks are balanced by batteries</td>
<td>• Good recovery of kinetic energy</td>
</tr>
<tr>
<td>• Additional electrical power</td>
<td>• Starting benefits from high power density</td>
</tr>
<tr>
<td>• Lower (Diesel) Power required</td>
<td>• High torque available, especially in the acceleration phase</td>
</tr>
<tr>
<td></td>
<td><strong>Electric hybrid allows storage of high amounts of energy</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Hydraulic hybrid allows storage of high amounts of powers</strong></td>
</tr>
</tbody>
</table>

In contrast to both of this: *Aircraft have a very even load profile during most time of the operation!*
Validation – Are we Doing the Right Thing?

Electric versus Hydraulic Hybrid Propulsion

Possible Applications

→ Slow vehicles with multiple start and stop situations in normal operation, such as...
... busses, underground, tram
... garbage trucks
... construction vehicles
...

Customer Benefits HRB System (Hybrid Hydraulic)

- Fuel Savings by up to 15-30%
  - Equal Reduction of emission
- Reduction of brake wear and fine dust abrasion thanks to hydraulic braking
- Improved performance/acceleration boost by hydraulic support (up to 10% increase)
- Easy integration in existing system (AddOn System)
- Low cost components (“from the shelf”)
- Functional safety according to ISO26262

Hydraulic Hybrid: short time energy storing in short start-stop-cycles (high power density)
Electric Hybrid: continuous storing of unused Power (high energy density)
HRB: Hydrostatic Regenerative Breaking

In contrast to this: Aircraft have a very even load profile during most time of the operation!
Validation – Are we Doing the Right Thing?

Summing up the Considerations for Validation

- Physics favor trains over aircraft \textit{(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 \textit{long range}.
  
  \textit{Ships are too slow and hence no regular service, bridges and tunnels are limited in length.}
- Trains better on \textit{short range} \textit{(less access time to station, less waiting time in station, ...)}.
- Trains better to connect adjacent megacities over land up to \textit{medium range} with high volume.
  
  \textit{A380 is too small and unfit, because designed for long range.}
- Aircraft over land, if ...
  
  - \textit{long range},
  - \textit{short range} and no train available due to \textit{low volume traffic}
    
    - aircraft need less investment into infrastructure than (high speed) trains.
      
      \textit{Construction costs for high speed trains: 5 \(€/km\) to 70 \(€/km\) (2005, Campos 2009)}
    - alternative: \textit{rail replacement bus service}
    - over \textit{remote areas}, if no train is available (mountains, deserts, polar regions).

So, again:

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

Aircraft Design Wisdom

- No discipline should dominate in Aircraft Design (see on right). Do not design your aircraft around your electric engine!
- 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 (electric hybrid propulsion).
- Engine integration is an important part of Overall Aircraft Design (OAD) and effects many disciplines. Do not put your engines somewhere on the aircraft based just on one (good) idea.
Aircraft Design Basics

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:

\[ m_{MTO} = m_{PL} + m_F + m_{OE} \]

\[ m_{MTO} - m_F - m_{OE} = m_{PL} \]

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

\[ m_{MTO} = \frac{m_{PL}}{1 - \frac{m_F}{m_{MTO}} - \frac{m_{OE}}{m_{MTO}}} \]

\[ m_{MTO} : \text{Maximum Take-Off mass} \]

\[ m_F : \text{Fuel mass} \]

\[ m_{OE} : \text{Operating Empty mass} \]

\[ m_{PL} : \text{PayLoad} \]

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

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

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 $V_{opt} = x_{opt} \cdot V_{md}$

\[
\frac{T_{TO}}{m_{MTO} \cdot g}
\]

Hypothetical matching chart (Scholz 2015)
Find detailed information on

**Aircraft Design**

at

**Hamburg Open Online University (HOOU)**

[http://hoou.ProfScholz.de](http://hoou.ProfScholz.de)

Scholz 2015
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 \( \frac{m_F}{m_{MTO}} \) 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 \( \frac{m_{OE}}{m_{MTO}} \) is too large (typical value: \( \frac{m_{OE}}{m_{MTO}} = 0.5 \)):
  - structure is too heavy
  - systems are too heavy
  - propulsion is too heavy

\[
m_{MTO} = \frac{m_{PL}}{1 - \frac{m_F}{m_{MTO}} - \frac{m_{OE}}{m_{MTO}}}
\]

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

- Viability of electric propulsion is strongly a matter of
  - range and
  - specific energy.
Savings due to a Large Number of (Electric) Engines?

- Engine Maintenance Costs:
  - Knowledge: Maintenance costs increase with number of engines.
  - Apparent fact: Maintenance costs increase strongly with number of jet engines.
  - Assumed: Maintenance costs increase only moderately with number of electrical engines.
  - Hence: A large number of engines can be used with little detrimental effect on maintenance costs, if engines are electrical (and hence simple!).

- A large number of engines reduces thrust requirements at engine failure (OEI) ... 
  - during climb (if CS-25 interpretation is favorable – separate page)
  - during take-off (if CS-25 remains unchanged – separate page)

- A large number of engines (distributed propulsion along wing span) ... 
  - does not help to increase maximum lift coefficient considerations, because lift needs to be achieved also with engines failed,
  - does help to reduces wing bending and hence reduces wing mass.
Savings due to a Large Number of (Electric) Engines? – Climb OEI: $\sin \gamma$

CS 25.121  
Climb: one-engine-inoperative

(b)  
Take-off; landing gear retracted.

In the take-off configuration existing at the point of the flight path at which the landing gear is fully retracted, ... the steady gradient of climb may not be less than

$\sin \gamma$ increased beyond 3% by 0.3%-points per engine

assumed:  
$E = L/D = 20$

$\sin \gamma$ kept constant at 3% for larger number of engines

\[ \frac{T_{TO}}{m_{MTO} \cdot g} = \left( \frac{n_E}{n_E - 1} \right) \left( \frac{1}{E} + \sin \gamma \right) \]

- It depends on the required climb gradient, $\sin \gamma$.
- It is not defined today, how a One-Engine-Inoperative (OEI) climb is treated by CS-25 with respect to $\sin \gamma$.
- Many engines could also lead to increased thrust requirements!?

\[ T_{TO} : \text{Take–Off thrust} \]
\[ m_{MTO} : \text{Maximum Take–Off mass} \]
\[ g : \text{earthacceleration} \]
\[ n_E : \text{number of engines} \]
\[ \sin \gamma : \text{climb gradient} \]
Savings due to a Large Number of (Electric) Engines? – One Engine Inop or More?

CS 25.107 Take-off speeds
(a)(1) $V_{EF}$ is the calibrated airspeed at which the [one] critical engine is assumed to fail.

CS 25.109 Accelerate-stop distance
(a)(1)(ii) Allow the aeroplane to accelerate ... assuming the [one] critical engine fails at $V_{EF}$

CS 25.121 **Climb: one-engine-inoperative**

- For a design with very many engines $n_E$, EASA / FAA could re-define the thrust factor.
- The number of engines assumed inoperative $n_{E,inop}$ could be increased: $n_{E,inop} > 1$, for larger $n_E$
- 4 engines with 1 failed need a thrust factor of 1.33. 20 engines with 4 failed need a thrust factor of 1.25 – only slightly less. However, probability for 4 engines failed from 20 is very low.
- Applied, this could reduce the advantage of many engines.
Aircraft Design for Electric Propulsion

Savings due to a Large Number of (Electric) Engines? – Propeller Efficiency

• A large number of engines can be used to reduce the propeller diameter, $D$ at constant disk area, $A$. This would only reduce propeller tip speed and tip Mach number $M_{tip}$ and result in higher propeller efficiency at constant RPM.

$$\lambda = \frac{U}{V} \quad U = \omega D / 2 = \pi n D$$

$$\lambda = \frac{\pi n D}{V} = \frac{\pi}{J} \quad J = \frac{V}{n D} = \pi / \lambda \quad \text{advance ratio}$$

$$M = \frac{V}{a} \quad M_{tip} = \frac{U}{a} \quad U = \lambda V$$

$$M_{tip} = \frac{\lambda V}{a} = \frac{\pi n D}{a}$$

However, $M_{tip}$ is independent of $D$ and only proportional to $V$. Smaller $D$ requires larger RPM, $n$.

• A large number of engines can be used to increase total propeller disk area, $A$ at constant propeller diameter, $D$. Propeller ground clearance is kept. This leads to lower disk loading and hence higher propeller efficiency.

$$\eta_{prop} \approx \frac{2 \cdot \left(1 - \lambda^2 \cdot \ln \left(1 + \frac{1}{\lambda^2}\right)\right)}{1 + \sqrt{1 + \frac{T}{q \cdot A} - 2 \cdot \lambda^2 \cdot \ln \left(1 + \frac{1}{\lambda^2}\right)}}$$

$\eta_{prop}$ without wave drag (Truckenbrodt 1999)
Investigation of Propeller Area ...

... at least 2 times bigger with only 4 engines instead of 8 engines!

length of landing gear, depends on number of engines.
Alternatively: shift propellers upwards, maybe mount on high wing.
Engine Integration – Examples

- **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 consequently 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.

e-Genius 2018
Engine Integration – Examples

Airbus:

- **Two ducted**, variable pitch fans are spun by two electric motors.
- The ducting increases the thrust [compared to an unducted propeller with the same diameter] while reducing noise. (Szondy 2014)

- **Ducted fans have lower propeller efficiency.** For the same thrust they only need a smaller diameter and move less air mass at higher velocity. This results in a lower propulsive efficiency (despite reduced tip losses). Detrimental also: higher friction drag and added weight from the shroud and support structure.

- **Ducted fans** were chosen to make the aircraft **look good**. (Oral: Corporate Technical Office, Airbus Group, 2015)
Aircraft Design for Electric Propulsion

Maximum Relative Battery Mass

\[ m_{MTO} = m_{OE} + m_{bat} + m_{PL} \]

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

\[ \frac{m_{OE}}{m_{MTO}} \approx 0.50 \quad \text{technology parameter} \]

\[ \left\{ \begin{array}{l}
\frac{m_{PL}}{m_{MTO}} = 0.25 \quad \frac{m_{bat}}{m_{MTO}} = 0.25 \\
\frac{m_{PL}}{m_{MTO}} = 0.10 \quad \frac{m_{bat}}{m_{MTO}} = 0.40 \\
\end{array} \right. \]

\[ 0.25 \leq \frac{m_{bat}}{m_{MTO}} \leq 0.40 \]

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.

\( m_{MTO} \): Maximum Take-Off mass
\( m_{bat} \): battery mass
\( m_{OE} \): Operating Empty mass
\( m_{PL} \): PayLoad
Aircraft Design for Electric Propulsion

Maximum Range for Electrical Propulsion

\[ e_{\text{bat}} = \frac{E_{\text{bat}}}{m_{\text{bat}}} \quad L = W = m_{\text{MTO}} \ g \quad E = \frac{L}{D} \quad D = \frac{m_{\text{MTO}} \ g}{E} \]

\[ P_D = D V = \frac{m_{\text{MTO}} \ g}{E} \quad V = P_T = P_{\text{bat}} \ \eta_{\text{prop}} \ \eta_{\text{elec}} \quad V = \frac{R}{t} \]

\[ P_{\text{bat}} = \frac{E_{\text{bat}}}{t} = m_{\text{bat}} e_{\text{bat}} \frac{V}{R} \]

\[ m_{\text{bat}} e_{\text{bat}} \frac{V}{R} \ \eta_{\text{elec}} \ \eta_{\text{prop}} = \frac{m_{\text{MTO}} \ g}{E} V \]

\[ R = \frac{m_{\text{bat}}}{m_{\text{MTO}}} \frac{1}{e_{\text{bat}} \ \eta_{\text{elec}} \ \eta_{\text{prop}} \ E} \]

\[ \eta_{\text{elec}} = 0.9; \quad \eta_{\text{prop}} = 0.8 \]

\( R \): realistic parameters

\( e_{\text{bat}} \): specific energy
\( E_{\text{bat}} \): 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
\( \eta \): efficiency (prop: propeller)
Aircraft Design for Electric Propulsion

The Major 6 Turbo / Electric / Hybrid Architectures

- **Series Hybrid**: Turboshaft, Generator, Electric Bus, Motor, Distributed Fans, Battery
- **Parallel Hybrid**: Electric Bus, Turbofan, Battery, Motor, Fan
- **Series/Parallel Partial Hybrid**: Turbofan, Electric Bus, Generator, Motor, 1 to Many Fans, Battery
- **All Electric**: Battery, Electric Bus, Motor(s), 1 to Many Fans
- **Turboelectric**: Turboshaft, Generator, Distributed Fans, Motor, Electric Bus, Fuel
- **Partial Turbo Electric**: Turbofan, Electric Bus, Generator, Motor, 1 to Many Fans, Fan, Fuel
Aircraft Design for Electric Propulsion

Ragone Diagram for Energy Storage Devices

Min. discharge time: 10 h 1 h 6 min 36 s 3.6 s

Specific Energy [Wh/kg]

Specific Power [W/kg]

based on Geerling 2017
Energy Storage Suitable for Take-Off and Initial Climb

Min. discharge time:
- 10 h
- 1 h
- 6 min
- 36 s
- 3.6 s

Specific Energy [Wh/kg]
- 1000
- 100
- 10
- 1
- 0.1
- 0.01

Specific Power [W/kg]
- 10
- 100
- 1000
- 10000
- 100000
- 1000000

- Battery
- Fly Wheel
- Ultracaps
- Hydraulic Accumulator
- Compound
- Bladder
- Piston type
- Elkos
Aircraft Design for Electric Propulsion

Collecting Aircraft Design Wisdom

- Thrust levels depend on flight phase. Decreasing thrust for:
  Take-Off → Climb → 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

<table>
<thead>
<tr>
<th></th>
<th>Gas Turbine (GT)</th>
<th>Electric Motor (EM)</th>
<th>Hydraulic Motor (HM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative component mass, $m_x/m_GT$</td>
<td>1.0</td>
<td>1.0</td>
<td>0.1</td>
</tr>
<tr>
<td>Efficiency, $\eta$</td>
<td>0.35</td>
<td>0.9 (with controller)</td>
<td>0.9 (with controller)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Kerosine (k)</th>
<th>Battery (b)</th>
<th>Accumulator (a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy density, $e$</td>
<td>43 MJ/kg = 11900 Wh/kg</td>
<td>300 Wh/kg</td>
<td>5.0 Wh/kg</td>
</tr>
<tr>
<td>Specific exergy, $b = \eta e$</td>
<td>$4165$ Wh/kg</td>
<td>270 Wh/kg</td>
<td>4.5 Wh/kg</td>
</tr>
<tr>
<td>Relative specific exergy, $b_x/b_k$</td>
<td>1.0</td>
<td>0.065</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Derivation of Exergy Density, $b$

$E = A + B$
$B = W$
$\eta = W/E = B/E$
$B = \eta E$
$E = m_F H_L$
$e = E/m_F = H_L$
$b = B/m_F = \eta E/m_F$

$b = \eta H_L$

$E$: energy
$A$: anergy
$B$: exergy
$W$: work
$\eta$: efficiency
$m_F$: fuel mass
$H_L$: lower heating value
$e$: specific energy
$b$: specific exergy
Aircraft Design for Electric Propulsion

**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): 0.9·0.9 = 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+0.2·0.1=> 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!
Evaluation in Aircraft Design
Evaluation in Aircraft Design

The 3 Dimensions of Sustainability

- **Economy**
  - profit, revenue, **cost**
  - shareholder value
  - market share

- **Environment**
  - resources & pollution
  - bio-diversity

- **Society**
  - human rights
  - democracy
  - equality
  - opportunity
  - infrastructure

Underlined parameters are calculated for the proposed evaluation in aircraft design.

→: disaster control
←: access limitation
Evaluation in Aircraft Design

Evaluation: Purpose
• evaluation of the aircraft for **optimum design** (definition of an objective function)
• **technology evaluation** (on an assumed aircraft platform)
• evaluation for **aircraft selection** (for aircraft purchase by an airline)

Evaluation in the 3 Dimensions of Sustainability: Measuring Socio-Eco-Efficiency
• Economic Evaluation
• Environmental Evaluation
• Social Evaluation

Schmidt 2004 (BASF SEE)

<table>
<thead>
<tr>
<th>Type of Evaluation</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic</td>
<td>DOC</td>
</tr>
<tr>
<td>Environmental</td>
<td>LCA</td>
</tr>
<tr>
<td>Social</td>
<td>S-LCA</td>
</tr>
</tbody>
</table>

Schmidt 2004 (BASF SEE)
Economic Evaluation
(DOC)
Economic Evaluation

Approaches to Economic Evaluation in Aircraft Design and Procurement

Return on investment – Net present value – Break-even point

<table>
<thead>
<tr>
<th>Manufacturer’s perspective</th>
<th>Operator’s perspective</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Revenues</strong></td>
<td><strong>Expenses</strong></td>
</tr>
<tr>
<td>• estimated aircraft price</td>
<td></td>
</tr>
<tr>
<td>• estimated sales figures</td>
<td></td>
</tr>
<tr>
<td>Cost methods according to</td>
<td></td>
</tr>
<tr>
<td>• Nicolai 1975</td>
<td></td>
</tr>
<tr>
<td>• Roskam VIII 1990</td>
<td></td>
</tr>
<tr>
<td>• Raymer 1992</td>
<td></td>
</tr>
<tr>
<td><strong>Revenues</strong></td>
<td><strong>Expenses</strong></td>
</tr>
<tr>
<td>• estimated ticket price</td>
<td></td>
</tr>
<tr>
<td>• estimated load factor</td>
<td></td>
</tr>
<tr>
<td>Cost methods according to</td>
<td></td>
</tr>
<tr>
<td>• LCC</td>
<td></td>
</tr>
<tr>
<td>• COC</td>
<td></td>
</tr>
<tr>
<td>• IOC</td>
<td></td>
</tr>
<tr>
<td>• TOC</td>
<td></td>
</tr>
<tr>
<td>• DOC:</td>
<td></td>
</tr>
<tr>
<td>• ATA 1967</td>
<td></td>
</tr>
<tr>
<td>• AA 1980</td>
<td></td>
</tr>
<tr>
<td>• DLH 1982</td>
<td></td>
</tr>
<tr>
<td>• AEA 1989</td>
<td></td>
</tr>
<tr>
<td>• AI 1989</td>
<td></td>
</tr>
<tr>
<td>• Fokker 1993</td>
<td></td>
</tr>
</tbody>
</table>

Scholz 2015
## Economic Evaluation

### Overview of DOC Methods

<table>
<thead>
<tr>
<th>Organization</th>
<th>Comment</th>
<th>Year of Publication</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Transport Association of America (ATA)</td>
<td>Predecessors to this method are from the year: 1944, 1949, 1955 and 1960.</td>
<td>1967</td>
<td>ATA 1967</td>
</tr>
<tr>
<td>Lufthansa</td>
<td>The Method was continuously developed further.</td>
<td>1982</td>
<td>DLH 1982</td>
</tr>
<tr>
<td>Association of European Airlines (AEA)</td>
<td>Method for Short- and Medium Range Aircraft</td>
<td>1989</td>
<td>AEA 1989a</td>
</tr>
<tr>
<td>Airbus Industries (AI)</td>
<td>The Method was continuously developed further.</td>
<td>1989</td>
<td>AI 1989</td>
</tr>
<tr>
<td>Fokker</td>
<td>The Method was produced to evaluate aircraft design project.</td>
<td>1993</td>
<td>Fokker 1993</td>
</tr>
<tr>
<td>TU Berlin</td>
<td>Method developed by Prof. Thorbeck</td>
<td>2013</td>
<td>Scholz 2013</td>
</tr>
</tbody>
</table>

Scholz 2015
Economic Evaluation

**DOC Cost Elements**

- depreciation $C_{DEP}$
- interest $C_{INT}$
- insurance $C_{INS}$
- fuel $C_F$
- maintenance $C_M$, consisting of the sum of
  - airframe maintenance $C_{M,AF}$
  - power plant maintenance $C_{M,PP}$
- crew $C_C$, consisting of the sum of
  - cockpit crew $C_{C,CO}$
  - cabin crew $C_{C,CA}$
- fees and charges $C_{FEE}$, consisting of the sum of
  - landing fees $C_{FEE,LD}$
  - ATC or navigation charges $C_{FEE,NAV}$
  - ground handling charges $C_{FEE,GND}$

\[
C_{DOC} = C_{DEP} + C_{INT} + C_{INS} + C_F + C_M + C_C + C_{FEE}
\]

**Annual Costs:**

\[
C_{DOC} = C_{a/c,a}
\]

**Trip-Costs:**

\[
C_{a/c,t} = \frac{C_{a/c,a}}{n_{t,a}}
\]

**Mile-Costs:**

\[
C_{a/c,m} = \frac{C_{a/c,t}}{R} = \frac{C_{a/c,a}}{n_{t,a} R}
\]

**Seat-Mile-Costs:**

\[
C_{s,m} = \frac{C_{a/c,t}}{n_{pax} R} \text{ or } \frac{C_{a/c,a}}{n_s n_{t,a} R}
\]

Utilization, annual, flight time: $U_{a,f} = \frac{t_f}{t_f + k_{U1}}$

Number of trips, annual: $n_{t,a} = \frac{U_{a,f}}{t_f}$
Environmental Evaluation (LCA)
Environmental Evaluation

Kerosene Versus Battery in Flight

<table>
<thead>
<tr>
<th>Type of Comparison</th>
<th>Kerosene</th>
<th>Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (wrong)</td>
<td>$E = m_F \cdot H_L$</td>
<td>$E = E_{bat} / \eta_{charge}$</td>
</tr>
<tr>
<td>Max. Exergy (not good)</td>
<td>$B_{max} = \eta_C \cdot H_L \cdot m_F$</td>
<td>$B_{max} = E$</td>
</tr>
<tr>
<td>Exergy (ok)</td>
<td>$B = \eta_{GT} \cdot H_L \cdot m_F$</td>
<td>$B = \eta_{EM} \cdot E$</td>
</tr>
<tr>
<td>Primary Energy (better)</td>
<td>$E_{prim} = 1.1 \cdot H_L \cdot m_F$</td>
<td>$E_{prim} = k_{PEF} \cdot E$</td>
</tr>
<tr>
<td>CO2 (without altitude effect)</td>
<td>$m_{CO2} = 3.15 \cdot 1.1 \cdot m_F$</td>
<td>$m_{CO2} = 3.15 \cdot x_{ff} \cdot E_{prim} / H_L$</td>
</tr>
<tr>
<td>Equivalent CO2 (good, simple)</td>
<td>$m_{CO2,eq} = m_{CO2} \cdot (k_{RFI} + 0.1)$</td>
<td>$m_{CO2,eq} = m_{CO2}$</td>
</tr>
</tbody>
</table>

\[ H_L = 43 \text{ MJ/kg} \]
\[ \eta_{charge} = 0.9 \]
\[ \eta_{GT} = 0.35 \quad \eta_{EM} = 0.9 \]

Carnot Efficiency:
\[ \eta_C = 1 - T/(h) / T_{TET} = 1 - \frac{2165}{1440} = 0.85 \]

Radiative Forcing Index:
\[ k_{RFI} = 2.7 \quad (1.9 \ldots 4.7) \]

Due to flight at altitude plus energy mix with renewables & nuclear power:
\[ m_{CO2,eq,kerosene} \approx 2.5 \cdot m_{CO2,eq,battery} \]

\[ y = -3.1164E-09x^6 + 3.7595E-05x^5 - 1.8897E-01x^4 + 5.0657E+02x^3 - 7.6385E+05x^2 + 6.1428E+08x - 2.0583E+11 \]
\[ R^2 = 9.9867E-01 \]

\[ y = -7.763E-03x + 1.610E+01 \]
\[ R^2 = 9.954E-01 \]
Environmental Evaluation

An Excel-Based Life Cycle Tool

<table>
<thead>
<tr>
<th>LCA-AD</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Goal and Scope Definition</td>
</tr>
<tr>
<td>2</td>
<td>Life Cycle Inventory Analysis</td>
</tr>
<tr>
<td>2.1</td>
<td>General Input and parameters</td>
</tr>
<tr>
<td>2.2</td>
<td>Design and Development</td>
</tr>
<tr>
<td>2.3</td>
<td>Production</td>
</tr>
<tr>
<td>2.4</td>
<td>Operation</td>
</tr>
<tr>
<td>2.5</td>
<td>End of life</td>
</tr>
<tr>
<td>2.6</td>
<td>Results of Inventory Analysis</td>
</tr>
<tr>
<td>3</td>
<td>Life Cycle Impact Assessment</td>
</tr>
<tr>
<td>3.1</td>
<td>Inputs for the impact assessment</td>
</tr>
<tr>
<td>3.2</td>
<td>Calculation of the impact assessment</td>
</tr>
<tr>
<td>3.3</td>
<td>Summary of the Impact Assessment Results</td>
</tr>
<tr>
<td>3.4</td>
<td>Uncertainty analysis</td>
</tr>
<tr>
<td>4</td>
<td>Interpretation</td>
</tr>
</tbody>
</table>

**CONCEPTUAL AIRCRAFT DESIGN BASED ON LIFE CYCLE ASSESSMENT**

Andreas Johanning, Dieter Scholz
Aircraft Design and Systems Group (AERO), Hamburg University of Applied Sciences, Hamburg, Germany

Johanning 2014 [http://Airport2030.ProfScholz.de](http://Airport2030.ProfScholz.de)


Johanning 2017
Environmental Evaluation

An Excel-Based Life Cycle Tool

Processes Considered in the Life Cycle Analysis – Cruise Flight Dominates the LCA

<table>
<thead>
<tr>
<th>Design &amp; Development</th>
<th>Electric energy due to computer use</th>
<th>Wind tunnel testing</th>
<th>Flight test campaign</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production</td>
<td>Material production</td>
<td>Use of production facilities</td>
<td></td>
</tr>
<tr>
<td>Operation</td>
<td>Maintenance Repair &amp; Overhaul</td>
<td>Cruise flight</td>
<td>Energy generation and consumption at airports</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Kerosene production</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LTO-cycle</td>
<td>Operation of ground handling vehicles</td>
</tr>
<tr>
<td>End-of-life</td>
<td>Reuse</td>
<td>Landfill</td>
<td></td>
</tr>
</tbody>
</table>
Environmental Evaluation

An Excel-Based Life Cycle Tool

OpenLCA
http://www.openlca.org

Inventory analysis results

<table>
<thead>
<tr>
<th>Emissions</th>
<th>Amount (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>10</td>
</tr>
<tr>
<td>CO</td>
<td>1</td>
</tr>
<tr>
<td>CH₄</td>
<td>0.5</td>
</tr>
<tr>
<td>O₂</td>
<td>5</td>
</tr>
<tr>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>.</td>
<td>.</td>
</tr>
</tbody>
</table>

Midpoint categories

- Climate change
- Ozone depletion
- Terrestrial acidification
- Freshwater eutrophication
- Marine eutrophication
- Human toxicity
- Photochemical oxidant formation
- Particulate matter formation
- Terrestrial ecotoxicity
- Freshwater ecotoxicity
- Marine ecotoxicity
- Ionising radiation
- Agricultural land occupation
- Urban land occupation
- Natural land transformation
- Water depletion
- Mineral resource depletion
- Fossil fuel depletion

From Inventory via Midpoint Categories and Endpoint Categories to a Single Score

ReCiPe
http://www.lcia-recipe.net
**Environmental Evaluation**

**Altitude Dependent Equivalent CO2**

\[ m_{CO2,eq} = EI_{CO2} \cdot \frac{1}{SAR \cdot n_{seat}} + EI_{NOx} \cdot \frac{CF_{midpoint,NOx}}{SAR \cdot n_{seat}} + \frac{L_{flight}}{SAR \cdot n_{seat}} \cdot CF_{midpoint,clouds} \]

### Sustained Global Temperature Potential, SGTP (similar to GWP):

\[ CF_{midpoint,NOx}(h) = \frac{SGTP_{O3,100}}{SGTP_{CO2,100}} \cdot s_{O3,S}(h) + \frac{SGTP_{O3L,100}}{SGTP_{CO2,100}} \cdot s_{O3,L}(h) + \frac{SGTP_{CH4,100}}{SGTP_{CO2,100}} \cdot s_{CH4}(h) \]

\[ CF_{midpoint,cloudiness}(h) = \frac{SGTP_{contrails,100}}{SGTP_{CO2,100}} \cdot s_{contrails}(h) + \frac{SGTP_{cirrus,100}}{SGTP_{CO2,100}} \cdot s_{cirrus}(h) \]

### Emission Index, EI (kg/kg fuel)

<table>
<thead>
<tr>
<th>Species</th>
<th>EI</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>3.15</td>
</tr>
<tr>
<td>H₂O</td>
<td>1.23</td>
</tr>
<tr>
<td>SO₂</td>
<td>2.00 \cdot 10^{-4}</td>
</tr>
<tr>
<td>Soot</td>
<td>4.00 \cdot 10^{-5}</td>
</tr>
</tbody>
</table>

### Species | SGTP₁₀₀

<table>
<thead>
<tr>
<th>Species (K/kg CO₂)</th>
<th>SGTP₁₀₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>3.58 \cdot 10^{-14}</td>
</tr>
<tr>
<td>Short O₃ (K/kg NOₓ)</td>
<td>7.97 \cdot 10^{-12}</td>
</tr>
<tr>
<td>Long O₃ (K/NOₓ)</td>
<td>-9.14 \cdot 10^{-13}</td>
</tr>
<tr>
<td>CH₄ (K/kg NOₓ)</td>
<td>-3.90 \cdot 10^{-12}</td>
</tr>
<tr>
<td>Contrails (K/NM)</td>
<td>2.54 \cdot 10^{-13}</td>
</tr>
<tr>
<td>Cirrus (K/NM)</td>
<td>7.63 \cdot 10^{-13}</td>
</tr>
</tbody>
</table>

---

**EMEP/EEA Guidebook**

http://www.eea.europa.eu

**Own Fuel Calculation**
Environmental Evaluation

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 stretched by 9 m to house batteries

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

### Requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Deviation from A320</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m_{MPL})</td>
<td>19256 kg</td>
<td>0%</td>
</tr>
<tr>
<td>(R_{MPL})</td>
<td>755 NM</td>
<td>-50%</td>
</tr>
<tr>
<td>(M_{CR})</td>
<td>0.76</td>
<td>0%</td>
</tr>
<tr>
<td>(\max(s_{TOFL}, s_{LFL}))</td>
<td>1770 m</td>
<td>0%</td>
</tr>
<tr>
<td>(n_{PAX}) (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>

### Main aircraft parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m_{MTO})</td>
<td>95600 kg</td>
<td>30%</td>
</tr>
<tr>
<td>(m_{OE})</td>
<td>54300 kg</td>
<td>32%</td>
</tr>
<tr>
<td>(m_{F})</td>
<td>22100 kg</td>
<td>70%</td>
</tr>
<tr>
<td>(S_{W})</td>
<td>159 m²</td>
<td>30%</td>
</tr>
<tr>
<td>(b_{W,geo})</td>
<td>36.0 m</td>
<td>6%</td>
</tr>
<tr>
<td>(A_{W,eff})</td>
<td>9.50</td>
<td>0%</td>
</tr>
<tr>
<td>(E_{max})</td>
<td>18.20</td>
<td>≈ + 3%</td>
</tr>
<tr>
<td>(T_{TO})</td>
<td>200 kN</td>
<td>38%</td>
</tr>
<tr>
<td>(BPR)</td>
<td>6.0</td>
<td>0%</td>
</tr>
<tr>
<td>(h_{ICA})</td>
<td>41000 ft</td>
<td>4%</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>
</tbody>
</table>

### Mission requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(R_{Mi})</td>
<td>294 NM</td>
<td>-50%</td>
</tr>
<tr>
<td>(m_{PL,mi})</td>
<td>13057 kg</td>
<td>0%</td>
</tr>
</tbody>
</table>

### Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m_{F,br})</td>
<td>7800 kg</td>
<td>72%</td>
</tr>
<tr>
<td>SS</td>
<td>0.0095</td>
<td>-45%</td>
</tr>
</tbody>
</table>
Environmental Evaluation

Battery Powered A320

A320 Reference Aircraft
• Contributions of In- and Outputs on Single Score (SS) (left)
• Considered Processes (right)
• SS = 0.0173 points
• CO2 = 0.0045 points in SS

Battery Powered Aircraft
• Contributions of In- and Outputs on Single Score (SS) (left)
• Considered Processes (right)
• SS = 0.0095 points
• CO2 = 0.0049 points in SS

⇒ The battery powered aircraft does not save CO2
⇒ Generation of electricity dominates SS. With regenerative electricity: SS = 0.0008 points
Social Evaluation
(S-LCA, Noise)
Social Evaluation

Social Life Cycle Assessment (S-LCA)

S-LCAs follow the ISO 14044 framework. They assess social and socio-economic impacts found along the life cycle (supply chain, use phase and disposal) of products and services. Aspects assessed are those that may directly or indirectly affect stakeholders positively or negatively. These aspects may be linked to the behaviors of socio-economic processes around enterprises, government, ... (UNEP 2009)

<table>
<thead>
<tr>
<th>Stakeholder categories</th>
<th>Subcategories</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stakeholder “consumer”</strong></td>
<td>Health &amp; Safety, Feedback Mechanism, Consumer Privacy, Transparency, End of life responsibility</td>
</tr>
<tr>
<td><strong>Stakeholder “local community”</strong></td>
<td>Access to material resources, Access to immaterial resources, De-localization and Migration, Cultural Heritage, Safe &amp; healthy living conditions, Respect of indigenous rights, Community engagement, Local employment, Secure living conditions</td>
</tr>
<tr>
<td><strong>Stakeholder “society”</strong></td>
<td>Public commitments to sustainability issues, Contribution to economic development, Prevention &amp; mitigation of armed conflicts, Technology development, Corruption</td>
</tr>
<tr>
<td><em><em>Value chain actors</em> not including consumers</em>*</td>
<td>Fair competition, Promoting social responsibility, Supplier relationships, Respect of intellectual property rights</td>
</tr>
</tbody>
</table>

Noise: Only one of many possible indicators in an S-LCA
Aircraft Noise

Aircraft noise is external noise and internal noise (cabin noise). Considered here: is only external noise:

- **Mechanical noise**
  - **engine** (turbo jet, turbo fan, turbo prop, piston prop)
    - jet noise (exhaust) of jet aircraft – dominant for jets on take-off
    - fan blades (*buzzsaw noise* when tips reach supersonic speeds)
  - noise from compressor, combustion chamber, turbine, after burner, reverse thrust
  - propeller noise (tips reach supersonic speeds) – dominant for turbo props
  - combustion engine (and propeller noise) – dominant for piston props

- **Aerodynamic noise**
  - **airframe noise** from flow around the surfaces of the aircraft (flying low at high speeds)
    - wing
      - high lift devices (flaps, slats) – dominant for jets on approach
    - tails with control surfaces
    - fuselage
  - landing gear – dominant for jets on approach
  - sonic boom

- **Noise from aircraft systems**
  - Auxiliary Power Unit, APU (important only at the airport)

Understand which noise source is dominant.
Substantial overall noise reduction can only be achieved, if the dominant noise source is made less noisy.
Social Evaluation

Aircraft Noise on Departure versus Arrival

Typical Departure Noise Distribution

Typical Arrival Noise Distribution

Dickson 2013
Social Evaluation

Noise Data (A321neo)

Example Data from Database:
Manufacturer AIRBUS
Type A321 Version 272NX (neo)
Engine Type PW1130G-JM
Maximum Take-Off Mass: 80000 kg

For newly developed aircraft use own measurements!

NOISE CERTIFICATION STANDARD
Noise Regulation ICAO Annex 16, Volume I
Chapter or Stage 4

<table>
<thead>
<tr>
<th>Lateral/Full-Power</th>
<th>Approach</th>
<th>Flyover</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise Level (EPN dB)</td>
<td>88</td>
<td>94.6</td>
</tr>
<tr>
<td>Noise Limit (EPN dB)</td>
<td>97.1</td>
<td>100.8</td>
</tr>
<tr>
<td>Margin (EPN dB)</td>
<td>9.1</td>
<td>6.2</td>
</tr>
</tbody>
</table>

Cumulative Margin (EPNdB) = 25.30

1.) read Cumulative Margin: $\sum(\Delta n_i)$
2.) determine Minimum Margin: $\min(\Delta n_i)$
Social Evaluation

Noise Data (TU 154)

For newly developed aircraft use own measurements!

Example Data from Database:
Manufacturer TUPULEV
Type TU 154 M/D01
Engine Type D-30KU-154
Maximum Take-Off Mass: 92000 kg


<table>
<thead>
<tr>
<th>Noise Level (EPN\text{dB})</th>
<th>Lateral/Full-Power</th>
<th>Approach</th>
<th>Flyover</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>99.5</td>
<td>101.5</td>
<td>91.5</td>
</tr>
<tr>
<td>Noise Limit (EPN\text{dB})</td>
<td>97.6</td>
<td>101.2</td>
<td>95.7</td>
</tr>
<tr>
<td>Margin (EPN\text{dB})</td>
<td>-1.9</td>
<td>-0.3</td>
<td>4.2</td>
</tr>
</tbody>
</table>

Cumulative Margin (EPN\text{dB})

1.) read Cumulative Margin: $\Sigma(\Delta n_i)$
2.) determine Minimum Margin: $\min(\Delta n_i)$
Social Evaluation

Noise Emission Fees (NEF)

**Johanning 2012** has created a method to calculate globally the **average noise charges per flight** $c_{n,f}$ in a given year $n_y$ (e.g. 2018) based on data from 2011, taking into account inflation with $p_{INF} = 2\%$ per year:

$$c_{n,f} = \left(1 + \frac{n_y - 2011}{41}\right) \cdot \frac{m_{MTO} (1 + p_{INF})^{n_y - 2011}}{143.5 \left(2 + \sum(\Delta n_i) + \min(\Delta n_i)\right)}$$

**With example data** from database of **A321neo**:

$$c_{n,f} = \left(1 + \frac{2018 - 2011}{41}\right) \cdot \frac{80000(1.02)^{2018-2011}}{143.5 \left(2 + 25.3 + 6.2\right)} = 22.3 \text{ USD} \quad \text{(TU154: 410.6 USD)}$$

- These costs can be added to the Direct Operating Costs (DOC) of an aircraft.
- These costs can also represent the **social noise impact** of an aircraft relative to another aircraft. Alternatively use the **Cumulative Noise Level** (sum of the 3 levels in EPNdB). 

Social Evaluation

Margins of the Cumulative Noise Level

Indicated are the Cumulative Noise Limits according to the ICAO Noise Chapters as a function of Maximum Take-Off Mass.

"Cumulative" means the sum of the 3 noise levels/limits in EPNdB from
- Approach
- Sideline
- Flyover

Dickson 2013

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Applicable Year</th>
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</thead>
<tbody>
<tr>
<td>2</td>
<td>1972</td>
</tr>
<tr>
<td>3</td>
<td>1978</td>
</tr>
<tr>
<td>4</td>
<td>2006</td>
</tr>
</tbody>
</table>
Combined Evaluation
Combined Evaluation

Multiple-Criteria Decision Analysis (MCDA)

- Many techniques exist => Literature

- Weighted Sums Analysis:  
  \[ SS_{total} = k_{DOC} \ DOC + k_{SS,LTA} SS_{LTA} + k_{SS,S-LTA} SS_{S-LTA} \]

- Pareto-Optimum:

  **Pareto optimality** is a state of allocation of resources from which it is impossible to reallocate so as to make any one individual or preference criterion better off without making at least one individual or preference criterion worse off.

  Usually Pareto-Frontiers are shown from two variables only.

  Here **three plots** could be used to overcome the limitations:
  - \( DOC - SS_{LTA} \)
  - \( DOC - SS_{S-LTA} \)
  - \( SS_{LTA} - SS_{S-LAT} \)

  ![Pareto-Frontier Diagram](image)

  **plotting** Eco-Efficiency

  Johanning 2017
Example
Example

**Hybrid-Electric ATR-42**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Original Data ATR-42</th>
<th>Calculated Data</th>
<th>Deviation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger number</td>
<td>48</td>
<td>48</td>
<td>0</td>
</tr>
<tr>
<td>Design range (NM)</td>
<td>800</td>
<td>800</td>
<td>0</td>
</tr>
<tr>
<td>MTOW (kg)</td>
<td>16,150</td>
<td>16,132</td>
<td>-0.11</td>
</tr>
<tr>
<td>OWE (kg)</td>
<td>10,253</td>
<td>9266</td>
<td>-9.63</td>
</tr>
<tr>
<td>Wing mass (kg)</td>
<td>1565</td>
<td>1558</td>
<td>-0.45</td>
</tr>
<tr>
<td>Fuselage mass (kg)</td>
<td>2587</td>
<td>2394</td>
<td>-7.46</td>
</tr>
<tr>
<td>Vertical tail plane mass (kg)</td>
<td>322</td>
<td>319</td>
<td>-0.93</td>
</tr>
</tbody>
</table>

**Battery strategies:**
1. Minimum battery sizing to provide energy for maximum power peak shaving of the gas turbine power rating. $H_P$ determines the peak shaving possibility.
2. Maximize the battery utilization. Hence, the battery supplies maximum mission energy in every mission segment depending on its maximum power rating and the maximum required power.

The battery usage is described with the battery strategy parameter $\lambda_{\text{Bat}}$ ranging from 0 to 1. Maximum power peak shaving strategy (1.) is reached with $\lambda_{\text{Bat}} = 0$.

$$H_P = \frac{P_{EM,max}}{P_{Total,max}}$$

Hoelzen 2018

http://doi.org/10.3390/en11010217
Example

**Hybrid-Electric ATR-42**

- The figure shows the total CO2 emissions (heat map) and Direct Operating Costs, DOC (contour lines) in dependence of hybridization $H_P$ and battery strategy parameter $\lambda_{\text{Bat}}$.
- CO2 emissions decrease with larger battery strategy parameters and reach an optimum at a degree of Hybridization of around 0.66.
- Points of min. DOC and min. CO2 do not fall together!

- Cost competitive HEA configurations do not promise the targeted CO2 emission savings.
  
  (electricity production from OECD mix; 0.42 kg CO2 per kWh)
Summary
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.

CO2 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.
Evaluating Aircraft with Electric and Hybrid Propulsion

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