Uncertainty Management & Quantification for Aircraft Industry

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DASSAULT-AVIATION

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Direction Générale Technique

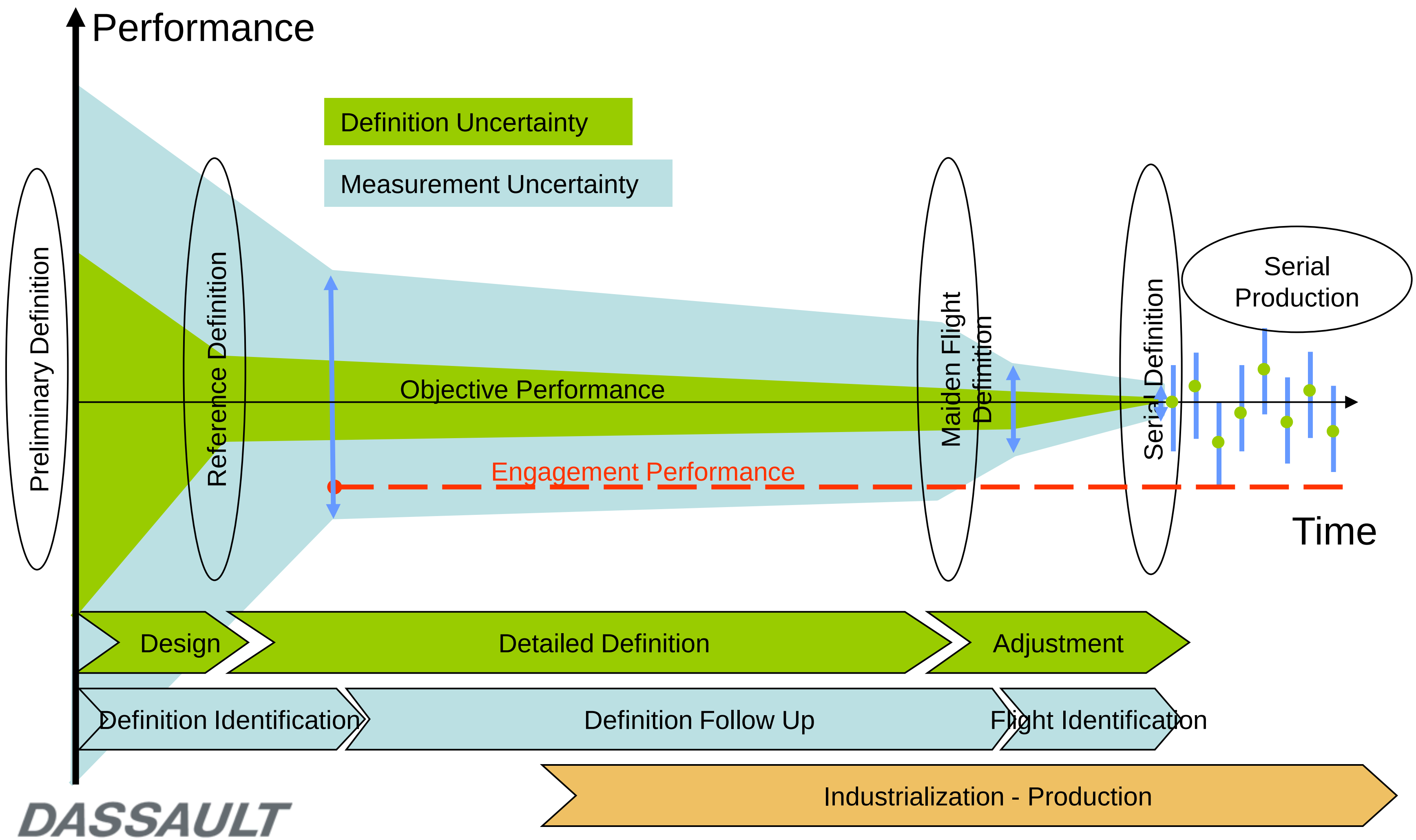
Outline

- Definition and Measurements of Uncertainties
- Uncertainty Quantification
- Design under uncertainties
- Conclusion

Aircraft Maker Point of View

- Uncertainty is an upper bound between:
  - The estimate of aircraft characteristics at a certain stage of its development
  - Characteristics of the aircraft once in service
- This Uncertainty can be the consequence of:
  - The quality of the means used during the development phase to estimate these characteristics
  - An inaccurate knowledge of the final definition of the aircraft

Uncertainties evolution

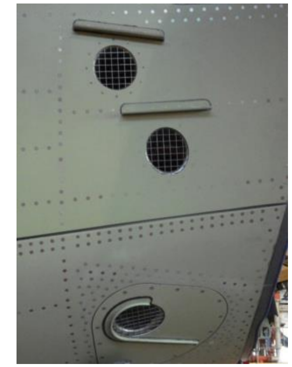


Measurements uncertainties

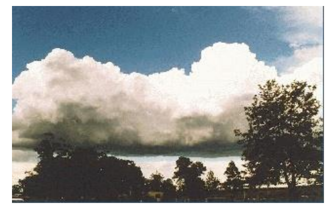
- For a given Definition, the ways to measure aerodynamic characteristics are the following:
  - Modelization, CFD (digital twin)
  - Wind Tunnel Testing
  - Flight Tests
- These ways are very different in terms of:
  - Design Cycles and Cost
  - Analysis Capacities
  - Validity Range
- Each way is associated to a degree of precision for the estimated aerodynamic characteristics, named here "Measurement Uncertainties"

CFD Uncertainties

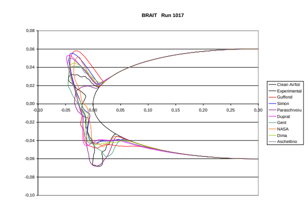
- **Geometry:**
  - Details: discontinuities, protuberances (antennas …) …
  - Permeability: engines, bleed …
  - Aeroelastic deformation, icing, …
  - Change of geometry during the lifetime of the aircraft (damage …)
  - Tolerance resulting from the manufacturing process …

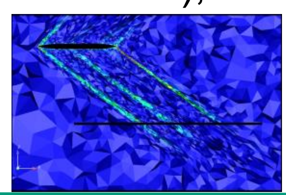


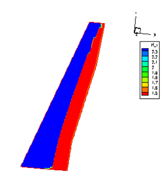
- **Atmospheric conditions- Operating conditions :**
  - Temperature, density, pressure, wind …
  - Weight of the aircraft, center of gravity …



- **Modelization**
  - Potential, Euler, Navier-Stokes, boundary layer, turbulence modeling, transition …
  - Steady / Unsteady
  - Mesh quality
  - Body or far field integration for the drag
  - Programming errors, round off (double precision …), convergence level of the iterative process (criteria …) …

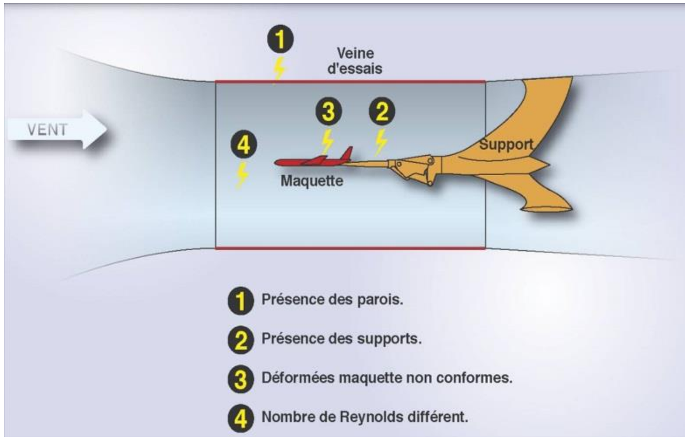




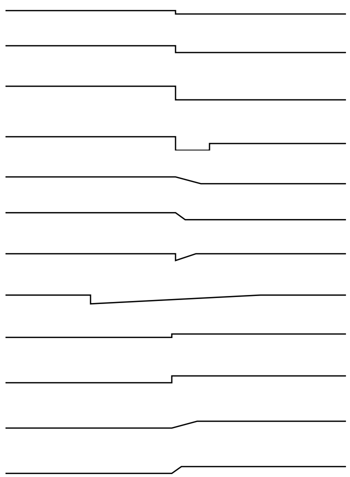


Wind Tunnel Testing Uncertainties

- Wind Tunnel effect
  - Wall (porosity …), fixing support of the mockup
  - Total pressure and temperature conditions
  - Homogeneity of the flow in the tunnel



- Mockup effect
  - Mockup scale / Reynolds number
  - Mockup representativeness
    - Details: discontinuities, roughness, protuberances …
    - Tolerance resulting from the manufacturing process
    - Boundary layer transition
    - Control surfaces positioning, mass flow ratio
    - Aeroelastic deformations

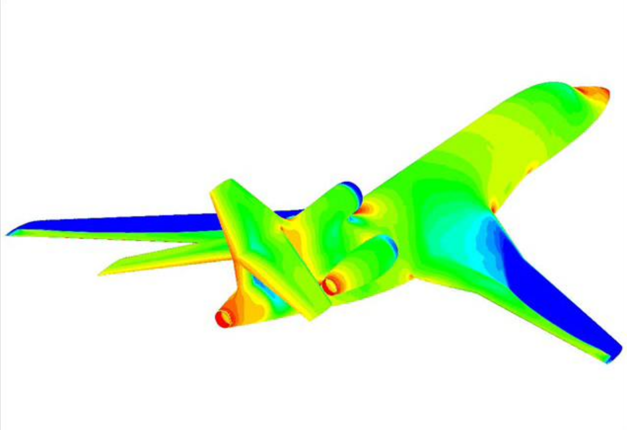


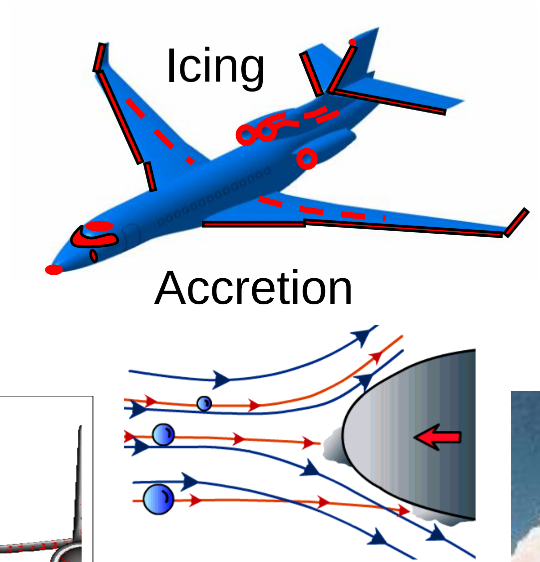
- Instrumentation and measurement post processing
  - Global or partial weighting
  - Wake measurements …

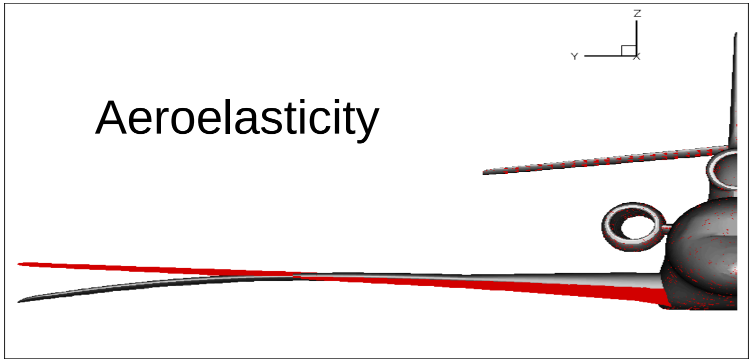
Flight test Uncertainties

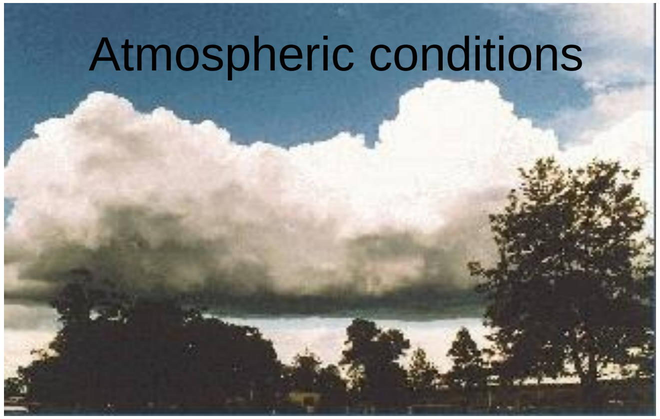
- Validity (sampling …) of the exchange rate Thrust - Fuel Consumption
- Weight of the aircraft, center of gravity, control surface positioning
- Atmospheric conditions, wind
- Aeroelastic deformation
- Measurement precision (altimeter, airspeed indicator, …)
- Differences between aircraft in service and serial definition
- Tolerance resulting from the manufacturing process …

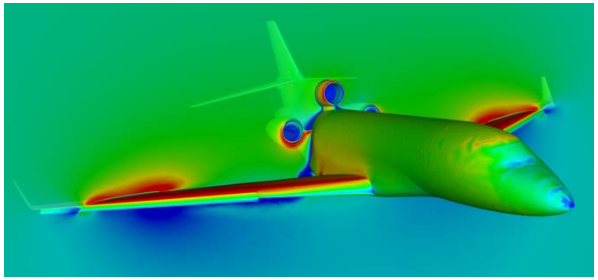
Dream … and Real Life



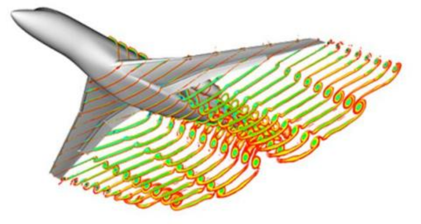




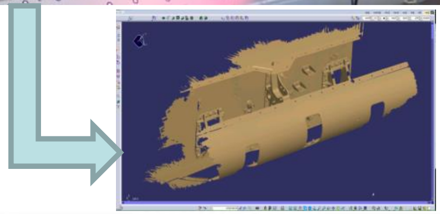


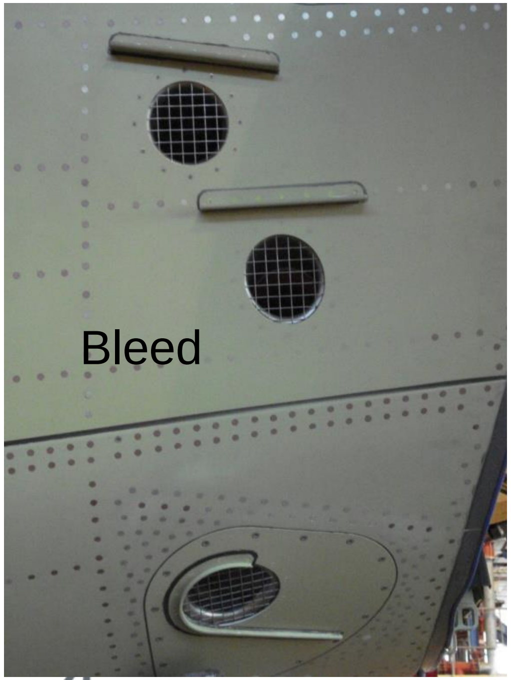


Dream … and Real Life

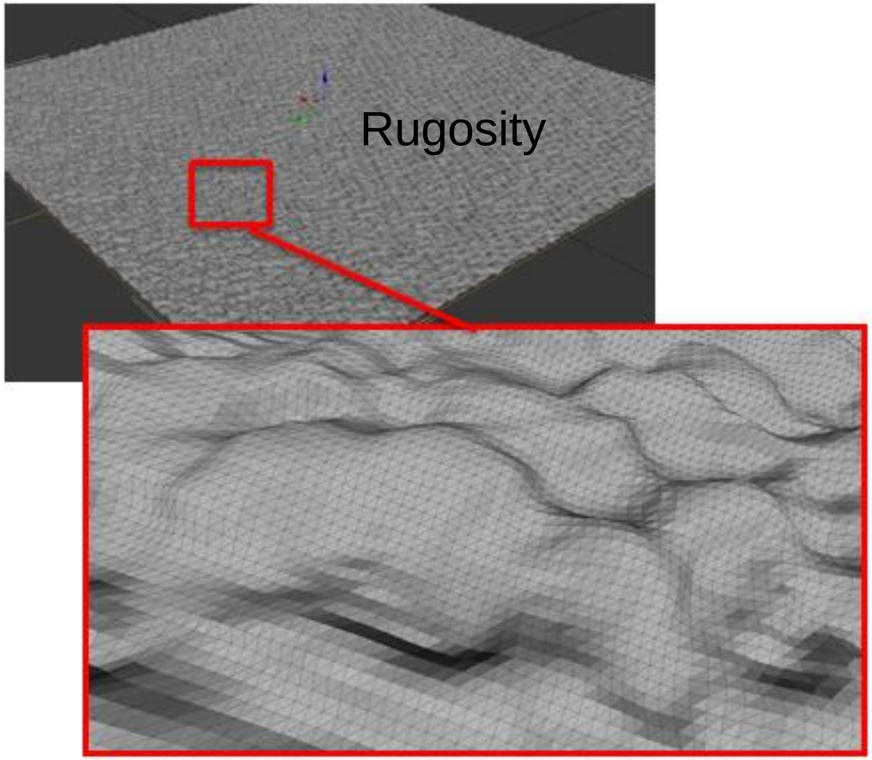


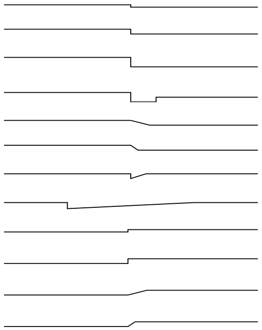
Scanner 3D

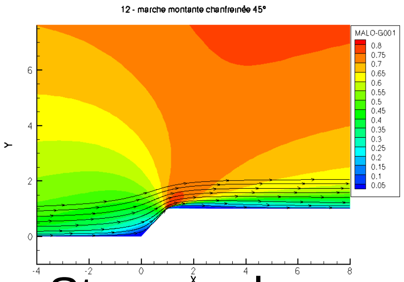




Rugosity







Steps and gaps

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- Definition and Measurements of Uncertainties
- Uncertainty Quantification
- Design under uncertainties
- Conclusion

UNCERTAINTY MANAGEMENT FOR ROBUST INDUSTRIAL DESIGN IN AERONAUTICS

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UQ and RDO Workshops 2015-2016 Falcon Jet Industrial Challenge 3 (IC-03)

Gilbert Rogé, Ximun Loyatho, Dassault Aviation

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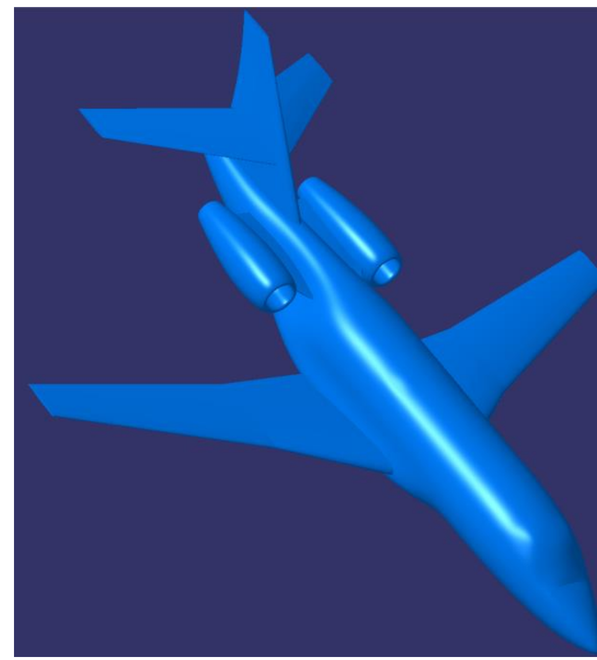
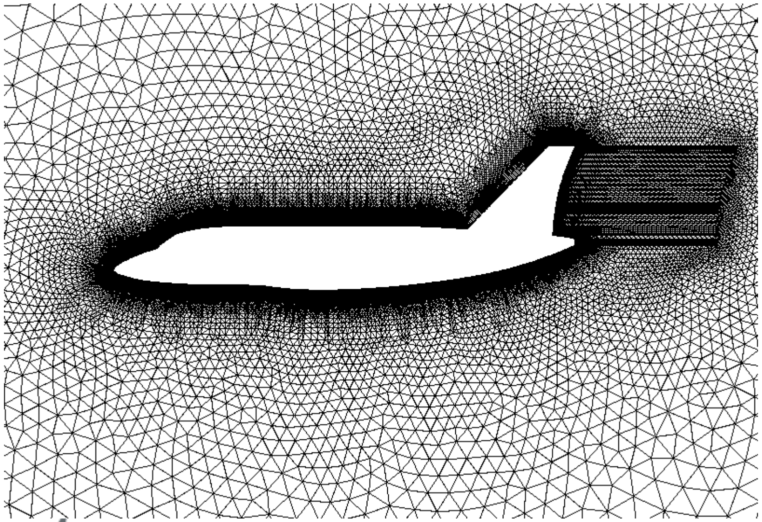
- Falcon Jet, IC-03 Test Case (Industrial Challenge)

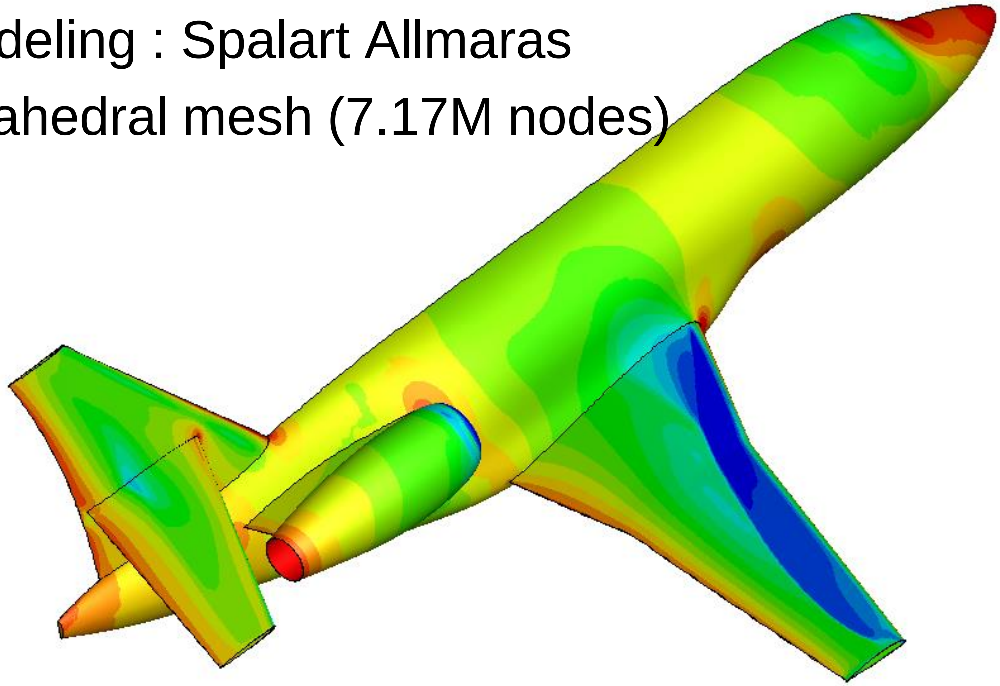
- Innovative database for UQ: Industrial relevant external flow test case. Database incorporating modelization (turbulence), numerical error (mesh), operational (aoa) and geometrical (wing spanwise twist distribution) uncertainties.



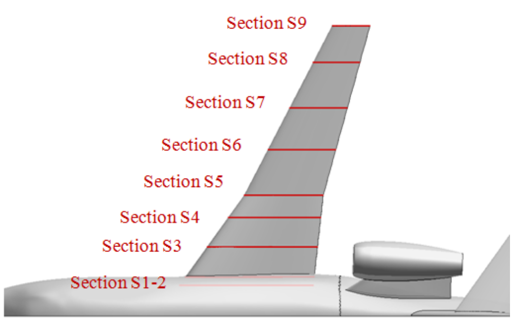
- 5 Partners:
- Alenia Aermacchi (Italy)
- INRIA (France)
- NUMECA (Belgium)
- TU Delft (Netherlands)
- Dassault Aviation (France)

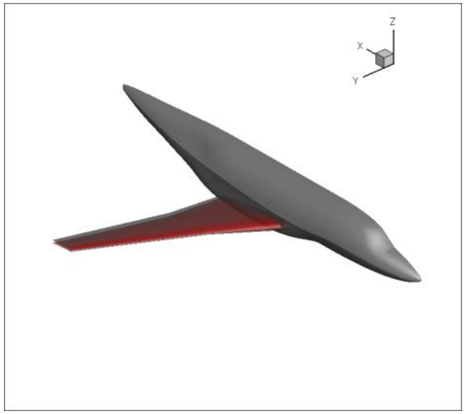
- Test case: Generic Falcon Jet
  - Mach number = 0.80
  - Angle of attack = 2 °
  - Altitude = 40000 ft
  - RANS; Turbulence modeling : Spalart Allmaras
  - FEM; unstructured tetrahedral mesh (7.17M nodes)

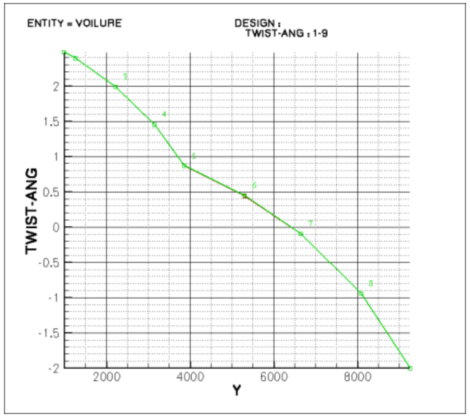




- # Uncertainties. Geometric parameters.
  - Wing spanwise twist angle distribution (x/c=0.25; rotation / control section plane)
  - 8 control sections: 0.999 y + 0.008 z = 1240.614 ; 2205.710 ; 3131.413 ; 3848.613 ; 5293.181 ; 6628.500 ; 8074.377 ; 9244.835 mm.
  - Bounded, asymmetric beta PDF distributions (Holland approach)
  - Delta twist angle min = -0.5 deg
  - Delta twist angle max = 0.2 deg
  - Most likely value for Delta twist angle = 0.01 deg







- Propagation study (for geometrical and operational uncertainties).
  - Method of Moment
  - Monte Carlo family
  - Polynomial Chaos family
  - …

Method of Moment : ***first order***

- X_{INPUT} ~ beta law → X_{OUTPUT} ~ beta law
- *mean value :* $\mu_{OUTPUT} = F(\mu_{INPUT})$
- *standard deviation :* $\sigma_{OUTPUT} = |\nabla F| \times \sigma_{INPUT}$

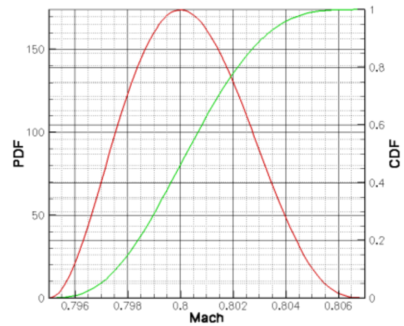
– 4 first statistical moments (mean value, standard deviation, skewness, kurtosis)
– PDF
– CDF
– Cl, Cm, CD
– Wing spanwise Cl distribution
– Cp

Quantified uncertainties : aerodynamic & geometric parameters

Beta law

Mach

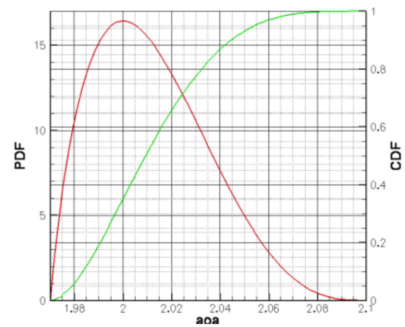
Most likely value 0.8
Min 0.795
Max 0.807



Mean value = 0.8003
Standard deviation = 0.002087
Skewness = 0.1509
Shape parameter P = 3.143
Shape parameter Q = 4.000

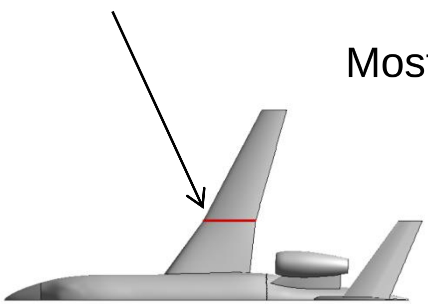
Angle of attack

Most likely value 2
Min 1,97
Max 2,1

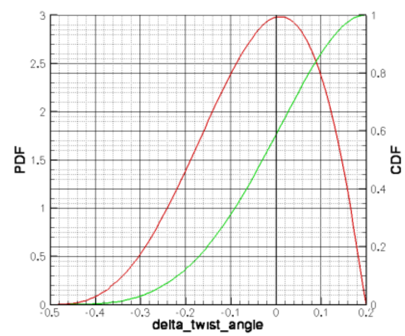


Mean value = 2.012
Standard deviation = 0.02312
Skewness = 0.5066
Shape parameter P = 1.900
Shape parameter Q = 4.000

Delta twist angle



Most likely value 0,01
Min -0,5
Max 0,2

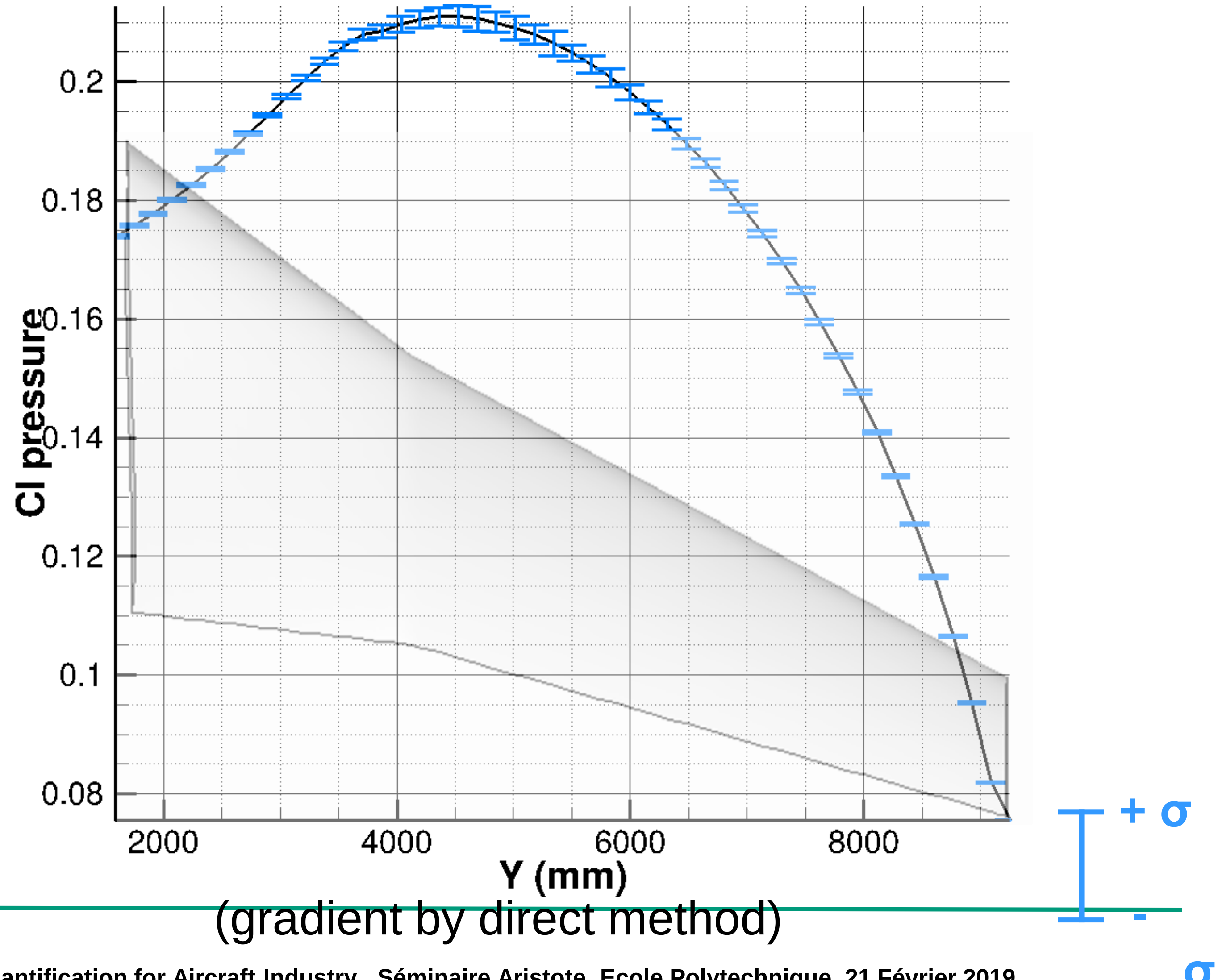


Mean value = -0.04231
Standard deviation = 0.1248
Skewness = -0.4251
Shape parameter P = 4.000
Shape parameter Q = 2.118

- ***Twist angle* uncertainty propagation : *Cl pressure distribution***

Case : Spalart Allmaras turbulence modeling, MESH 1

Cl wing = 0.349 / 2

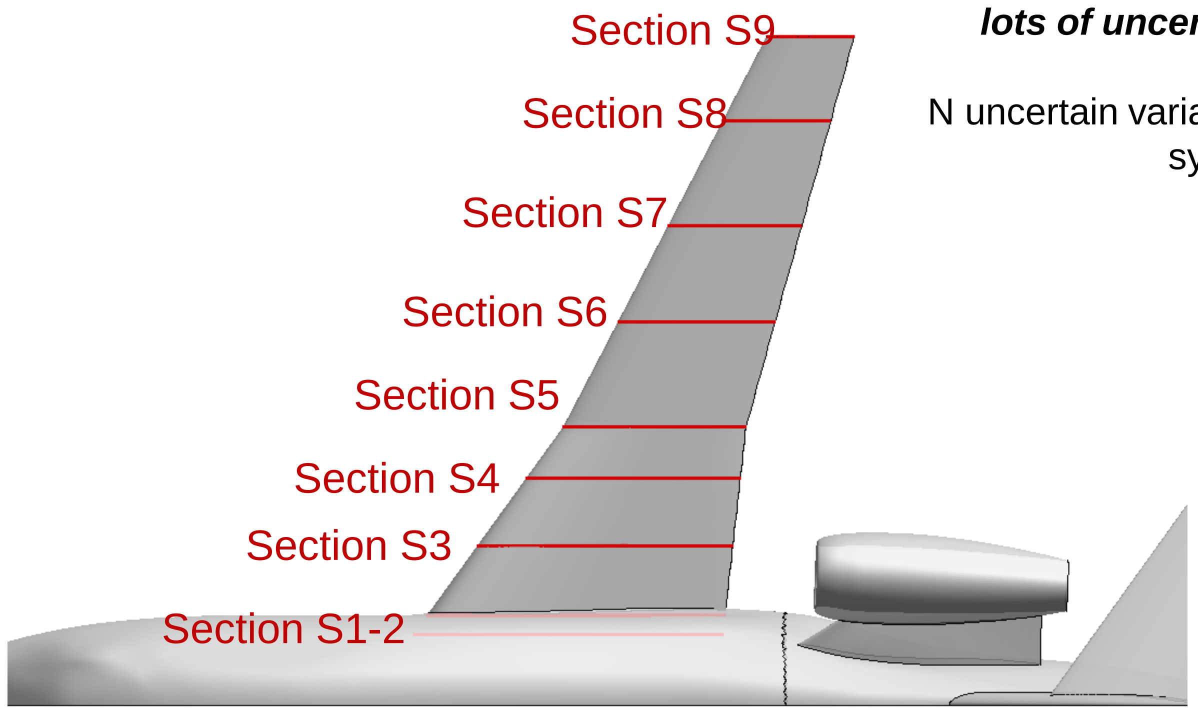


(gradient by direct method)

- **Several uncertain variables …**

Method of Moment :
allows to deal with lots of uncertain variables

N uncertain variables → N linear systems



Method of Moment : ***first order*** *with N independent inputs*

X^i_{INPUT} ~ beta law → X_{OUTPUT} ~ beta law

$X_{OUTPUT} = F(X^1_{INPUT}, \ldots, X^N_{INPUT})$

mean value : $\mu_{OUTPUT} = F(\mu^1_{INPUT}, \ldots, \mu^N_{INPUT})$

standard deviation : $\sigma_{OUTPUT} = \sqrt{\sum_i^N (\nabla_{X^i} F)^2 \times (\sigma^i_{INPUT})^2}$

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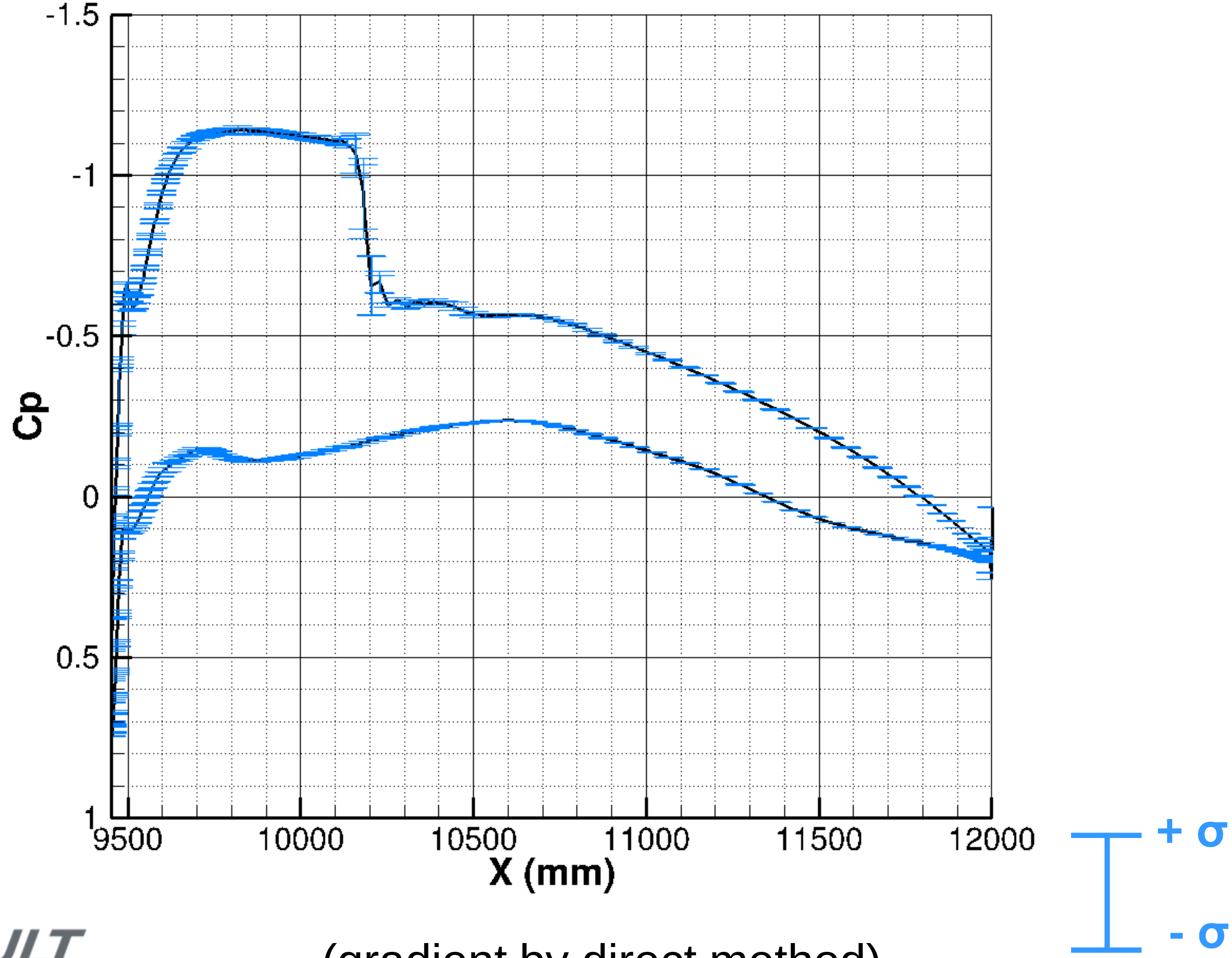
- ***8 twist angle* uncertainties propagation**

Case : Spalart Allmaras turbulence modeling, MESH 1

Section 5



(gradient by direct method)

Outline

- Definition and Measurements of Uncertainties
- Uncertainty Quantification
- Design under uncertainties
- Conclusion

RDM

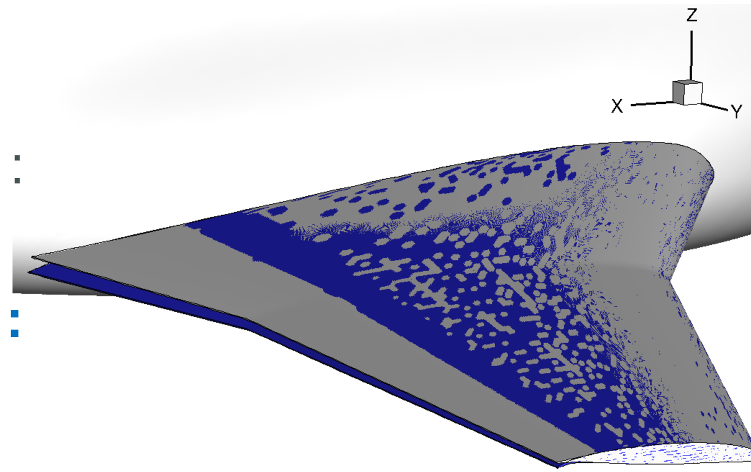
- Robust Design: find a design insensitive to small changes of uncertainties
- Reliability-Based Design: seek a design with a probability of failure less than an acceptable value

Optimization & uncertainties

Two kinds of geometrical variables :

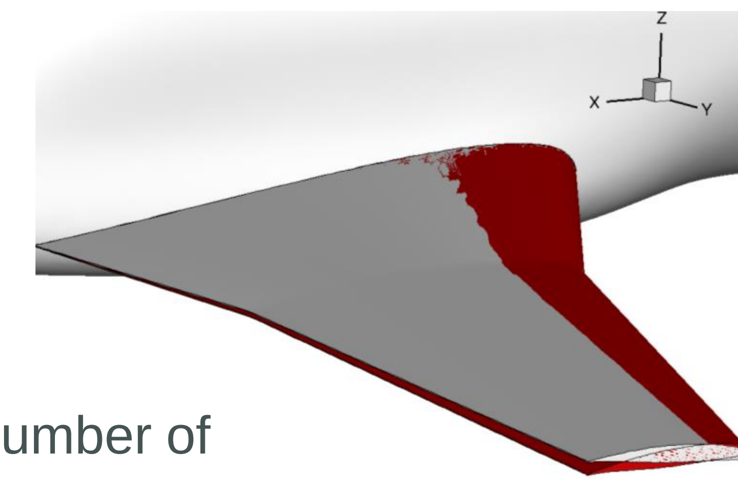
- Optimization variables for design conception :
  e.g. wing trailing edge **camber** angle

camber = -15° :



- Uncertainties variables :
  e.g. wing tip **twist** angle

twist = +5° :



Adjoint method → complexity **independant** of number of variables

Deterministic optimization

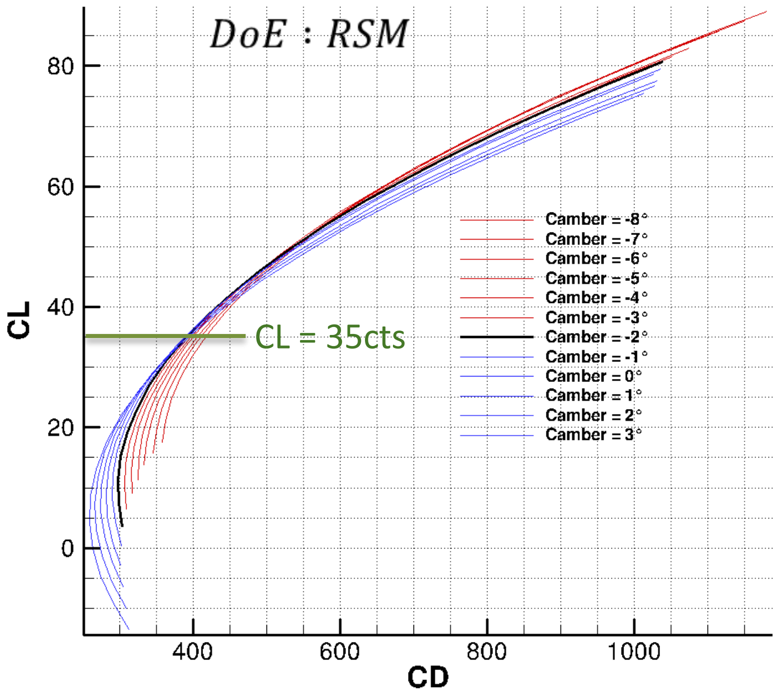
Deterministic optimisation :

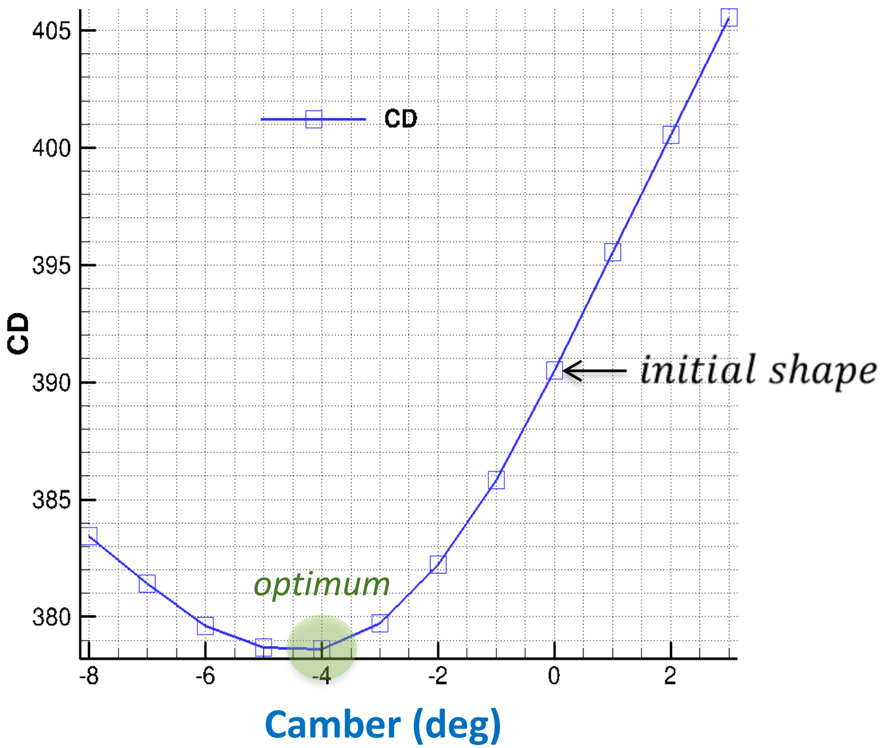
$$\min CD$$

Variables : AoA, $Camber$

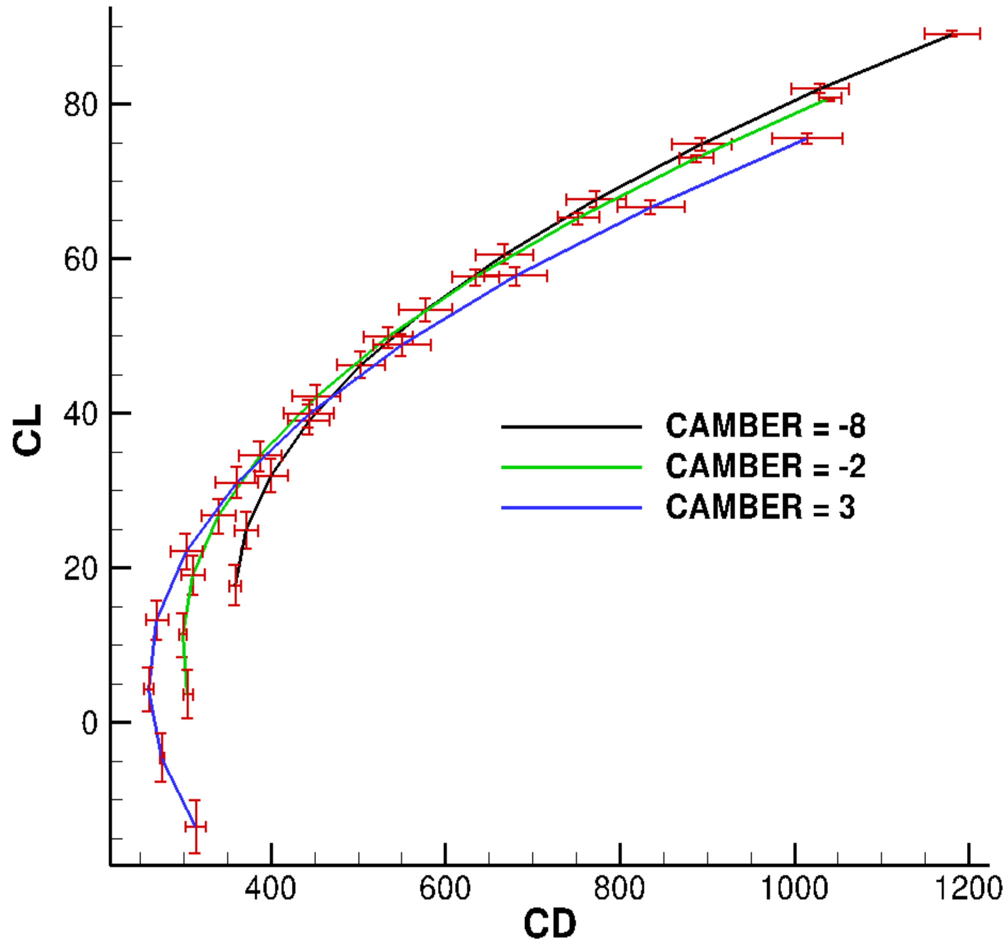
Constraint :

$$CL = 35 \text{ cts}$$





Uncertainty quantification



Uncertain variable=twist angle

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Optimization & uncertainties

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σ constraint optimisation :

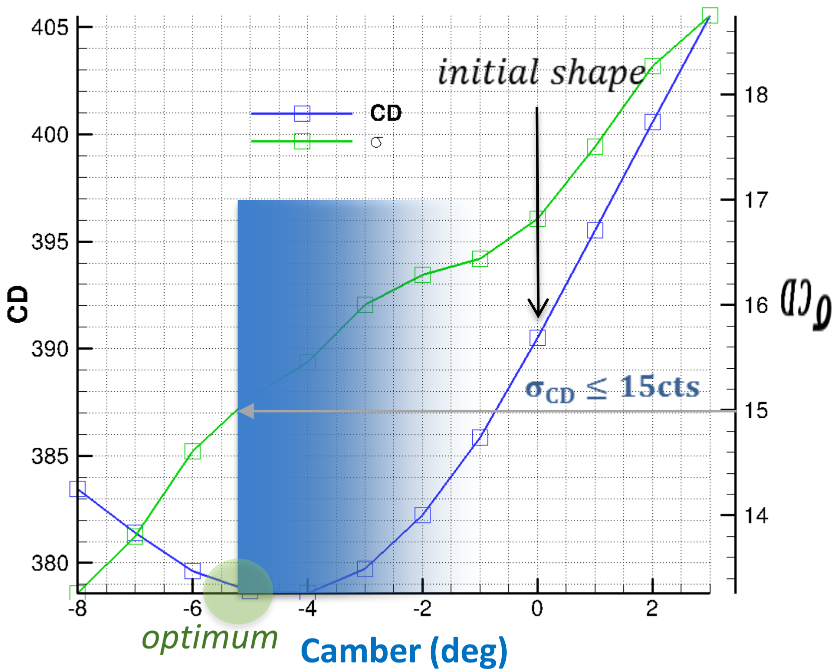
$$\min \mu_{CD}$$

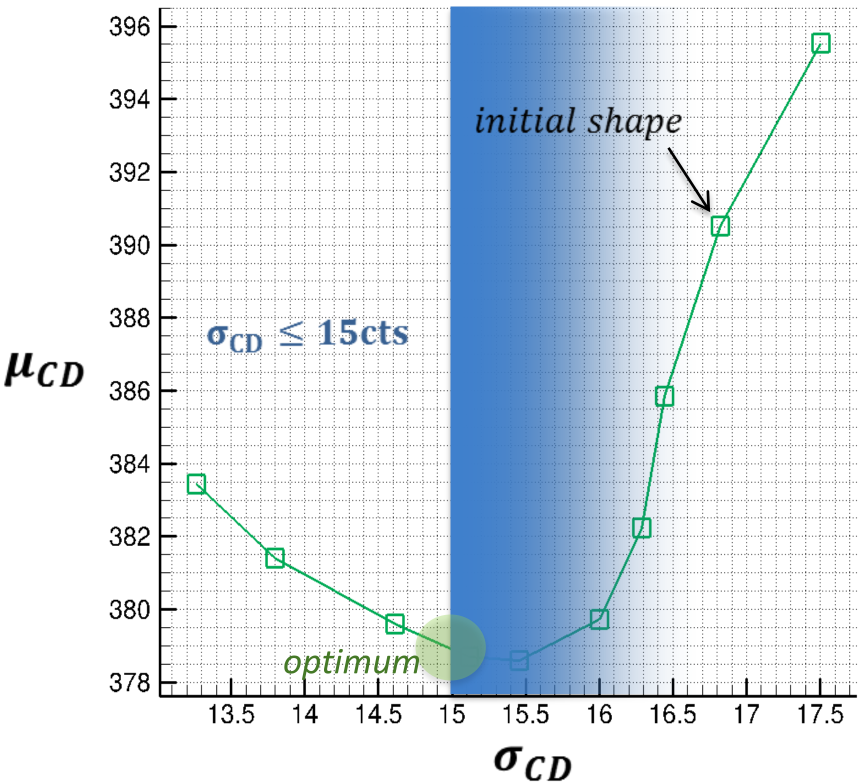
Variables : AoA, **Camber**

Constraints :

$$CL = 35\ cts$$

$$\sigma_{CD} \leq 15\ cts$$





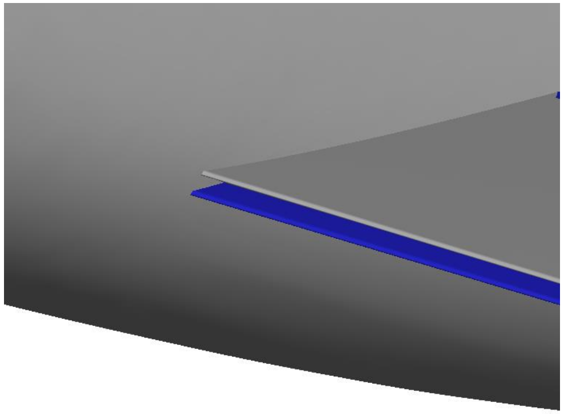
Optimization & uncertainties

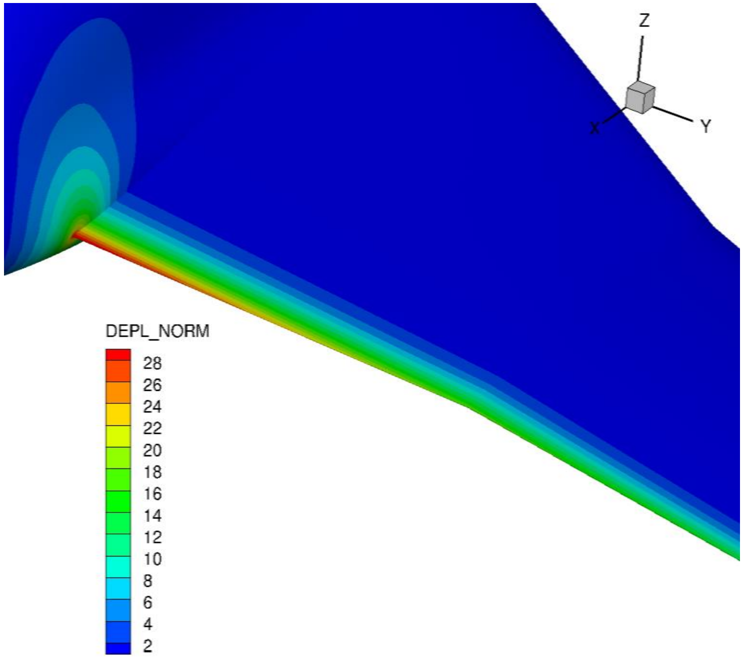
σ constraint optimum :

camber = -5.2°

min CD = 379.0 cts

→ Gain : 11.5 cts





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Optimization & uncertainties

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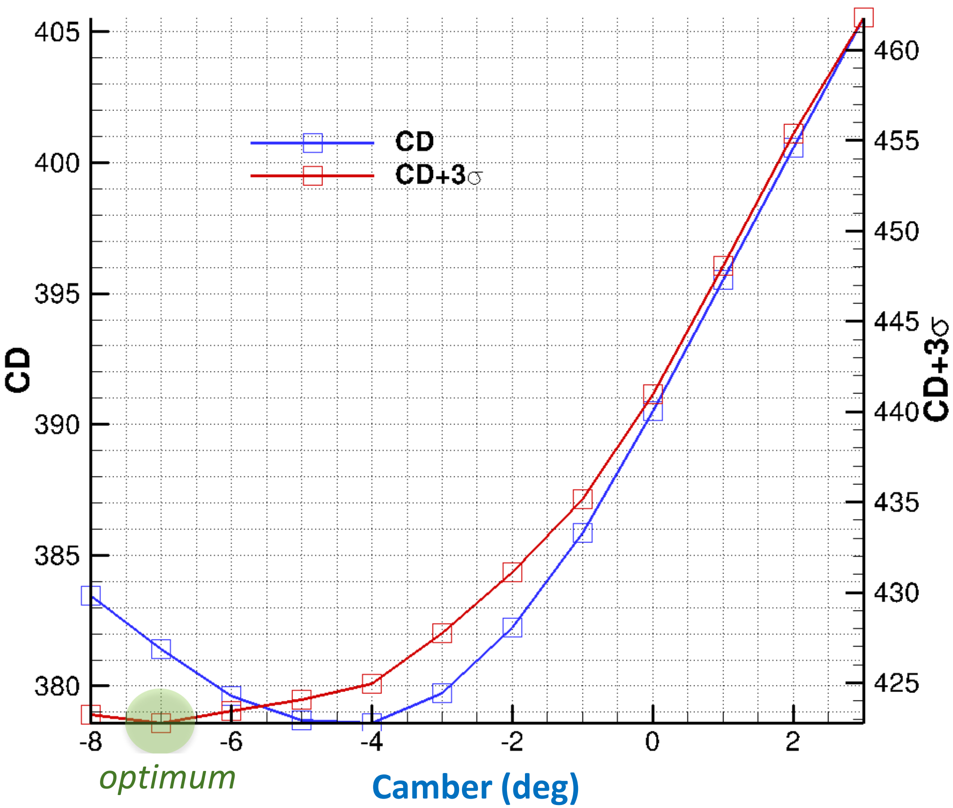
MinMax optimisation :

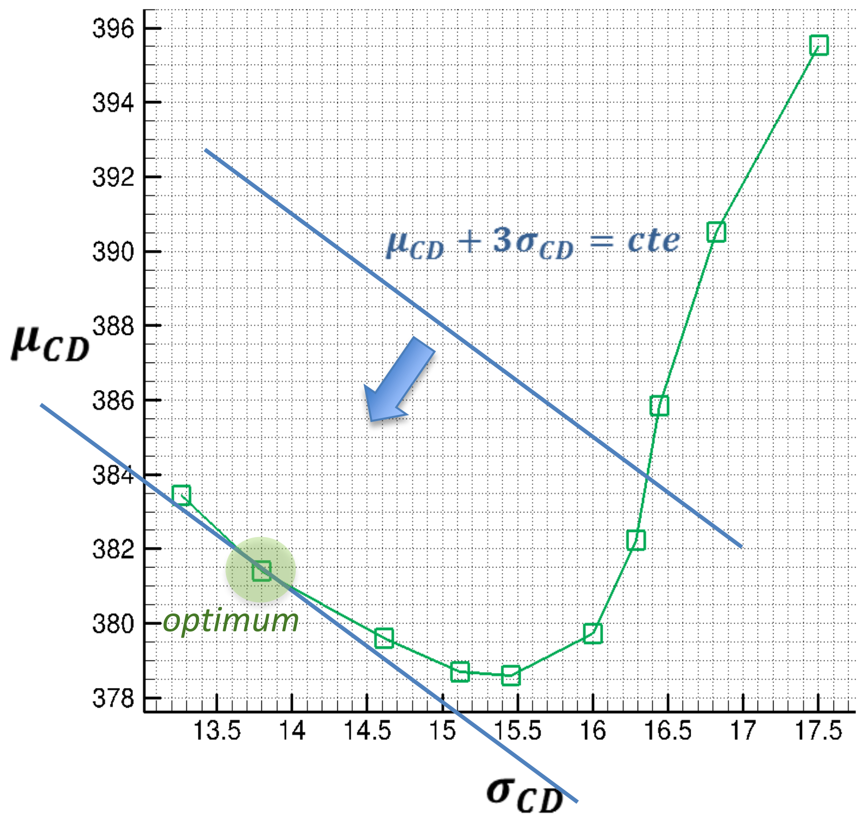
$$\min \mu_{CD} + 3\sigma_{CD}$$

Variables : AoA, $Camber$

Constraint :

$$CL = 35\ cts$$





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Optimization & uncertainties

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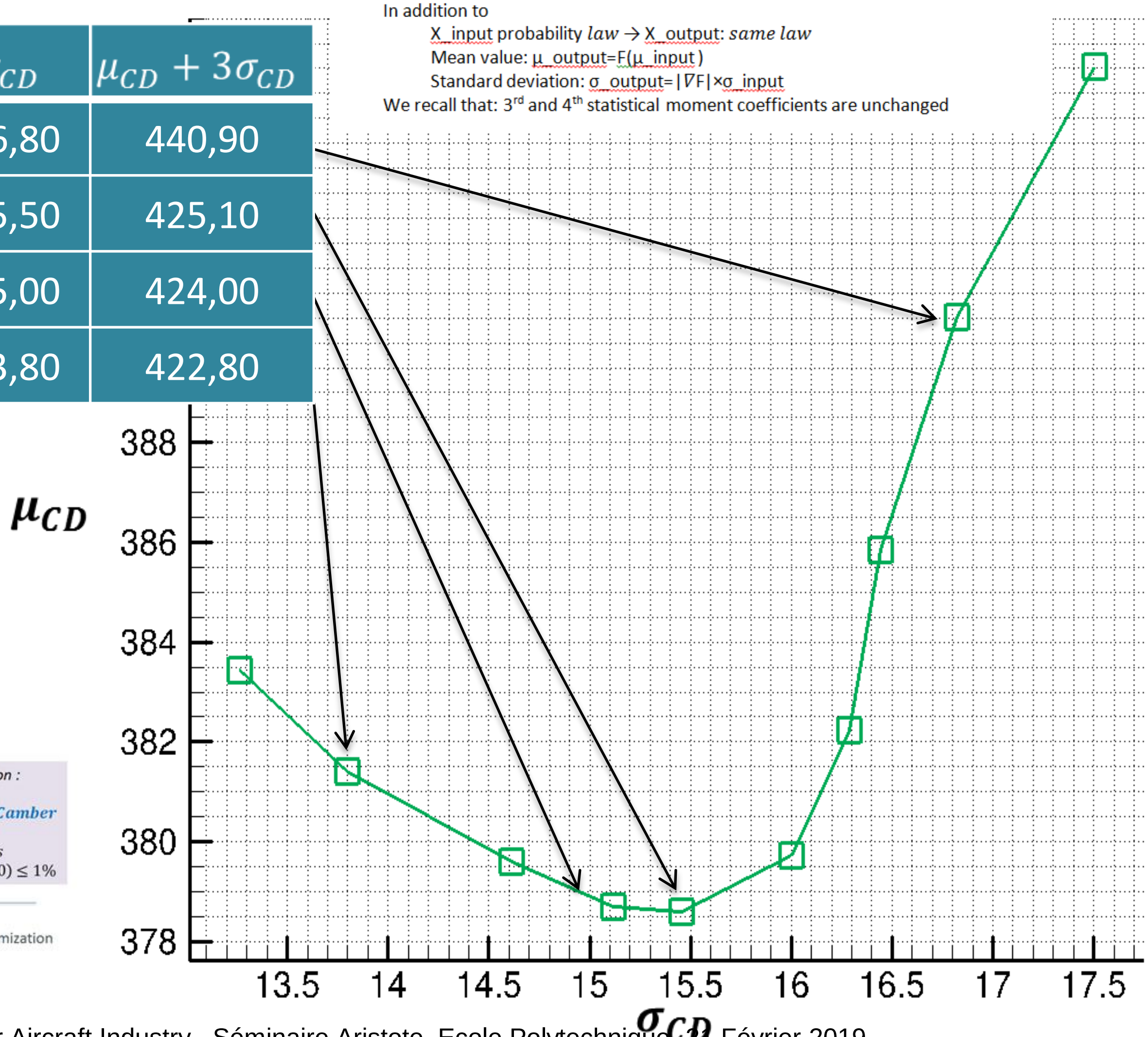
Remark: According to MoM order 1 methodology and Pearson approach, for the same price as σ constraint optimization, we are in position to solve Reliability Optimization.

In addition to
- X_input probability *law* → X_output: *same law*
- Mean value: μ_output=F(μ_input)
- Standard deviation: σ_output=|∇F|×σ_input

We recall that: 3rd and 4th statistical moment coefficients are unchanged

	Camber	μ_{CD}	σ_{CD}	$\mu_{CD} + 3\sigma_{CD}$
Initial shape	0,0°	390,50	16,80	440,90
Determ opt	-4,0°	378,60	15,50	425,10
σ opt	-5,2°	379,00	15,00	424,00
MinMax opt	-7,0°	381,40	13,80	422,80



σ constraint optimization :
$\min \mu_{CD}$
Variables : AoA, $Camber$
Constraints :
$CL = 35\ cts$
$\sigma_{CD} \leq 15\ cts$

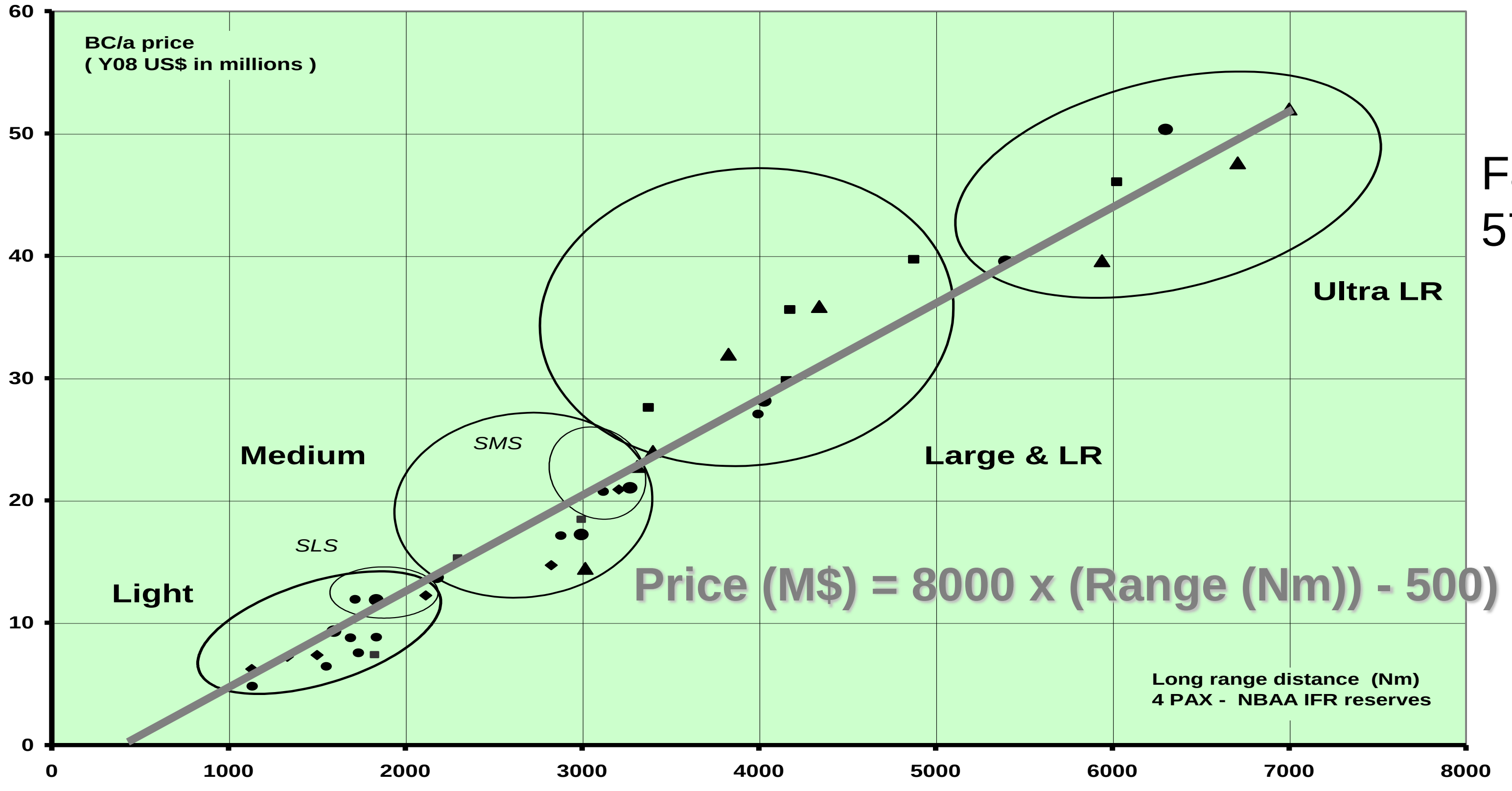
MinMax optimization :
$\min \mu_{CD}+3\sigma_{CD}$
Variables : AoA, $Camber$
Constraint :
$CL = 35\ cts$

Probability optimization :
$\min \mu_{CD}$
Variables : AoA, $Camber$
Constraints :
$CL = 35\ cts$
$P(CD \geq 380) \leq 1\%$

Robust design optimization

Reliability design optimization

Price of Uncertainties

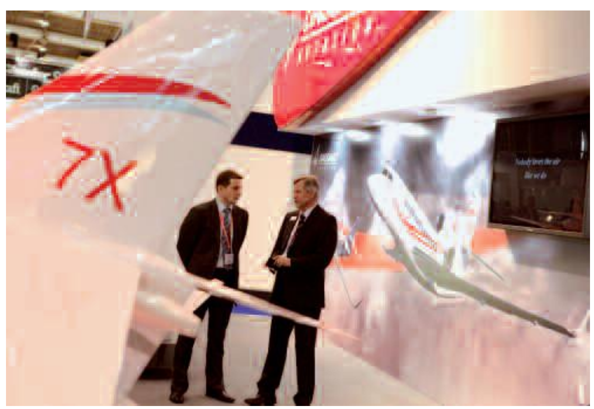


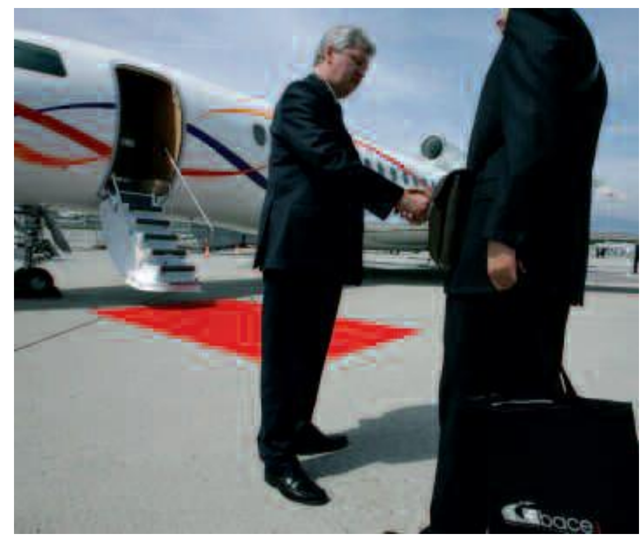
Falcon F7X
5700 Nm

- ΔRange of 2 to 3% ~ around 1M$/aircraft sailed
- ΔConsumption of 2% ~ fuel cost 0.5 to 1M$ during aircraft lifetime

Conclusion

- Evaluation of uncertainties associated to each Measurement should be the result of a detailed and justified methodology
- Treatment of uncertainties enables a rigorous management of Performance Engagements and associated Risks






Q&A