A data-driven scalable problem to compare MDO formulations

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H2020 MADELEINE Project

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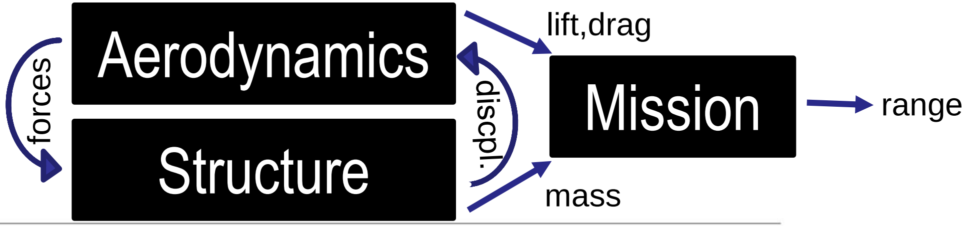
Multidisciplinary design

- Find the design of an aircraft
  e.g. its shape
- Maximizing a performance over a mission
  e.g. its maximum total range
- Respecting specifications
  e.g. strength stress
- By numerical optimization from coupled computer codes:

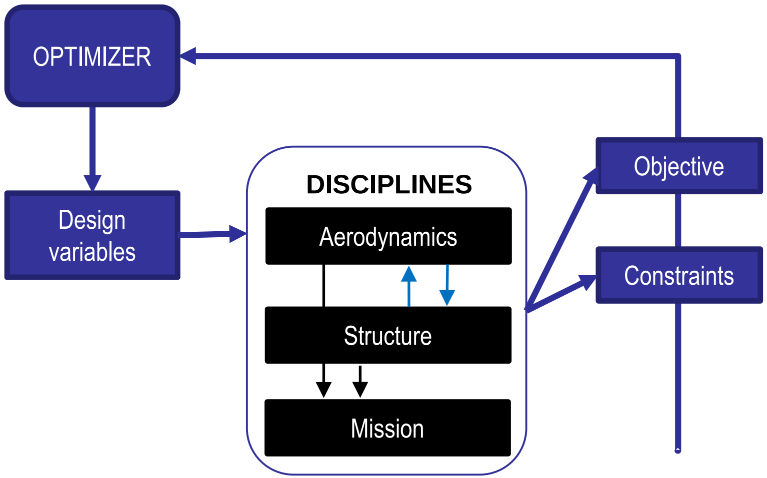
disciplines

There are several *mathematically equivalent* **<u>formulations</u>** of this optimization problem leading to the same optimal design solution

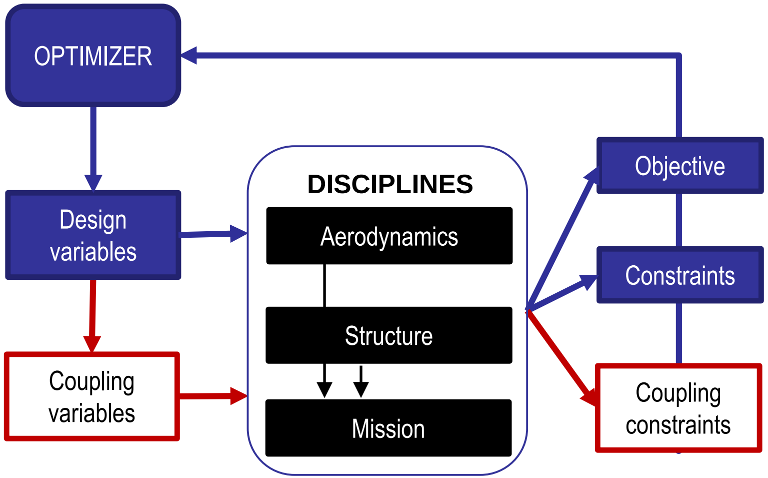


Two classic MDO formulations

- **M**ultidisciplinary **D**esign **F**easible

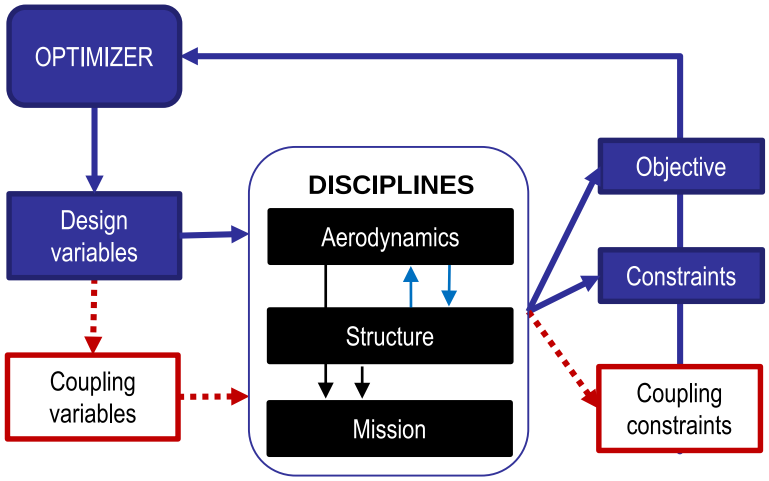


- **I**ndividual **D**esign **F**easible



What is the best MDO formulation?

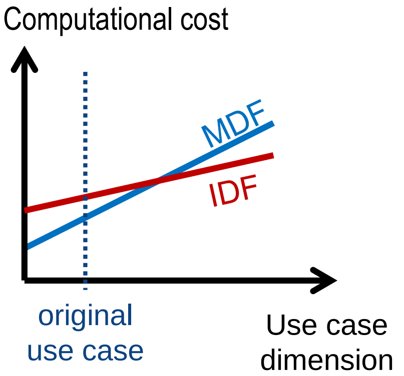
- IDF or MDF?



- Or a bi-level formulation?

  (➔ use sub-optimizers)

- It depends on the use case
- And if the dimension varies?

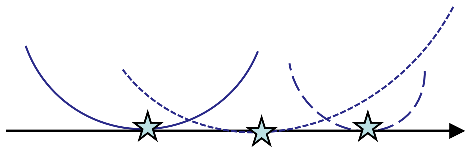


- Still depends on the use case!

Given an use case, compare MDO formulations…

- The use of the original computer codes is too expensive.
- The construction of *accurate* surrogate models is expensive.

- **Trick:** approximate the mathematical properties coming from the computer codes rather than the computer codes

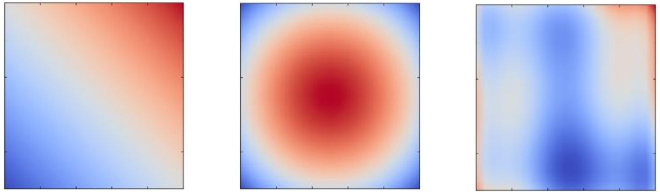


« We do not want to minimize a given quadratic function but quadratic functions. »

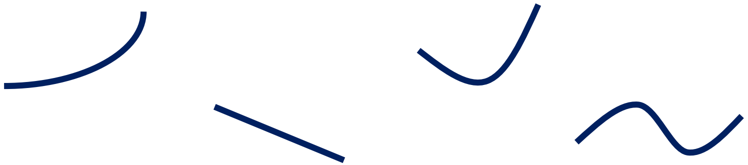
- **How:** build a family of use cases made of cheap models sharing these mathematical properties

Methodology | Scaled discipline

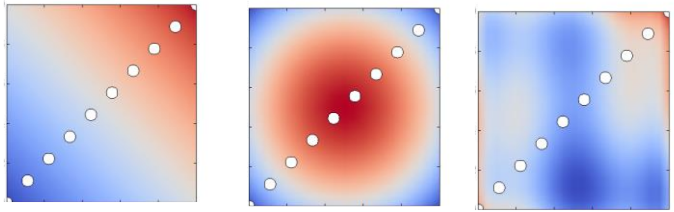
1. Let us consider a discipline with 2 inputs and 3 outputs:



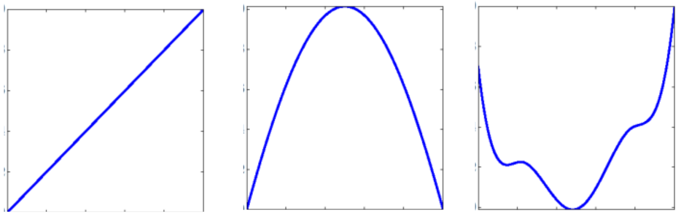
2. We look for patterns like:



3. We sample a diagonal of the input space with 10 points



4. We obtain 3 basis functions:

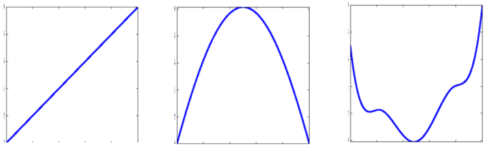


On the Consequences of the "No Free Lunch" Theorem for Optimization on the Choice of an Appropriate MDO Architecture, Charlie Vanaret, Francois Gallard, and Joaquim Martins, 18th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, 2017

Methodology | Scaled discipline

5. We create a *scaled* version of the original discipline, with new numbers of inputs and outputs:

$$f_j(x) = \sum_i w_{ij} \times \mathrm{rand}_j \Big[$$



$$\Big](x_i)$$

where w_{ij} is a random number, either in $[0,1]$ or in $\{0,1\}$

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Methodology | Scaled MDO problem

I. Build the MDO problem

1. Set the dimension
   of the use case:
   # local design variables,
   # global design variables,
   # coupling variables,
   # constraints.
2. Build the design space.
3. Build the scaled
   disciplines.

II. Solve the MDO problem with $\neq$ MDO formulations

1. Solve the MDO problem.
2. Estimate
   the computational time
   from the numbers of evaluations,
   linearizations, sub-optimizations, …

III. Compare the formulations

in terms of computational time

Application | XRF-1 | Ad-hoc formulations

XRF-1 use case from Airbus
Learning data from DLR

Design variables: 126 spanwise profiles, 24 planform parameters and 392 thicknesses

Constraints: 10 / OAD and 10,000 / Structure

Objective: range(CL,CD,mass)

SEQUENTIAL

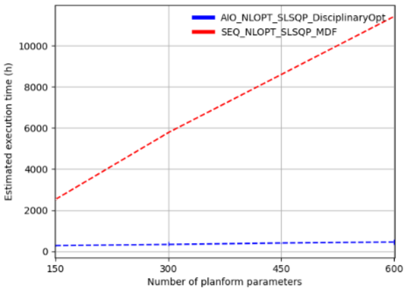
Optimizer	Planform Parameters	Shape Parameters	Shape Parameters
Global aircraft constraints	OAD		
Mass		Structure Sizing	Thicknesses Mass
Cl, Cd			AeroElastic-Performance Analysis

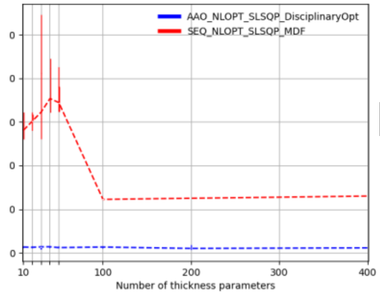
$$\mathrm{Cost(sequential)} = n_a \times \mathrm{Cost}_a + n_s \times (7'050 + 7.67 \times n_{\mathrm{thicknesses}})$$

$$\mathrm{Cost(AAO)} = n_{aao} \times \mathrm{Cost}_{aao} + n_{linearization,aao} \times \mathrm{Cost}_{\mathrm{linearization,aao}}$$

ALL-AT-ONCE

Optimizer	Planform Parameters	Shape Parameters Thicknesses	Shape Parameters Thicknesses
Global aircraft constraints	OAD		
Mass & Structure constraints		Structure Analysis	Mass
Cl, Cd			AeroElastic-Performanc eAnalysis

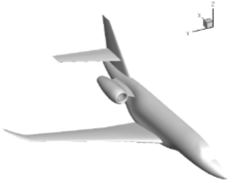




AAO seems to be more relevant

Application | GBJ | State-of-the-art formulations

GBJ use case from Dassault Aviation (DA)
Learning data from DA and ESI



IDF or MDF?

Design variables: angle of attack, 4 wing twist angles, 4 material parameters

Constraints: plasticity criterion, pitching moment, lift-base criterion

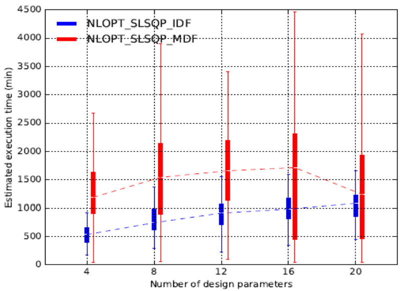
Objective: Fuel Burn

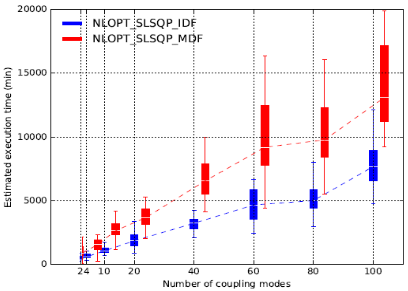
$$\mathrm{Cost(MDF)} = n_a \times (0.3 \times \mathrm{Cost}_a) + n_s \times \mathrm{Cost}_s + n_{\mathrm{linearization,MDA}} \times n_{coupling} \times \mathrm{Cost}_{\mathrm{adjoint,a}}$$

$$\begin{aligned} \mathrm{Cost(IDF)} &= n_a \times \mathrm{Cost}_a + n_s \times \mathrm{Cost}_s \\ &+ n_{\mathrm{linearization,a}} \times n_{\mathrm{coupling,aero,out}} \times \mathrm{Cost}_{\mathrm{adjoint,a}} \\ &+ n_{\mathrm{linearization,s}} \times \left(n_{\mathrm{coupling,structure,in}} + n_{\mathrm{material\ parameters}}\right) \times \mathrm{Cost}_s \end{aligned}$$

Optimizer	**AoA, xA**	**xM**	
Constraints	Aerodynamics	FS	CD, CL
Constraints	US	Structure	ZFW
Fuel burn, constraints			OAD

coupling modes





IDF seems to be more relevant

Conclusion

- The scalable methodology is a quite innovative method to compare the convergence rate of MDO formulations.
- It is generic because it is applicable:
  - to any multidisciplinary design use case,
  - to both state-of-the-art and *ad-hoc* MDO formulations.
- It allows to advise on the choice of MDO formulations for both the current and future dimensions of the use case
- It has been applied for the very first time to industrial level use cases.

Perspectives

- Go beyond the diagonal trick:
  - Idea: include cross-effects between input variables
  - How: use a coarse surrogate model
  - Issue: make it scalable
  - Trick: use a kernel-based surrogate model, e.g. Kriging
- Improve the estimation of the computational time
- Compare both formulations and optimizers
- www.gemseo.org, an open source MDO library
  to experience and improve the scalable methodology

MADELEINE

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