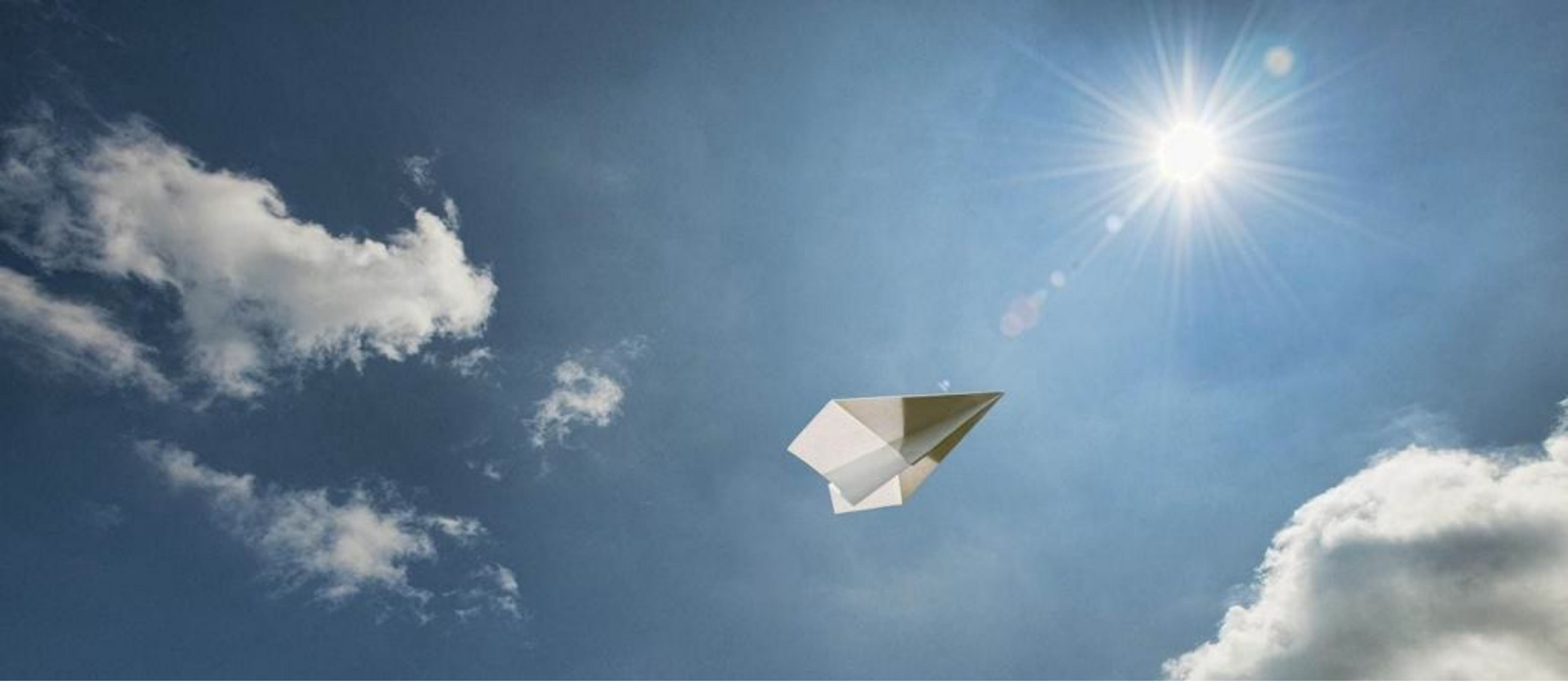

Optimization in industrial contexts in a nutshell !!!

SMAI MODE, March 2016

Airbus Group Innovations, Applied Mathematics & Simulation department
Presented by *Fabien MANGEANT*
Prepared with Vassili SRITHAMMAVANH, Régis LEBRUN, Lionel FINE, Matthieu MEAUX, Nabil RACHDI

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Key Challenges to make Numerical Optimization an Industrial Success at Global Company Level

Outline

- « DIGITALIZATION » applied in aeronautics
- « INNOVATION » at stake and link with numerical optimization activities
- « RESEARCH »: Focus on a research activities
- « FUTURE »: Perspectives

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1. **3 Divisions & Corporate targets to align**
2. **Size, time-to-market, competitors**

Airbus Group Management structure

Airbus Group Innovations is part of Chief Technical Officer Organization

Denis Ranque — *Chairman of the Board of Directors (BoD)*

Tom Enders — *Chief Executive Officer (CEO)*

Chief Financial Officer	Chief Strategy & Marketing Officer	Chief Technical Officer	CEO Airbus Group Inc.	Chief Human Resources Officer
Harald Wilhelm	Marwan Lahoud	Jean J. Botti	Allan McArtor	Thierry Baril

Airbus

Fabrice Brégier (CEO)

Airbus Helicopters

Guillaume Faury (CEO)

Airbus Defence and Space

Bernhard Gerwert (CEO)

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1

General Trends around classical industrial activities
=
Digitalization

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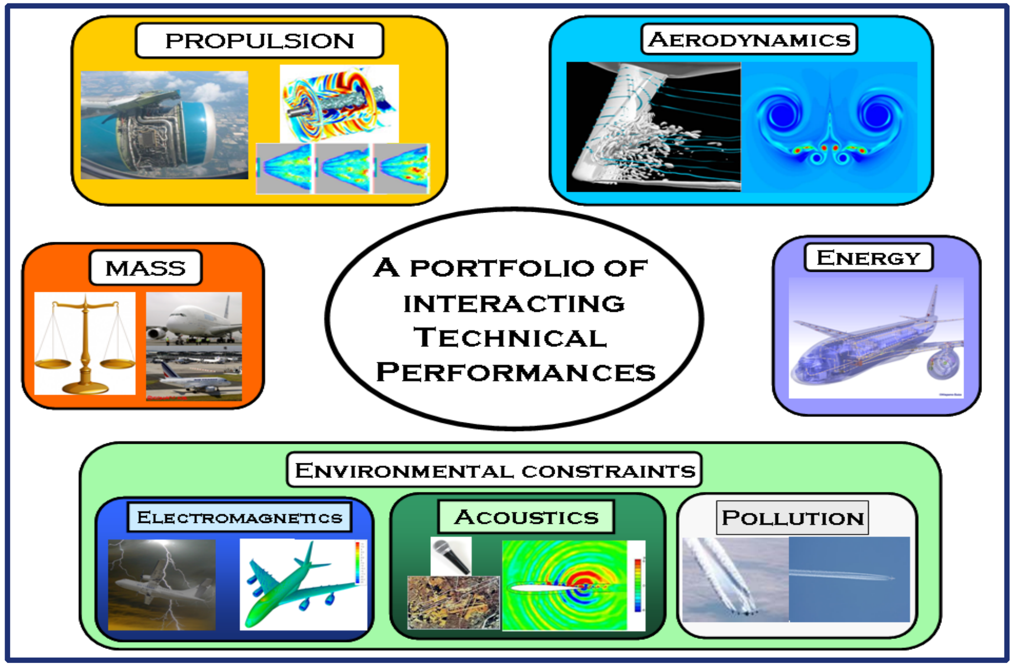
CURRENT ASSETS & PRODUCT PORTFOLIO

Flying platforms governed by **complicated physical** laws

« Pure » **physical** behaviors **interacting** with **Systems & Software**

Delivered through **complex** supply-chain **organisations**



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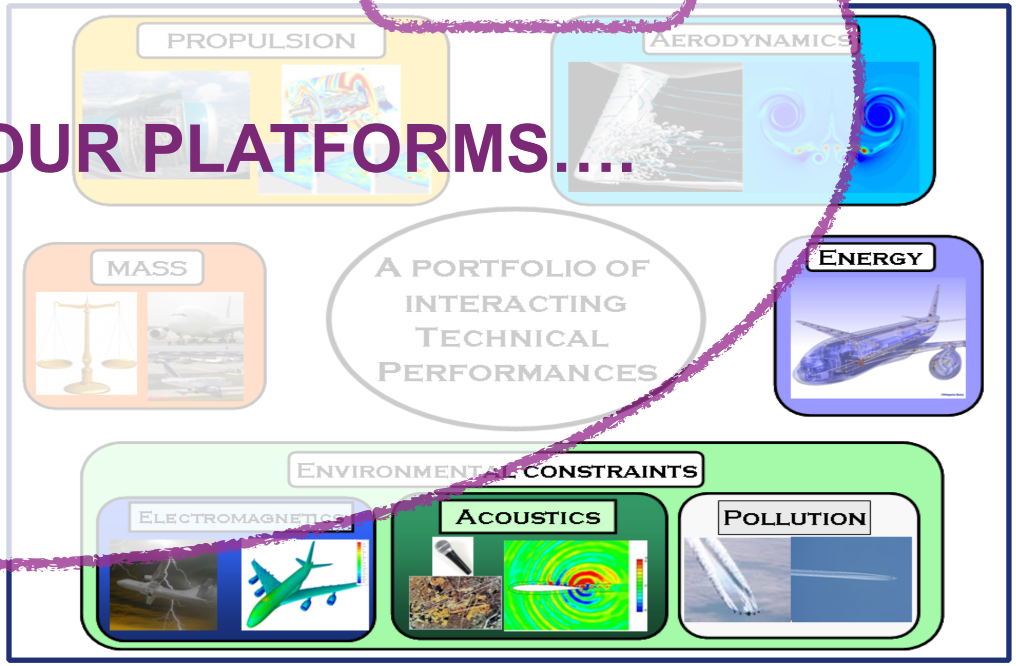
CURRENT ASSETS & PRODUCT PORTFOLIO

OUR GOOD UNDERSTANDING OF PHYSICS WAS KEY TO BUILD OUR PLATFORMS….

Flying platforms governed by complicated physical laws

« Pure » physical behaviors interacting with Systems & Software

Delivered through complex supply-chain organisations



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EXTERNAL Technological trends in the context of Numerical Optimization

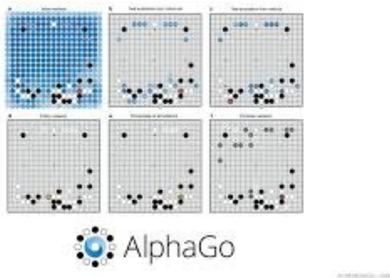
Design & operations are getting closer !

Design & manufacturing are getting closer (3D ALM) !

Interactions between vehicles & external systems will increase !

Newcomers have adopted more collaborative ways to integrate suppliers !

AI algorithms are now available technologies !



Computing capabilities are still increasing even if Moore's law is dead!

Open Source communities set-up new standards

Altair SIMULIA esi get it right® MATLAB ANSYS LMS ENGINEERING INNOVATION

Big software editors are world players covering 80% of the needs

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EXTERNAL Technological trends in the context of Numerical Optimization

NEW BUSINESS NEEDS & NEW WAYS OF WORKING ARE EMERGING

Design & operations are getting closer !

Interactions between vehicles & external systems will increase !

Design & manufacturing are getting closer !

Newcomers have adopted more collaborative ways to integrate suppliers !

NEW TECHNICAL CAPABILITIES & ACTORS HAVE EMERGED

AI algorithms are now available technologies !

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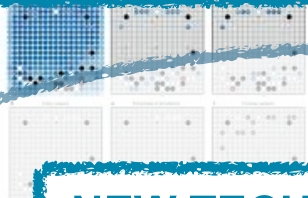

Computing capabilities are still increasing even if Moore's law is dead!

Big software editors are world players covering 80% of the needs

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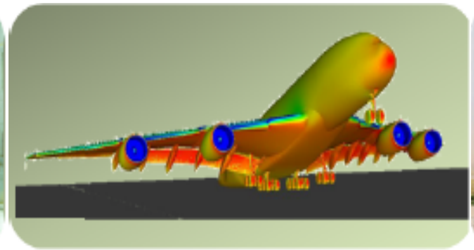
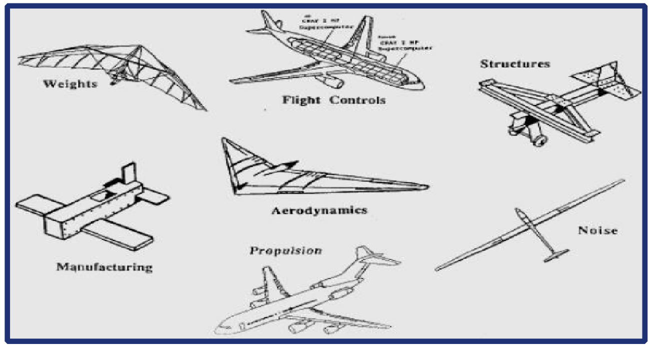
WHAT IS COMING AROUND ?

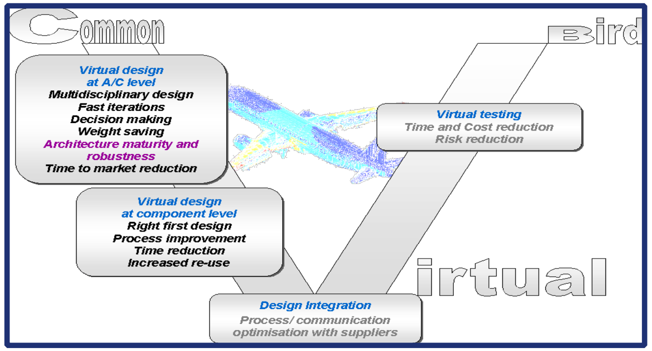
FACTS

FACT The **aerospace engineering knowledge** of our physical products is **already partly digitalized and detained by Risk Sharing Partners**



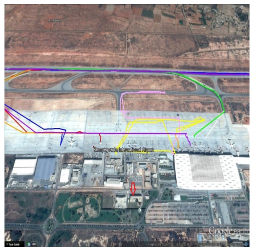
FACT: The **organisation of simulation** is managed **in silos mode** for **different decision gates thus feedback loop is weak** between design, testing, manufacturing & operations





FACT: **New digital** systems/ apps **already collect data/ information**

Flightradar24 PRO
Rome2rio
FLIGHTSTATS



Predix™ From GE. To Everyone.

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WHAT IS COMING AROUND ?

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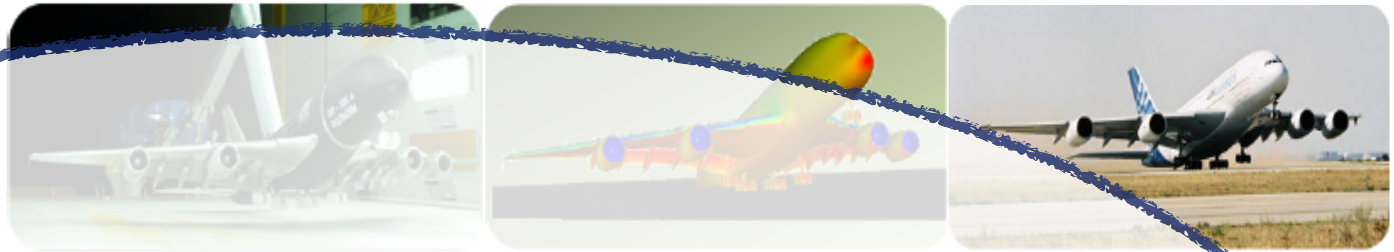

FACT : The **organisation of simulation** is **managed in silos mode for different decision gates thus feedback loop is weak** between design, testing, manufacturing & operations

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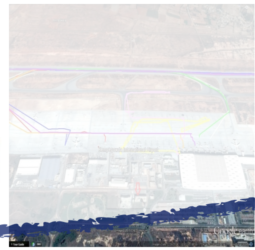
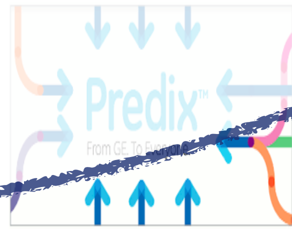
Flightradar24 PRO

Rome2rio

FLIGHTSTATS





…. « DIGITALIZATION » IS ALREADY THERE

AND WILL CHALLENGE IT RADICALLY !

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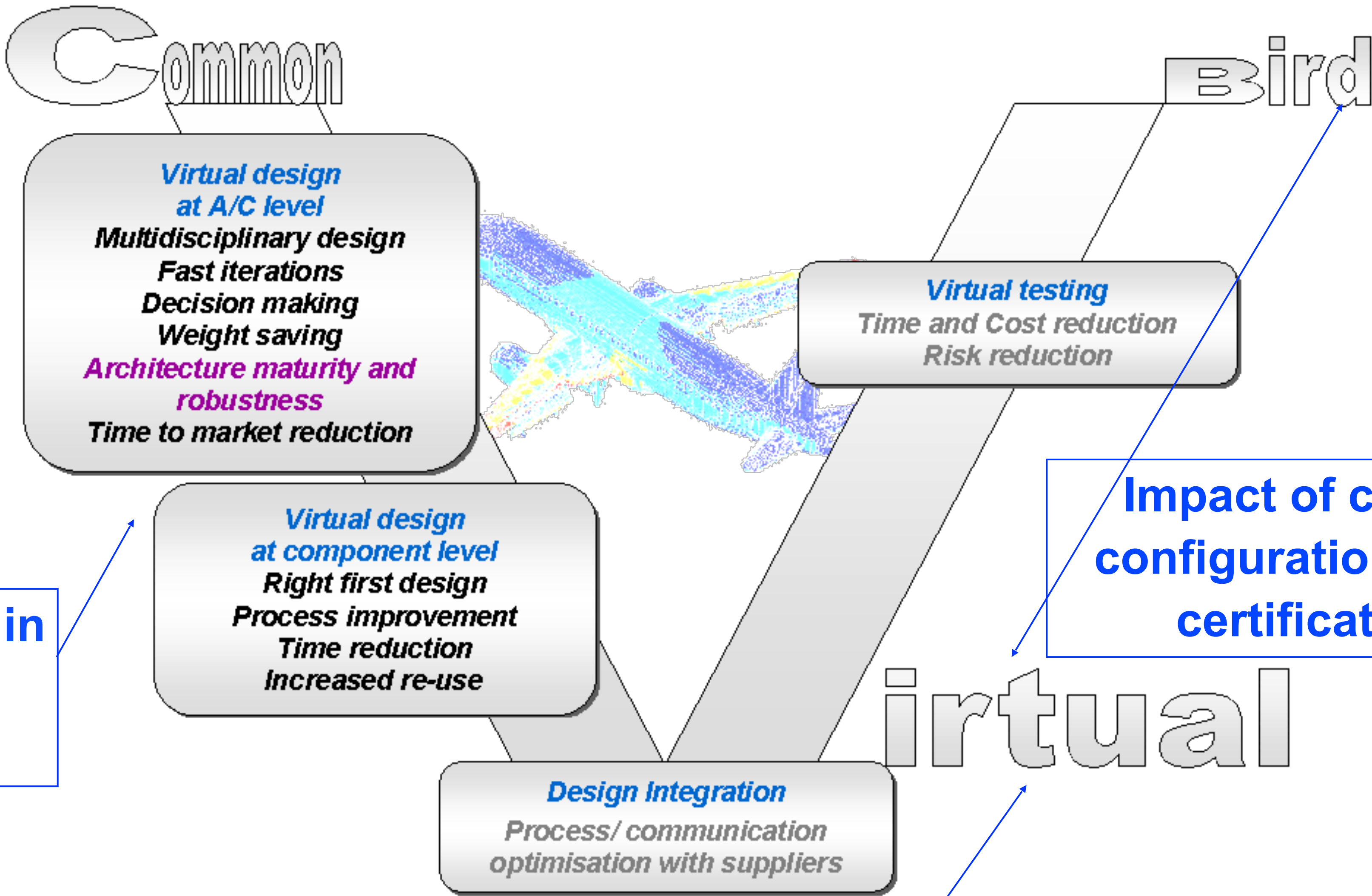
2

Architects of
complex systems
=
The Challenge in
Innovation

CLASSICAL objectives associated to Modelling & Simulation processes along the design-cycle



Limit risks in decision making

Impact of change configuration (up to certification)

reduce development cycle

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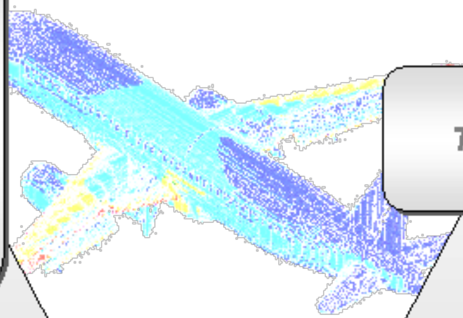
NEW objectives associated to Modelling & Simulation processes along the design-cycle

Learn & feed-back & redesign from operational usage

Common Bird Virtual

Virtual design at A/C level
Multidisciplinary design
Fast iterations
Decision making
Weight saving
Architecture maturity and robustness
Time to market reduction



Virtual testing
Time and Cost reduction
Risk reduction

Virtual design at component level
Right first design
Process improvement
Time reduction
Increased re-use

Design Integration
Process/ communication optimisation with suppliers

Limit risks in decision making

Impact of change configuration (up to certification)

reduce development cycle

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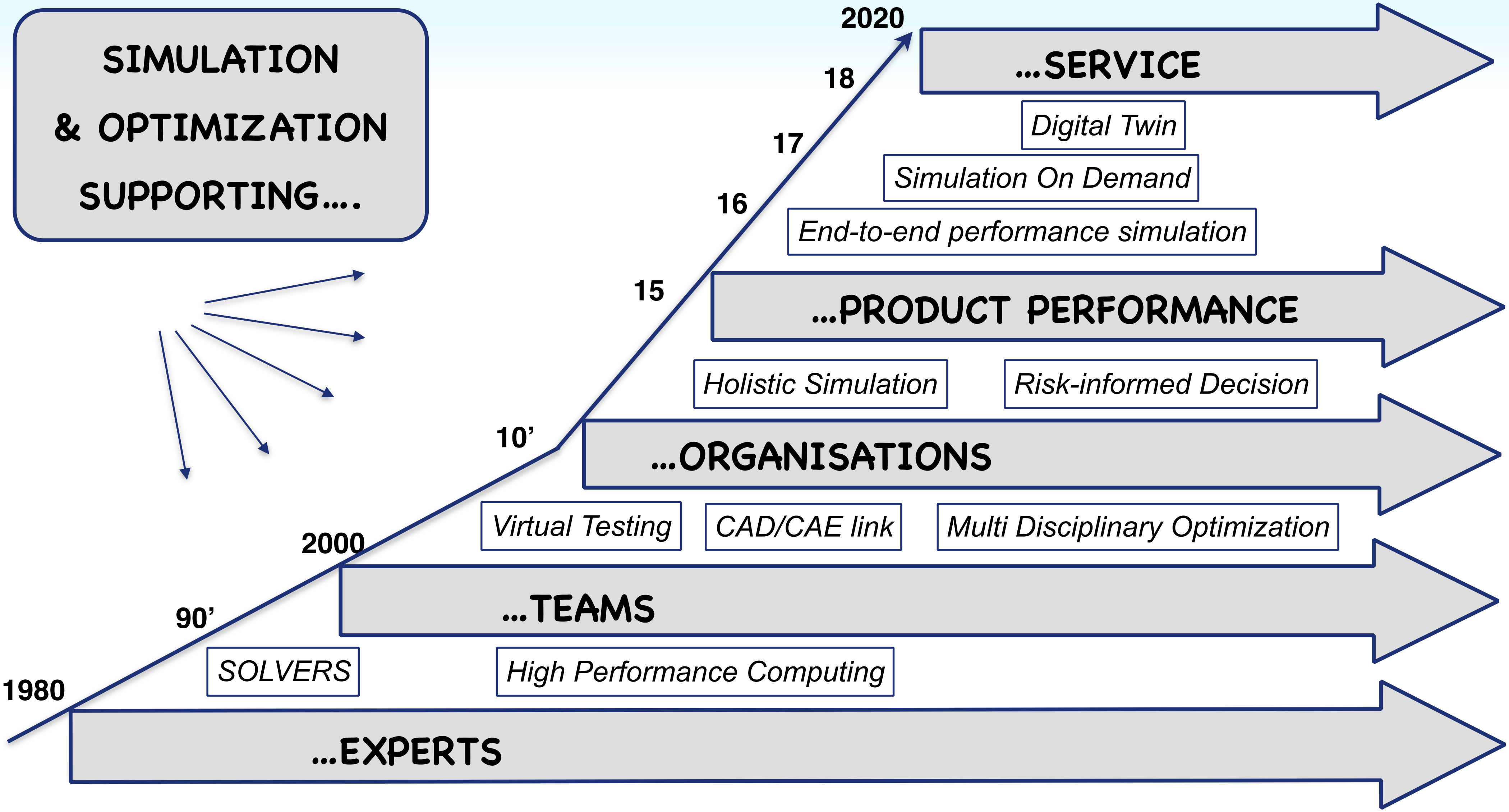
EVOLUTION OF THE CAPABILITIES



Simulation&optimisation in industry is <u>not only</u> a matter of developing the right numerical solvers & models !
It is also related to the stakeholders, their intentions & the organisation around them !

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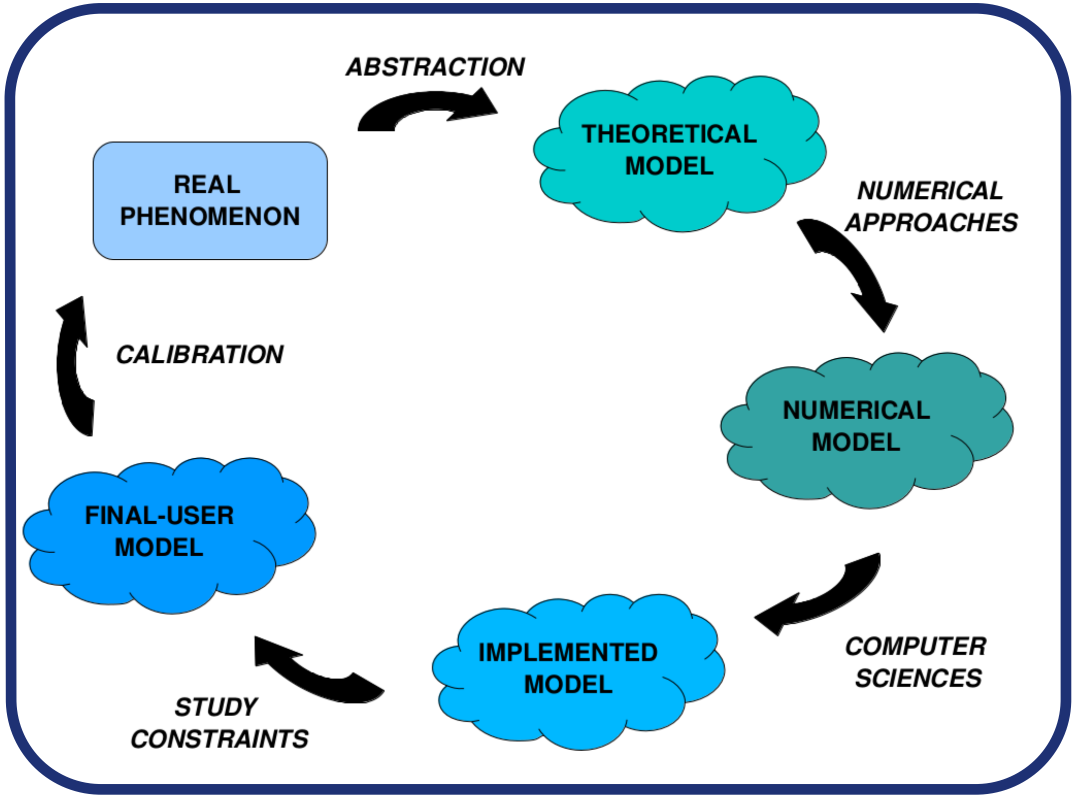
3

Architect of simulations
=
The Challenges in **Optimization**

MAKE THE DIFFERENCE BETWEEN THE APPLICATIVE WORLD & THE NUMERICAL WORLD

APPLICATIVE OBJECTIVES

Problem set-up
Cost
Physical Constraints
Optimization
Value engineering
Robustness
Margin
Performances
Cost
Validation
Systems Engineering



NUMERICAL WORLD

Convergence
Algorithms
Mathematical Properties
Parametrization
Modelling set-up
Numerical optimization
Numerical strategy
...

TOOLS

Information Technology	Software
Deployment	Scalibility
Ergonomy	Verification
Hardware	

MOVE FROM A PURE MATHEMATICAL MINDSET TO AN ENGINEERING CAPABILITY

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Challenge 1: MODELLING AN OPTIMIZATION PROBLEM

Challenge 2: PARAMETRIZE DESIGN SPACES

Challenge 3: MULTI ….. DISCIPLINES / ACTORS / PHYSICS

Challenge 4: IDENTIFY & MEASURE ROBUSTNESS

Challenge 5: SCALABILITY & INTERPRETABILITY OF ALGORITHMS & RESULTS

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CHALLENGE 2: PARAMETRIZE DESIGN SPACES

PARAMETRIZATION

3

On-going research activities

A FEW EXAMPLES TO ILLUSTRATE THE TYPE OF DIFFICULTIES WE ENCOUNTER !

GO FROM SPECIFIC CAPABILITIES TO GENERIC CAPABILITIES !

- Optimal Positioning of sensors
- Topological Optimization in mechanical engineering
- Multi Disciplinary Optimization in Aero Elasticity
- Uncertainty Management of a Flight Controller
- Robust Optimization

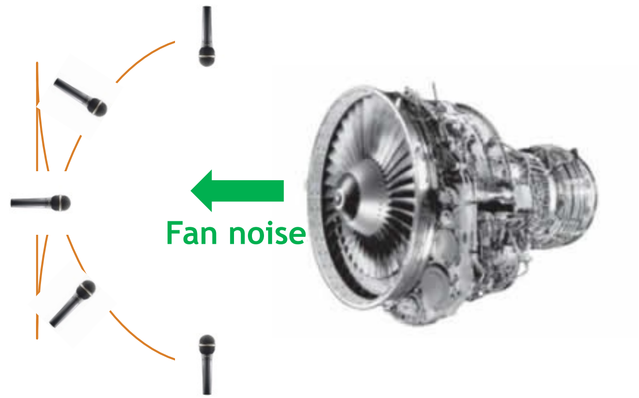
CHALLENGE 2: PARAMETRIZE DESIGN SPACES

PARAMETRIZATION

OPTIMAL POSITIONING OF MICROPHONES

Objective

- Quieter aircrafts design : need of precise knowledge of noise sources
- Noise is due to interactions between moving parts inside the nacelle
- Once generated, noise propagates inside nacelle and is radiated outside
- Intensive use of numerical modelling
  - **DIRECT model**
  - **INVERSE model** : link with real-life measurements



- Measurement systems using microphones

OPTIMIZATION PROBLEM

⇒ Find the most robust microphones positioning that allows to identify at best acoustic sources

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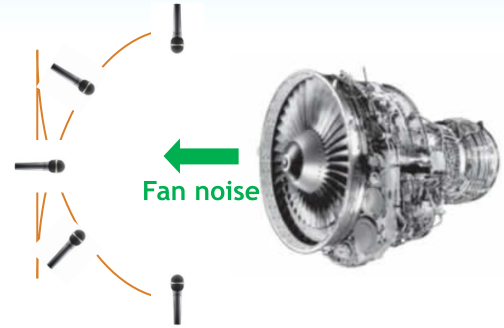
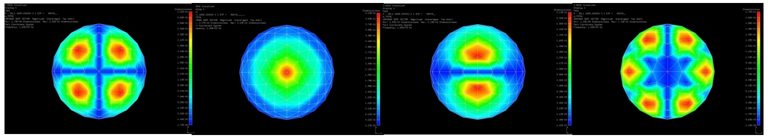
OPTIMAL POSITIONING OF MICROPHONES



Global Methodology

Step 0 Direct problem : governing equations

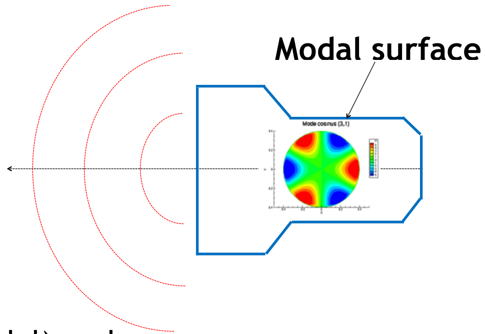
$$\Delta u - \frac{1}{a^2}\frac{\partial^2 u}{\partial t^2} = 0$$



Step 1: Inverse problem

- **Problem :** given measurement at microphones, find values of modal sources
- Least-squares problem:

$$\alpha^* = \arg\min_{\alpha} \frac{1}{2}\left\|[T]\cdot\alpha - u\right\|^2$$



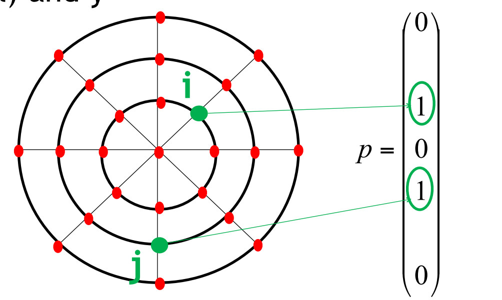
Step 2: Robustness of least-squares problem

- **Problem**
  - For the linear least-squares problem $\min_x \|y - Ax\|$: how does the solution x changes if A (model) and y (measurements) are perturbed ?

$$p^* = \arg\min_p \left(cond\ T(p)\right)$$

Step 3: Optimal positioning problem - Discrete Formulation

$$p^* = \arg\min_{p \in Sphere} \text{cond}\ (\text{T(p)})$$



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OPTIMAL POSITIONING OF MICROPHONES

Direct problem : governing equations

- Sound : waves of pressure propagating through a compressible medium

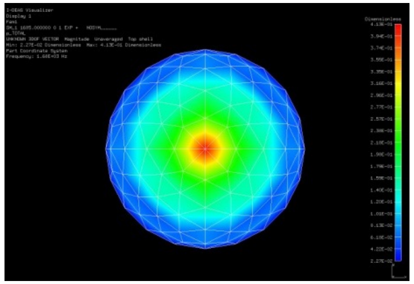
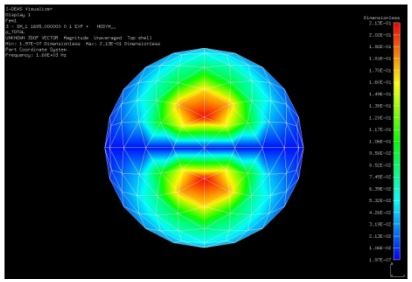
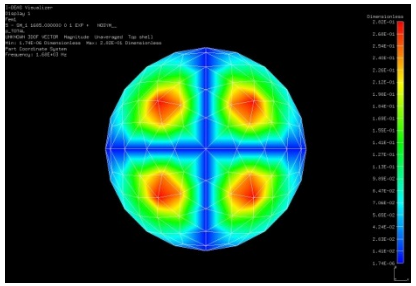
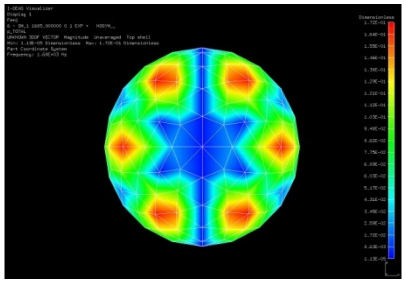
- Pressure u is solution of wave equation (time domain)

$$\Delta u - \frac{1}{a^2}\frac{\partial^2 u}{\partial t^2} = 0$$

- HELMHOLTZ equation (frequency domain)

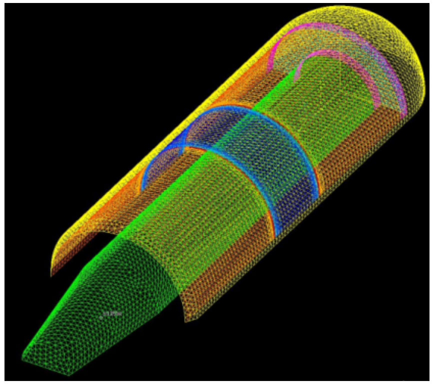
$$\Delta u + k^2 u = 0 \quad \text{with} \quad k = \frac{\omega}{a} = 2\pi \frac{f}{a}$$

- Solution are called the modes U_{mn} (propagative or evanescent) & **Coefficients of modes u_{mn}= modal sources**

OPTIMAL POSITIONING OF MICROPHONES

Direct problem : numerical resolution



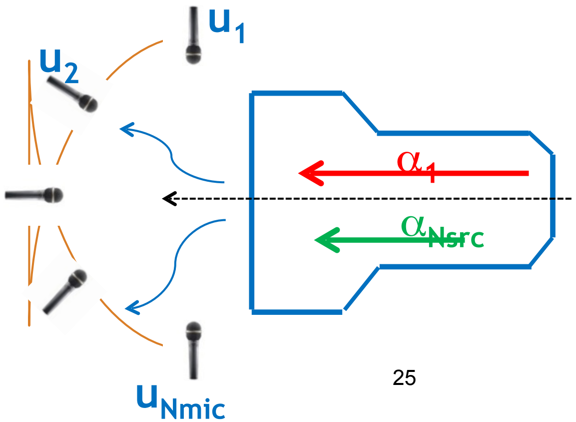
- **Numerical resolution of HELMHOLTZ equation :**
  - Integral equation formulation
  - Boundary elements method on a triangular mesh
  - Representation theorem

- For a given frequency, pressure at microphones depends linearly on acoustic modal sources

$$\begin{bmatrix} T_{1,1} & \cdots & T_{1,Nsrc} \\ \vdots & \ddots & \vdots \\ T_{Nmic,1} & \cdots & T_{Nmic,Nsrc} \end{bmatrix} \cdot \begin{pmatrix} \alpha_1 \\ \vdots \\ \alpha_{Nsrc} \end{pmatrix} = \begin{pmatrix} u_1 \\ \vdots \\ u_{Nmic} \end{pmatrix}$$

Nmic : number of microphones
Nsrc: number of modal sources

- T : **TRANSFER MATRIX**



OPTIMAL POSITIONING OF MICROPHONES

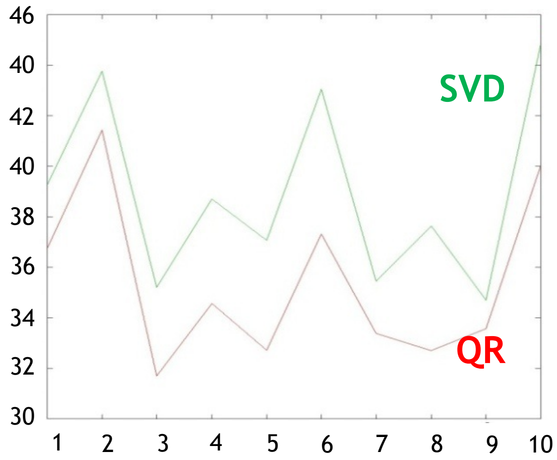
Step 1: Inverse problem

- **Problem :** given measurement at microphones, find values of modal sources
- Least-squares problem:

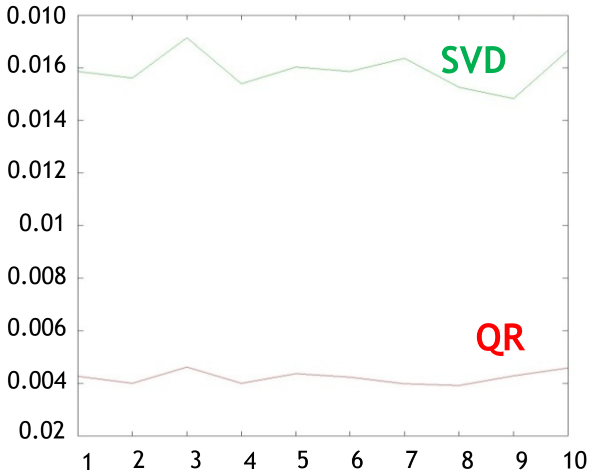
$$\alpha^* = \arg\min_{\alpha} \frac{1}{2}\left\|[T]\cdot\alpha - u\right\|^2$$

- Until recently, resolution based on **SVD**

- Comparisons SVD - QR on typical samples



Solution error



Computation time

⇒ QR more suitable for solving inverse problem

⇒ Nevertheless, SVD useful for computing condition number

⇒ What is the robustness of the solution α with respect to error on microphones positioning ?

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OPTIMAL POSITIONING OF MICROPHONES

Step 2: Robustness of least-squares problem

- **Problem**
  - For the linear least-squares problem $\min_x \|y - Ax\|$: how does the solution x changes if A (model) and y (measurements) are perturbed ?
- **Sensitivity analysis**
  - Note Δx the perturbation on sources due to a perturbation Δy (resp. ΔA) on measurements (resp. model)

$$\frac{\|\Delta x\|}{\|x\|} \leq cond(R)\frac{\text{lub}(\Delta A)}{\text{lub}(A)} + cond(R)^2 \frac{\|r\|}{\text{lub}(A)\|x\|}\frac{\text{lub}(\Delta A)}{\text{lub}(A)} + cond(R)\frac{\|y\|}{\text{lub}(A)\|x\|}\frac{\|\Delta y\|}{\|y\|}$$

- **Interpretation**
  - $\frac{\|\Delta x\|}{\|x\|}, \frac{\|\Delta y\|}{\|y\|}, \frac{\text{lub}(\Delta A)}{\text{lub}(A)}$: relative errors on source, measurements & model
  - Error on source identification proportional to matrix R conditioning (from QR decomposition of A)
- **Conclusion :**

Robust positioning p in regard to sources accuracy
=
Find the positioning that minimizes the condition number of R (and consequently T) !

$$p^* = \arg\min_p \left(cond\ T(p)\right)$$

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OPTIMAL POSITIONING OF MICROPHONES

Step 2: Optimal positioning problem

- Optimal positioning problem

$$p^* = \arg\min_p \left(cond\ T(p) \right)$$

- Classical gradient-based method not adapted for such a cost function
- Global Optimization problem with many local minima
- Discretization of search space to switch to a combinatorial problem
- Link to methods of Operational Research
- Original approach in Acoustics

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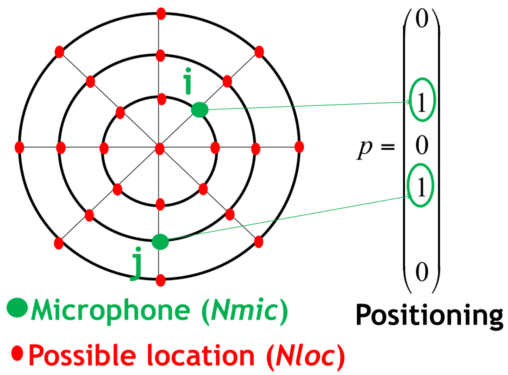
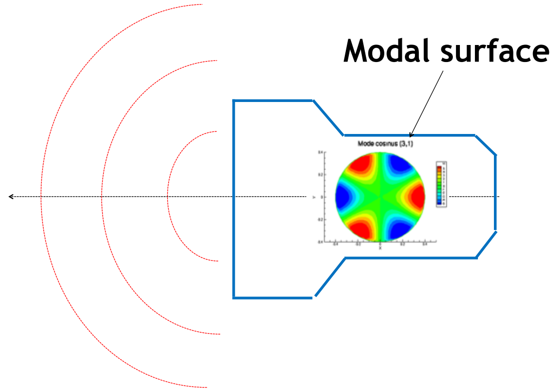
OPTIMAL POSITIONING OF MICROPHONES

- Noise propagation assumed to be isotropic outside the engine
- Radiation on a semi-sphere contains information of a same modal surface
- Hence, microphones are searched on a discretized semi sphere of Nloc possible positions





•Step 3: Optimal positioning problem - Discrete Formulation

$$p^* = \arg\min_{p \in Sphere} \text{cond}\,(T(p))$$

- Transfer matrix

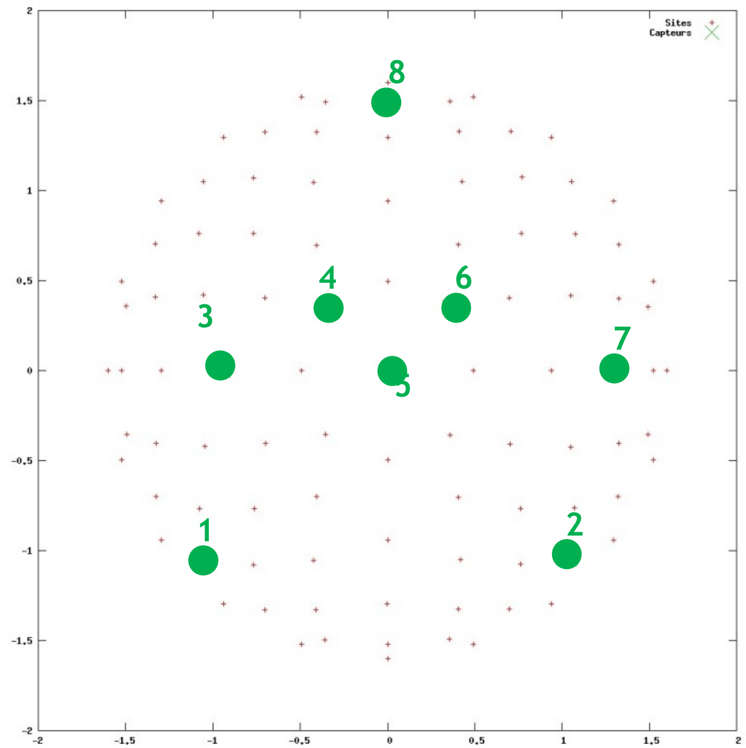
Global transfer matrix : [T^{GLOB}]
&
Transfer matrix restriction
to microphones subspace : [T(p)]

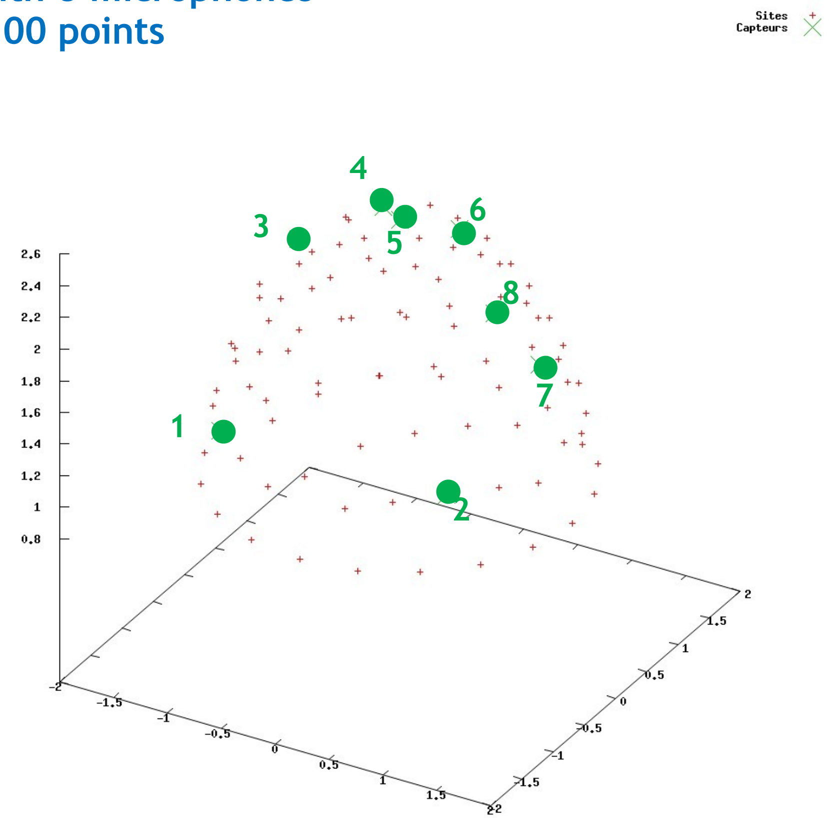
$$\begin{bmatrix} T_{1,1} & T_{1,2} & \cdots & T_{1,Nsrce} \\ T_{2,1} & T_{2,2} & \cdots & T_{2,Nsrce} \\ \cdots & & \cdots & \\ T_{i,1} & T_{i,2} & \cdots & T_{i,Nsrce} \\ T_{j,1} & T_{j,2} & \cdots & T_{j,Nsrce} \\ \cdots & & & \\ T_{Nloc,1} & T_{Nloc,2} & \cdots & T_{Nloc,Nsrce} \end{bmatrix}$$

OPTIMAL POSITIONING OF MICROPHONES

Case with a good condition number

Reconstruction of 8 modal sources with 8 microphones
Semi shere discretization : 100 points





Optimal positioning: far from practitioner experience !

OPTIMAL POSITIONING OF MICROPHONES

Next steps

- **Validate/Enrich** the Optimization Positioning capabilities for test engineering
  - Validation, tests & benchmarks
  - Integrate test set-up constraints
- **Generalize** this approach to other physics
  - Electromagnetism
  - Vibro acoustics,
  - Thermics
  - Aerodynamic
- **System View**: Make the link with test engineering practices

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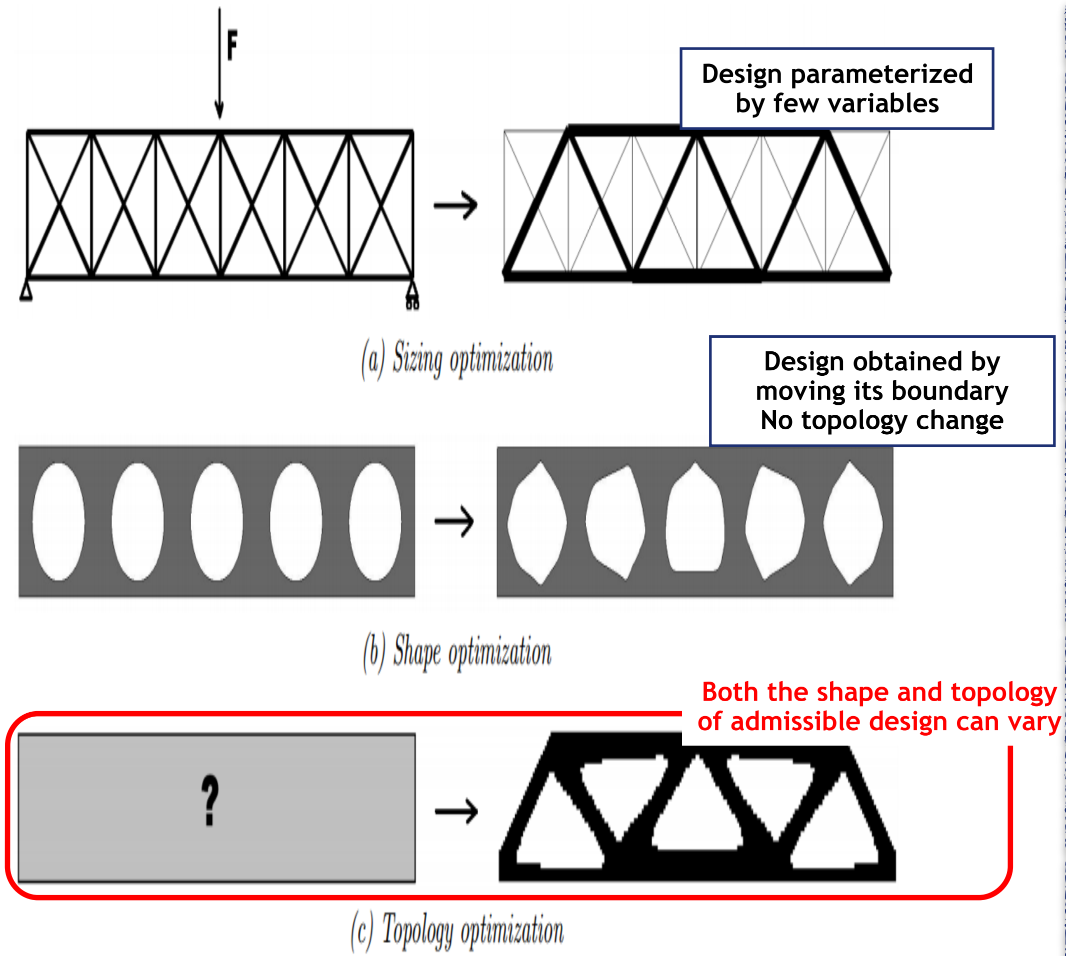
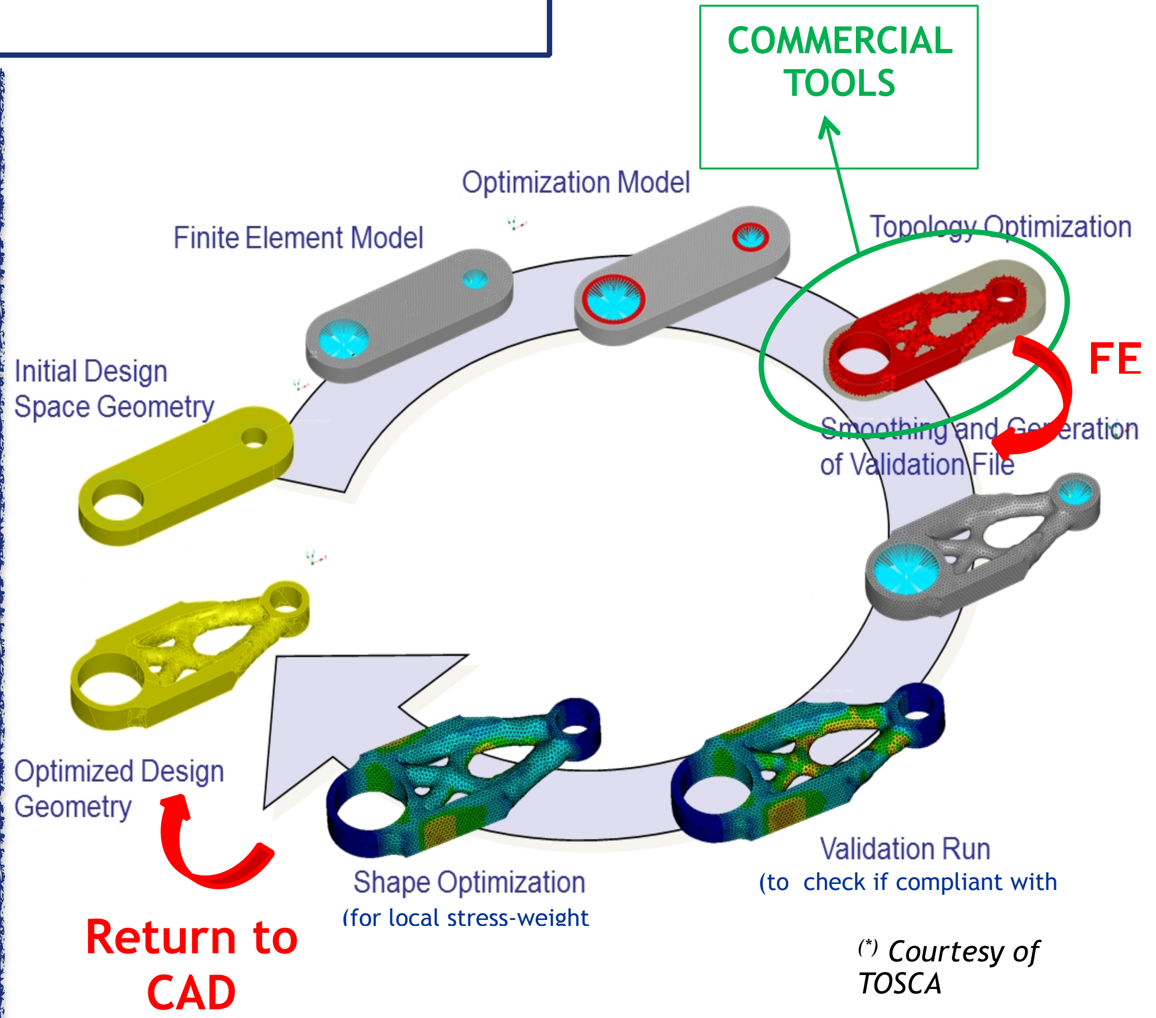
TOPOLOGICAL OPTIMIZATION



Typology of optimization problems

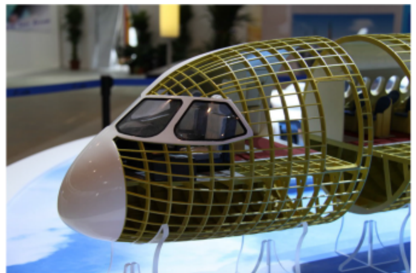


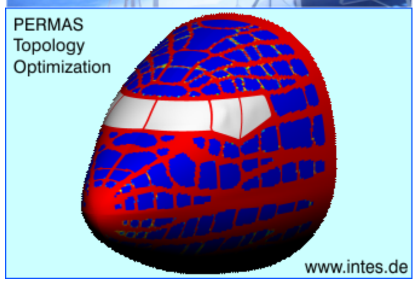
Goal: From numerical optimization to engineering capability

TOPOLOGICAL OPTIMIZATION

- **Why industrials could be interested in Topology Optimization (TO)**
  - Ease of use : "just" to provide specifications & design space in geometrical terms
  - Gain in mass : between 3% & 15% obtained on "simple" structu
  - Find new "breakthrough" configurations

- **Therefore,** TO is not used systematically & field of applications remains modest
- **Mainly due to** the fact that today methods & tools :
  - Generate only a concept, far from being manufactured
  - Limited to simple structures, physical analysis & constraints
  - Not easily pluggable into the design process (remeshing, no return [illegible])





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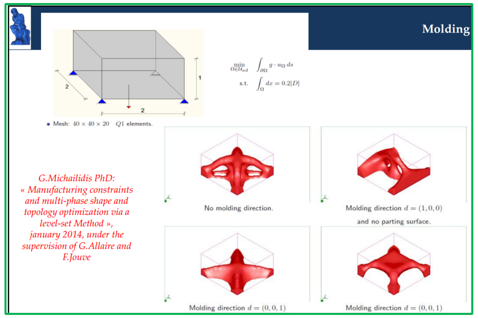
TOPOLOGICAL OPTIMIZATION

Results of the **RODIN project** (FUI project supported, System@tic)
Industrial Partners: Renault, Airbus Group, Safran Tech, ESI, DPS, EuroDecision
Academic Partners: Ecole Polytechnique CMAP, University Paris VI Lab JLL, INRIA

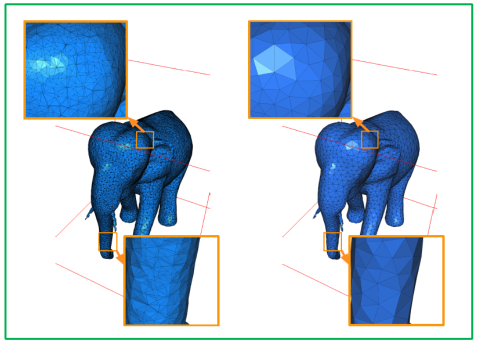
Numerical ingredients:
Level-set method
Shape sensitivity analysis
Topological derivative
FEM mesh & cartesian grid - Local remeshing

Molding

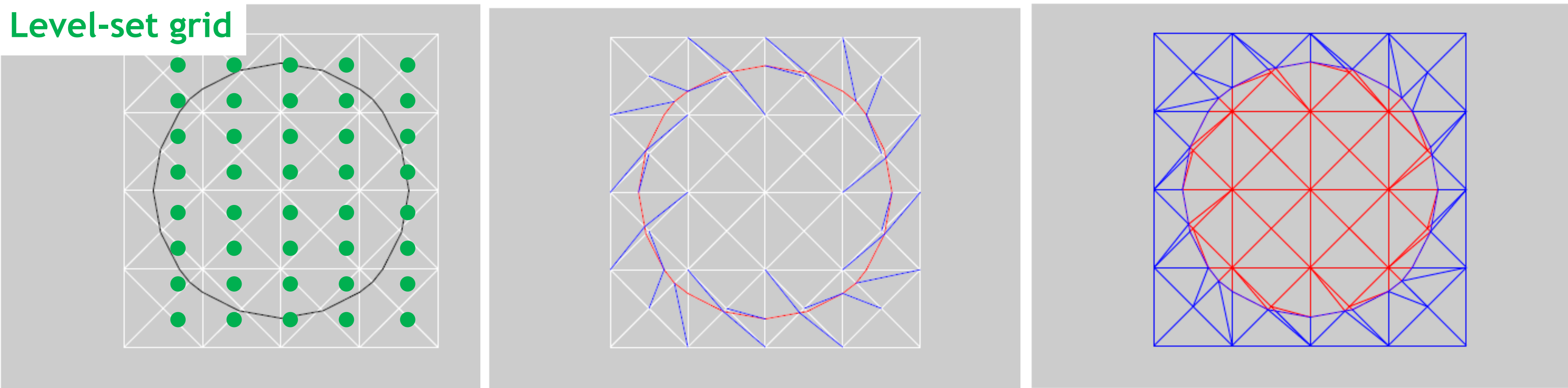


PhD G. Michailidis

Local remeshing

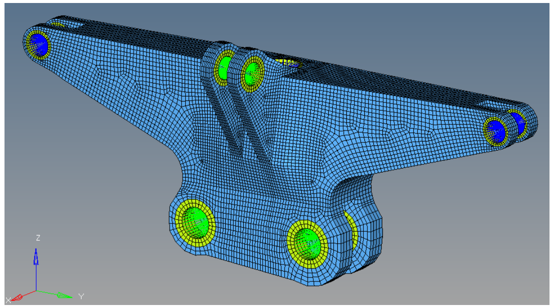


PhD Ch. Dapogny

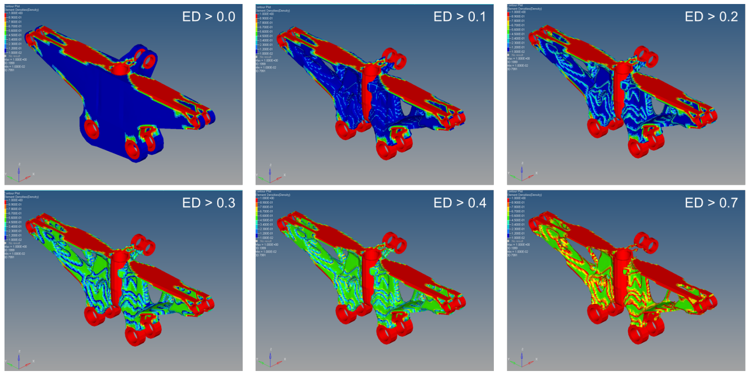


TOPOLOGICAL OPTIMIZATION

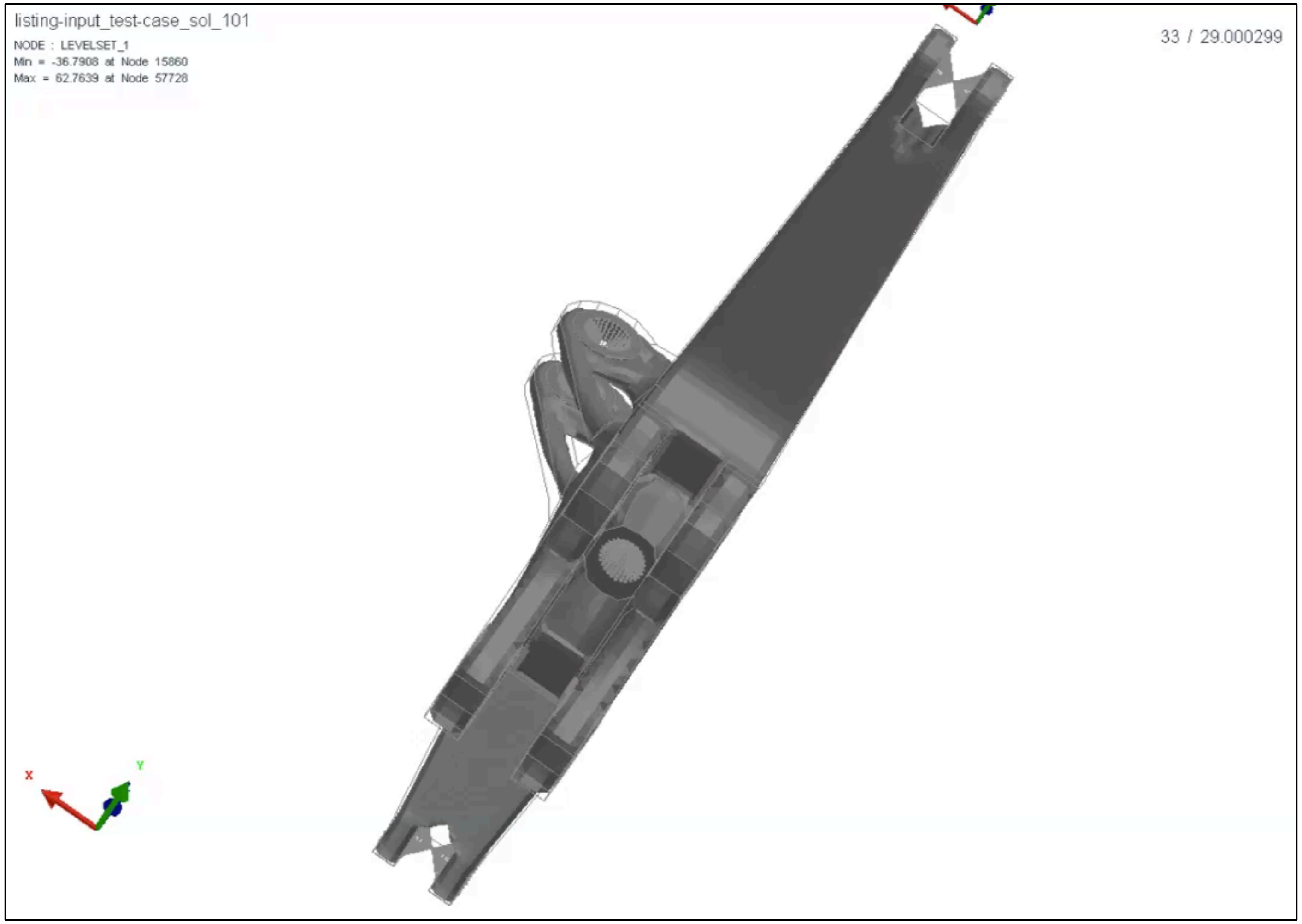
Engine bracket test-case



- Based on NASTRAN model: All Solid elements retained
- Displacement constraint set to 6 mm
- 14 Loads used from NASTRAN model
- Mass minimization s.t. displacement constraints



Results based on SIMP method



Results obtained within RODIN project

TOPOLOGICAL OPTIMIZATION

Next steps

- **Validate/Enrich** the Topological Optimization capabilities for mechanical engineering
  - Validation, tests & benchmarks
  - Extension of physical analysis (contact, thermo-elasticity,…)
  - Multi-phases structures & non-linear materials
  - Introduction of ALM constraints both from geometrical or simulation viewpoint
- **Generalize** the Topological Optimization capabilities for other physics
  - Vibro acoustics,
  - Thermics
  - Aerodynamic
- **System view**: Make the link with detailed design engineering & classical work breakdown structures organisations

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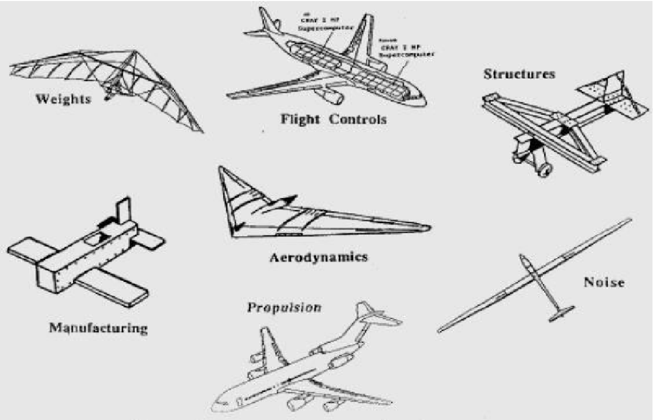
MULTI DISCIPLINARY OPTIMIZATION

- **Challenge in aircraft design**
  - Design “next generation” aircrafts, with conceptual & technological breakthrough
  - Many disciplines are concerned
  - But, today disciplines are generally handled separately and sequentially



Sequential design = risk of local solutions & antagonistic decisions

- **Goal of MDA/MDO**
  - Handle the disciplines simultaneously and exploit efficiently their interactions

Simultaneous design = better optimum & trade-off analysis

- **Our current challenge is focused on wing aero-structure coupling but the mathematical formulation is general and can be extended to any number of disciplines**

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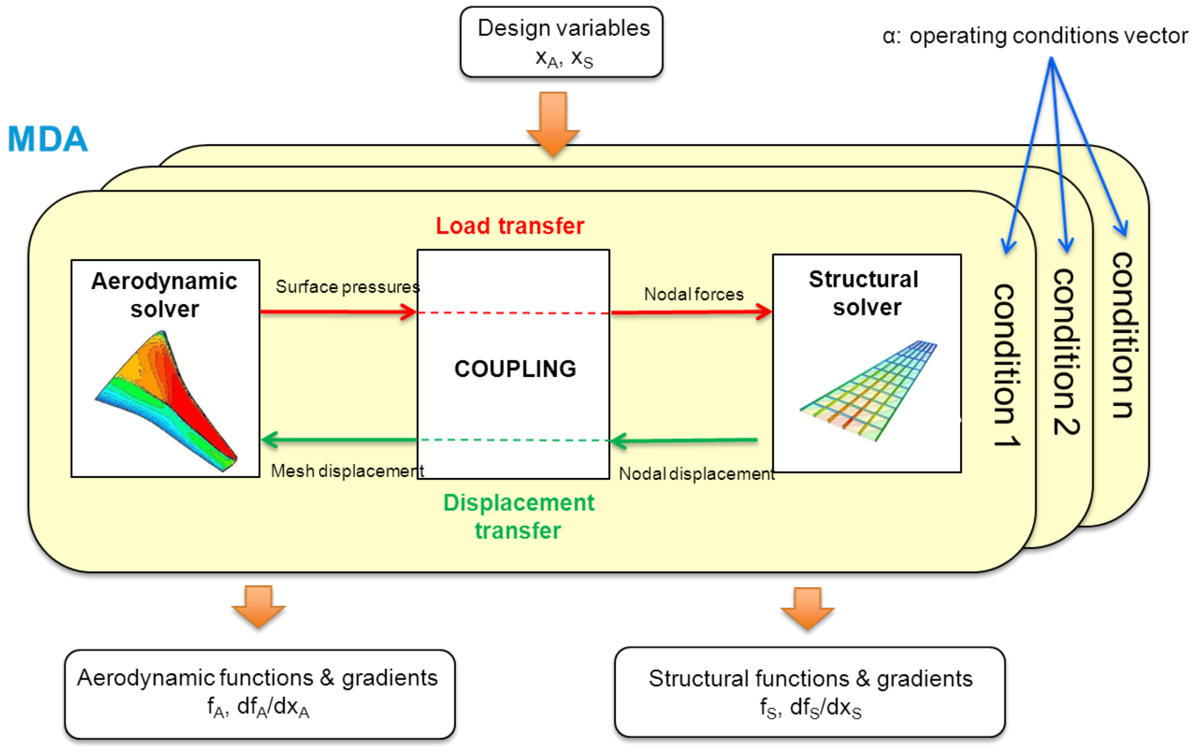
MULTI DISCIPLINARY OPTIMIZATION

MDA : Multidisciplinary Design Analysis

- Shape is fixed
- Aims at finding the physical equilibrium between disciplines



2 important topics

1. Operating conditions

A very important concept that determines the choice of disciplinary fidelity level

2. Coupling

Methods for solving efficiently the MDA problems

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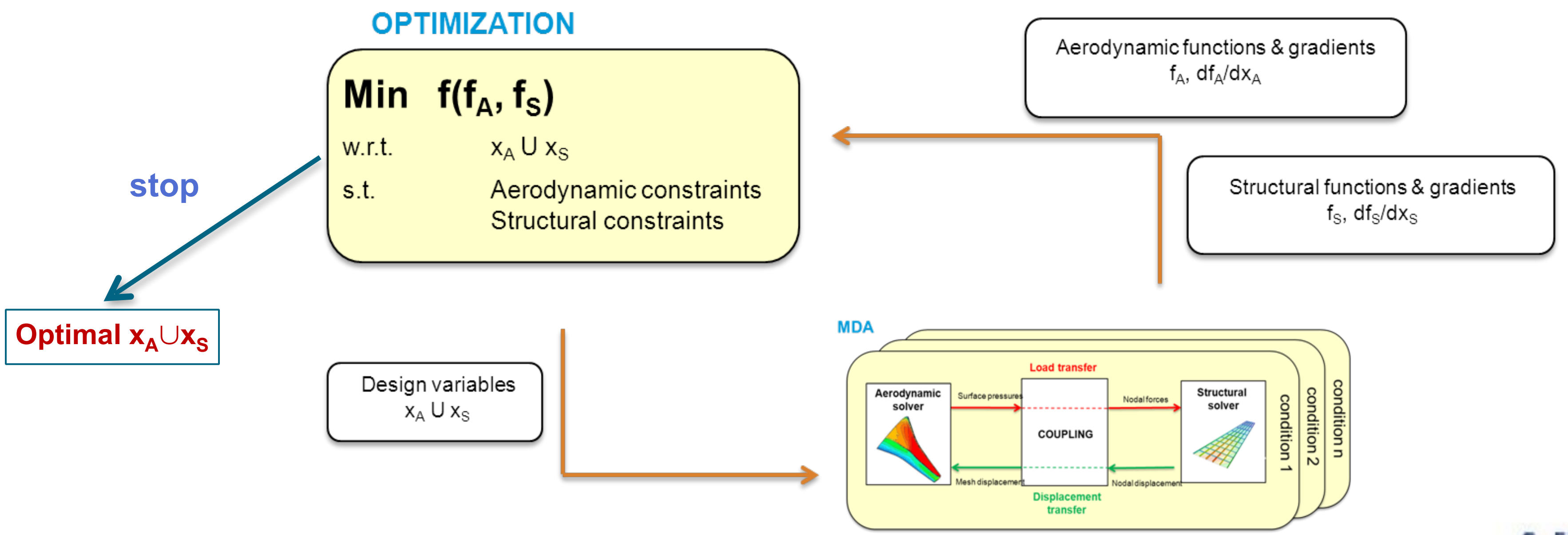
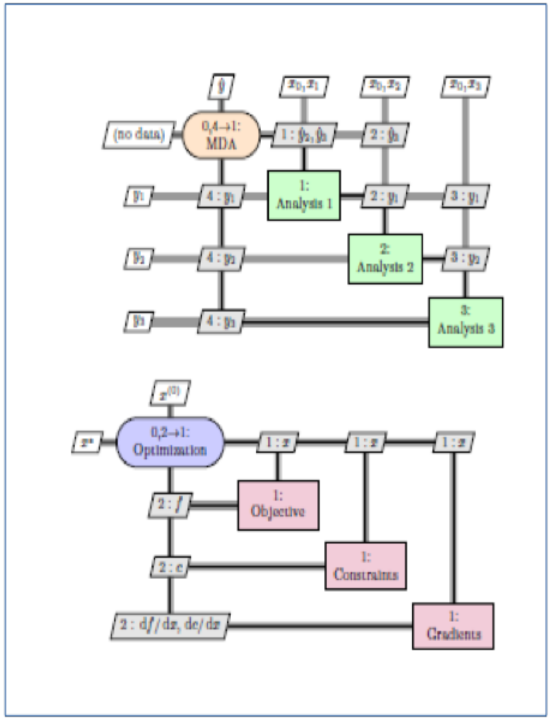
MULTI DISCIPLINARY OPTIMIZATION

- Search to find the best shape that minimizes one or several criteria
- Could just consist in plugging an optimization algorithm to MDA process
- But many others strategy could be implemented (IDF, BLISS,..) ⇒ **this is the goal of MDO as research field**

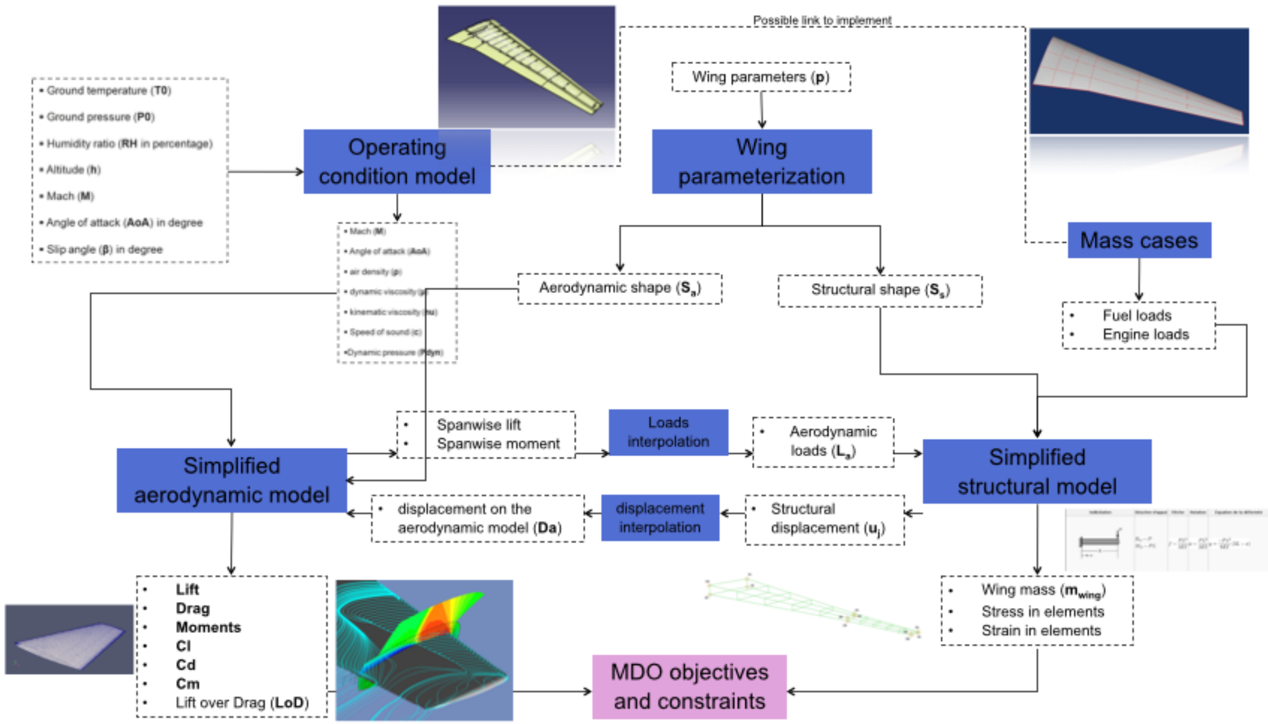


MULTI DISCIPLINARY OPTIMIZATION

MDO data exchange



Generic representation of a numerical MDO process

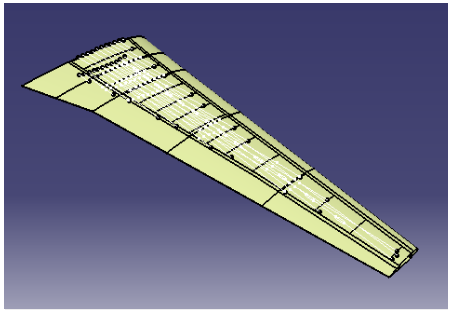


Use-case associated to the aero elastic context

MULTI DISCIPLINARY OPTIMIZATION

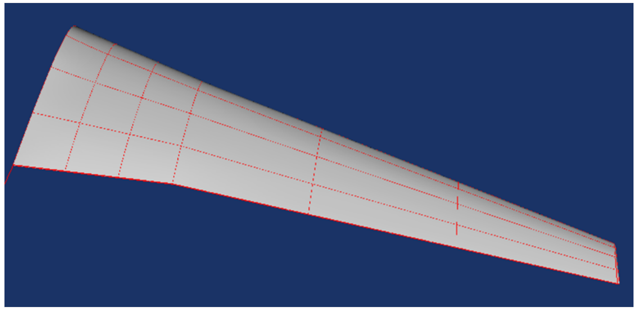
Purpose of Multi-disciplinary parameterization

The purpose of the multidisciplinary parameterization is to ensure the **models consistency required by MDO** activities. The different models (struct, Aero, …) has to **be consistent according to their sets of parameters** and the set of parameter is considered as the **only way to monitor geometry update/transformation** !



Catia

Consistency (synchronization)



Padge

Challenges:

- Impact changes of **structure model to aerodynamic model**
- Impact changes of **aerodynamic model to structure model**
- Ensure models integration between two **different geometric kernels**
- **Automatize model interaction** for optimization loops

MULTI DISCIPLINARY OPTIMIZATION

Next steps

- **Understand** the Multi Optimization capabilities for aero elastic problems
  - Validation, tests & benchmarks
  - Extension of physical analysis (low/high fidelity —> adequacy)
- **Generalize** the Multi Optimization capabilities for other physics
  - Acoustics,
  - Thermics
  - System models (0D-1D)
- **System view**: Make the link with detailed design engineering & classical work breakdown structures organisations

UNCERTAINTY MANAGEMENT

System of interest

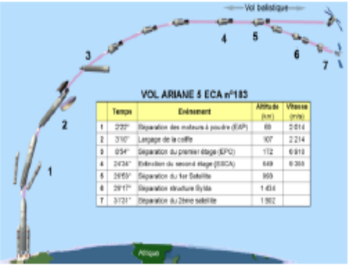


Figure: Mission description

Figure: Atmospheric flight

- A controller (*ie* a numerical strategy) **C** is defined over a set of input variables $(\mathbf{x}, \theta)$ to perform a virtual test corresponding to the flight time interval **[0,T]**.
- The behaviour of the system is observed through the state variables **s** (*deflection, consumption, attitude, ...*).
- The performances of the controller **C** are qualified through the belonging of the output variables $\mathbf{y} = (\kappa \circ C)(\mathbf{x}, \theta)$ to a given numerical domain $\mathcal{D}$ (*exceedance or not of a threshold, ...*).

Uncertainty arising in the applicative context

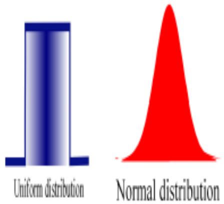


Figure: Uncertainties

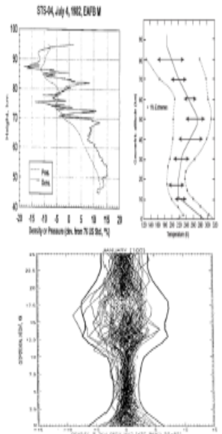


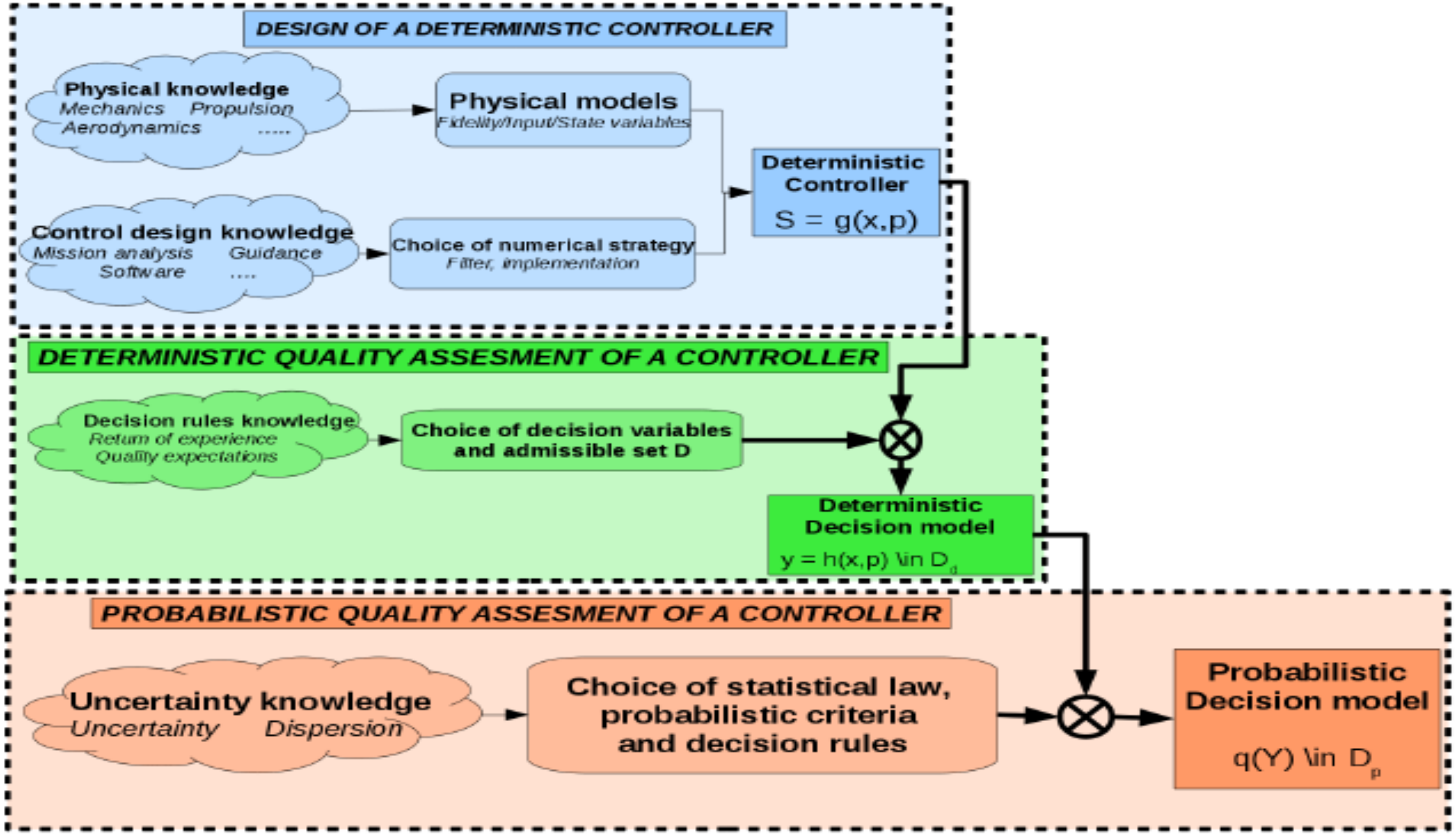
Figure: Wind model

Uncertainties and dispersions in this context

- **Uncertainties** correspond to the lack of knowledge of the values taken by some input variables (*rigid dynamic, bending modes*). This uncertainty could be reduced in some cases by an increase of knowledge (better model, return of experience) or NOT (unknown unknown!).
- **Dispersions** correspond to observed variability, most often small variability around a nominal value.

UNCERTAINTY MANAGEMENT

Synoptic of the technical activities



UNCERTAINTY MANAGEMENT

Application to the design of a deterministic controller

- **Input variables** $\mathbf{x} \in \mathbb{R}^P$ ($P = 35$):
  $\mathbf{x}$ = (Rigid Dynamic, Bending Modes, Wind Model)
- **State/ouput variables** $\mathbf{y} \in \mathbb{R}^Q$ ($Q = 6$)):
  $\mathbf{y}$ = (Deflection ($d(t)$), Consumption ($c(T)$), Dynamical Load ($q_\alpha(t)$), Attitude During Flight ($\alpha(t)$), Final Attitude ($\alpha(T)$), Final Angular Rate ($\dot{\alpha}$))
- **Controller**: $h : \mathbf{x} \in \mathbb{R}^{35} \rightarrow \mathbf{y} \in \mathbb{R}^6$ considered like a black-box

Deterministic requirements

$$\begin{cases} \text{D:} & y_1 & \leq d_0 \\ \text{C:} & y_2 & \leq c_T \\ \text{DL:} & y_3 & \leq q_\alpha^0 \\ \text{ADF} & y_4 & \leq a_0 \\ \text{FA:} & \|y_5\| & \leq k * \alpha_T \\ \text{FAR:} & y_6 & \leq \alpha_0 \end{cases}$$

Probabilistic requirements

$$\begin{cases} \text{D:} & \mathbb{P}(\{\omega \in \Omega : y_1(\omega) \leq d_0\}) & \leq \beta_1 \\ \text{C:} & \mathbb{P}(\{\omega \in \Omega : y_2(\omega) \leq c_T\}) & \leq \beta_2 \\ \text{DL:} & \mathbb{P}(\{\omega \in \Omega : y_3(\omega) \leq \overline{q}_\alpha\}) & \leq \beta_3 \\ \text{ADF} & \mathbb{P}(\{\omega \in \Omega : y_4(\omega) \leq a_0\}) & \leq \beta_4 \\ \text{FA:} & \mathbb{P}(\{\omega \in \Omega : y_5(\omega) \leq k * \alpha_T\}) & \leq \beta_5 \\ \text{FAR:} & \mathbb{P}(\{\omega \in \Omega : y_6(\omega) \leq \alpha_0\}) & \leq \beta_6 \end{cases}$$

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UNCERTAINTY MANAGEMENT

Propagation of uncertainty

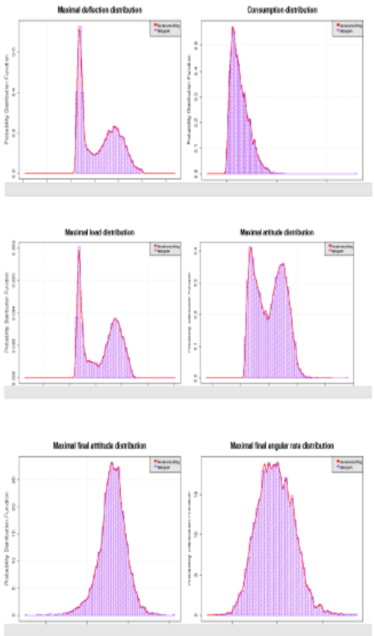

Figure: Uncertainties on outputs

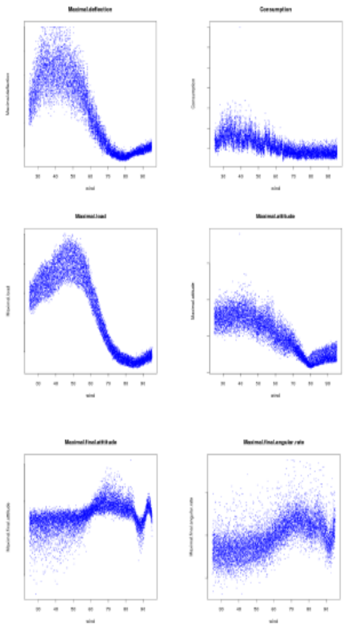

Figure: Outputs vs wind model inputs

Sensitivity indexes of a probability

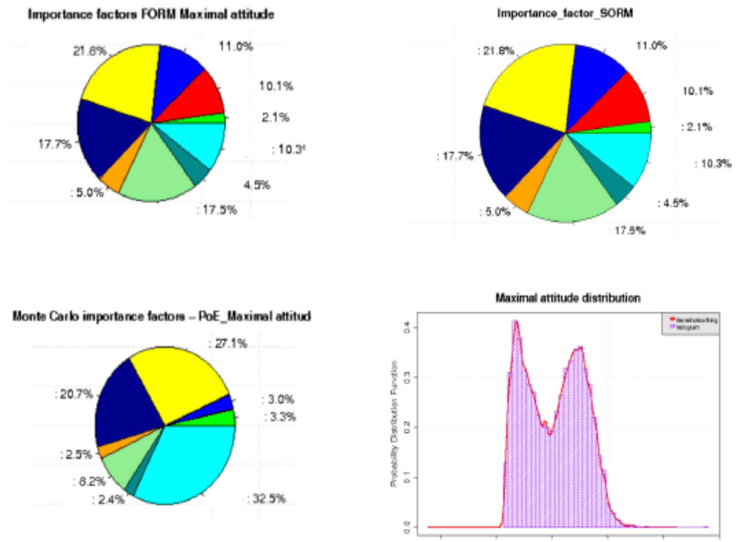

Figure: Sensitivity to the probability

UNCERTAINTY MANAGEMENT

Next steps

- Integrate classical UQ techniques in the post analysis of optimization processes
  - Validation, tests & benchmarks
- Link with Robust Optimization capabilities to each scalability
- System view: Make the link with detailed design engineering & classical work breakdown structures organisations

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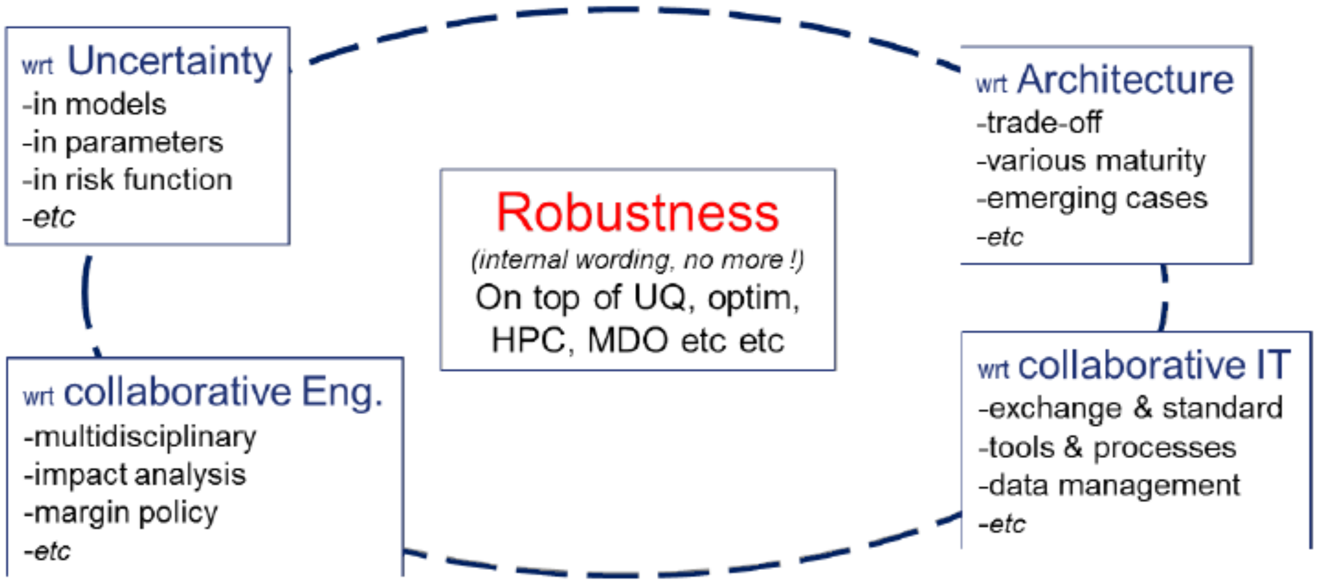
ROBUST OPTIMIZATION

What do we mean by "robustness" within an industrial context ?



It's not a pure matter of tool or math, neither an issue in data or model exchange;
it's a pure collaborative challenge: wording, methodology, common understanding etc
And each team to be at the right place to solve each bit of the set of difficulties ☺

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ROBUST OPTIMIZATION

Global Context

- Cost function J is derived mainly from "functional/system" consideration (mass, consumption, range of action, etc.)
- Constraints $\mathbf{g}$ are very often "complex physical simulation" (no analytical expression): temperature, aerodynamic coeff., displacement, etc.
- The interaction between the objective function J and constraints $\mathbf{g}$ induces couplings "physics-system" (e.g thermal regulation: system = air conditioning pack / physics = fluid behavior in the cabin)

Margins are **everywhere** due to the way our products were designed. Value will be created by rigorously chasing them !

Optimization strategies also impact organisations !

ROBUST OPTIMIZATION

Global Context

- From a classical (parametrized) optimization problem …

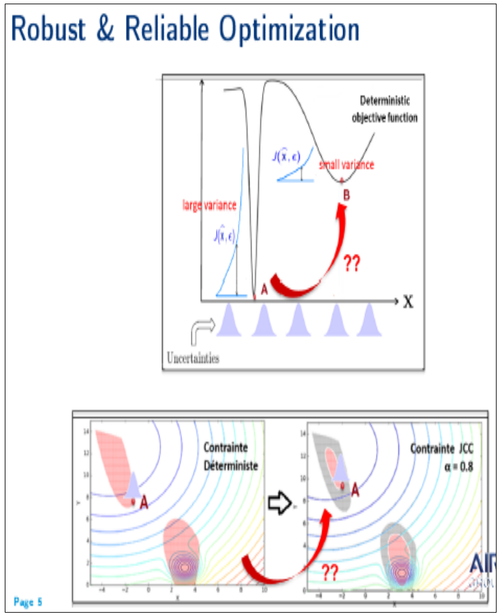
$$\min_{\mathbf{x},\mathbf{g}(\mathbf{x},\mathbf{u})\leq 0} J(\mathbf{x},\mathbf{u})$$

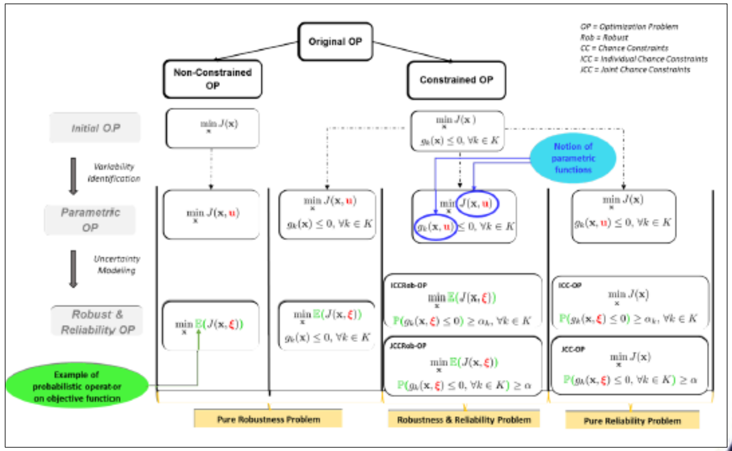
where $\mathbf{u}$ is some vector of values used in the problem (often hidden!)

- how to take into account uncertainties on $\mathbf{u}$ and/or on the design $\mathbf{x}$?
- For simplicity, data $\boldsymbol{\xi}$ will aggregate all sources of uncertainties (on design, on environmental constants, etc.)
- $\boldsymbol{\xi}$ is modelled as a random vector with distribution $\mathbb{P}_{\boldsymbol{\xi}}$
- In practice, the engineer solves a parametrized optimization problem

$$\min_{\mathbf{x},\mathbf{g}(\mathbf{x},\boldsymbol{\xi}(\omega))\leq 0} J(\mathbf{x},\boldsymbol{\xi}(\omega))$$

for some scenario $\boldsymbol{\xi}(\omega)$ of the uncertainties that he has fixed before





MULTI DISCIPLINARY OPTIMIZATION

Next steps

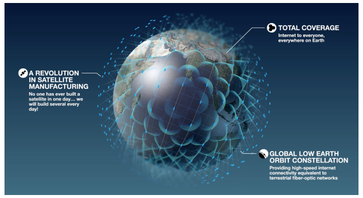
- **Understand** the Robust Optimization capabilities for a set of applicative problems
  - Validation, tests & benchmarks
  - Extension of physical analysis (low/high fidelity —> adequacy)
- **Develop** the Robust Optimization capabilities to each scalability
  - Acoustics,
  - Thermics
  - System models (0D-1D)
- **Capitalize** in an open source software
- **System view**: Make the link with detailed design engineering & classical work breakdown structures organisations

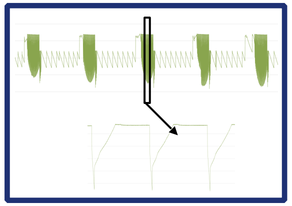
4

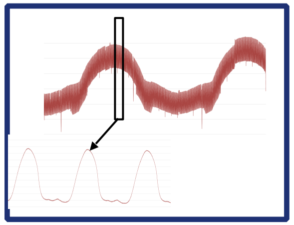
Perspectives

NEW TOPICS: DATA ANALYTICS

SATELLITE FLEET WATCH







Operability of single satellite based on telemetry gathered at fleet level

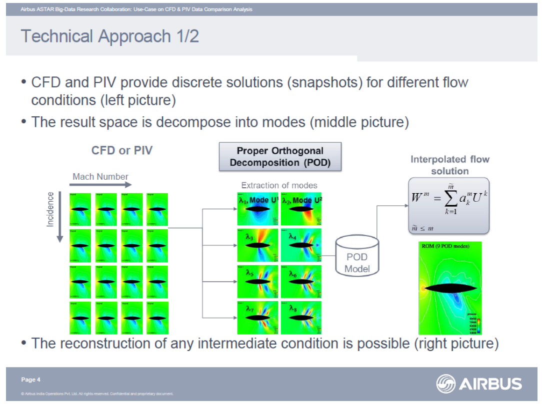
Many sensors
Year/month/day/min/sec datasets
Active fleet of satellites

FLIGHT-TEST DATA

Flight-Test plan reduction
Better maturity @ EIS

500 sensors
10 physical parameters
100 Flights

SIMULATION CFD // MEASUREMENT PIV



Calibration & data mining in large simulation datasets

SPECIFIC OPTIMIZATION PROBLEMS FOR SPECIFIC HARDWARE INFRASTRUCTURES

D:WAVE
The Quantum Computing Company™

- Quantum Computing is emerging and seems to be very promising for specific optimization problems

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CONCLUSION

- Mathematical algorithms make the difference but this is not sufficient !
- Engineers are not used to build/model optimization problems and this is not only a numerical problem
- On-going research to embrace the Robust Multi Disciplinary Optimization vision
- New topics to arise in optimization to take advantage of future on-line learning capabilities of our platforms (Big Data,

Quantum Computing

- Communities to be built between Uncertainty Quantification (GDR MASCOT-NUM/SIAM UQ) & Optimization (You !)

Thank you !

For the invitation !

For the disrupted schedule !

For your questions !

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