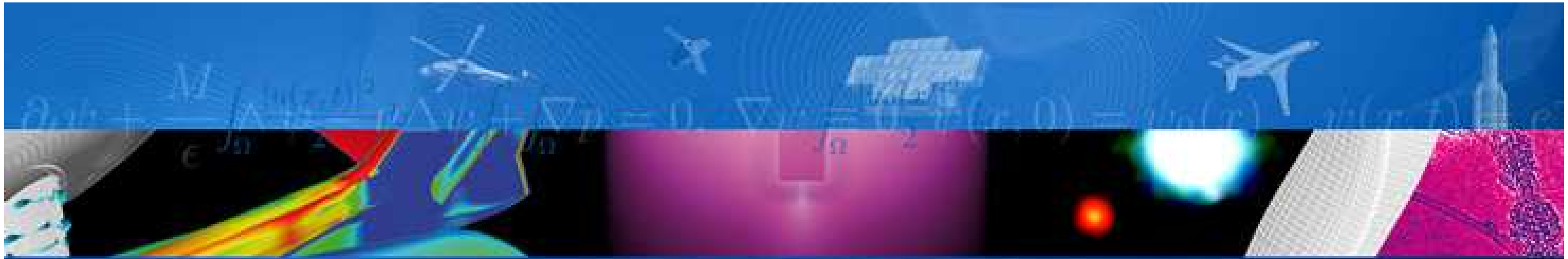


MDO advances for aircraft design in ONERA

T. Lefebvre, M. Balesdent +, N. Bartoli*, L. Brevault +, S. Defoort +, R. Lafage*, P. Schmollgruber**

(ONERA/DCPS Toulouse & Palaiseau+)*

4th SCAD Symposium,

25-27 November, Toulouse, France

ONERA

THE FRENCH AEROSPACE LAB

retour sur innovation

Outline of the presentation

Intro

- ONERA/DCPS presentation
- The aircraft design problem

Overview of MDO activities in aircraft design at ONERA

- The MDO in conceptual design
- The aircraft design roadmap

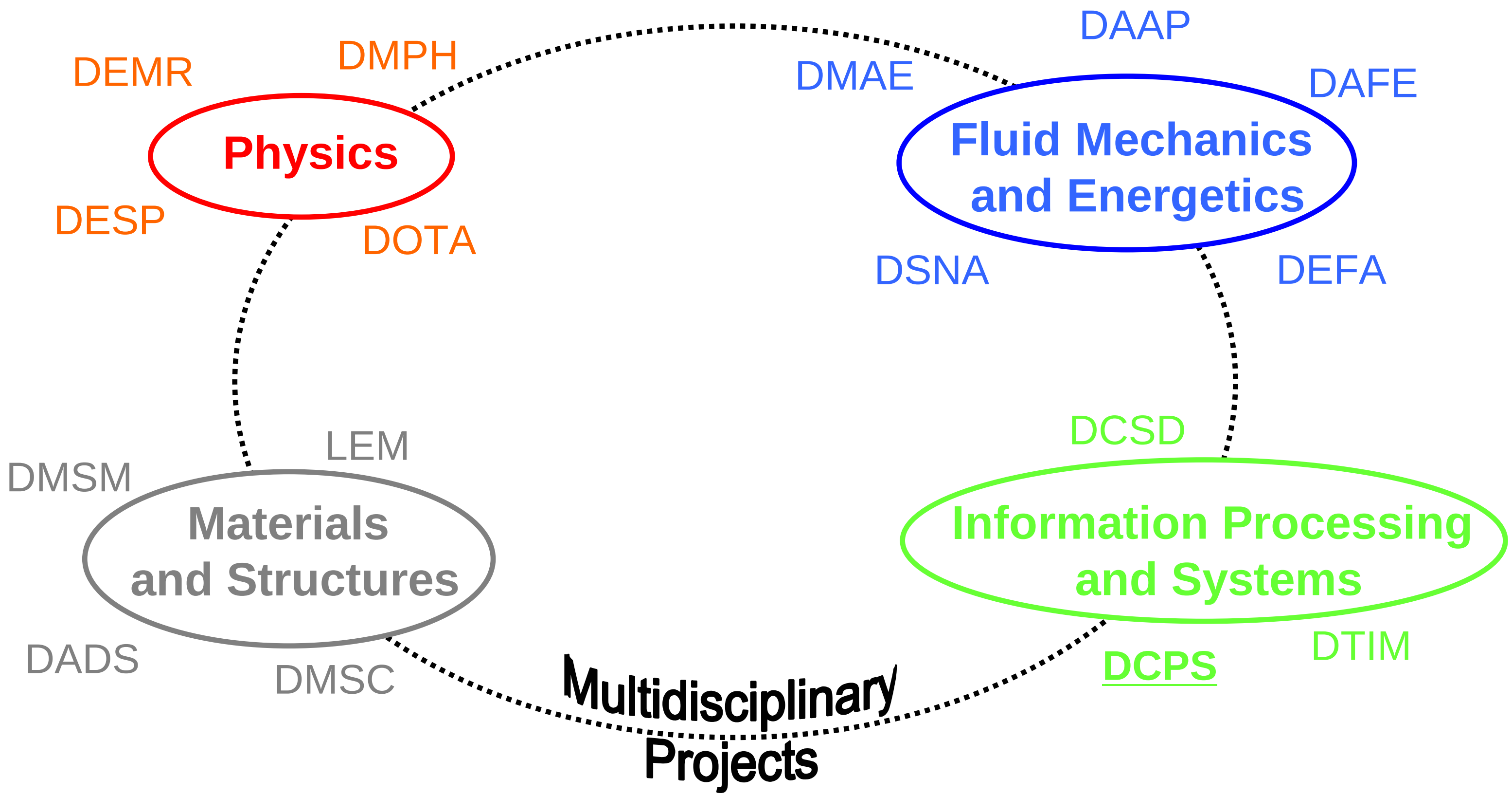
Focus on some MDO advances activities

- Meta-modelling investigations
  - Integration of new disciplines
    - Selection of MDO formulations
      - MDO with uncertainty management

Conclusion

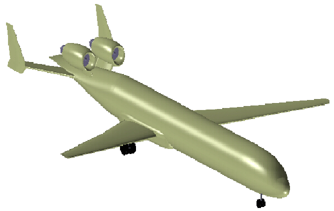
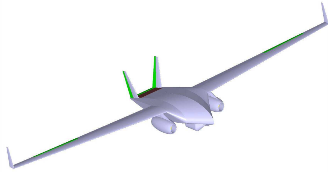
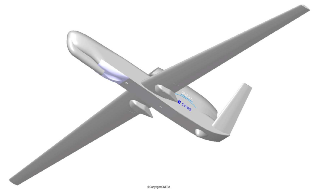
Onera – The French Aerospace Lab

The structure of Onera is based on 16 expert departments regrouped in 4 scientific branches

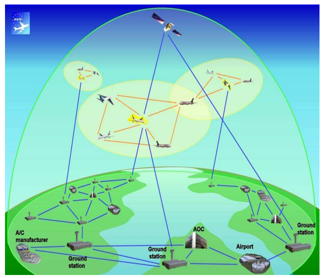
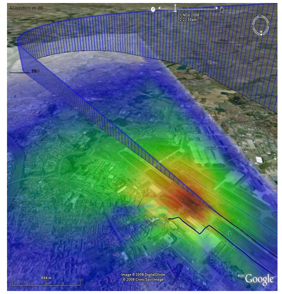


System Design and Performance Evaluation Department (ONERA/DCPS)

- Objectives
  - To promote synergy and complementarities between the expert departments within Onera
  - To develop competences in specific fields (system design, navigation and guidance, …)

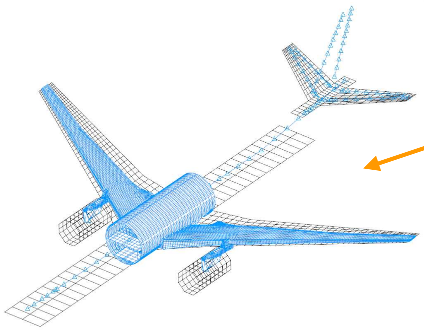
- Domains of expertise
  - Performance of aerospace systems
  - **New concepts for aerospace vehicles**
  - Monitoring, tracking and defense systems
  - **Civil aviation and air traffic**

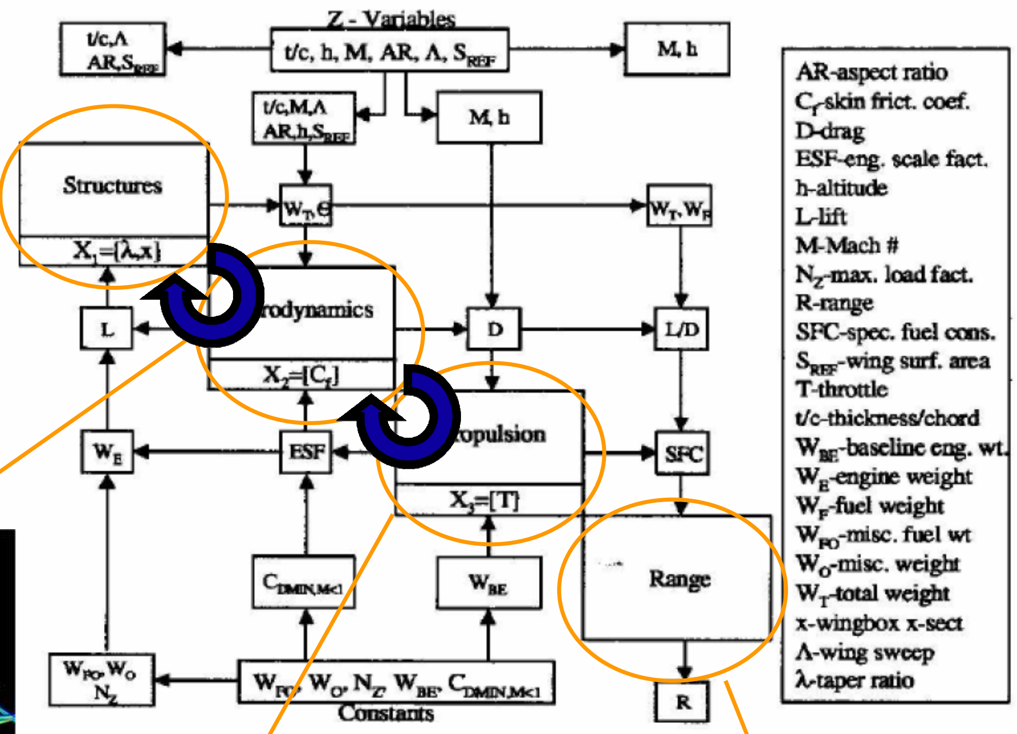



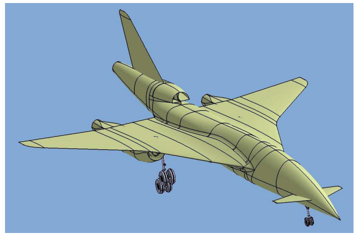
→ Focus on Aircraft Design methods and tools to develop and/or assess new concepts at the conceptual / early-preliminary level

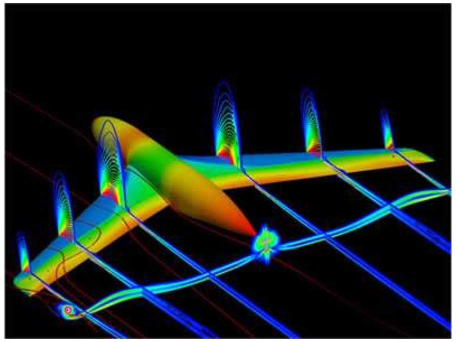
Aircraft Design : a multi-disciplinary problem

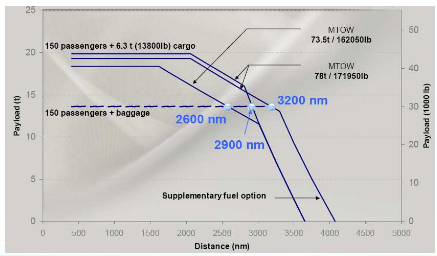
Simplified View of Interdisciplinary couplings











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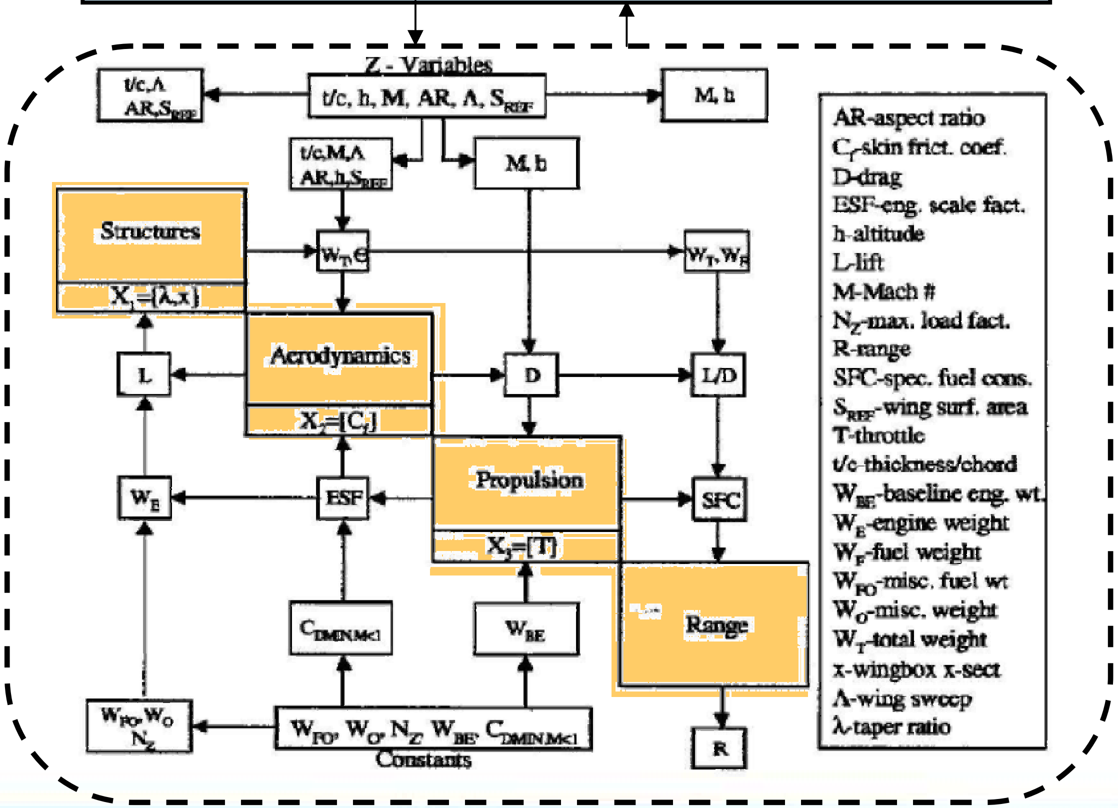
Aircraft Design : a multi-disciplinary problem for optimisation

The MDO problem

Max (Range)

w.r.t. system variables (eg. planform)

s.t. MTOW < M0



A "classical" optimisation problem

- **Mono or multiobjectives**
- **Usually with constraints**

… But some specificities

- **Heterogeneous physical modules**
- **Design variables, shared or not, continuous / discrete, etc…**
- ***Numerous multidisciplinary couplings to be solved***

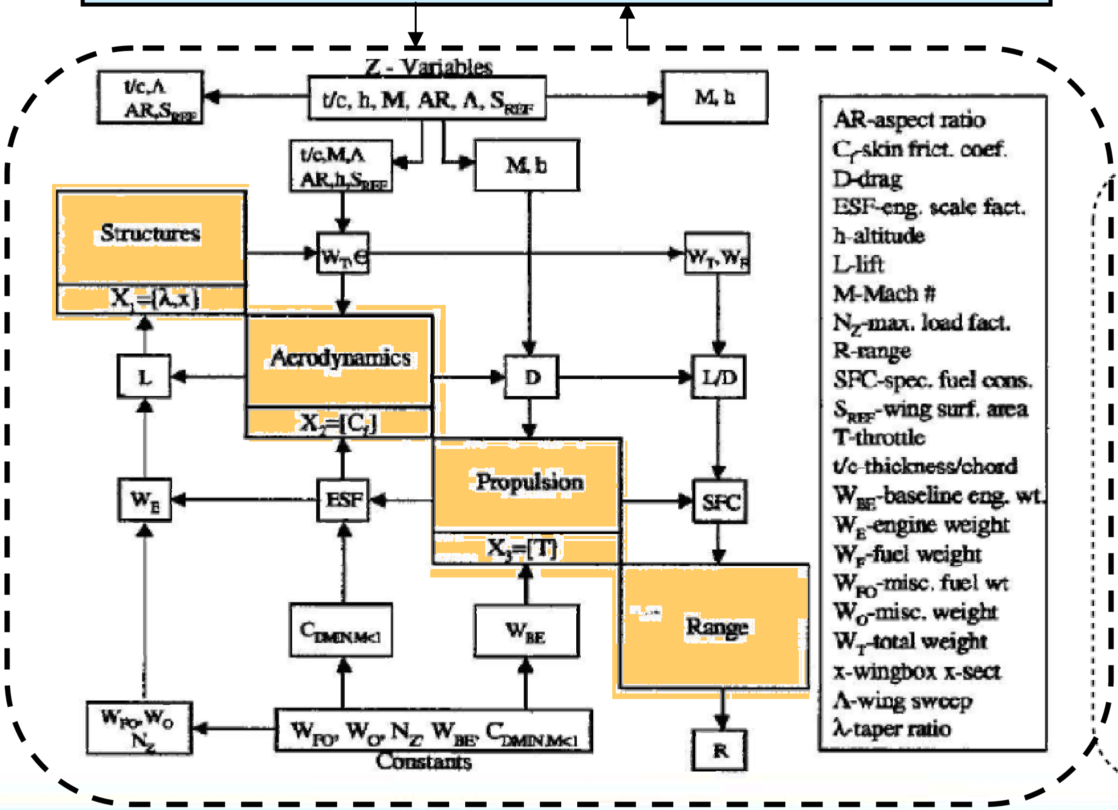
ONERA

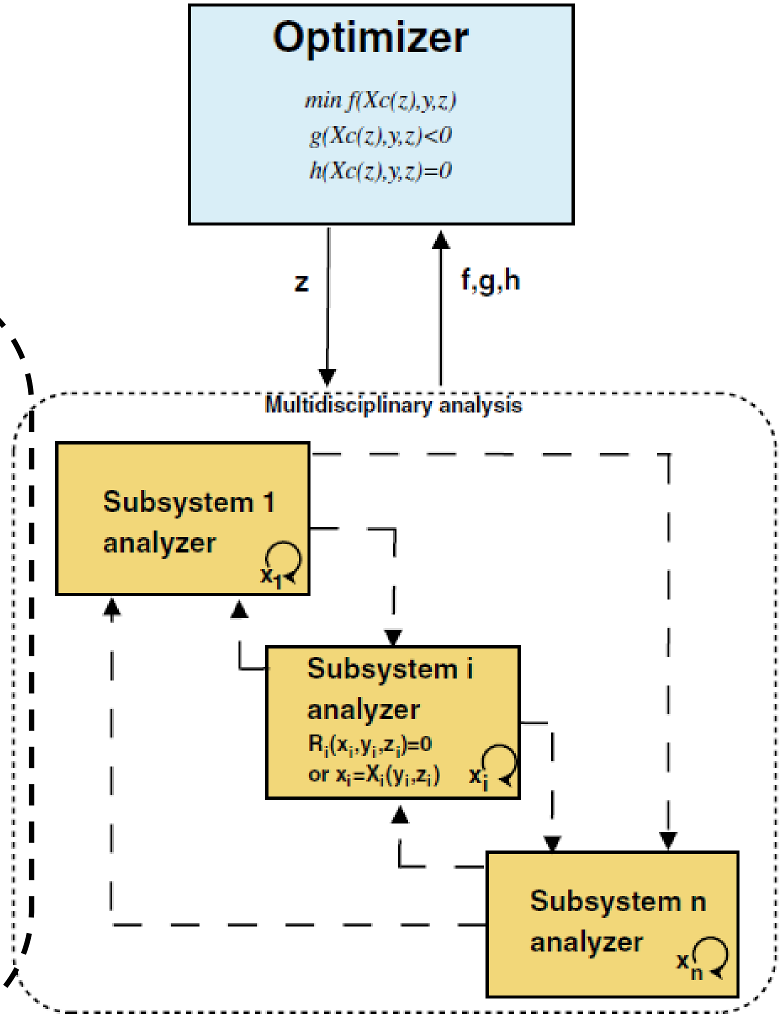
Aircraft Design : the mathematical formulation

Max (Range)

w.r.t. system variables (eg. planform)

s.t. MTOW < M0

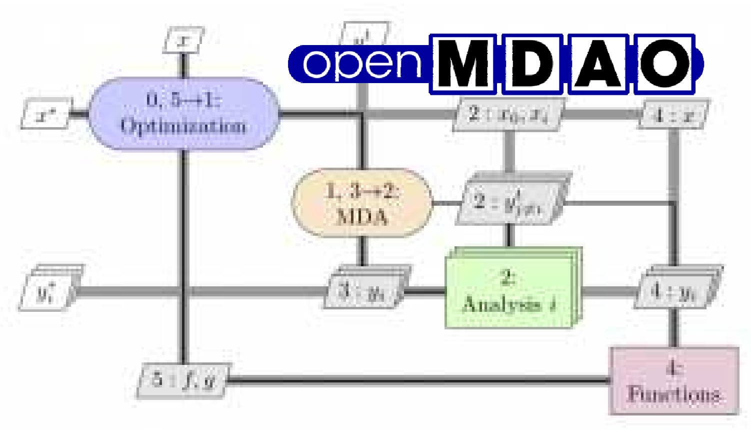


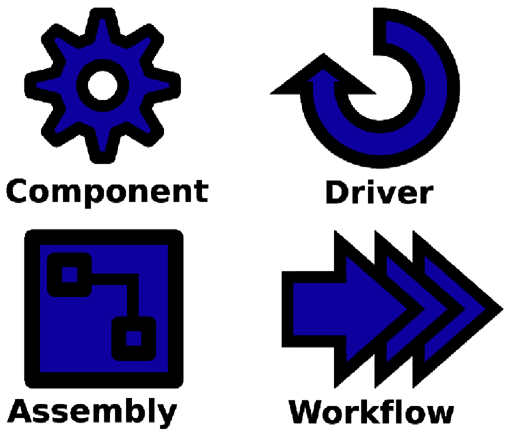


ONERA on-going evolutions in Aircraft Design

To aim at a more efficient process

- Selection of "open-source" **Integration Plateform**, enabling collaborative work and facilitating MDO formulation developments





NASA Glenn initiative (2010), python framework dedicated to complex system modelisation

Still under development (V0.10.3)

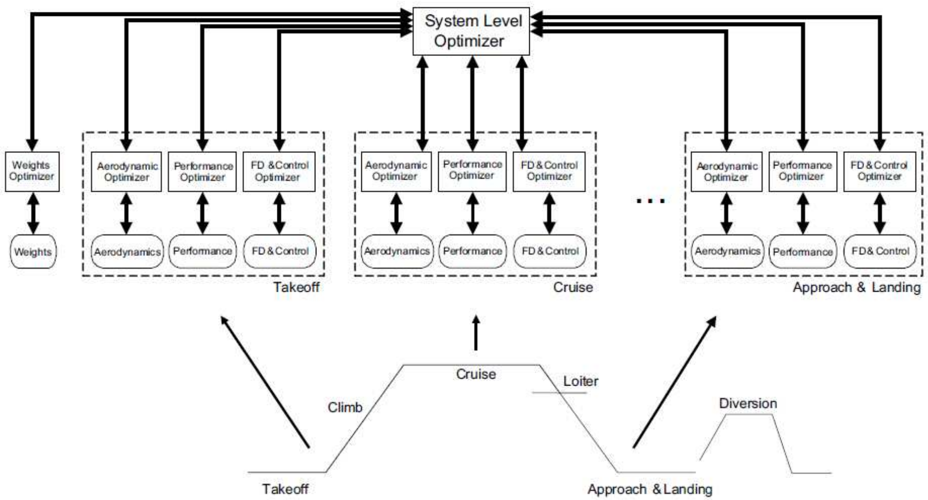
"J. Gray et al. "Standard Platform for Benchmarking Multidisciplinary Design Analysis and Optimization Architectures", AIAA Journal, Vol 51, N°10, October 2013

ONERA on-going evolutions in Aircraft Design

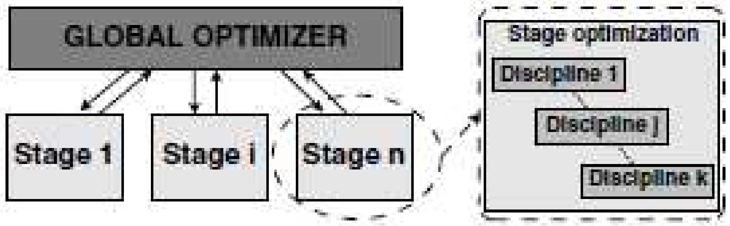
To aim at a more efficient process

• Selection of "open-source" **Integration Plateform**, enabling collaborative work and facilitating MDO formulation developments

• Investigation of **MDO formulations**, including multi-levels formulation with local optimisation



"Relaxed Static Stability Aircraft Design via Longitudinal Control-Configured MDO Methodology", *R. E. Perez and al., Journal aéronautique et spatial du Canada, 2006, 52(1): 1-14*



"Stagewise Multidisciplinary Design Optimization Formulation for Optimal Design of Expendable Launch Vehicles", *M. Balesdent and al., JOURNAL OF SPACECRAFT AND ROCKETS Vol. 49, No. 4, July – August 2012*

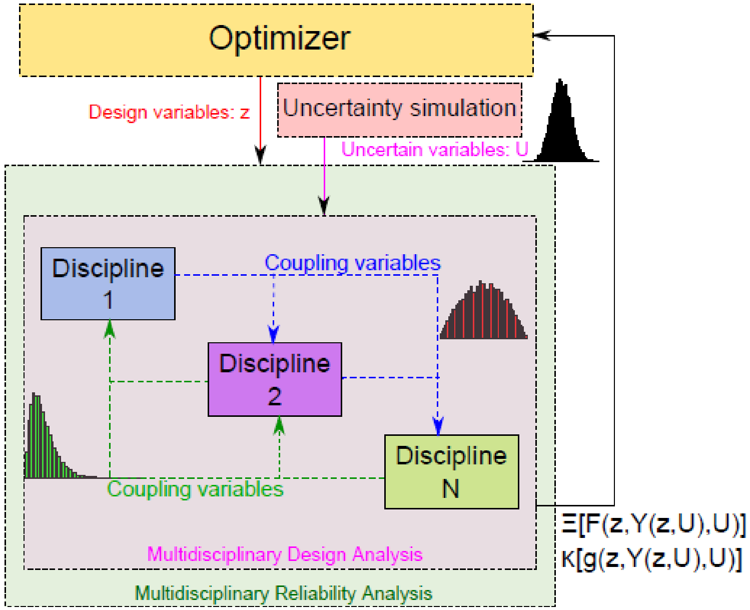
ONERA on-going evolutions in Aircraft Design

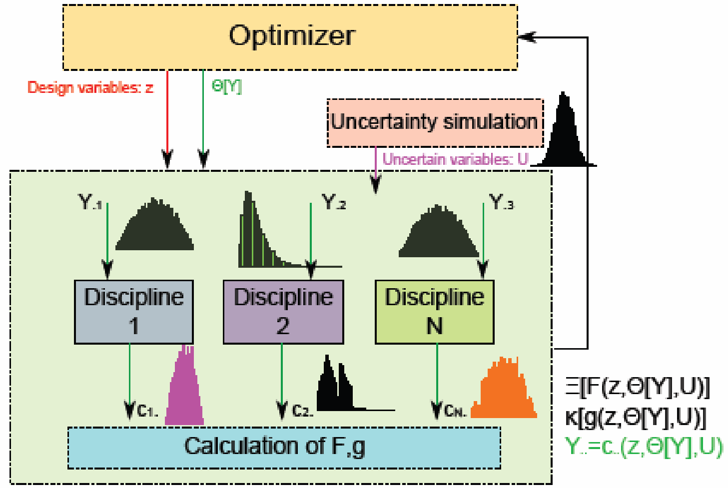
To aim at a more efficient process

- Selection of "open-source" **Integration Plateform**, enabling collaborative work and facilitating MDO formulation developments

- Investigation of **MDO formulations**, including multi-levels formulation with local optimisation

- Taking into account **uncertainty** related to design process (robust optimisation, reliability analysis, ..)

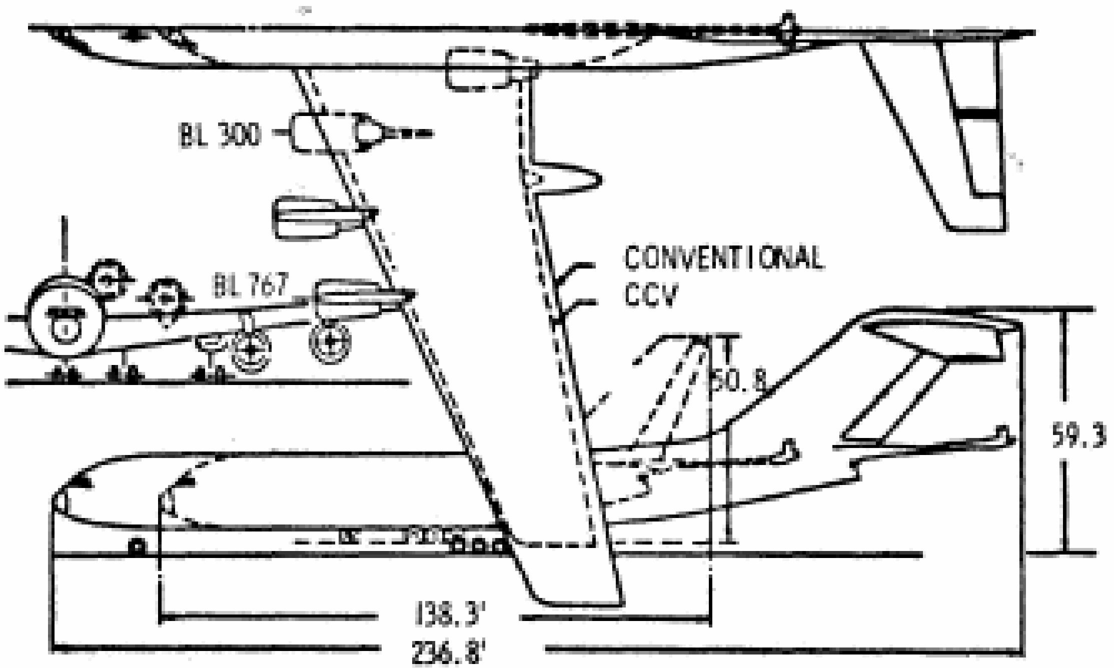




ONERA on-going evolutions in Aircraft Design

To adapt to innovative concept studies

- Adding **new disciplines** earlier in the design process (Flight Dynamics, Certification, …)



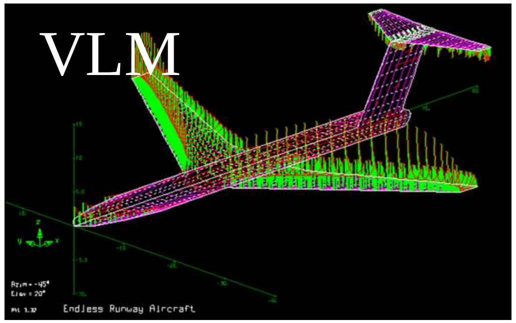
Control configured vehicle

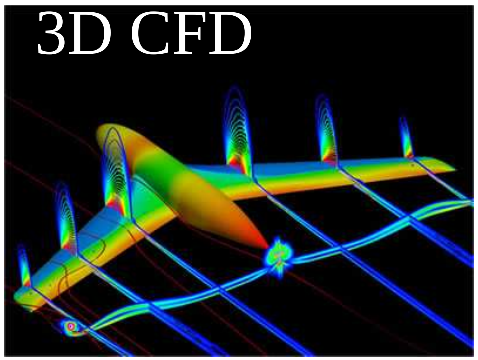
“Design of a control configured tanker aircraft”, S. A. Walker, NASA 76N31158, 1976

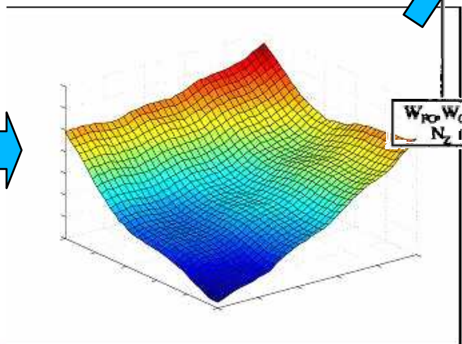
ONERA on-going evolutions in Aircraft Design

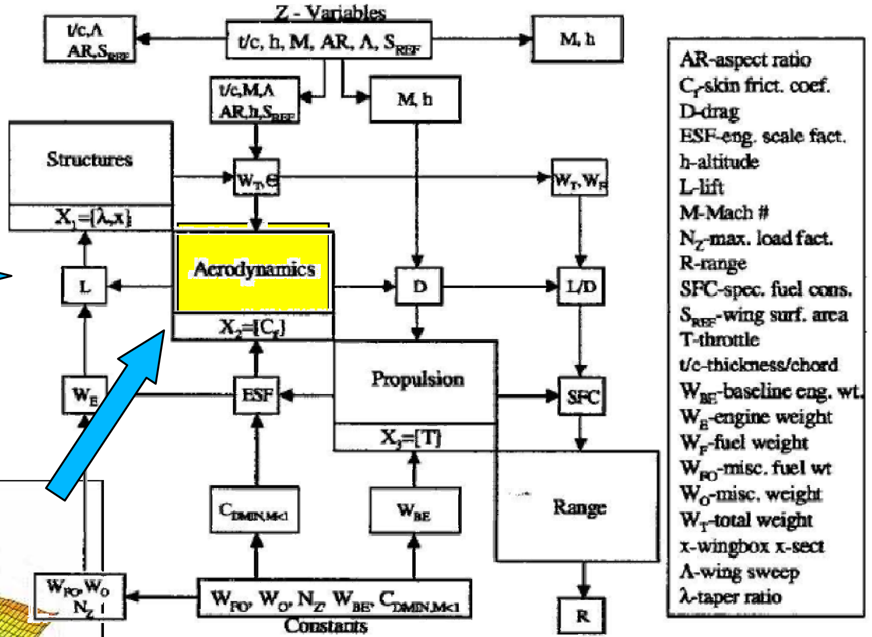
To adapt to innovative concept studies

- Adding **new disciplines** earlier in the design process (Flight Dynamics, Certification, …)
- Implementing models of medium to **high-fidelity** → Implementing **meta-modelling** capacities









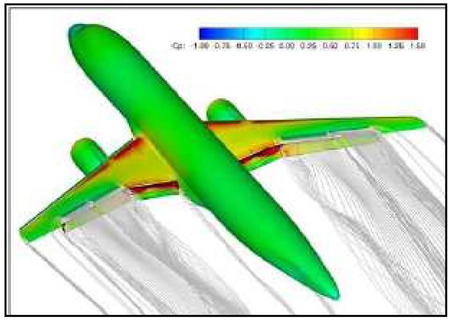
Metamodels for aircraft design

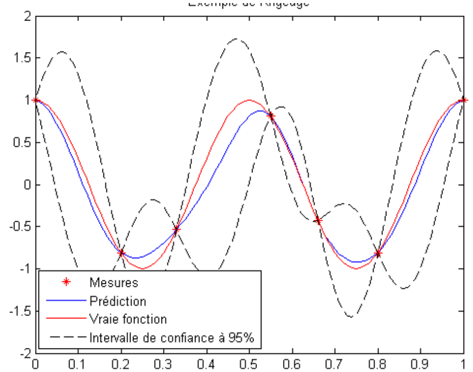
• Metamodels are useful on aircaft design (AD) when integrating new disciplines or aiming at higher fidelity:

- •In order to simplify some parts of the overall MDA process (including internal convergence loop)
- •In order to approximate costly High Fidelity models

• But AD has some specificities to be taken into account when selecting metamodels :

- •Hi-fidelity points are -always- expensive
  → limit the number of calls (or recalls)
- •A lower fidelity model is often available
  →benefit from that available information
- •Aiming at an optimal aircraft design
  →need to monitor the accuracy of the approximation of the metamodel





Current developments (in AD field)

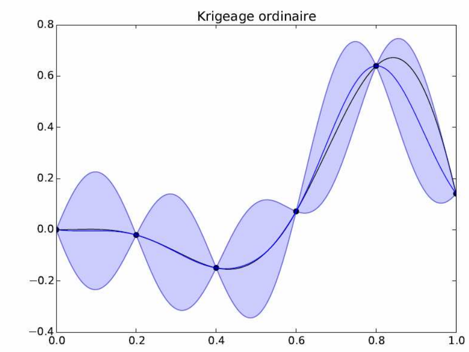
•**Single fidelity metamodels** :
Selection of **kriging** model in good adequation with OAD specificities

•**Multiple-fidelity metamodels** :
Investigation on **co-kriging** process to mix 2 levels of fidelity

•**Optimisation through metamodels**:
Investigations of **EGO** (mono and multi) process to converge towards optimal design with limited amount of points

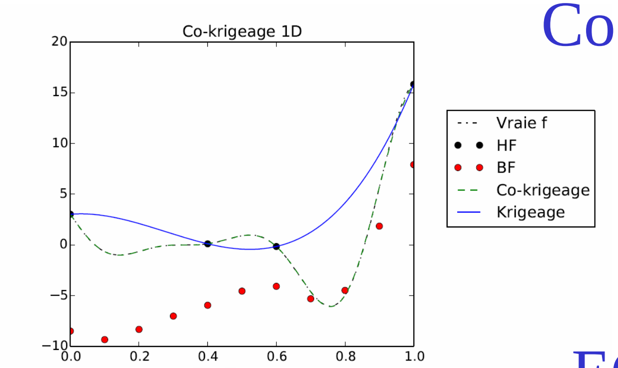
•**Implementation within OpenMDAO framework**:

- Co-kriging class developpment (nov. 2014)
- Plugin(s) development strategy for in-house models

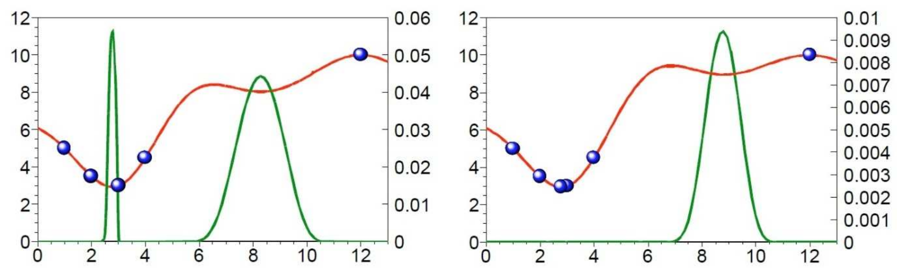


Kriging:
•Average prediction
•Standard deviation prediction

Co-kriging



EGO



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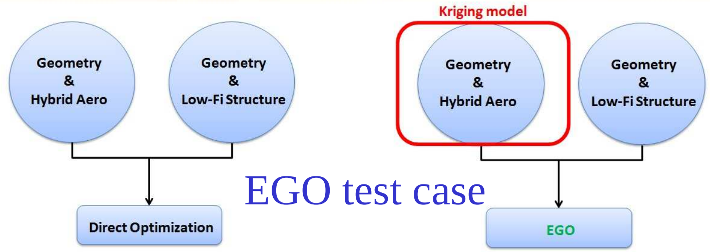
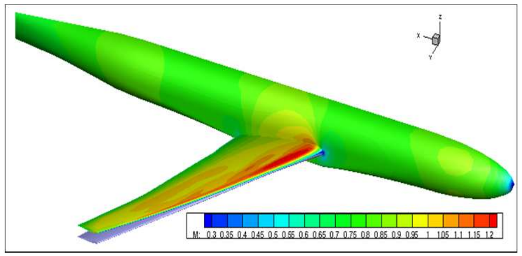
Use of metamodels: examples

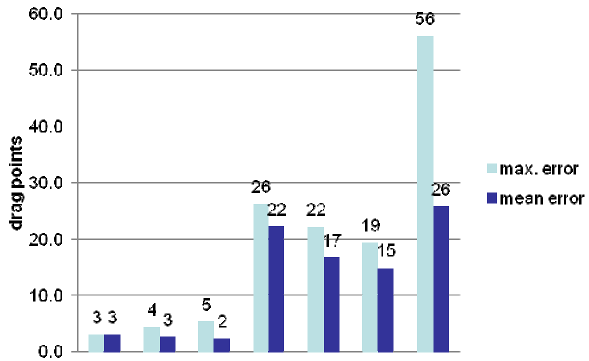
- **Investigation of Kriging and EGO**:
  - Test case : comparison of aero-structural wing optimisation using AVL code comparison with EGO approach
    → optimisation time / number of calls divided by 2

- **Investigation of co-Kriging** :
  - Test case: mixing semi-empirical results with CFD data for wing aerodynamic performance in cruise
    → Mean error get down to 5 drag counts (25 dc for reference)



EGO test case





Co-Kriging

Use of metamodels: examples

- **Investigation of Kriging and EGO**:
  - •Test case : comparison of aero-structural wing optimisation using AVL code comparison with EGO approach
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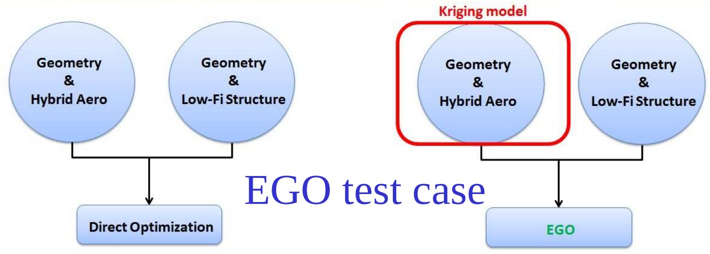
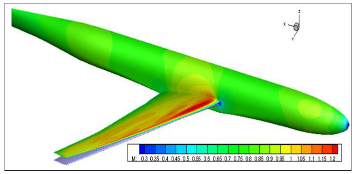
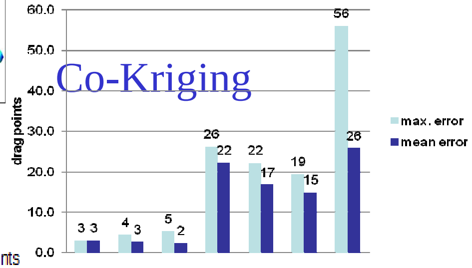
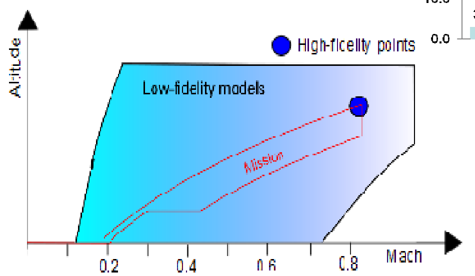
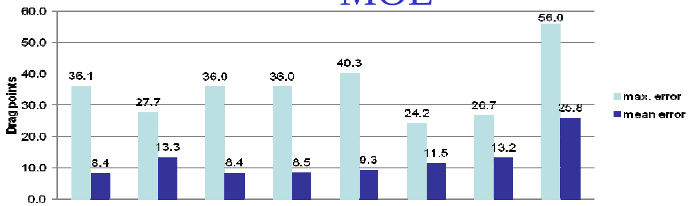
- **Investigation of co-Kriging** :
  - •Test case: mixing semi-empirical results with CFD data for wing aerodynamic performance in cruise
    → Mean error get down to 5 drag counts (25 dc for reference)
- **Investigation of "mixture of experts" technique to insert small area of high-fidelity data**
  → 2-3 times less mean error on validation base with MoE than before







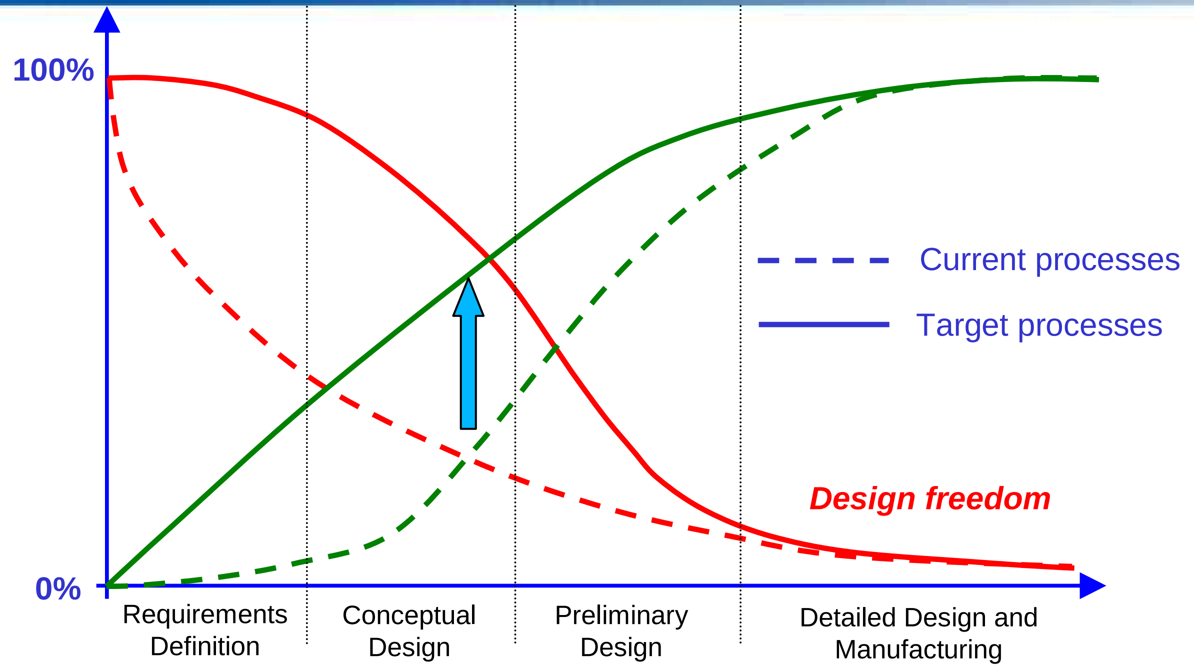




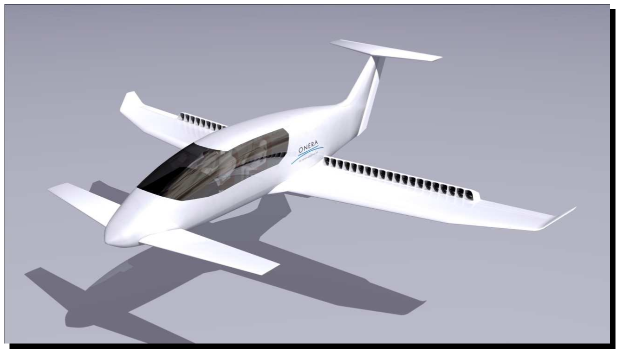
"Improving Metamodelling Approximation through a Gaussian Mixture of Experts", D. Bettebghor et al., SMDO 2011

New disciplines in aircraft design

- Objective :



Sometimes mandatory for innovative configurations !



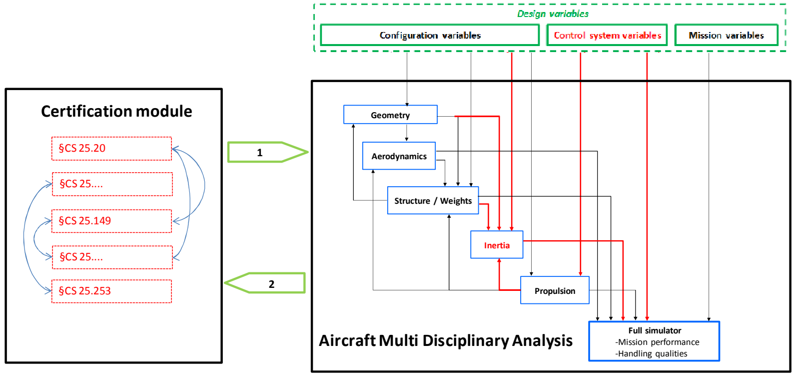
Examples of new discipline impact

Taking into account a specific domain at conceptual level :

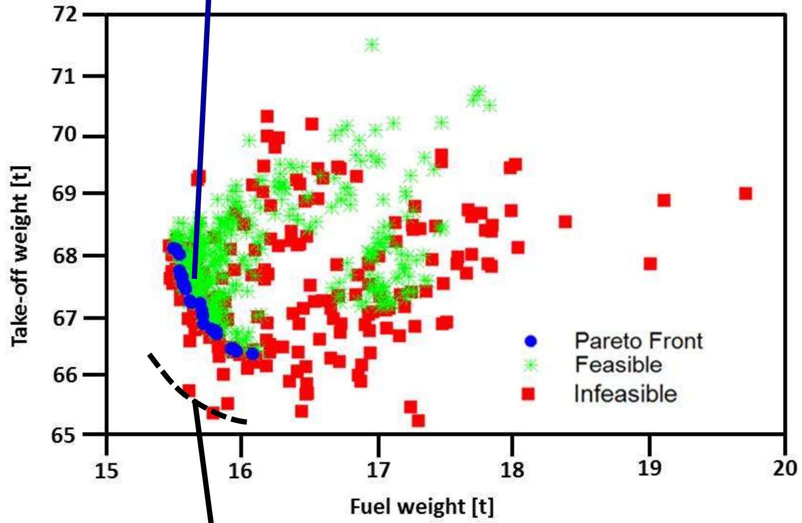
Ex : CS 25 certification constraints

GABRIEL FP7 EU project (2011-2014) :

- Assessing the impact of an assisted take-off and landing system at the aircraft level
- Modeling the take-off phase
- Assessing changes to the aircraft (new engine, no belly fairing, fixation system)



Pareto front with certification constraints



Pareto front without certification constraints

"Developpment of a certification module tailored to Aircraft Multi Disciplinary Optimization ", *P. Schmollgubber et al., 15th ATIO/AIAA conference, June 2015 (sub.)*

Examples of new discipline impact

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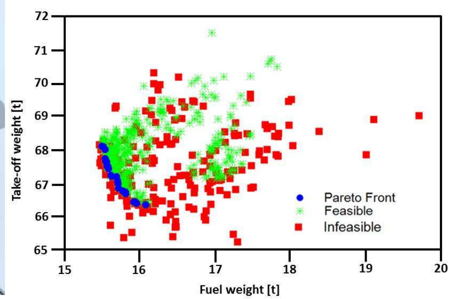
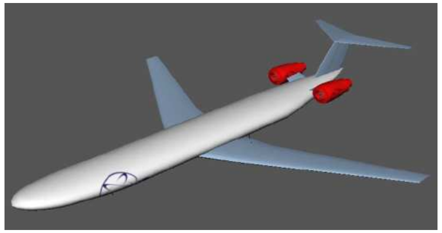


Taking into account airport and ATM constraints :

Ex : innovative airport architecture

Endless Runway FP7 EU project (2012-2014):

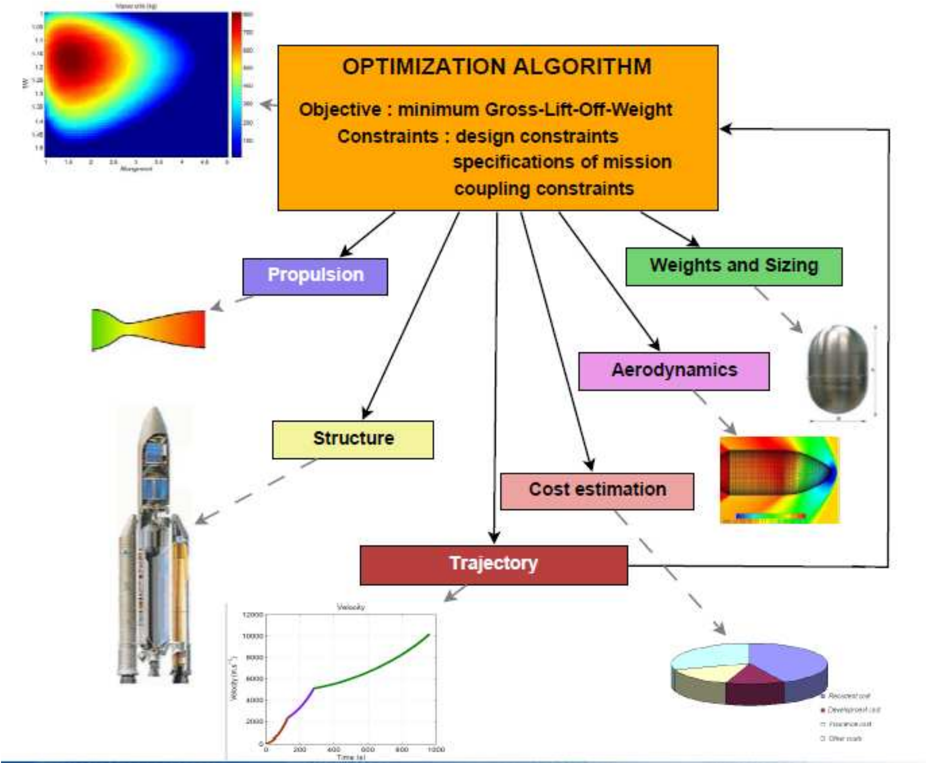
- Study the feasibility, benefits and drawbacks of an airport with a circular runway
- Evaluate interactions between airport design, aircraft behaviour, and ATM considerations



=> An innovative solution for the future of air transport is viable only if benefits are observed considering at the same time the aircraft, the airport, the air traffic management

MDO formulation – the launcher case : design problem

- Optimisation of a multi-stage launcher



Typical MDO problem

Specificities of the problem:

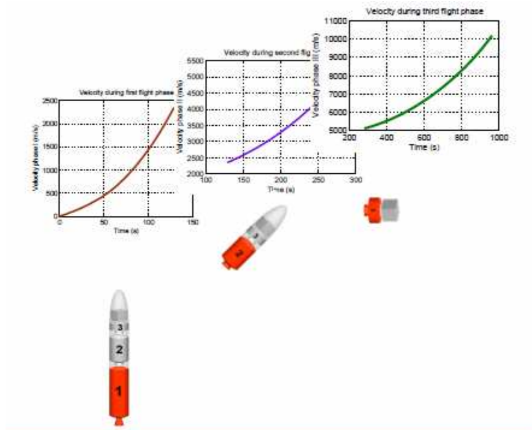
Dynamic system

Sequential flight with stage separation

Objective: find an "specific" MDO formulation :

Reducing design space and equality constraints (reference : MDF)

..



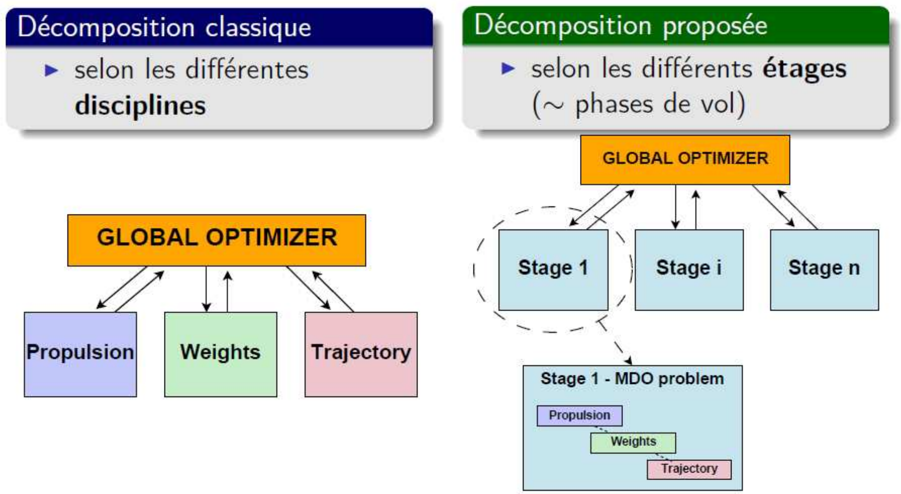
→ Stagewise decomposition

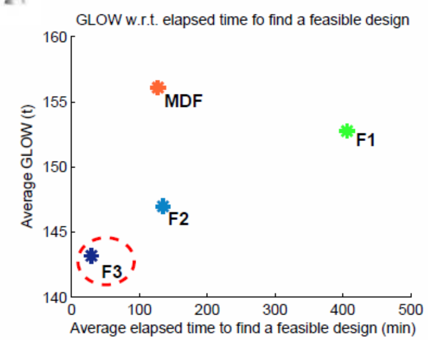
"Stagewise Multidisciplinary Design Optimization Formulation for Optimal Design of Expendable Launch Vehicles", *M. Balesdent et al., JOURNAL OF SPACECRAFT AND ROCKETS Vol. 49, No. 4, July – August 2012*

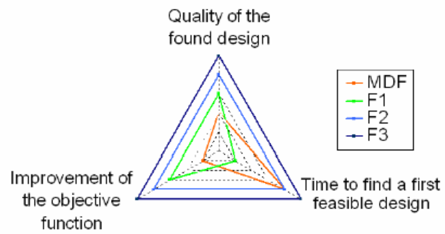
MDO formulation – the launcher case: Stage-Wise decomposition for Optimal Rocket Design

- SWORD decomposition :
  - Bi-level approach
  - Each stage considered as an "easy" MDO problem
  - Coupling between stages (mass, state vector)
- 3 SWORD formulations investigated
- Main results obtained:
  - Comparison on launcher test case (31 variables, 14 constraints)
  - Best results obtained by last SWORD formulation ("sequential" optimisation)

  → Promising approach







MDO formulation – application for Aircraft Design Formulation (on going)

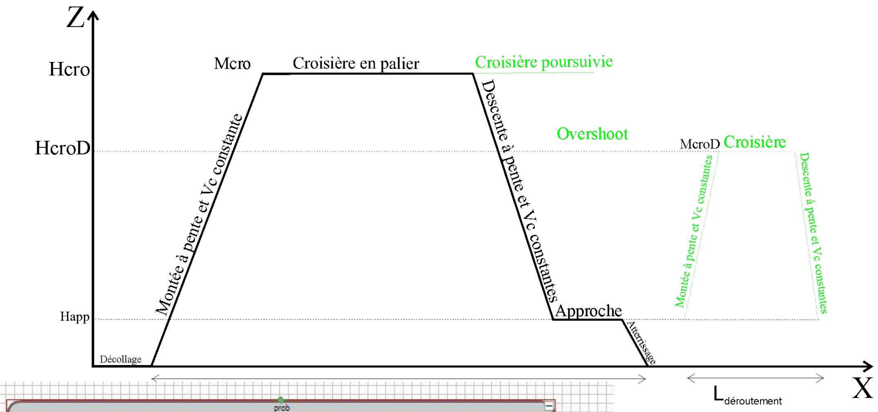
- Objective :

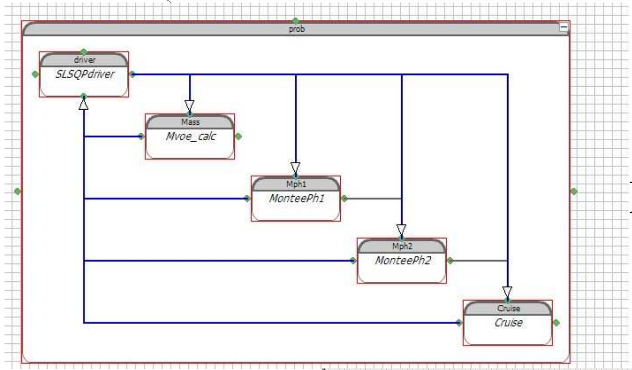
Investigate the MDO formulation per mission phase (take-off / climb/ cruise ..)

- Expected gains :
  - •Easier integration of "adapted" disciplinary models depending on mission phase
  - •Easier integration of additionnal modules per phase
  - •Easier increase of the complexity of mission description (ex: UAV design)

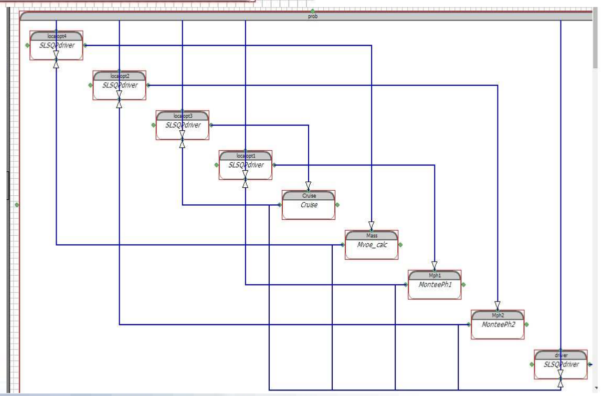
- Implementation within OpenMDAO framework :

→ Investigation of various formulations for aircraft design specificities (on going activity)





MDF



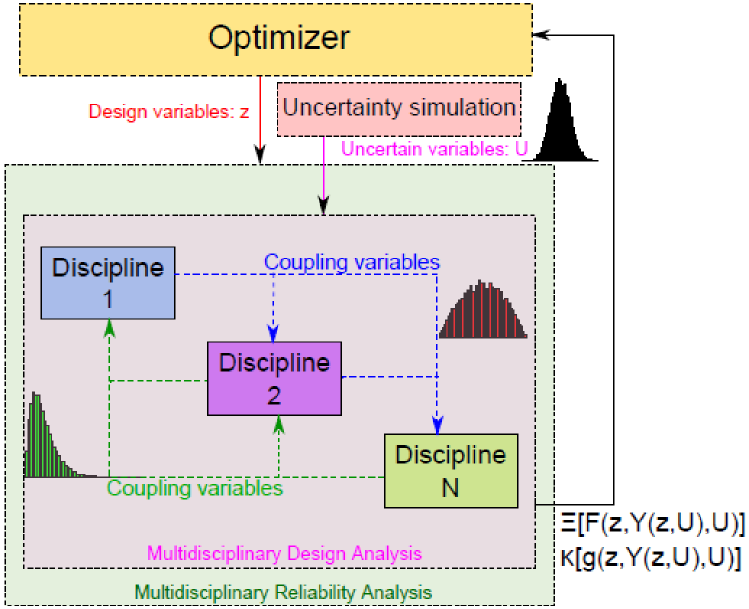
CO

Handling uncertainties in MDO problem

Handling interdisciplinary coupling under uncertainty in MDO

Development of methods aiming at statisfying the coupling for all the instantiations of the uncertain variables

UMDO problem



Solution : decoupled formulation (IDF) using a surrogate model representing the coupling functional relations (PCE)

- Iterative construction of a surrogate model of the interdisciplinary coupling functional relations
- Mean : Polynomial Chaos Expansion truncated to a degree d

$$c(\mathbf{U}) \simeq \sum_{j=0}^{d} \alpha_j \Psi_j(\mathbf{U}) = \hat{y}(\mathbf{U}, \boldsymbol{\alpha})$$

- The optimiser handles the PCE coefficients α ; at convergence, they represent the coupling relations

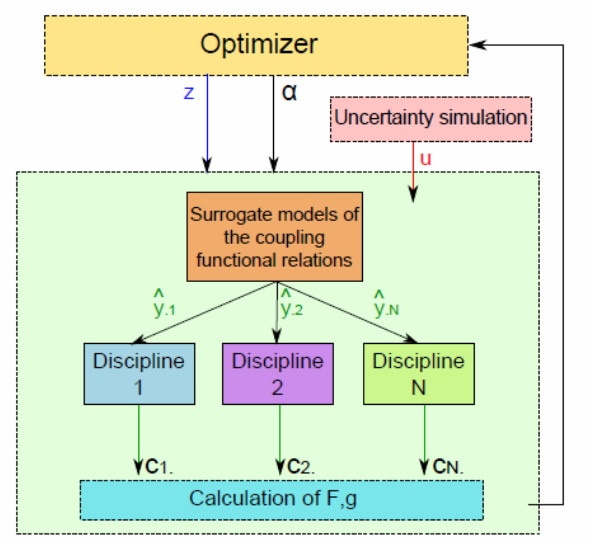
"Decoupled UMDO Formulation For Interdisciplinary Coupling Satisfaction Under Uncertainty ", *L. Brevault et al., 14th AIAA/ISSMO conference, june 2014*

Handling uncertainties in MDO problem

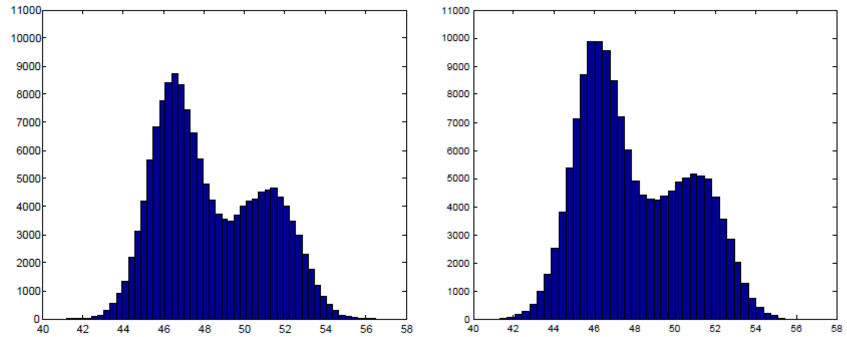
Handling interdisciplinary coupling under uncertainty in MDO

Results : IDF-PCE methods (Individual Discipline Feasible - Polynomial Chaos Expansion**)**

- Agreement of the distribution of the coupling variables at convergence (even multimodal probability density)
- Decrease by a factor > 400 in the number of calls to each discipline compared to refrence MDF + MonteCarlo



MDF



IDF-PCE (MC)

Résultats	MDF-MDA (ref)	IDF-PCE (MC)	IDF-PCE (quadrature)	IDF-PCE (PCE)
Objectif	$\mu_F = 0.928$ (0.64%)	$\mu_F = 0.926$ (0.65%)	$\mu_F = 0.926$ (0.70%)	$\mu_F = 0.914$ (0.49%)
Variables conception	$z_{sh} = 0.520$ (0.63%) $z_1 = 0.340$ (1.13%) $z_2 = 0.658$ (1.55%)	$z_{sh} = 0.511$ (0.86%) $z_1 = 0.339$ (1.11%) $z_2 = 0.661$ (1.30%)	$z_{sh} = 0.514$ (1.34%) $z_1 = 0.340$ (1.27%) $z_2 = 0.661$ (1.68%)	$z_{sh} = 0.523$ (1.03%) $z_1 = 0.349$ (1.13%) $z_2 = 0.649$ (0.95%)
Nb itérations optimisation	$N_i = 2016$ (5.34%)	$N_i = 5608$ (14.5%)	$N_i = 5501$ (9.56%)	$N_i = 5262$ (8.10%)
Nb appels disciplines	$N_d = 1512 * 10^6$	$N_d = 841.2 * 10^6$	$N_d = 3.52 * 10^6$	$N_d = 3.37 * 10^6$
Division du nb d'appels	1 (ref)	1.80	429.55	448.66

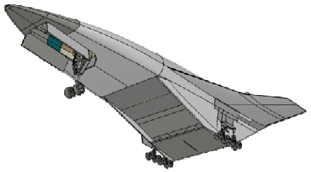
Conclusion

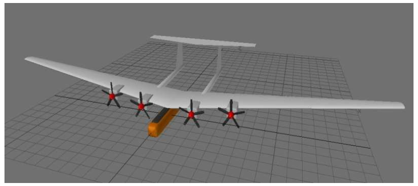
Main characteristics for aircraft design in ONERA

- Internal MDO roadmap for AD :

  Objective: increase the efficiency of the process & adapt to innovative configurations

  Means : more adapted MDO formulation, new disciplines integration, metamodelling developpment, uncertainties management, ….





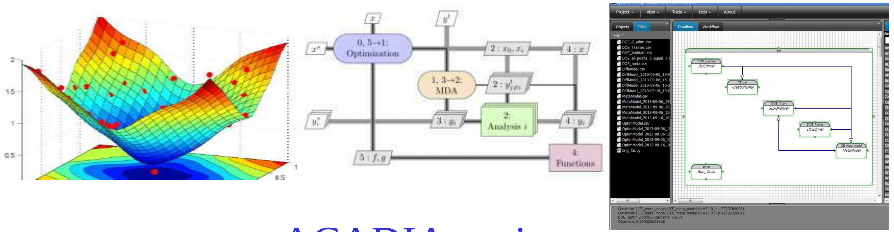
- Benefit from activities made at :

  - DCPS for other aerospace vehicles applications (launcher, hypersonic vehicles, ..)

  - other ONERA Disciplinary Departments involved in OAD (aerodynamic, structure, flight dynamics, …)

- Mutualise the methods and disciplinary modules developped for specific applications

→ launch of internal project (ACADIA)

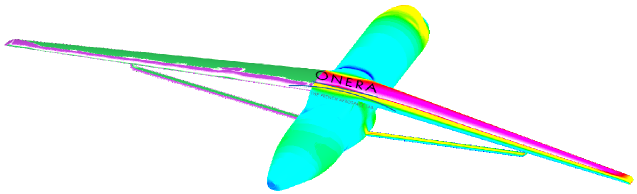


ACADIA project

Next steps

Next steps

- Increase the fidelity of the disciplinary tools use in conceptual design
  - Ex: CFD (aerodynamics), F.E.M (structures), 6 DOF model (mission)



ALBATROS project

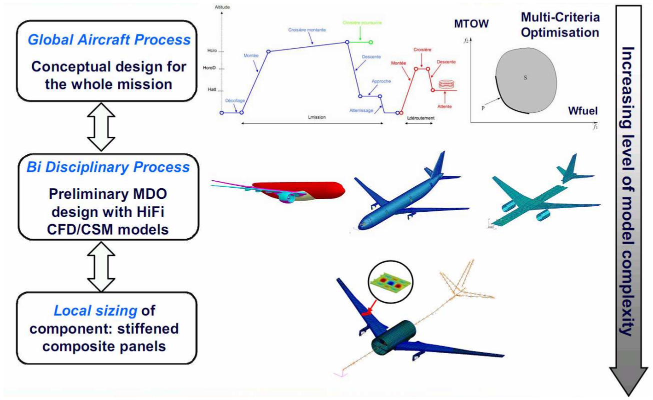
- Evaluate our tools on innovative aircraft concepts (EU H2020 and internal projects):
  - Involved in SPEARHEAD, FLY-AHEAD and EFRA2 projects, involved in AGILE project
  - Involved in CS2 project
  - Internal project on BWB design: CICAV

  (2015 – 2018) : long range, 300-500 pax

FLY-AHEAD

EFRA2

- Explore new approach, coupling Conceptual Design (CD) to Detailed Design (DD) :
  - Transfer the knowledge about the system acquired at CD stage into the DD optimisation problem (trade off factors, AD constraints, …)



ARTEMIS project (2009-2012)

Thank you for your attention

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