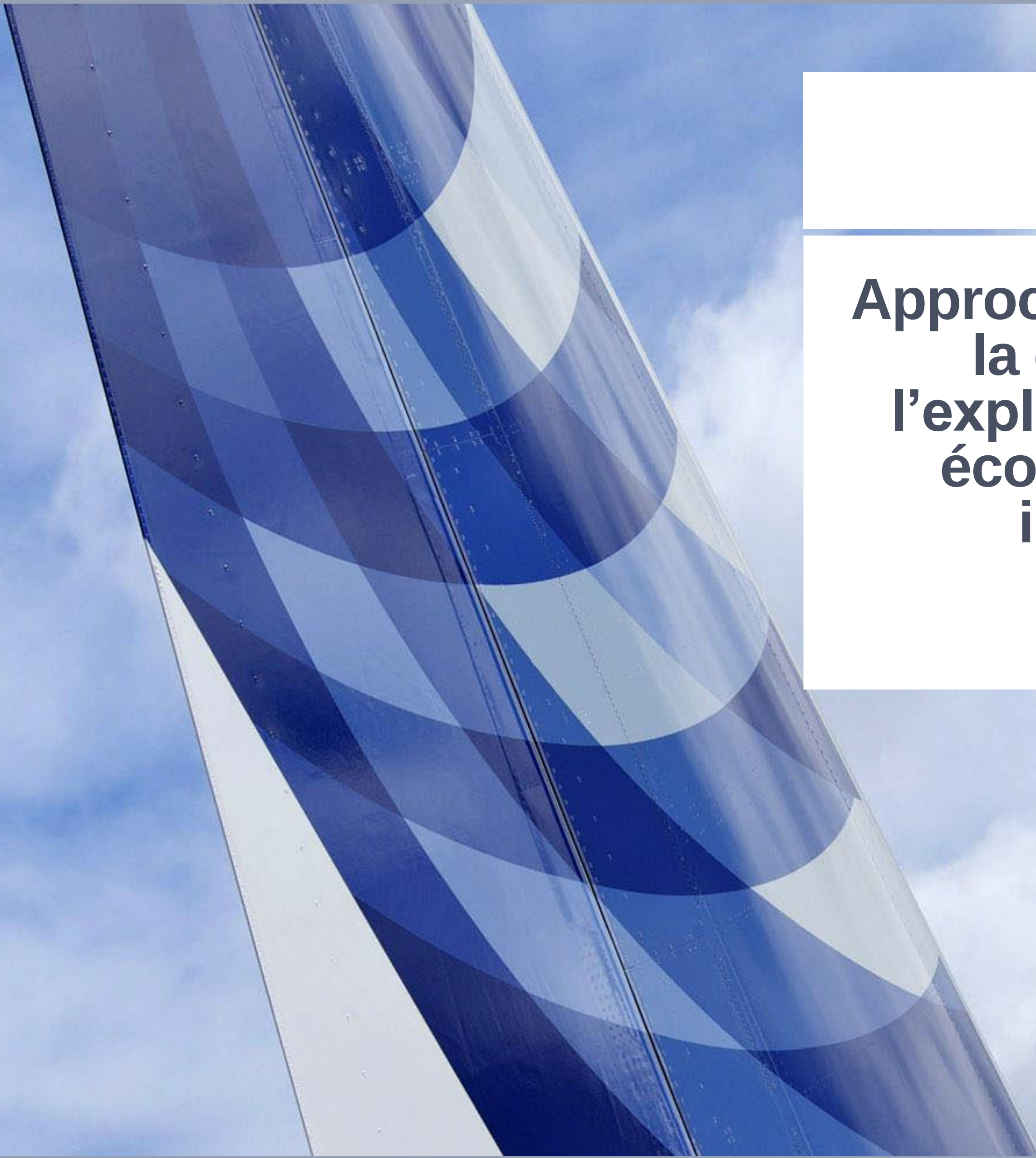
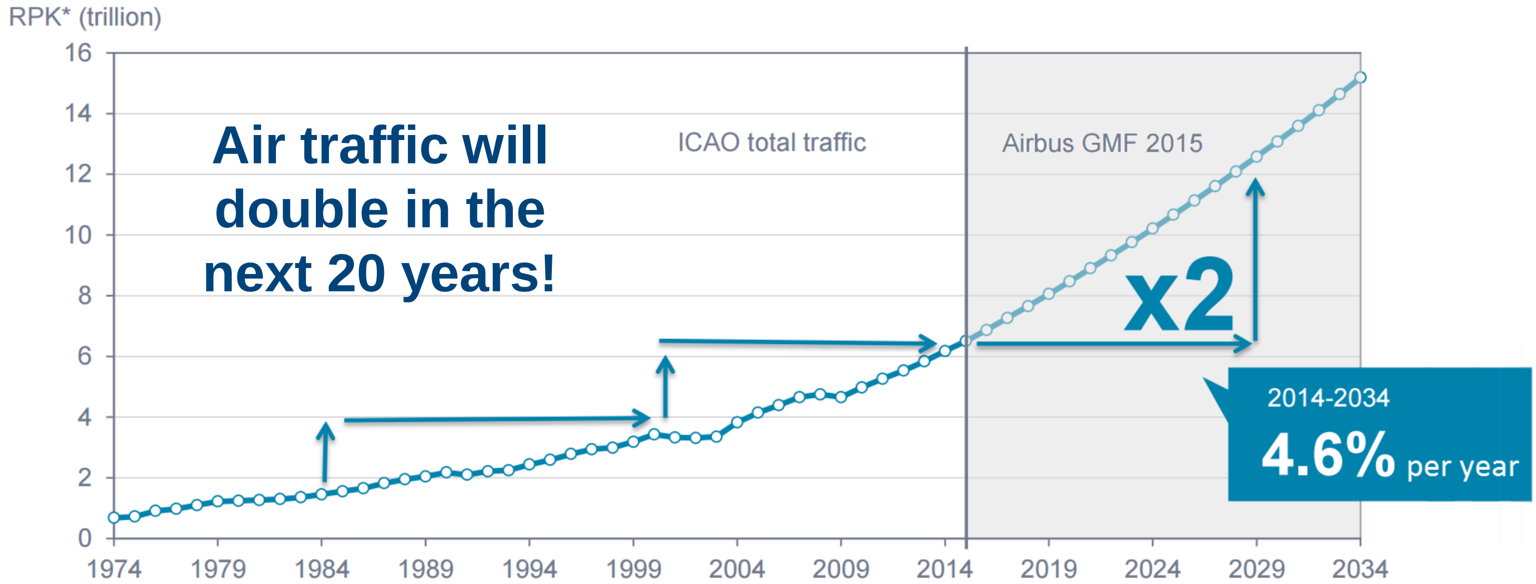


Sylvain Prigent

Approche novatrice pour la conception et l'exploitation d'avions écologiques, sous incertitudes.

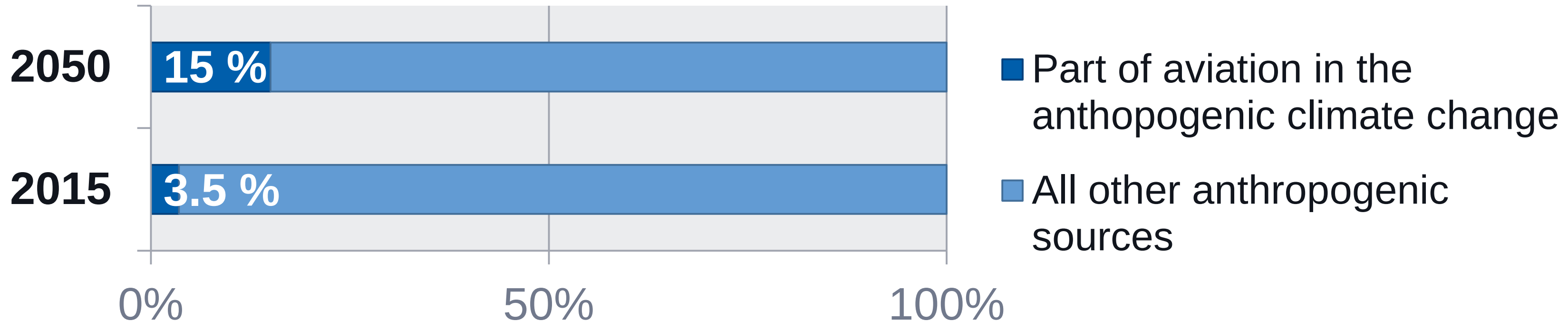
INSTITUT de MATHEMATIQUES de TOULOUSE
INSA TOULOUSE
isae SUPAERO
AIRBUS

Challenges



*Revenue passenger kilometers

(number of revenue-paying passengers aboard multiplied by the traveled distance)



- *Airbus Global Market Forecast based on the International Civil Aviation Organization numbers, 2015.*
- *J. E. Penner, **Aviation and the global atmosphere: a special report of IPC.** Cambridge University Press, 1999.*

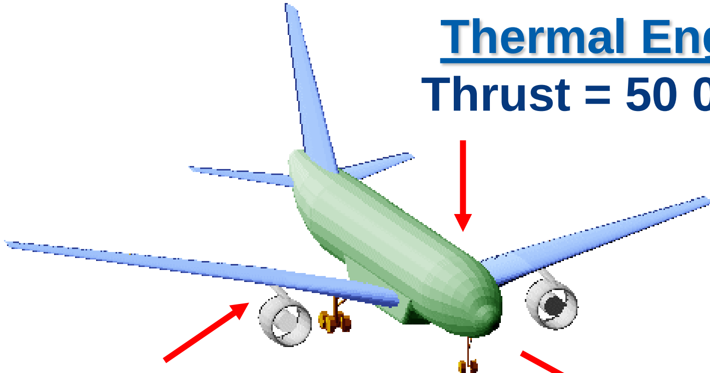
Following a promising commercialized model…

We have electric cars, What about looking for an **Electric Aircraft** ?

Aircraft and Electrical Power

Thermal Engine

Thrust = 50 000 N



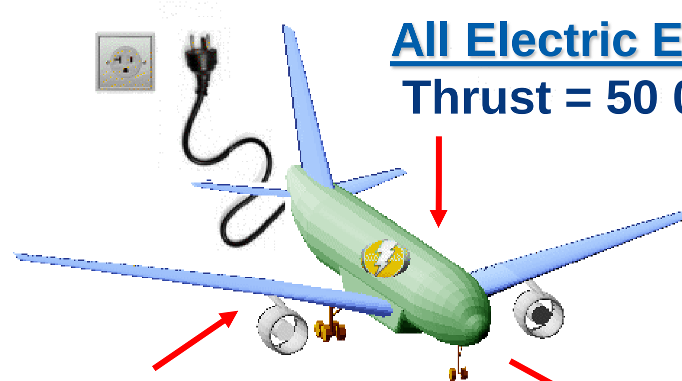
Kerosene
10 t

2015

Range
4000 km

All Electric Engine

Thrust = 50 000 N



Batteries
10 t

2015

Range
200 km

	Energy Density (MJ/kg)	
	2015	2030 (prediction)
Fuel	45 MJ/kg	45 MJ/kg
Batteries	1.3 MJ/kg	2.2 MJ/kg

Batteries
10 t

All Electric Engine
Thrust = 50 000 N

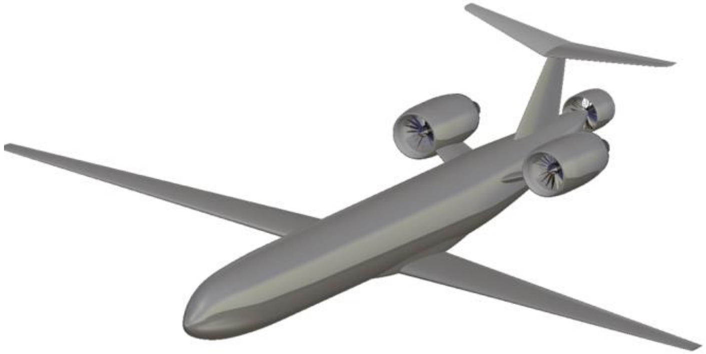
2030

Range
400 km

Try another commercialized efficient model…

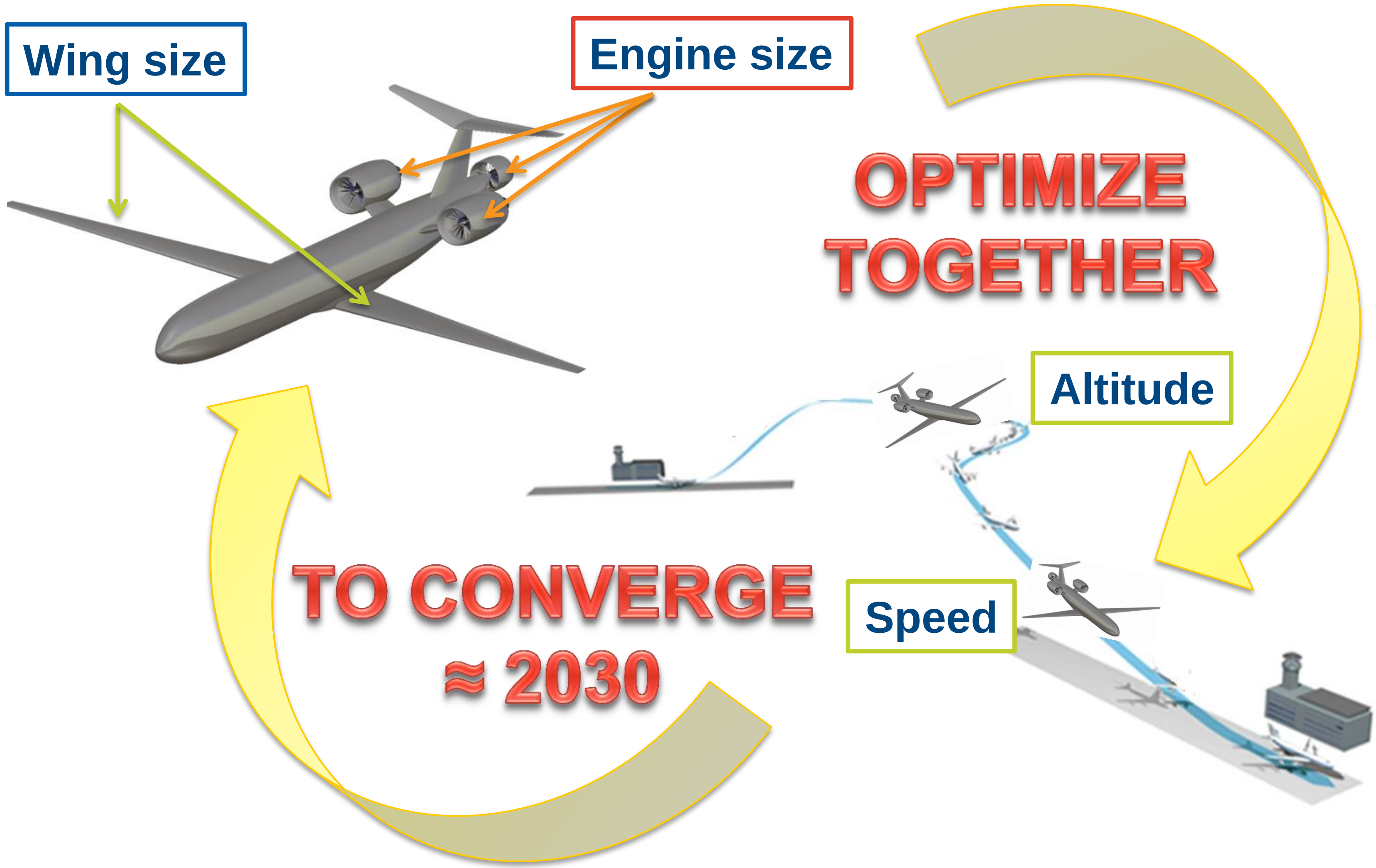
May the **Hybrid Aircraft** be a solution?

By using Electric and Thermic propulsion + Batteries

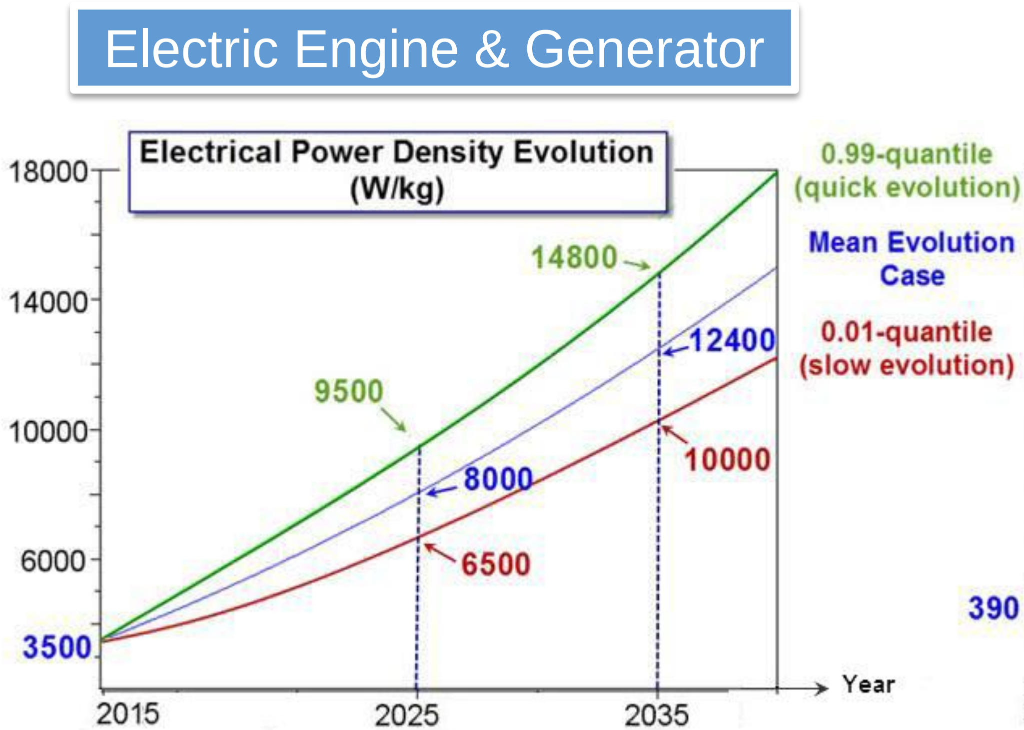


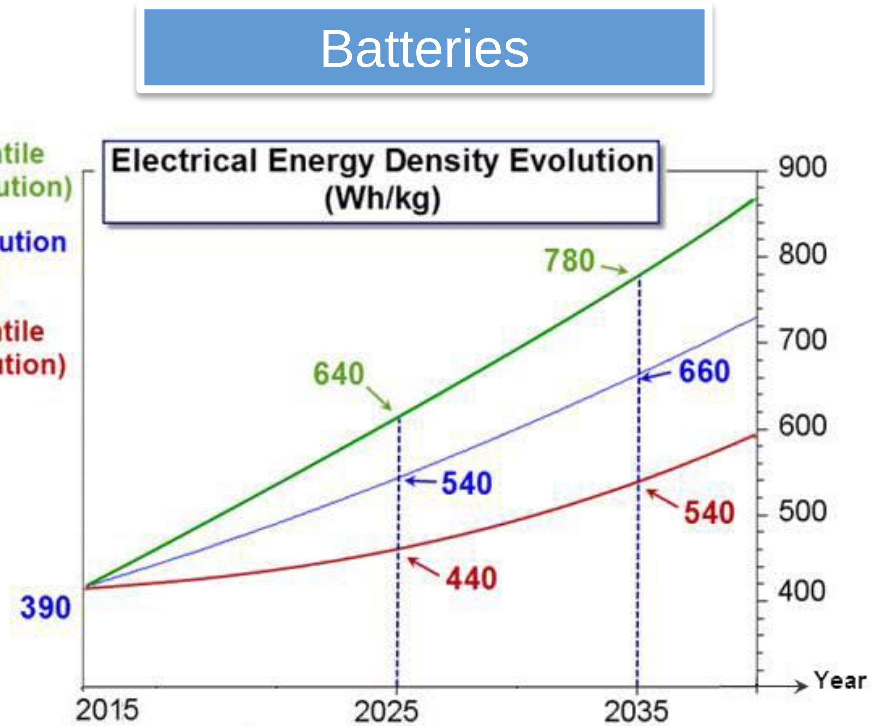
And manage the Energy !

Need of merging operations, engine and airframe



Carefulness with the uncertainty





Accounting for **uncertainty** about **technologies**,
when could fly the first **competitive hybrid aircraft**?

- *P. Simon, Storage technologies including trends for batteries and super-capacitors for power quality and energy management improvement, Airbus, 2012.*
- *J. Dahn, Electrically rechargeable metal-air batteries compared to advanced lithium-ion batteries, 2009*

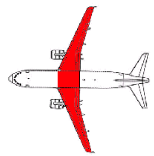
Outline

Aircraft design models

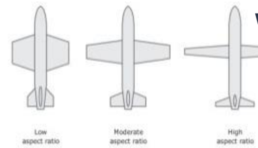
Aircraft design optimization

Conclusion & Perspectives

Classic Aircraft Design process



Wing Area

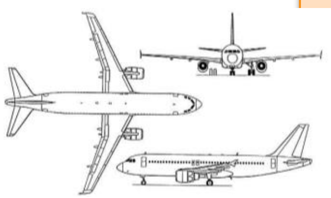


Wing Aspect Ratio

Engine size (SLSThrust)

Design Parameters

Airframe Model
Geometry
Weights
Aerodynamics



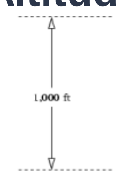
Engine Model
Geometry
Weights
Thermodynamics

TO BE OPTIMIZED

Simulation
Mission

Climb Profile

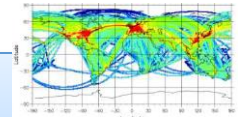
Altitude



Mach

Descent Profile

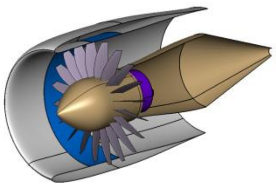
Performances
Operationnal constraints
Fiel length, Climb speed, Approach speed



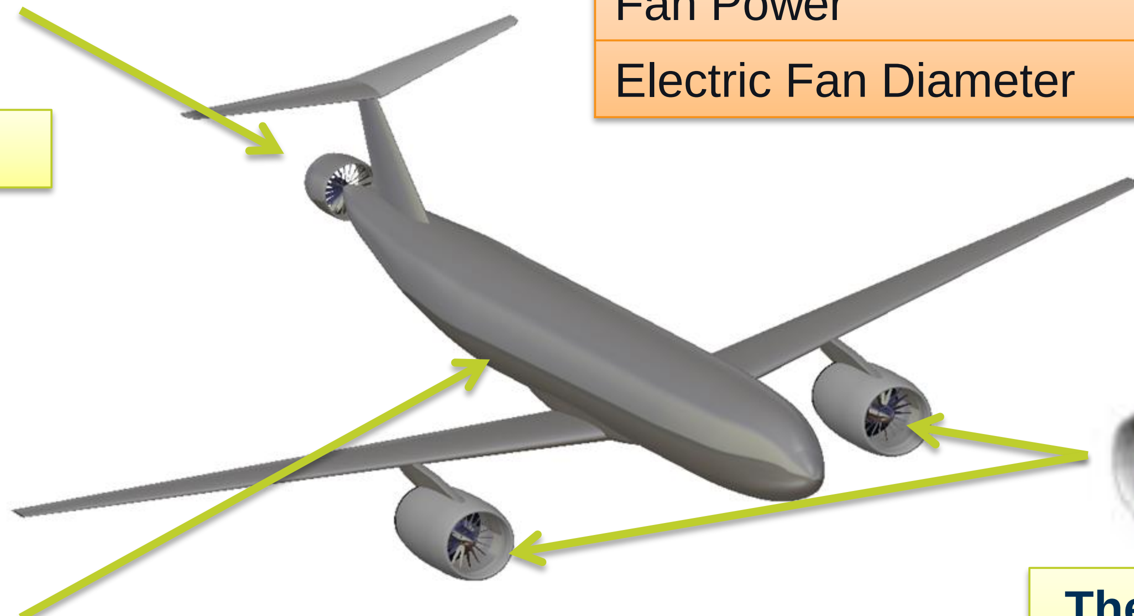
Criteria
Fuel - Cost – Weigths – Climatic Impact

Hybrid Aircraft

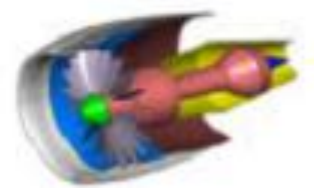
Generator Electric Ratio	[0.01 , 0.2]
Fan Power	[0.5 ,1.5] MW
Electric Fan Diameter	[0.5 , 3] m



Electric Fan



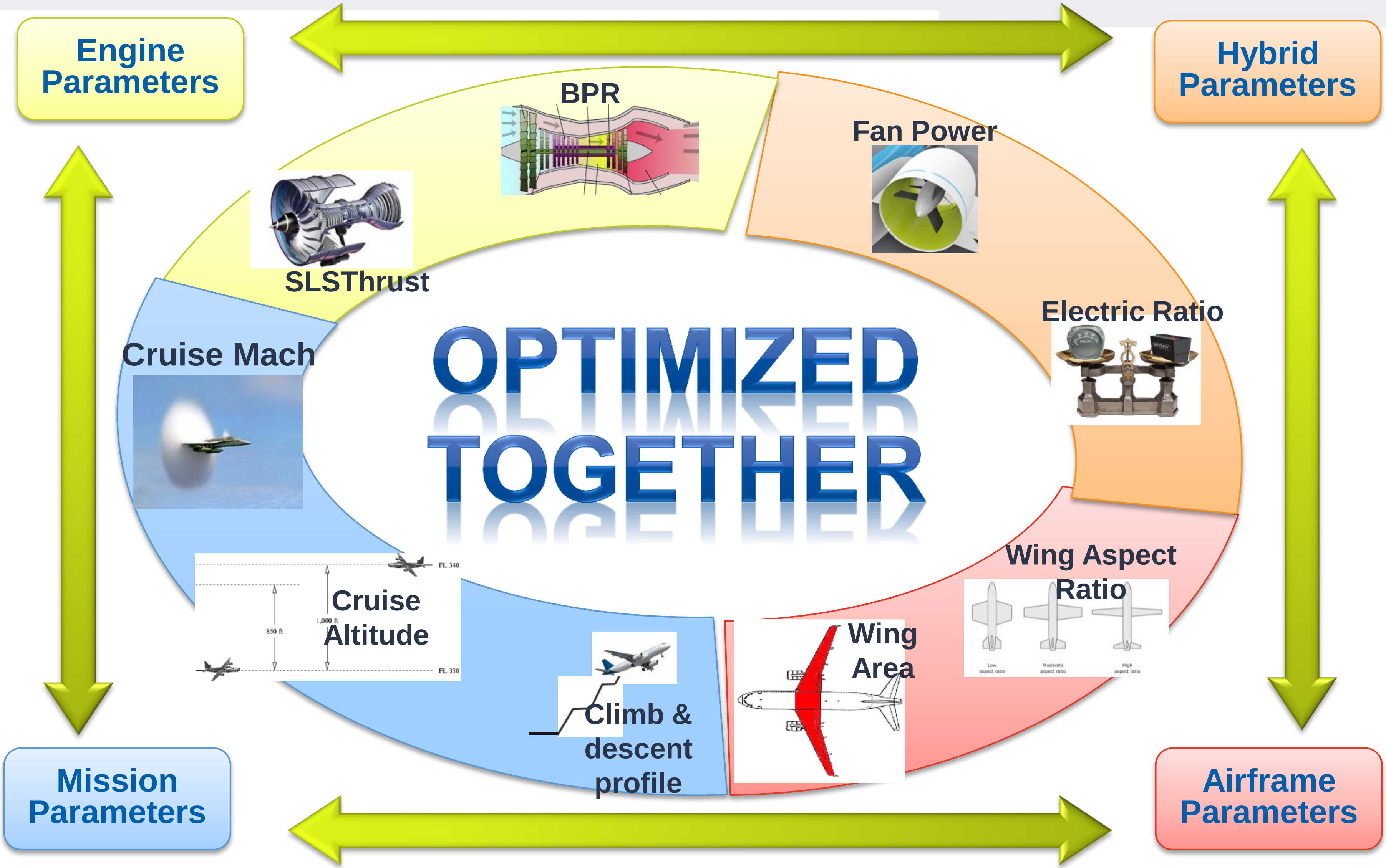
Batteries



Thermal Engine + Electric Generator

+ Improved Energy Management

The proposed aircraft design process



Outline

Aircraft design models

Aircraft design optimization

Conclusion & Perspectives

Aircraft design deterministic optimization

$$\min_{\substack{X\in\Omega \\ \Omega\subset\mathbb{R}^n}} \quad f(X),$$
$$\text{s.t.} \quad g_i(X) \le 0\ , \quad i = 1,\dots,l.$$

Criteria

Fuel, Cost , MTOW or Climate Impact (APGWP).

Performances

Take-Off Field Length (1 or 2)
Landing Speed
Climb Vertical Speed
Cruise Vertical Speed

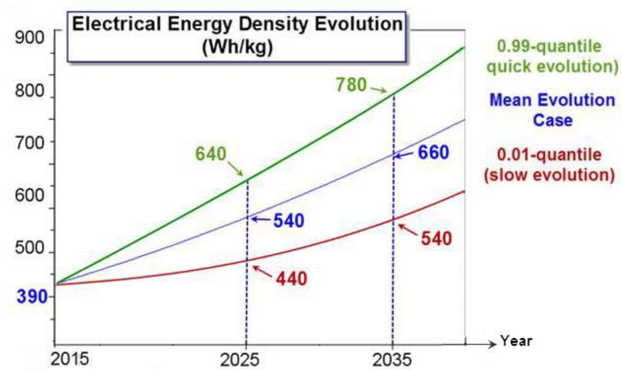
Airframe, engine and mission parameters.

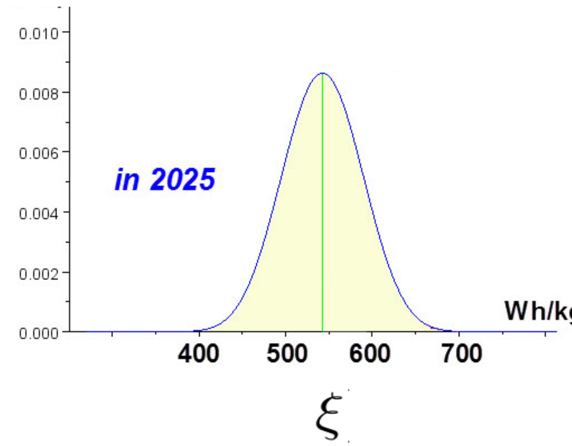
Sea Level Static Thrust
Wing Area
+
Wing Aspect Ratio
Engine By-Pass ratio
+
Cruise Altitude
Cruise Mach
+
Mission speeds (x5)
+
Hybrid (x3)

- No proof of convexity
- Differentiable almost everywhere
- With gradients (automatic differentiation)
- Few variables & constraints

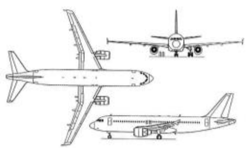
Considering two types of uncertainties

- **From prediction**

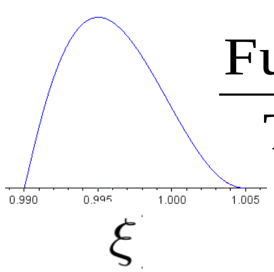




- **From modeling process**

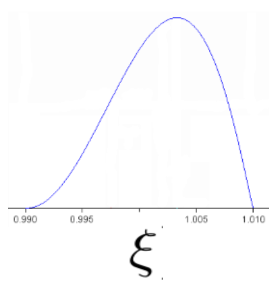


Propulsion



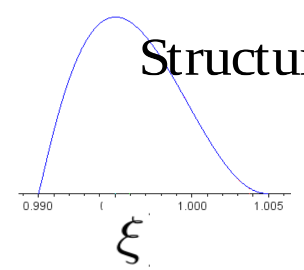
$$\frac{\text{Fuel Flow}}{\text{Thrust}}$$

Aerodynamics



$$\frac{\text{Lift}}{\text{Drag}}$$

Mass



Structural Weight

How to optimize under uncertainty

The Chance constrained optimization approach

$$\left| \begin{array}{ll} \min\limits_{\substack{X\in\Omega \\ \Omega\subset\mathbb{R}^n}} & E[f(X,\xi)], \\ \text{s.t.} & \text{Prob}\big(g_i(X,\xi)\leq 0\big) > p_i,\ p_i\in[0,1],\ i=1,\dots,l. \end{array} \right.$$

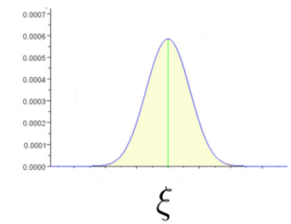
Robust optimization approach

$$\left| \begin{array}{ll} \min\limits_{\substack{X\in\Omega \\ \Omega\subset\mathbb{R}^n}} & \sup\limits_{\xi\in\mathcal{U}}[f(X,\xi)], \\ \text{s.t.} & g_i(X,\xi)\leq 0\ ,\ \forall\xi\in\mathcal{U},\ i=1,\dots,l. \end{array} \right.$$

Requires Uncertainty Quantification and Propagation

Uncertainty Quantification & Propagation

To get information on ξ .



- **By Probability distribution of uncertainty**
- **By Intervals of uncertainty** $\xi \in [\xi_{min}, \xi_{max}]$

To get information on $f(X, \xi)$ and $g_i(X, \xi)$

$f(X, \xi)$ $g_i(X, \xi)$

- Monte Carlo methods
- Stochastic Expansion methods
- Taylor Based methods
- Quadrature methods

carefulness

Required output accuracy ⇒ Available input accuracy

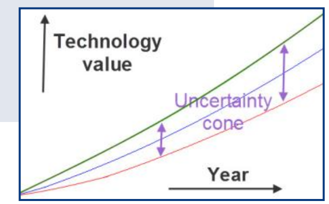
trade

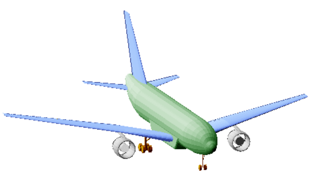
Computational cost ⇔ Required output accuracy

The application to the hybrid aircraft design

Conventional Aircraft **Deterministic** Optimization

Hybrid Aircraft **Chance Constrained** Optimization





$$\begin{cases} \min\limits_{X\in\Omega} \quad f(X), \\ s.t.\ g_i(X)\le 0, \quad i=1,\dots,l. \end{cases}$$

$$f_{conv}^{\min}$$

$$\begin{cases} \min\limits_{X\in\Omega} \quad Year \\ s.t. \begin{cases} \mathrm{Prob}(g_i(X,\xi)\le 0)\ge 0.95, \quad i=1,\dots,l, \\ \mathrm{Prob}(f(X,\xi)\le f_{\mathrm{conv}}^{\min})\ge 0.95. \end{cases} \end{cases}$$

Using a sequential chance constrained optimization method (SORA)

With the suitable uncertainty propagation method

Hybrid aircraft design Results

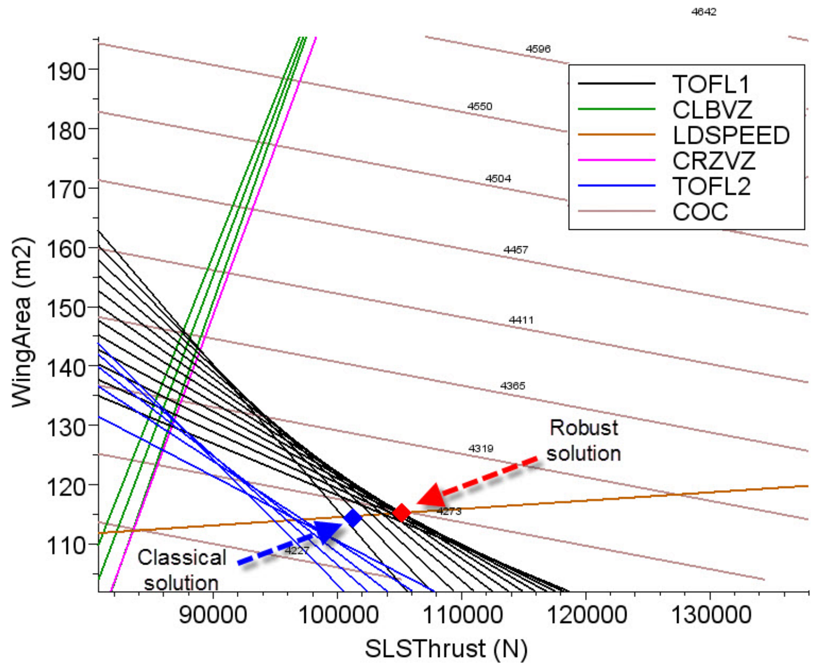
Optimized versus	Fuel (Cost Mission)		Cost (COC)		Mass (MTOW)		Climatic Impact (APGWP)	
	Conv.	Hyb.	Conv.	Hyb.	Conv.	Hyb.	Conv.	Hyb.
Year		2026		2025		2030		2020
SLSThrust (daN)	11620	11160	12260	11760	12130	11580	10950	11120
WingArea (m²)	152	152	150	154	142	148	175	175
WingAR	17	17	15	16	14	14	10	8
BPR	8	8	8	8	8	8	12,9	12,2
ZpRef (ft)	**35000**	**35000**	**35000**	**35000**	**35000**	**35000**	**31400**	**30000**
CruiseMach	**0,63**	**0,61**	**0,744**	**0,747**	**0,662**	**0,6**	**0,66**	**0,61**
eFanPower (MW)	X	1,1	X	1	X	1,2	X	1,7
ElectricRatio	X	0,01	X	0,01	X	0,016	X	0,012
Cost Mis. Fuel (kg)	**1650**	**1650**	1780	1780	1730	1730	2100	2300
MTOW (kg)	79400	78900	80650	81200	**78650**	**78650**	83900	86000
COC ($/trip)	4400	4470	**4200**	**4200**	4300	4470	4600	4920
APGWP (W/m²/km/year)	3,1^{e}-5	3,06^{e}-5	3,25^{e}-5	3,2^{e}-5	3,16^{e}-5	3,1^{e}-5	**2,77^{e}-5**	**2,77^{e}-5**
Active Constraints	TOFL	TOFL	TOFL LdSpeed	TOFL LdSpeed	TOFL	TOFL	TOFL ClbVz	TOFL

First steps towards a robust optimization approach

Robust optimization approach

$$\left|\begin{array}{ll} \min\limits_{\substack{X\in\Omega \\ \Omega\subset\mathbb{R}^n}} & \sup\limits_{\xi\in\mathcal{U}} [f(X,\xi)], \\ \text{s.t.} & g_i(X,\xi)\leq 0 \;, \forall\xi\in\mathcal{U},\; i=1,\ldots,l. \end{array}\right.$$

- 100% reliable optimum,
- Affine constraint set, and linear objective,
- Conservative approach,
- Application to the Aircraft design in 2D & 3D,
- Uncertainty from mass, aerodynamics and propulsion.



A. Ben-Tal, L. El Ghaoui, and A. Nemirovski. *Robust optimization. Princeton,* University Press, 2009.

Conclusion and perspectives

- **A new hollistic approach of the aircraft preliminary design, merging airframe, engine, regulations and trajectory.**

- **Application of this approach to the uncertain optimization of a hybrid aircraft configuration to propose a solution to the aviation climatic impact growth, taking into account uncertainty around the hybrid technology evolution**

→ *Improve hybrid aircraft synergies, apply to another innovative configuration.*

- **Writing guidelines for uncertainty propagation methods, and adapt of the chance constrained optimization method to accurately use uncertain input informations.**

→ *Automatic selection of the uncertainty propagation method, joint probability case.*

- **First steps towards a robust optimization of a conventional aircraft design.**

→ *Generalize the approach, application to component design.*

Thanks

“Anytime you have a 50-50 chance of getting something right, there's a 90% probability you'll get it wrong.”

Andy Rooney