

EPE'19
ECCE EUROPE



September 2-5, 2019
Genova, Italy
www.EPE2019.com



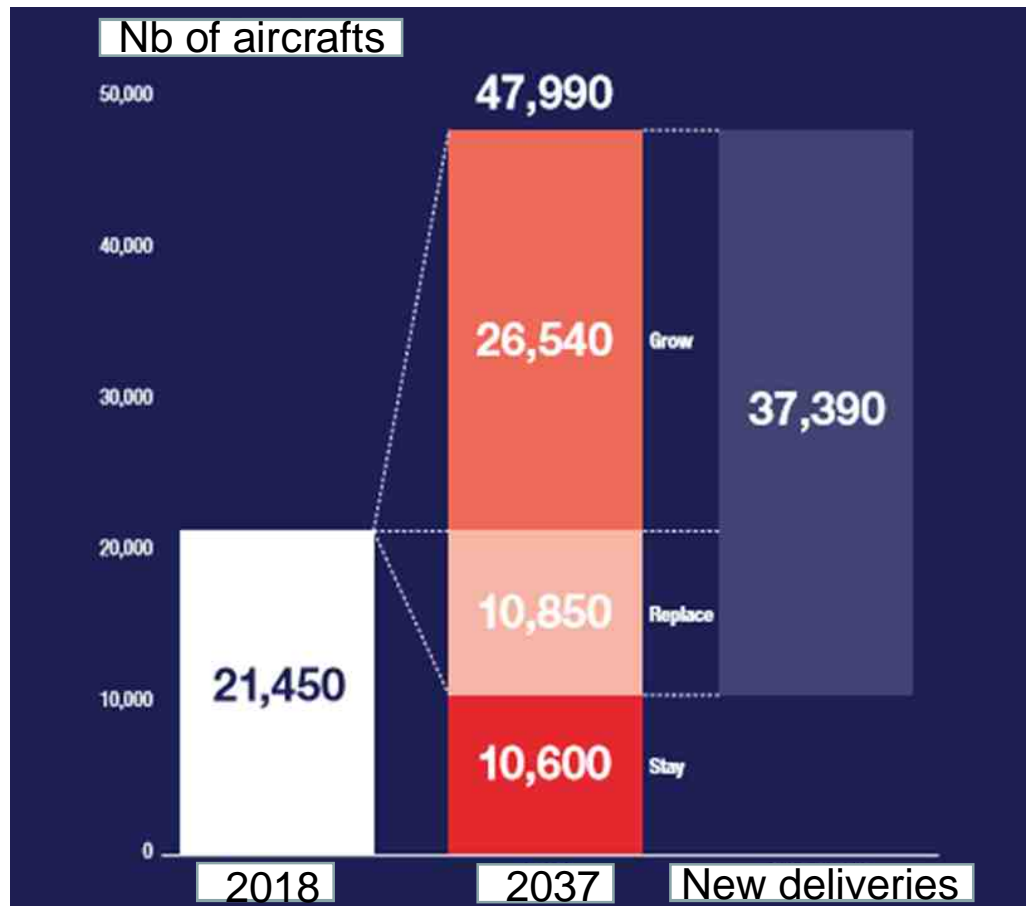
Integrated optimal design trends from non propulsive systems to hybrid power train of more electric aircraft

SAS

**Xavier
Roboam**

Sept 5th 2019

860 million Tonnes of CO2 from airlines (2017)
 ~ **2%** of human emissions



Rapport ATAG 2018 :

**Air traffic growth expected to double over the next 20 years
 + 3% per year (ref IATA)**

Context: towards greener aircrafts

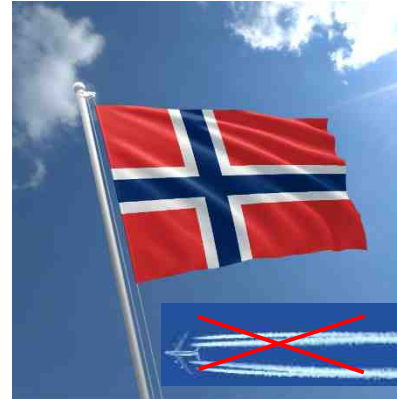
“Flygskam”: a shame to take plane !



Greta Thunberg

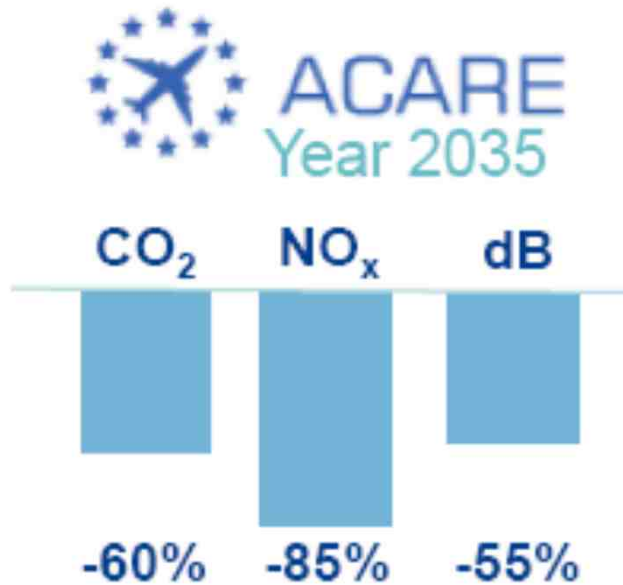


Sweden



To forbid “pollutant” aircraft in Norwegian domestic flights by 2025 !

GOALS*



* Relative to 2005

Context: towards greener aircrafts

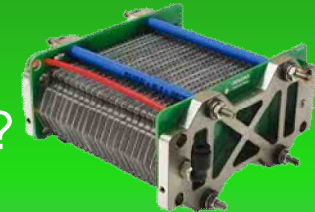
- More efficient aircrafts: fuel burn currently below 3 liters / passenger for 100 km
- Some alternative solutions to be found:



Use of biofuels
50 % less pollutant



Hydrogen
a future track ?



Electrification of systems and drive powertrain is a key driver !!!

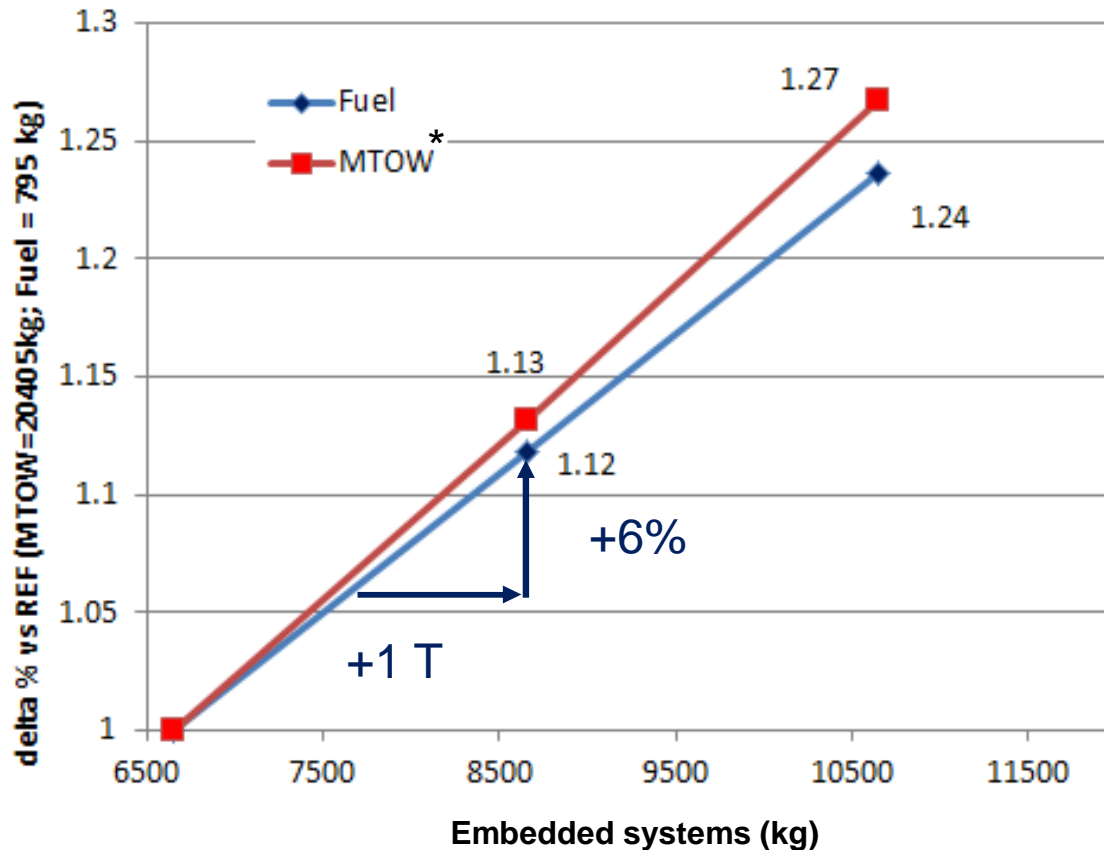


But embedded power devices and systems have to be optimized

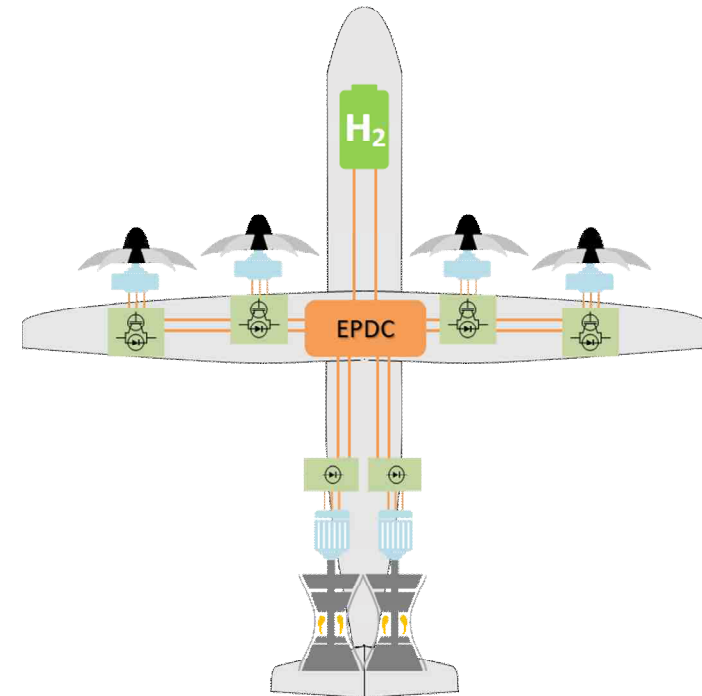
Context: "weight is the enemy" !



✓ Fuel saving vs embedded Weight



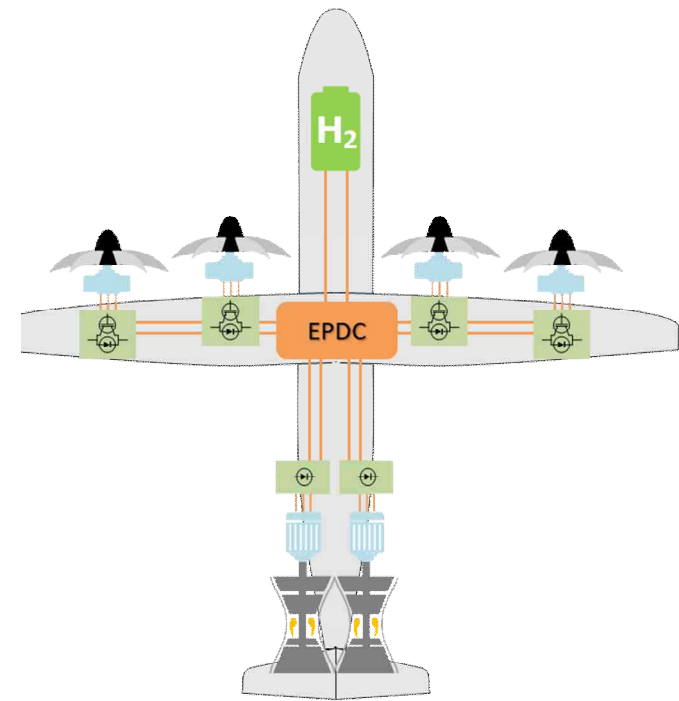
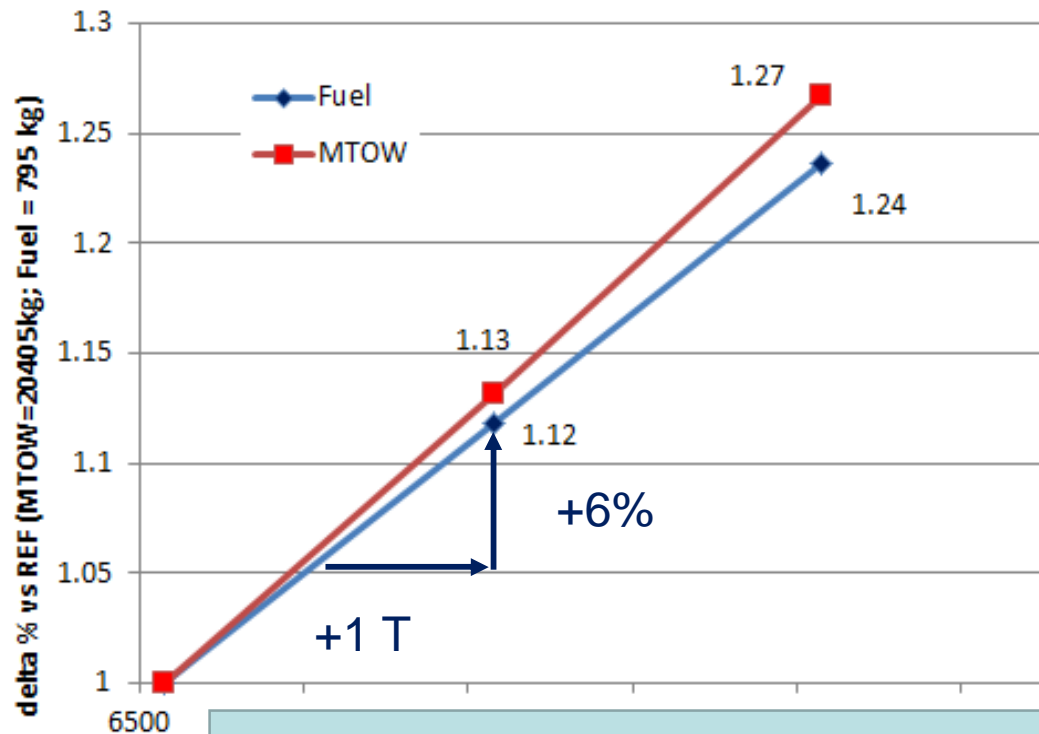
Case study: regional aircraft
(short range ~ 400 nm)



➤ **Snowball effect: +6% of fuel / ton of additional embedded systems**

MTOW*: Max takeoff Weight

Context: weight is the enemy!



Additional weight also means additional costs

For a design

- Case 1: p
- Case 2: p

1kg of systems ~1000US\$ [Rob 12]

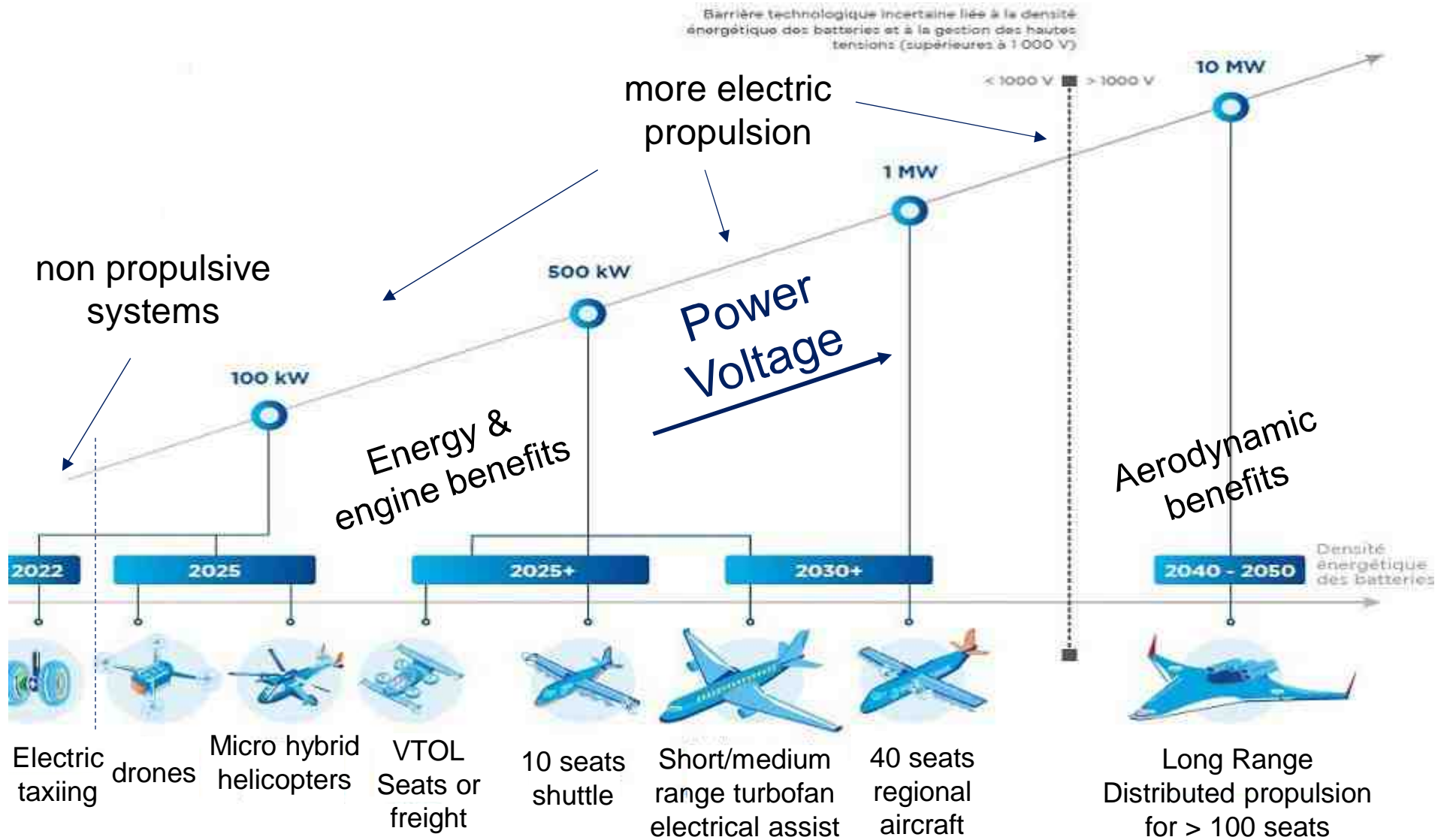
Fuel vs MTOW*
Aircraft (400 nm)

(2%)

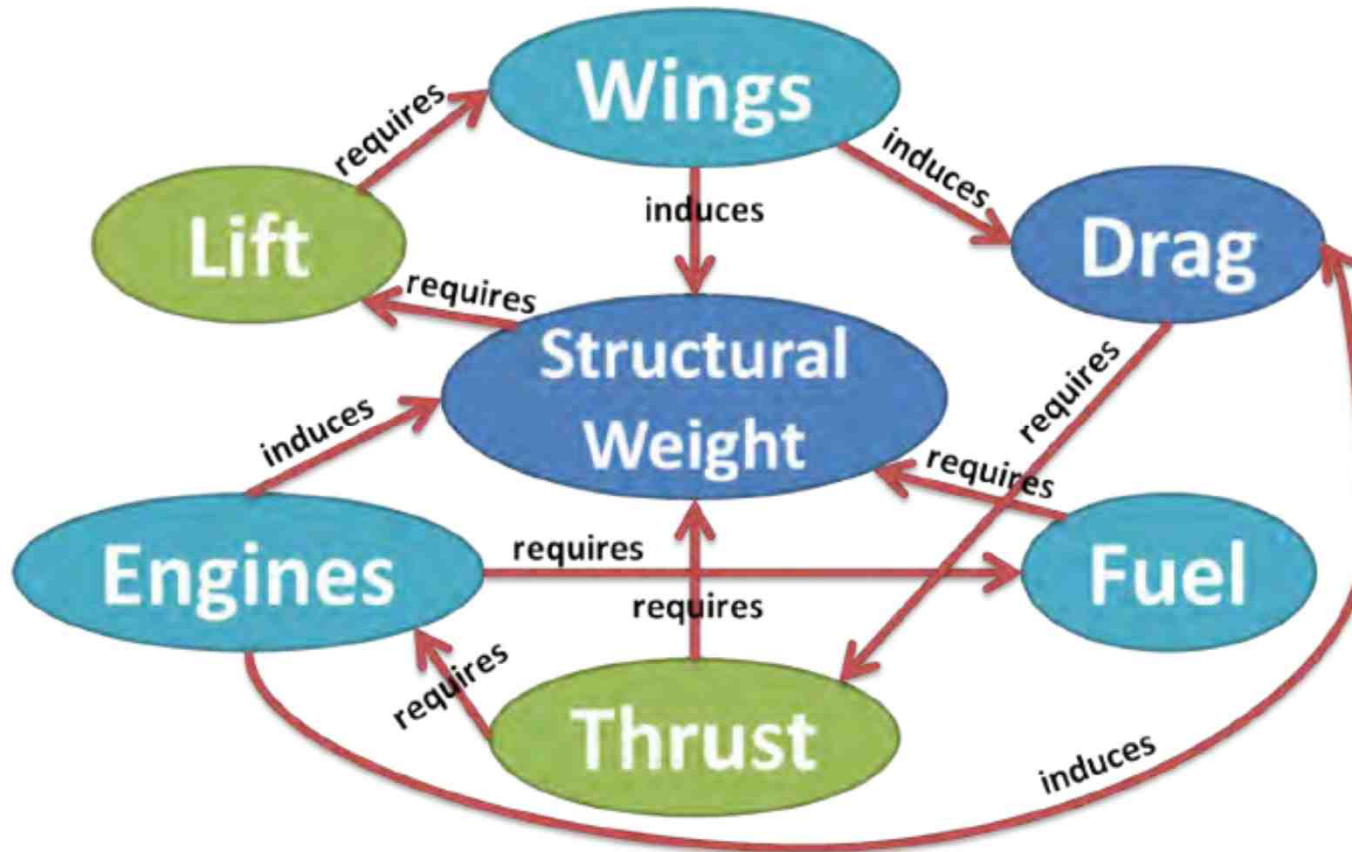
➤ **Snowball effect: +6% of fuel / ton of additional payload**

X. Roboam, "More electricity in the air: Towards optimized electrical networks embedded in "more electrical aircraft", IEEE Industrial Electronics Magazine, 2012

Road map for more electric aircrafts



✓ Numerous interactions in aircraft design



If the problem is complex, why not simplifying it by optimizing each discipline separately ?

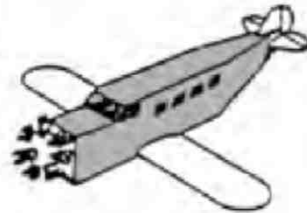
Integrated design by optimization: a complex issue

✓ Caricature of “ideal” planes optimized for each discipline

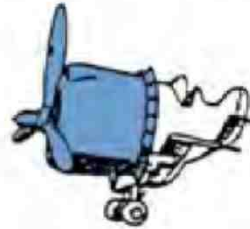
Aerodynamic Group



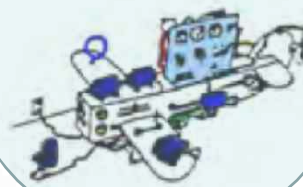
Fuselage Group



Power Plant Group



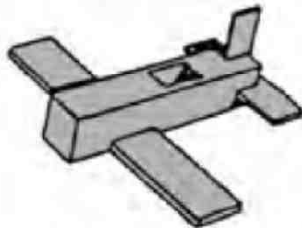
Electrical Group



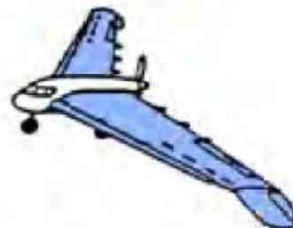
Equipment Group



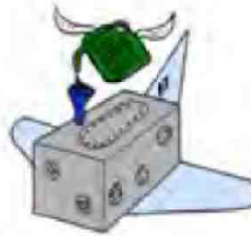
Loft Group



Wing Group



Fuel Group



Controls Group



Production Group



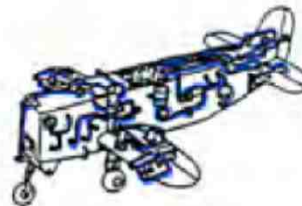
Stress Group



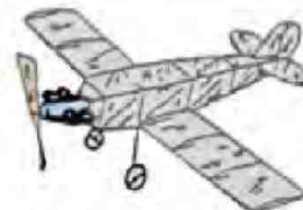
Empennage Group



Hydraulic Group



Weight Group

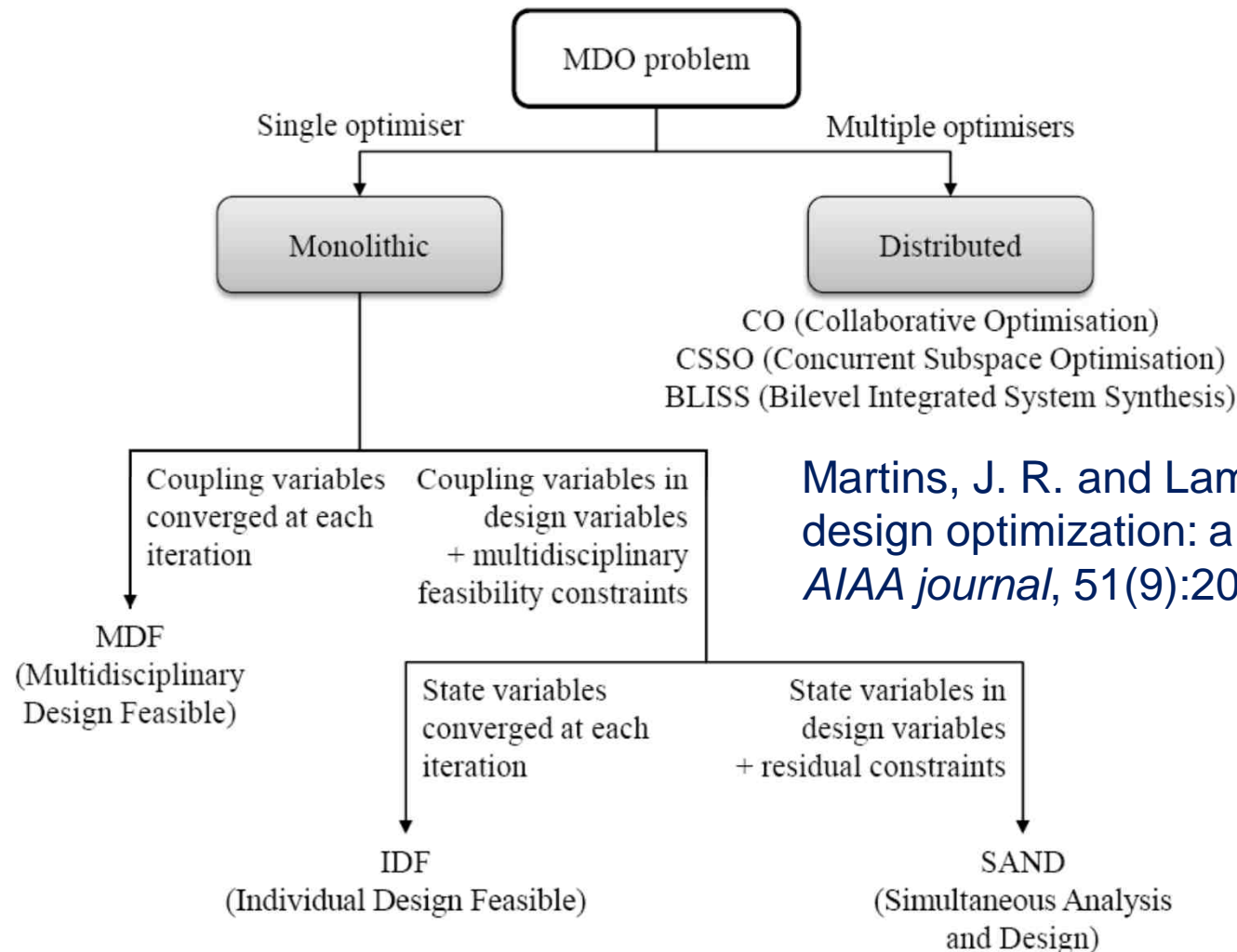


Service Group



If the problem is complex, why not simplifying it by optimizing each discipline separately ?

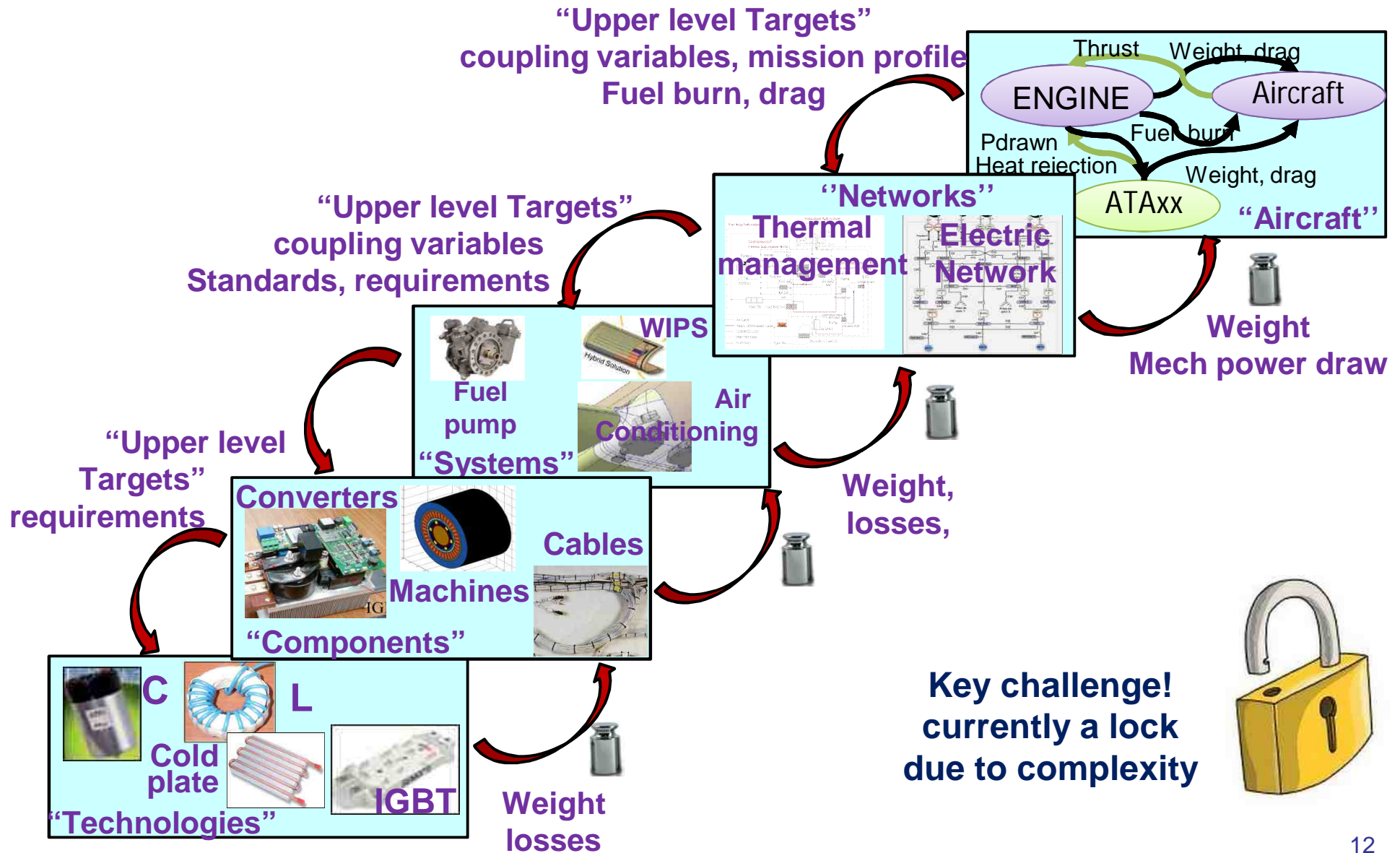
- ✓ **Multi disciplinary Design Optimization (MDO):**
 - **to face multi level and multi fields of design setting coupling variables to be close to the global optimum.**



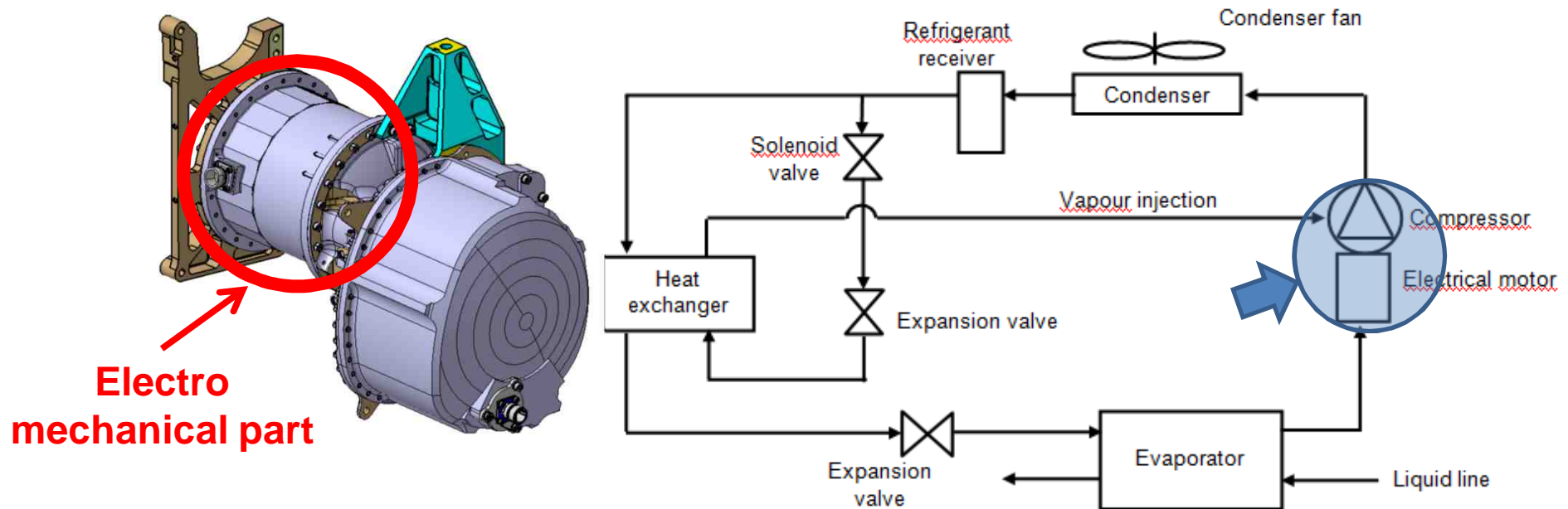
Martins, J. R. and Lambe, A. B. Multidisciplinary design optimization: a survey of architectures. *AIAA journal*, 51(9):2049–2075. (2018).

Integrated design by optimization: a complex issue

- Multi (5) level optimization from “technologies” to “Aircraft”



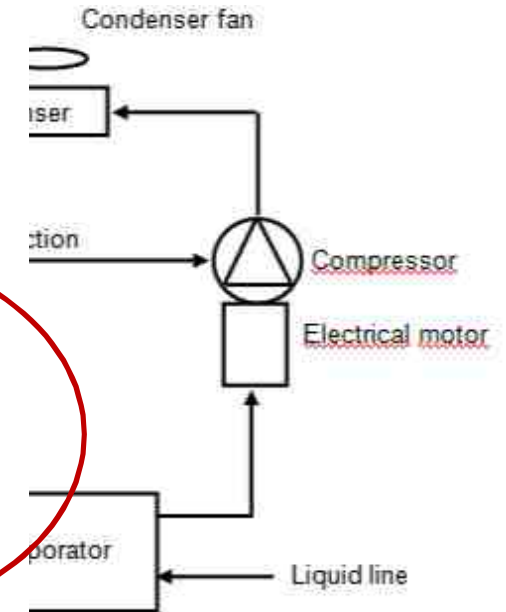
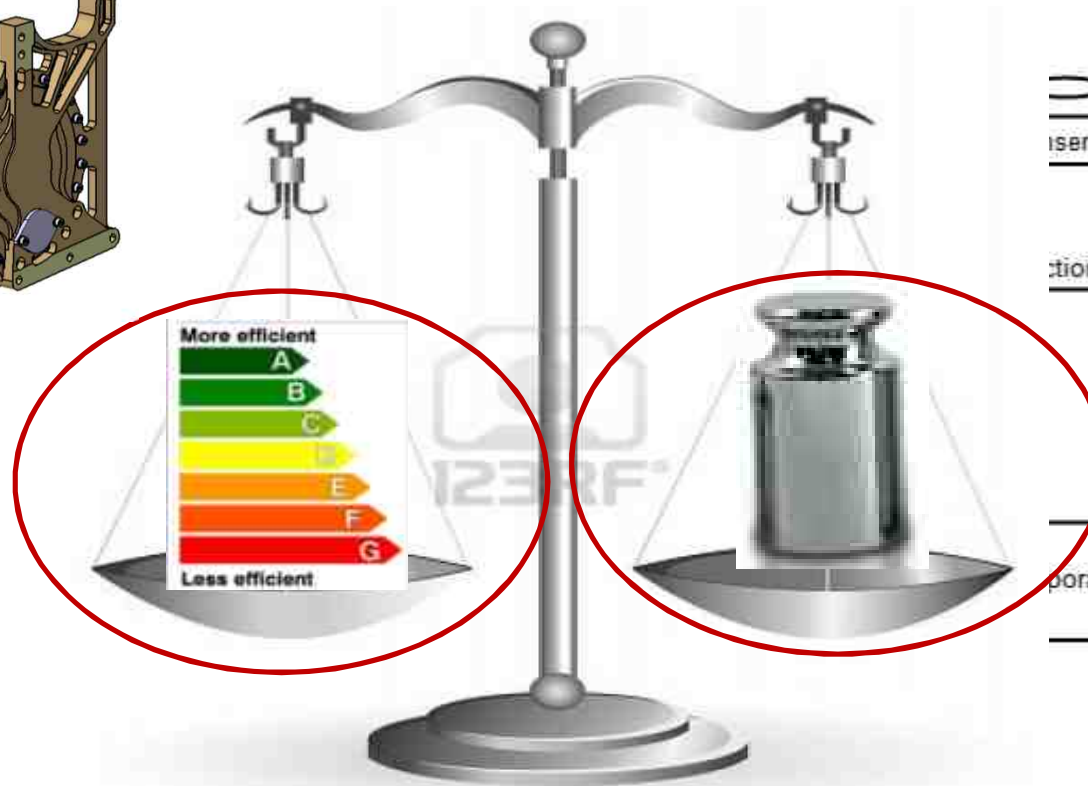
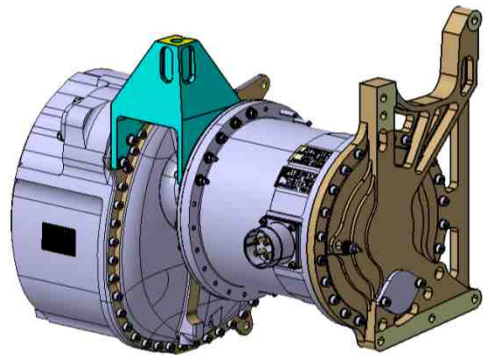
Typical case study: global optimization of electromechanical part of a VCS (Vapour Cycle System) for supplemental cooling of A380



The VCS ensures power electronics cooling by means of motor-compressor device involving a high speed electromechanical power drive

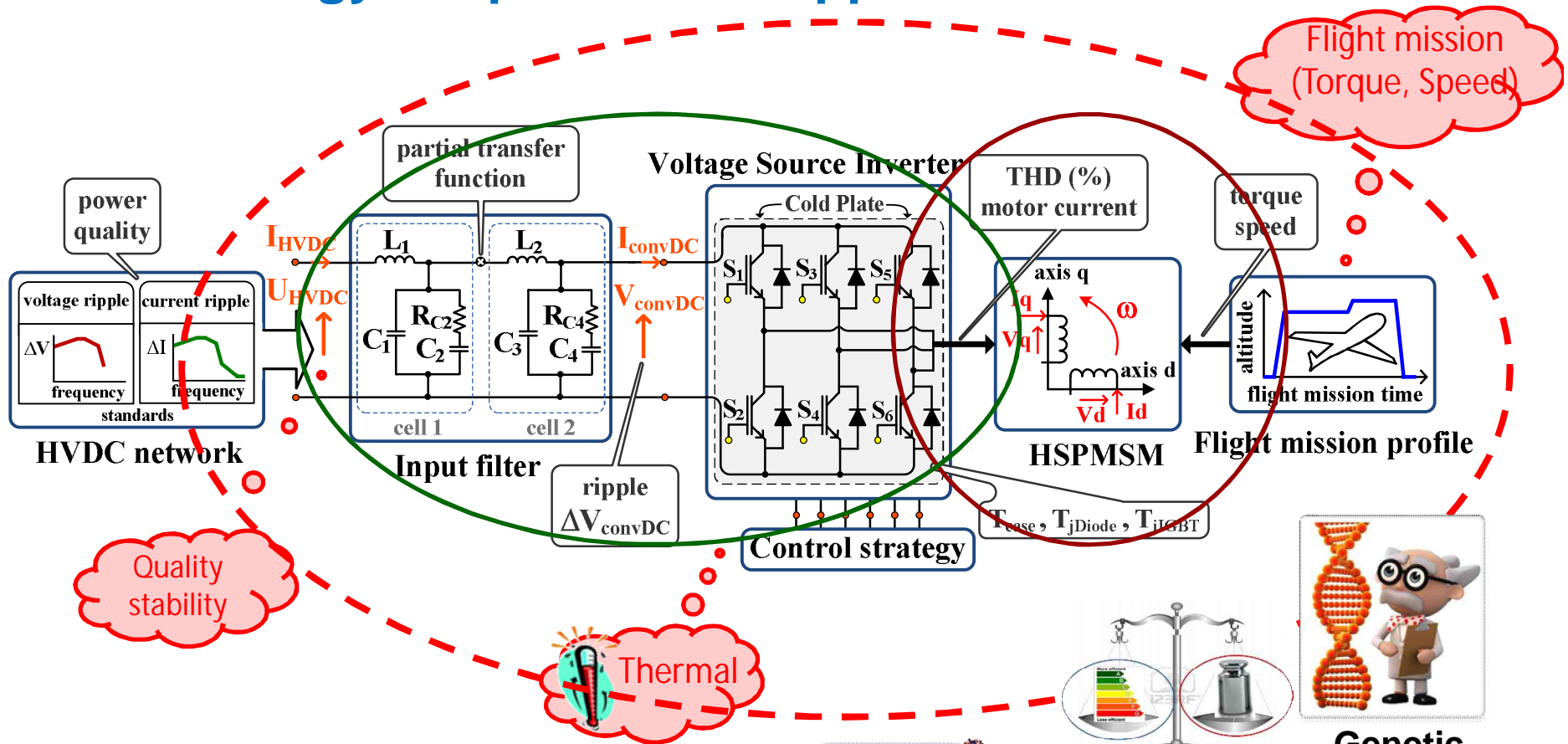
H.Ounis, B. Sareni, X. Roboam, A. De Andrade, "Multi-level integrated optimal design for power systems of more electric aircraft", Elsevier MATCOM (Mathematics and Computers in Simulation, 130 (2017) 1–2.

Optimizing non propulsive systems

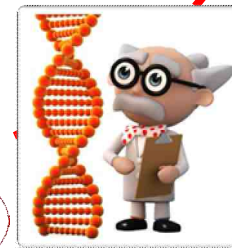
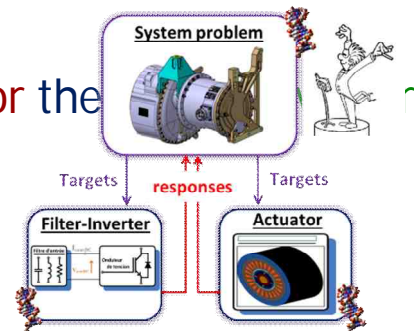


To seek the optimal tradeoff between weight and losses at system level

Methodology: 3 optimization approaches



- 1- Sequential optimization : 2 loops (Actuator the
- 2- **Global** optimization : 1 single loop
- 3- Multi level optimization (N loops)

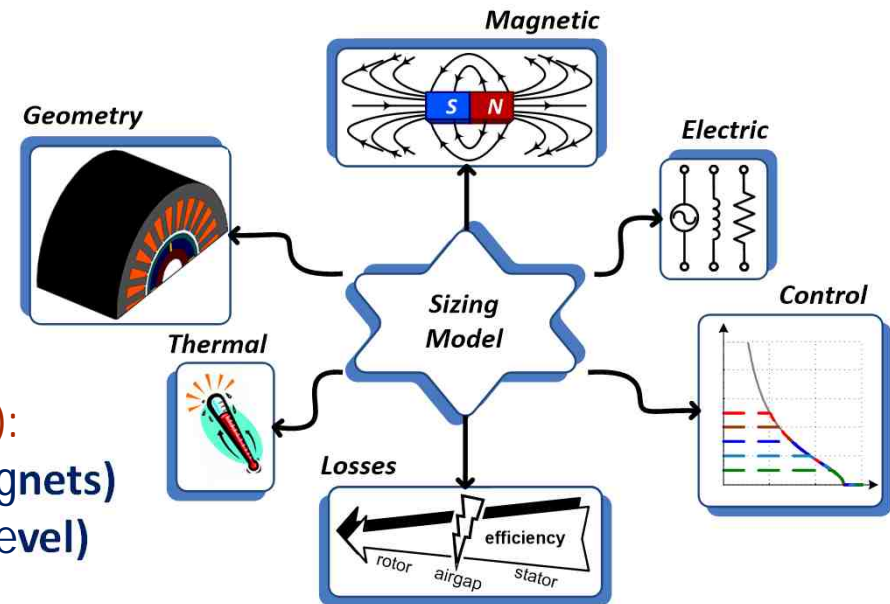


**Genetic algorithm
NSGA II**

1st part: electromechanical actuator

☑ Analytic multiphysical model

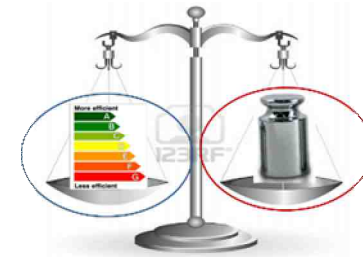
- 12 design variables (2 discretés, 10 continuous):
- Geometry (radius, airgap, slots, polarity, magnets)
 - Electromagnetic (current density, induction level)
 - Mechanical (base torque and speed)



→ 18 constraints:

- Quality (motor current harmonics)
- Thermal
- Environment : flight mission
-

→ 2 objectives : weight vs average losses

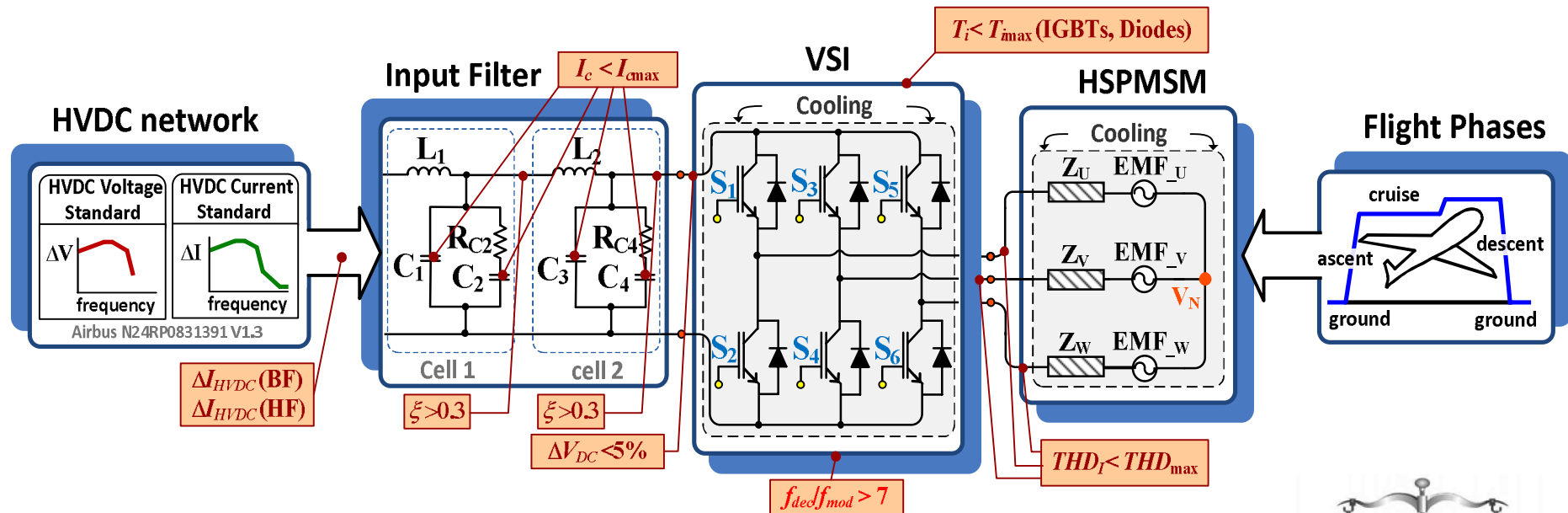


2nd part: voltage source inverter and input filter

→ 6 design variables (continuous):

- 4 parameters for input filter (R, L, C)
- 2 parameters for inverter: IGBT rating and switching frequency

→ 11 constraints for quality (HVDC standards,...), stability and thermal operation



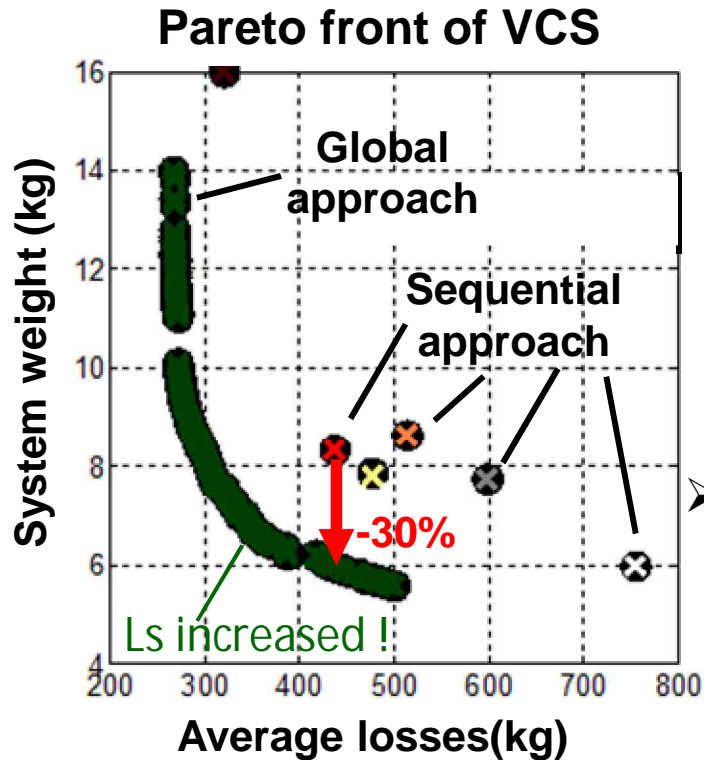
→ 2 objectives :

- Weight minimization (L,C filter, IGBTs, cooling plate)
- Losses minimization: inverter (switching, conduction) + filter



Optimizing non propulsive systems

Sequential (2 loops) vs global approach (single loop)



Sequential optimization clearly outperformed by the global approach involving system couplings (L_s, Φ, ρ)

➤ ***L_s: typical coupling parameter involved in filtering***

BUT Global Optimization

- reaches "convergence limit": initialized with solutions issued from sequential approach



To search an intermediate approach with:

- Easier convergence
- Acceptable computational (CPU) time



Towards a multi level optimization: a typical MDO approach

Optimizing non propulsive systems

A multi (2) level optimization process

N (here 2) subsystems
=> N+1=3 optimization loops

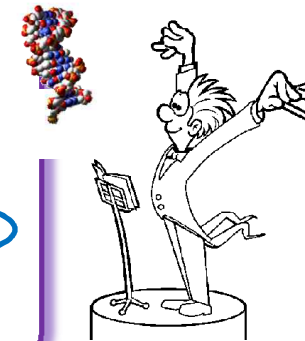
$[R_s, L_{syn}, \phi, \rho]$
Design variables are the coupling variables between Subproblems

System problem

Min $M_{sys} = M_{HSPMSM} + M_{Inv}$
 $\delta P_{sys} = \delta P_{HSPMSM} + \delta P_{Inv}$

$X_{Global} = [R_s, L_{syn}, \rho, \phi]$

Constraints
 $G_{sys} = [G_{HSPMSM}, G_{Fil-VSI}]$



- Constraints
- Objectives
- Local Variables
- System variables

Targets ↓ ↑ responses

$[R_s, L_{syn}, \rho, \phi]$ (to SubSys1)
 $M_{Inv}, \delta P_{Inv}, G_{Fil-VSI}$ (from SubSys1)
 $M_{HSPMSM}, \delta P_{HSPMSM}, G_{HSPMSM}$ (from SubSys2)
 $[R_s, L_{syn}, \rho, \phi]$ (from SubSys2)

SubSys1 (Filter-Inverter)

Min $M_{Fil-Inverter1}$
 $\delta P_{Fil-Inverter}$

$X_{Fil-VSI} = [L_1, C_1, C_2, R_{C2}, F_{sw}, I_{op}]$

Constraints:
 $G_{Fil-VSI} = [g_1, g_2, \dots, g_{11}]$

SubSys2 (Actuator)

Min M_{HSPMSM}
 δP_{HSPMSM}

$X_{HSPMSM} = [J_s, N_{app}, g, D_y, R_{dr}, R_{lr}, K_p, K_r, N_{bp}, T_{pb}]$

Constraints:
 $G_{Act} = [g_1, g_2, \dots, g_{18}]$
 $g_{19}(R_s - R_s)^2 < \epsilon_1$
 $g_{20}(L_{syn} - L_{syn})^2 < \epsilon_2$
 $g_{21}(\phi_s - \phi_s)^2 < \epsilon_3$

No direct interaction between subsystems

“Coordination” constraints
 $[R_s, L_{syn}, \phi]$ are not decision variables but targets in the actuator Problem



Optimize each component (SubSystem) in a local loop while global objectives are explored at the system level !

Optimizing non propulsive systems

A multi (2) level optimization process

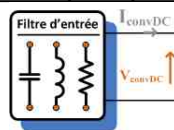
N (here 2) subsystems
=> N+1=3 optimization loops

$$[R_s, L_{syn}, \phi, \rho]$$

Design variables are the coupling variables between Subproblems

$$[R_s, L_{syn}, \dots]$$

SubSys1 (Filter)



$$\text{Min } M_{Fil}, \delta P_{Fil-1}$$

$$X_{Fil-VSI} = [L_1, F_{sw}, I_{op}]$$

Constraints:

$$G_{Fil-VSI} = [g_1, g_2, \dots, g_{11}]$$

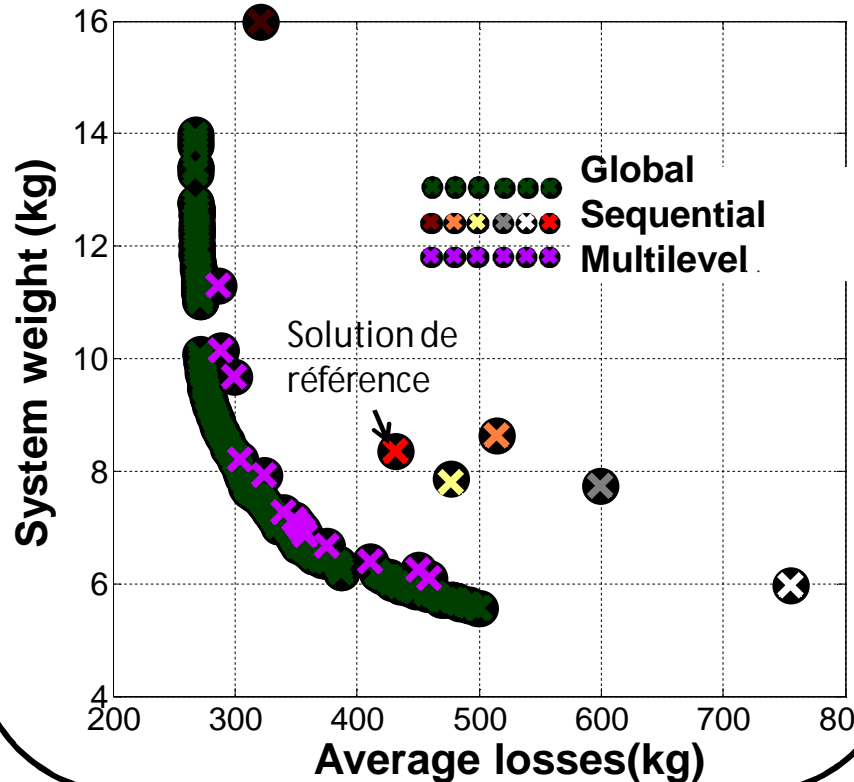
No direct interaction between subsystems



Optimize each component (SubSystem) in a local loop while global objectives are explored at the system level !

System problem

Pareto front for VCS (3 methods)



- Constraints
- Objectives
- Local Variables
- System variables

Targets ↓ responses ↑

"Coordination" constraints

$[L_{syn}, \phi]$ are not in variables but in the actuator Problem

$$g_{20}(L_{syn} - L_{syn})^2 < \epsilon_2$$

$$g_{21}(\phi_s - \phi_s)^2 < \epsilon_3$$



Join Over 200 International Experts Discussing
Electric & Hybrid Propulsion Technology For The
Next Generation of Aircraft



A strongly emergent topic



Prof Dr. Josef Kallo, Coordinator Energy System Integration, German Aerospace Center

THE NEW ERA OF ELECTRIC AVIATION IN FIXED-WING, EVOTL & UAM

**DEVELOPMENTS IN ENERGY STORAGE FOR MEA AND AEA:
HEALTH MONITORING AND HYDROGEN FUEL CELLS**

**FROM MORE-ELECTRIC TO ALL-ELECTRIC: HYBRID & ELECTRIC
PROPULSION AND DRIVE TRAIN**

EVENING WORKSHOP

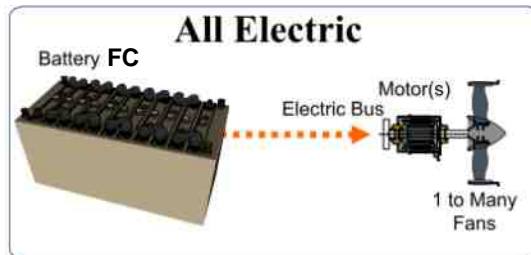
**TECHNOLOGY NEED FOR ELECTRICAL COMPONENTS WITH GROWTH OF AIRCRAFT MARKET FROM
URBAN AIR MOBILITY TO LARGE AIRCRAFT WITH MEGAWATT SCALE PROPULSION SYSTEM**

The electrical and hybrid aircraft : objectives, orientations and stakes
Urban air mobility : scientific and technical challenges
The real roadmap to the future of electric air mobility
Perspectives and activities on hybrid/electric propulsion
Challenges and solutions for certified electric aircraftin commercial applications
Electric propulsion units : design aspects & performance levels

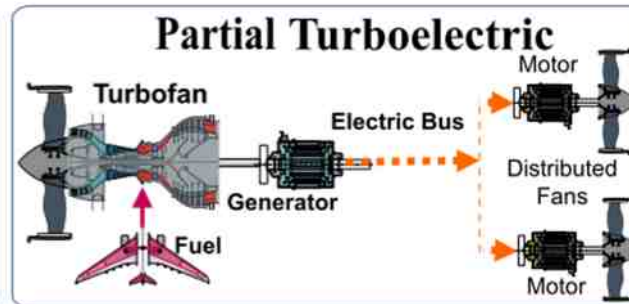
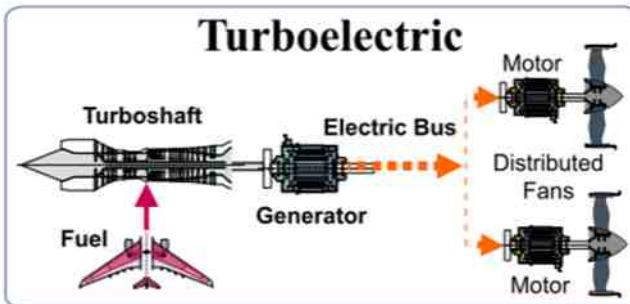
Optimizing more electric propulsive systems

Several Hybrid Architectures (as for ground EV, HEV vehicles)

➤ 3 main categories:

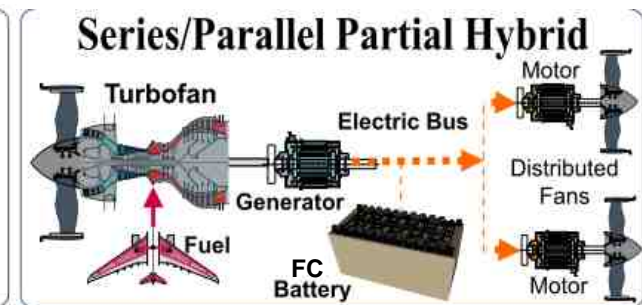
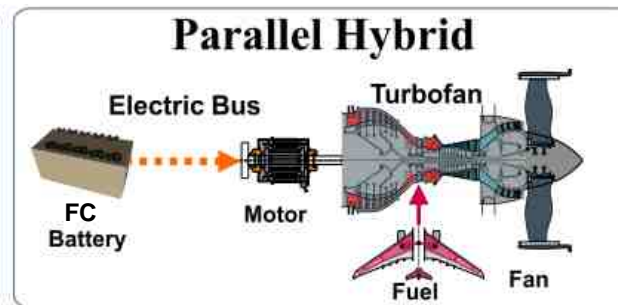
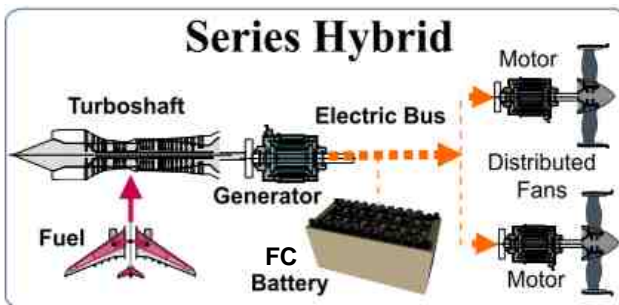


all electric



turboelectric

hybrid electric



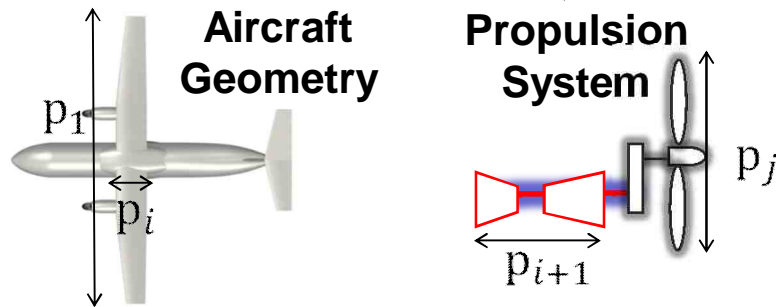
Optimizing more electric propulsive systems

MDO for hybrid architecture and sizing optimization integrating energy management and flight mission

Regional aircraft case

- p : vector of design variables (Large number !)

$$\vec{p} = [\underbrace{p_1, \dots, p_i}_{\text{Aircraft Geometry}}, \underbrace{p_{i+1}, \dots, p_j}_{\text{Propulsion System}}, \underbrace{p_{j+1}, \dots, p_k}_{\text{Energy Management Trajectory}}, \underbrace{p_{k+1}, \dots, p_l}_{\text{Mission Profile}}]$$

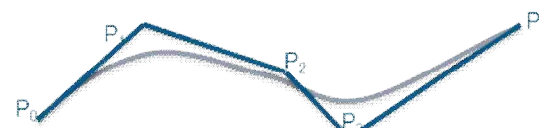


Energy Management Trajectory Mission Profile

- Hybrid ratio, priority rules, ...
- Propeller rpm, ...
- Flap deflection angle, ...

- Altitudes
- Speeds (V_x, V_z)
- Distances

Temporal parametric B-splines



- Linked through flight equations:

$$\begin{cases} m(t,p) \frac{dV(t,p)}{dt} = Thrust(t,V,h,T0,p) \cdot \cos(\alpha + \epsilon) - Drag(t,\alpha,V,h,T0,p) - m(t,p) \cdot g \cdot \sin(\gamma(t,p)) \\ m(t,p) V(t,p) \frac{d\gamma(t,p)}{dt} = Thrust(t,V,h,T0,p) \cdot \sin(\alpha + \epsilon) + Lift(t,\alpha,V,h,T0,p) - m(t,p) \cdot g \cdot \cos(\gamma(t,p)) \end{cases}$$

J. Thauvin, Exploring the design space for a hybrid-electric regional aircraft with Multi-Disciplinary Design Optimisation methods, PHD Thesis of Univ Toulouse, 2018

*MDO: Multi disciplinary Design Optimization

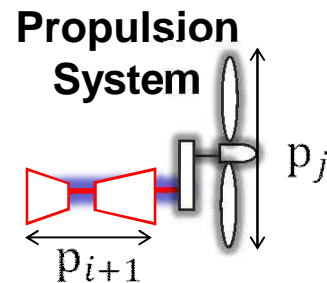
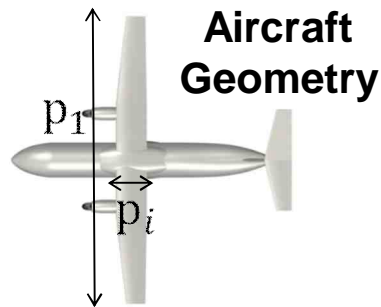
Optimizing more electric propulsive systems

MDO for hybrid architecture and sizing optimization integrating energy management and flight mission

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Energy Management Trajectory

- Hybrid ratio, priority rules, ...
- Propeller rpm, ...
- Flap deflection angle, ...

Mission Profile

- Altitudes
- Speeds (V_x, V_z)
- Distances

Temporal parametric B-splines



Selected optimisation algorithms

- Non-convexity/multimodality of the design space identified with gradient-based algorithms



Combination of gradient-free algorithms:
CMA-ES + Subplex
global stochastic local deterministic

Typ 30-50 design variables

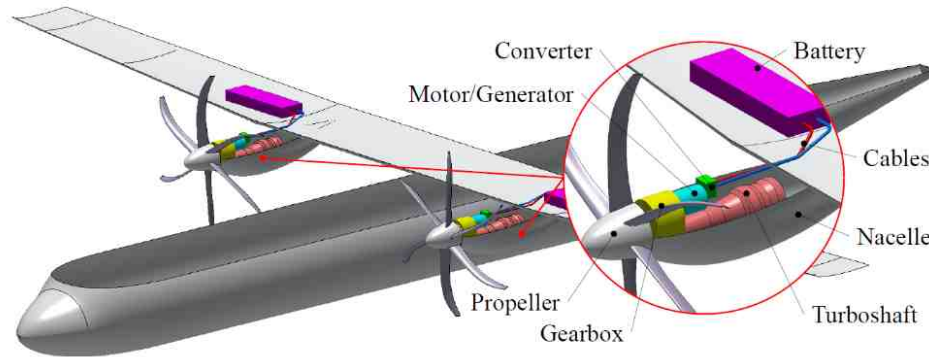
Optimisation criteria

Minimise fuel burn of design mission

*MDO: Multi disciplinary Design Optimization

Optimizing More electric propulsive systems

Parallel Hybrid (PH) architecture for regional flight (400nm):

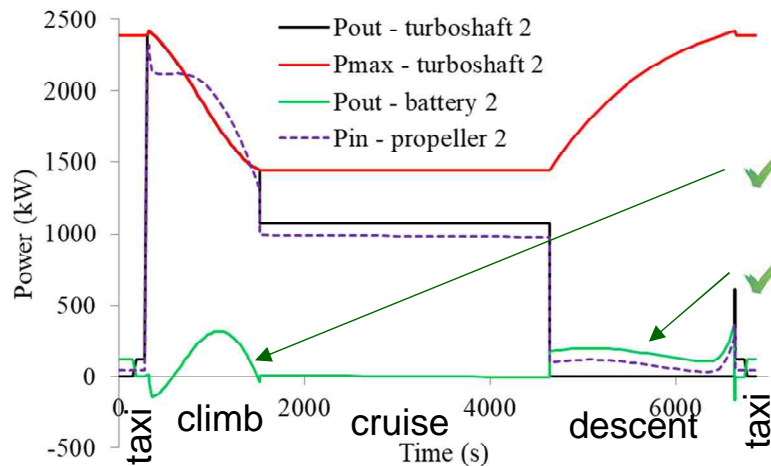


- Results for 2025 technologies

	REF	PH	$\Delta\%$
Max Take-Off Weight [kg]	20,000	22,900	14%
Fuel burn (400nm) [kg]	808	735	-9%

Batt: 1,500 kg

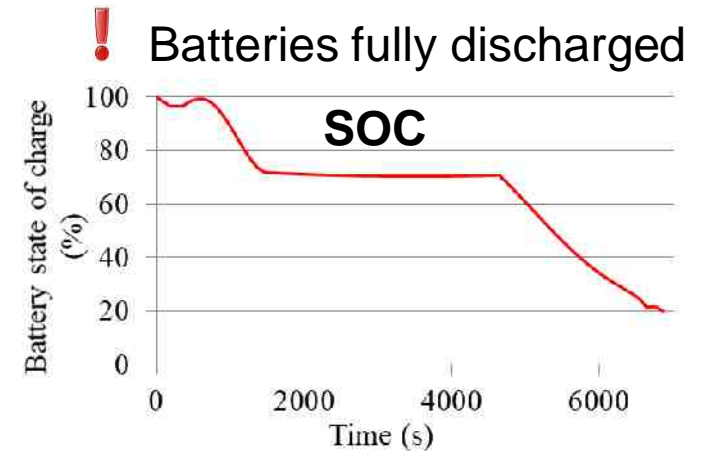
Total design variables: 36



Energy use:

✓ Engine downsizing
(15% e-boost)

✓ Start & Stop taxi & descent



J. Thauvin, Exploring the design space for a hybrid-electric regional aircraft with Multi-Disciplinary Design Optimisation methods, PHD Thesis of Univ Toulouse, 2018

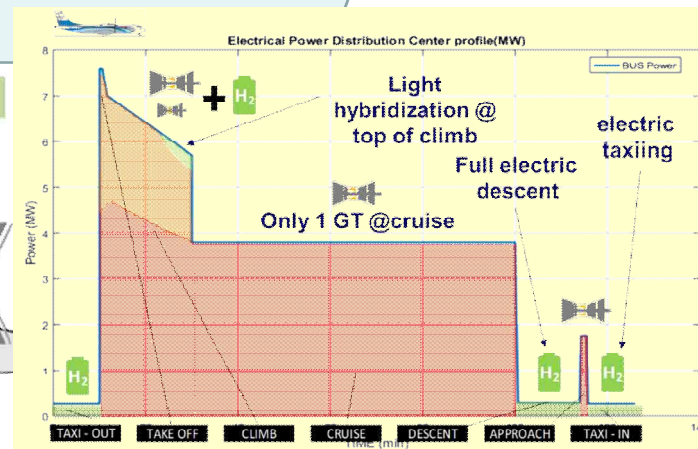
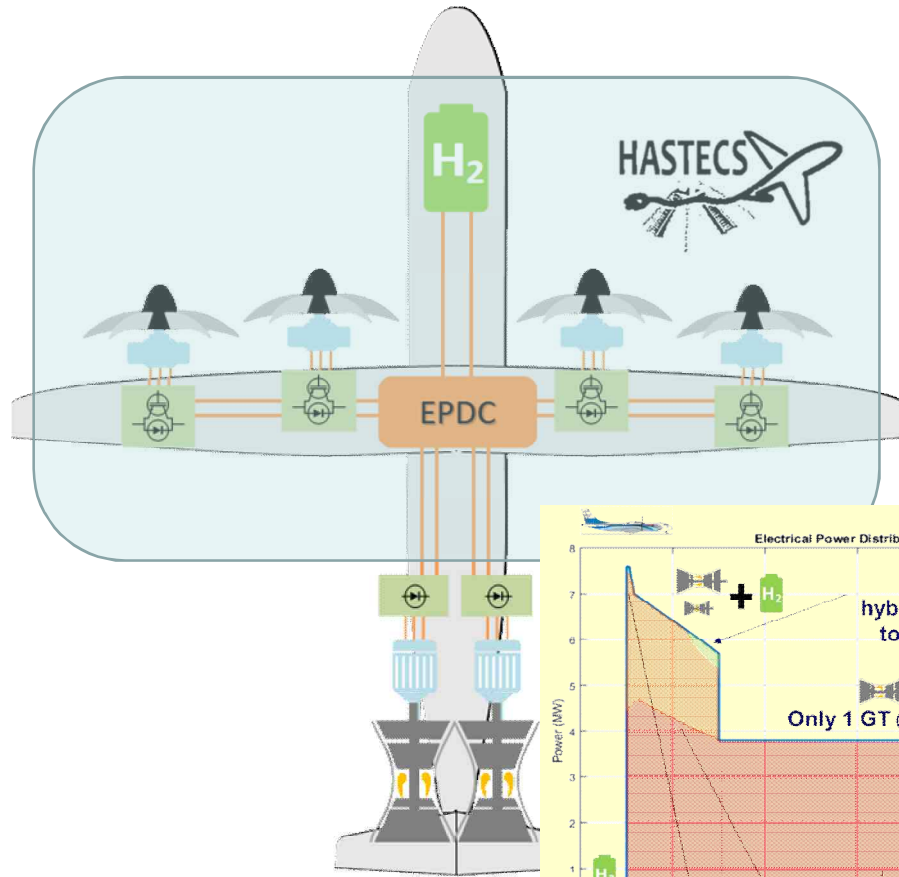
AIRBUS



Hybrid Aircraft
Academic re**S**earch on **T**hermal
 & **E**lectrical **C**omponents and **S**ystems



AIRBUS



**SERIES HYBRID ELECTRIC
 ARCHITECTURE
 FOR REGIONAL AIRCRAFT**

PROPELLER + GEARBOX	
E-MOTOR	
CABLE	
DC/AC CONVERTER	
ELECTRICAL POWER DISTRIBUTION CENTER	
BATTERY/FUEL CELL	
AC/DC CONVERTER	
E-GENERATOR	
TURBOSHAFT	

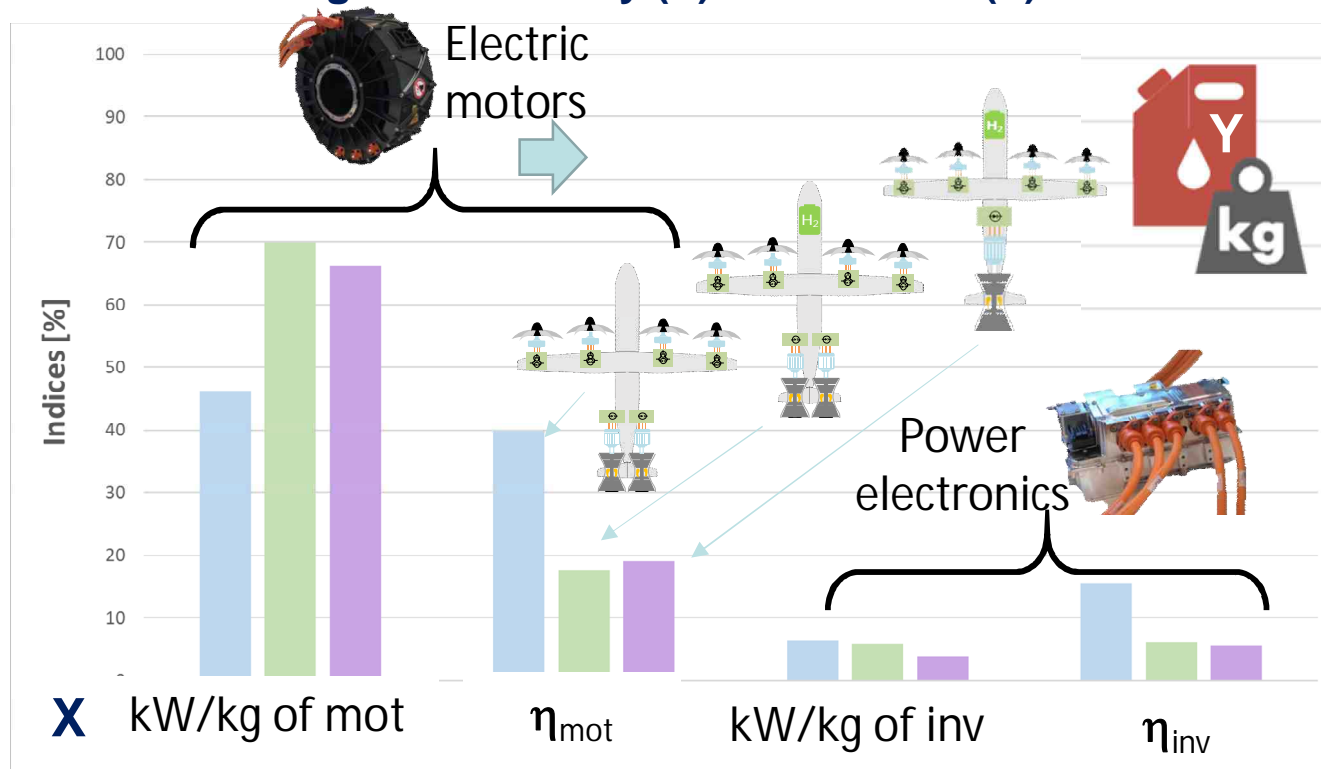
Sensitivity Analysis of power train devices

An important topic “on the road of” the integrated optimal design !

- ✓ Sobol indices: the higher an index (S_i) the higher the sensitivity of the output Y related to the input X_i “effect of the X_i variable alone”

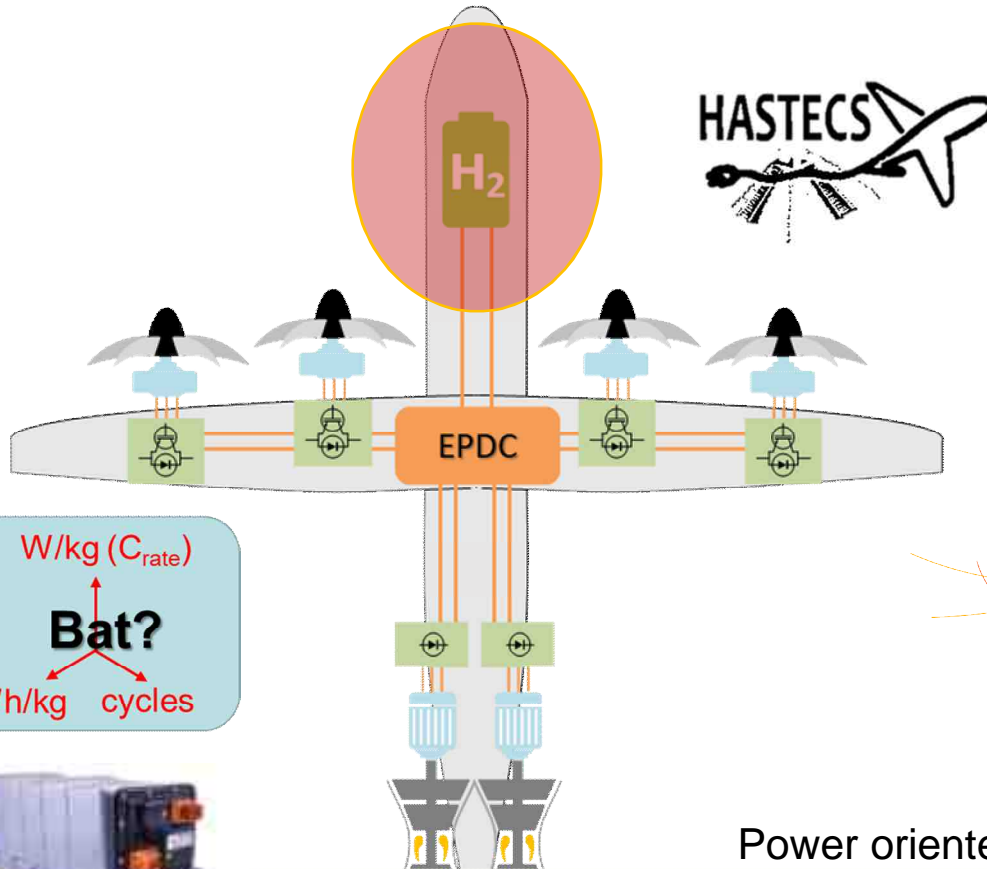
$$\text{First order indices: } 0 \leq S_i = \frac{\text{Var}(E[Y|X_i])}{\text{Var}(Y)} \leq 1$$

Sobol indices based analysis of motor and power electronic weight & efficiency (X) on fuel burn (Y)

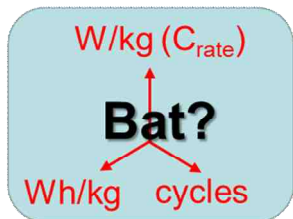


Electric motor weight and efficiency more sensitive on the fuel weight than power electronics

About alternative electrical sources: Batteries or Fuel Cells (FC) ?



A promising device !



Batteries



H₂ liq storage



FC System

		Power oriented	Energy oriented	
Specific energy e_m		LTO / TNO ^{1,4}	NMC Solid State ³	FC System (LH ₂)
Perspectives (5 – 10 years)	Cell level	~ 180 – 200 Wh/kg	~ 650 Wh/kg	~ 1 kW/kg
	System level	~ 100 Wh/kg	~ 325 Wh/kg	~ 560 Wh/kg

x 1.8

Why not a full electric aircraft with H2 ?

Rough assessment of a Full Hydrogen Aircraft with liquid H2 storage

➤ MTOW = 28.5 Tons => + 3 T vs Hybrid Electric Aircraft **+ 10-12%**

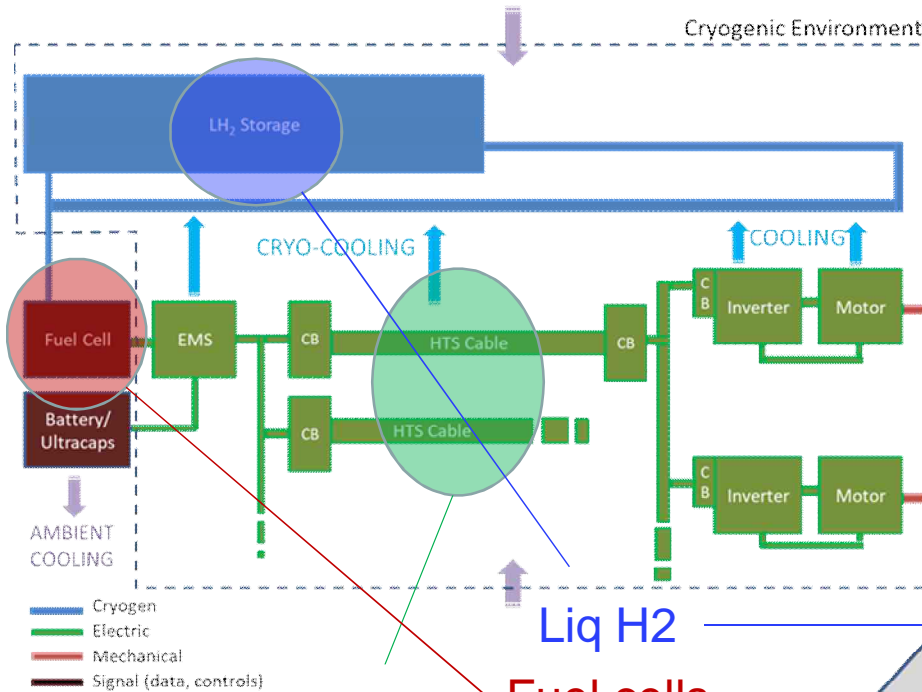
Components	Weights (kg)
Propeller	4 x 134 kg
Gearbox	4 x 100 kg
Electric motors	4 x 176 kg
Cables	93 kg
Inverters	4 x 71 kg
Fuel cell + Aux + H2	1 x 6388 kg

Assessments:
 Liquid H2 storage @20°K
 with 20% of H2 weight in tank
 $\eta_{FC} = 60\%$
 FC stack : 4kW/kg
 Auxiliaries : 2.7 kW/kg
 Vbus @ 2 kV

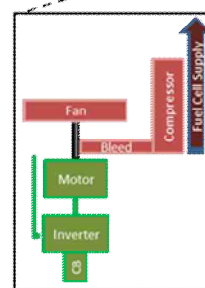
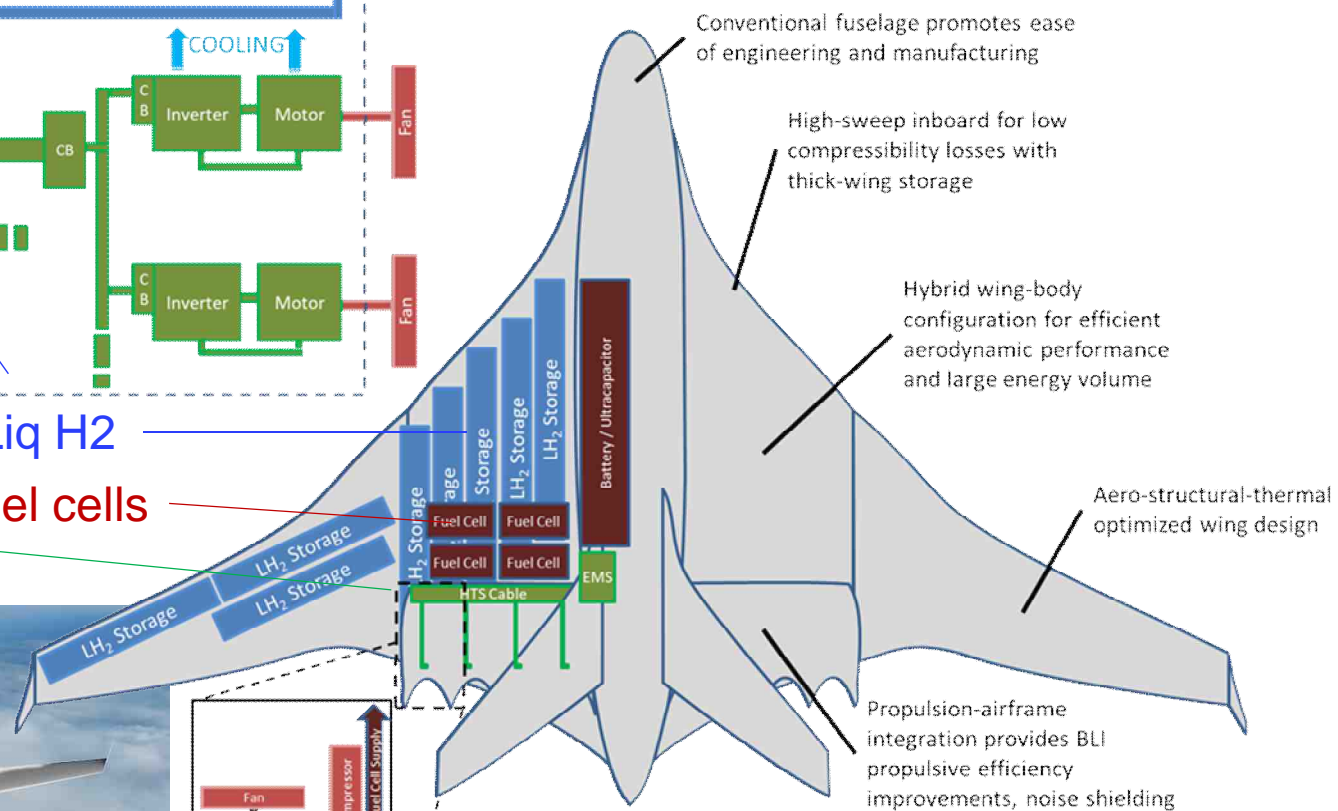
When thinking of cryogenic H2 @20°K why not mutualizing with superconductor devices ?

About full electric aircraft: why not with H2 and supra ?

Some people are thinking...



Liq H2
Fuel cells
HTS cables



About full electric aircraft: why not with H2 and supra ?

Some people are thinking...

May we “dream” of a zero emission aircraft ?

Huge challenges on new technologies, devices, systems !

Whatever these solutions, they will have to be optimized and integrated with efficient methodologies and relevant models facing the design COMPLEXITY !



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de Toulouse



Integrated optimal design trends from non propulsive systems to hybrid power train of more electric aircraft

SAS

**Xavier
Roboam**



Many Thanks

Sept 5th 2019