AGILE
Aircraft 3rd Generation MDO for Innovative Collaboration of Heterogeneous Teams of Experts

MDO ARCHITECTURES

A COMPARISON STUDY OF MDO PLATFORMS

DLR

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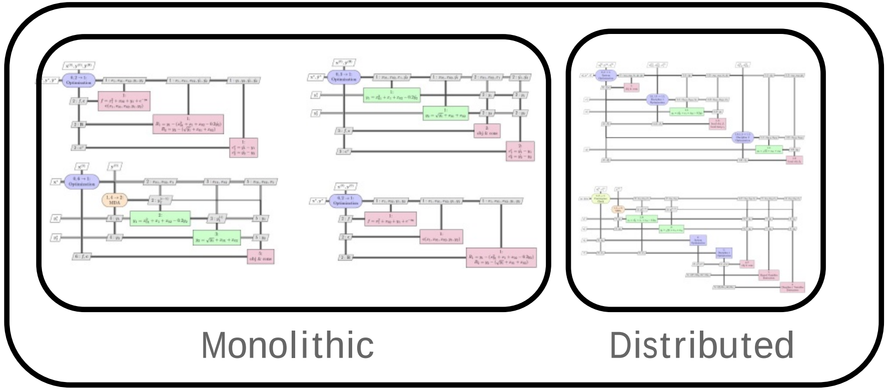
HORIZON 2020 PROJECTS

MDO Architectures Benchmarking Challenges



MDO Architectures

HYBRID PLATFORM

1. Distributed architectures are seldom considered.
2. MDO results strongly depend on the implementation.

MDO Architectures Benchmarking Challenges

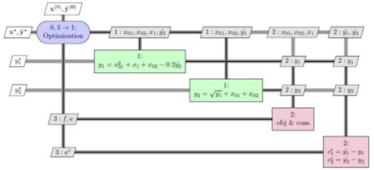
Analytical Problem

Sellar Problem

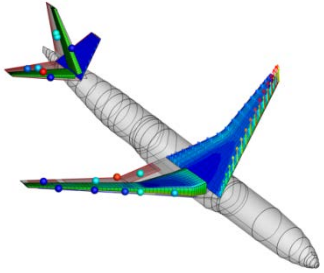
$$\min \; x_1^2 + x_{02} + y_1 + e^{-y_2}$$

with

$$y_1 = x_{01}^2 + x_1 + x_{02} - 0{,}2 y_2$$
$$y_2 = \sqrt{y_1} + x_{01} + x_{02}$$



Large Scale Problem



OAD workflow

3. Often, low dimensional (analytical) use case.

OUTLINE

- The Sellar Problem
  - SAND
  - MDF
  - IDF

  Monolithic

  - CO
  - BLISS

  Distributed
- Architectures Comparison
- Platforms Comparison

- The OAD Problem
  - MDF Gauss-Seidel
  - MDF Jacobi
  - IDF

  Monolithic

  - CO

  Distributed
- Results

- The HYBRID PLATFORM

THE SELLAR PROBLEM

- The Sellar Problem
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THE SELLAR PROBLEM

One of the most used benchmark problem

Objective	Constraints	Disciplinary eq.
$\min \; x_1^2 + x_{02} + y_1 + e^{-y_2}$ $\boxed{\text{respect to } x_{01}, x_{02}, x_1}$	$1 - y_1/3{,}16 \leq 0$ $y_2/24 - 1 \leq 0$ $-10 \leq x_{01} \leq 10$ $0 \leq x_{02} \leq 10$ $0 \leq x_1 \leq 10$	$y_1 = x_{01}^2 + x_1 + x_{02} - 0{,}2y_2$ $y_2 = \sqrt{y_1} + x_{01} + x_{02}$

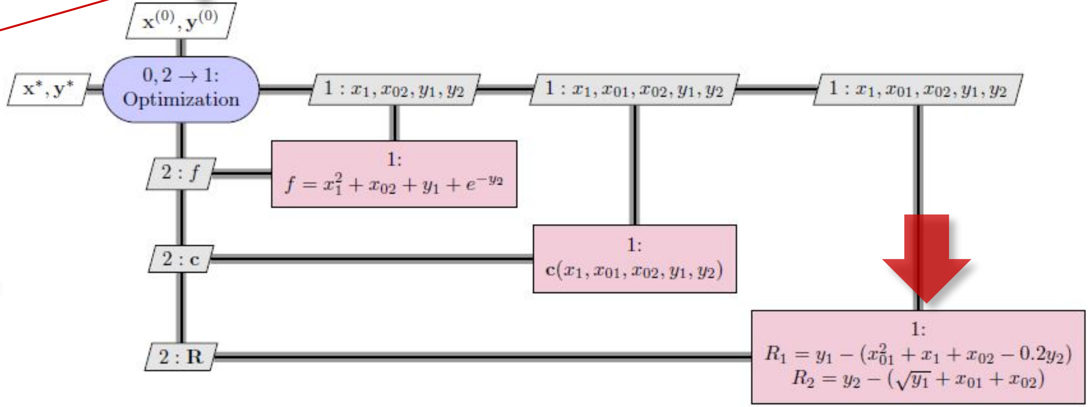
- Design variables: shared x_{01}, x_{02} ; local x_1
- State variables: shared y_1, y_2 ; no local design variables

THE SELLAR PROBLEM
Simultaneous Analysis aNd Design - SAND

Objective	Constraints	Disciplinary eq.
$\min\ x_1^2 + x_{02} + y_1 + e^{-y_2}$ respect to $x_{01}, x_{02}, x_1, \boxed{y_1, y_2}$	$1 - y_1/3{,}16 \leq 0$ $y_2/24 - 1 \leq 0$ $-10 \leq x_{01} \leq 10$ $0 \leq x_{02} \leq 10$ $0 \leq x_1 \leq 10$	$y_1 - (x_{01}^2 + x_1 + x_{02} - 0{,}2y_2) = 0$ $y_2 - (\sqrt{y_1} + x_{01} + x_{02}) = 0$

Shared Design var	x_{01}, x_{02}
Local Design var	x_1
Shared State var	y_1, y_2

- Residual form of the disciplinary equations.
- Optimizer controls local and shared state variables.
- The optimization algorithm is free to explore discipline unfeasible regions.

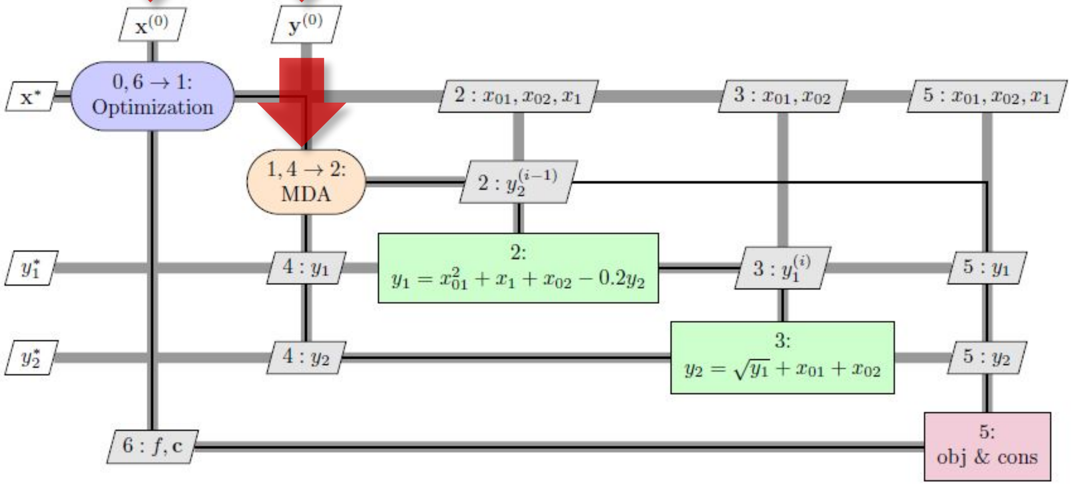


THE SELLAR PROBLEM
Multi Discipline Feasible - MDF

Objective	Constraints
$\min \; x_1^2 + x_{02} + y_1(x_{01}, x_{02}, x_1) + e^{-y_2(x_{01}, x_{02}, x_1)}$ respect to $\boxed{x_{01}, x_{02}, x_1}$	$1 - y_1(x_{01}, x_{02}, x_1)/3{,}16 \leq 0$ $y_2(x_{01}, x_{02}, x_1)/24 - 1 \leq 0$ $-10 \leq x_{01} \leq 10$ $0 \leq x_{02} \leq 10$ $0 \leq x_1 \leq 10$

Shared Design var	x_{01}, x_{02}
Local Design var	x_1
Shared State var	y_1, y_2

- Optimizer controls only design variables
- Disciplinary feasibility guaranteed by MDA loop.
- Initial guess needed for MDA loop
- Convergence loop nested in optimization loop.

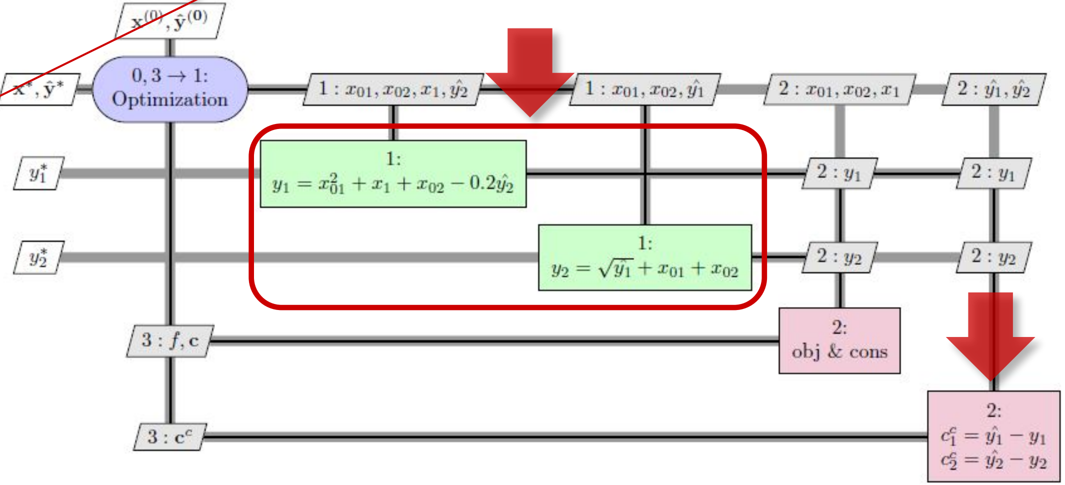


THE SELLAR PROBLEM
Individual Discipline Feasible - IDF

Objective	Constraints	Consistency
$\min\ x_1^2 + x_{02} + y_1(x_{01}, x_{02}, x_1, \hat{y}_2) + e^{-y_2(x_{01}, x_{02}, \hat{y}_1)}$ respect to $x_{01}, x_{02}, x_1, \boxed{\hat{y}_1, \hat{y}_2}$	$1 - y_1(x_{01}, x_{02}, x_1, \hat{y}_2)/3{,}16 \leq 0$ $y_2(x_{01}, x_{02}, \hat{y}_1)/24 - 1 \leq 0$ $-10 \leq x_{01} \leq 10$ $0 \leq x_{02} \leq 10$ $0 \leq x_1 \leq 10$	$\hat{y}_1 - y_1 = 0$ $\hat{y}_2 - y_2 = 0$

Shared Design var	x_{01}, x_{02}
Local Design var	x_1
Shared State var	y_1, y_2

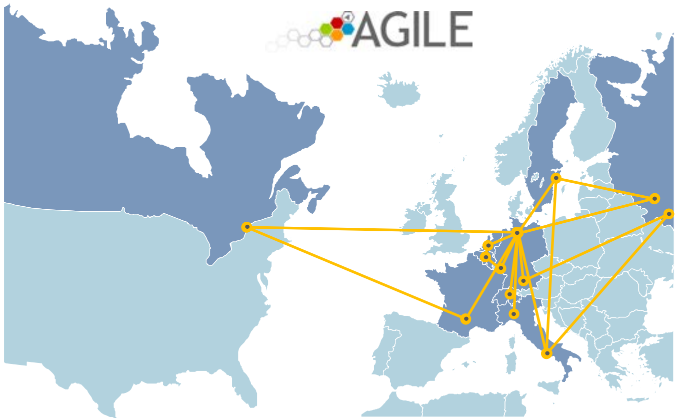
- Discipline analyses in parallel
- Optimizer controls also copies of shared state variables.
- Consistency constraints guarantee the disciplines feasibility only after reaching the optimum.



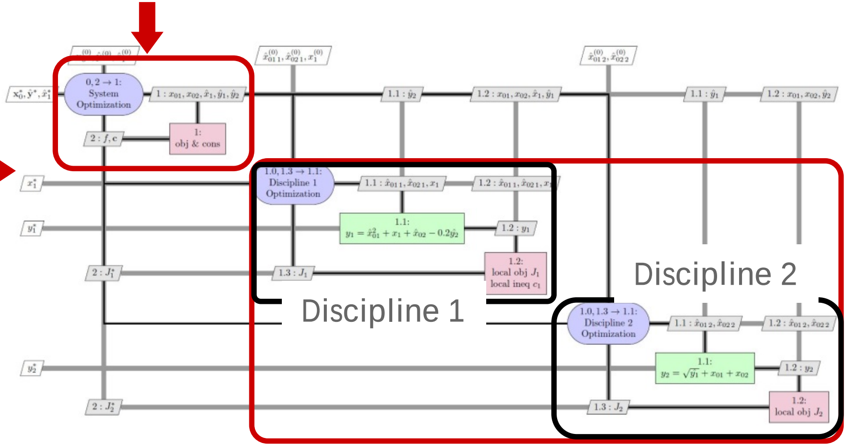
THE SELLAR PROBLEM
Distributed Architectures

DISTRIBUTED MDO ARCHITECTURES

Network of distributed competences



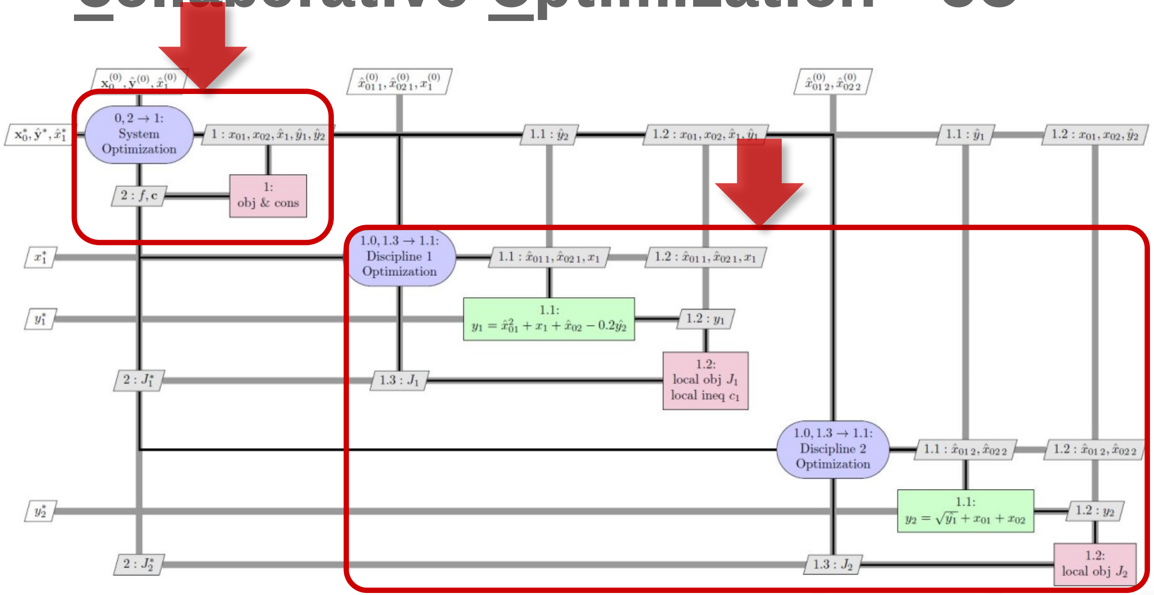
System Optimization Subproblem



Discipline Optimization Subproblems

MDO architectures: a comparison study of MDO platforms

THE SELLAR PROBLEM
Collaborative Optimization - CO



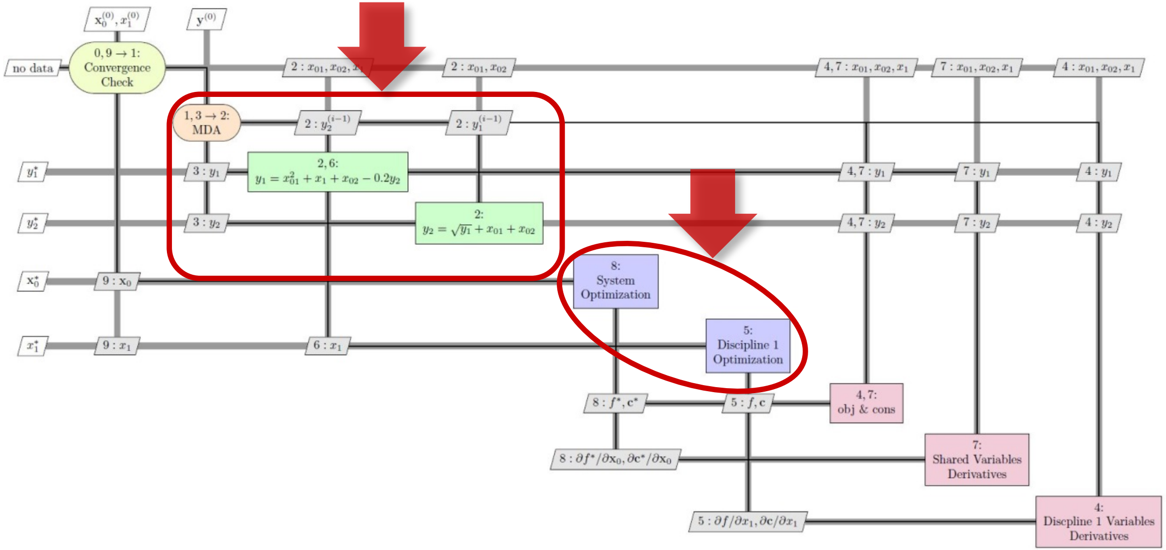
- Extension of IDF
- Discipline subproblems guarantee disciplinary feasibility
- System subproblem minimizes the original objective function
- Discipline subproblems nested in System subproblem
- Null derivative of consistency constraints at the optimum

Low convergence rate

$$J_1 = \left\|\hat{x}_{01\_1} - x_{01}\right\|^2 + \left\|\hat{x}_{02\_1} - x_{02}\right\|^2 + \|x_1 - \hat{x}_1\|^2 + \left\|\hat{y}_1 - y_1(\hat{x}_{01\_1}, \hat{x}_{02\_1}, x_1, \hat{y}_2)\right\|^2$$

$$J_2 = \left\|\hat{x}_{01\_2} - x_{01}\right\|^2 + \left\|\hat{x}_{02\_2} - x_{02}\right\|^2 + \left\|\hat{y}_2 - y_2(\hat{x}_{01\_2}, \hat{x}_{02\_2}, \hat{y}_1)\right\|^2$$

THE SELLAR PROBLEM
Bi-Level Integrated System Synthesis - BLISS



- Path of linear approximations points
- Discipline subproblem controls local design variables
- System subproblem controls shared design variables
- MDA guarantees disciplinary feasibility at each step

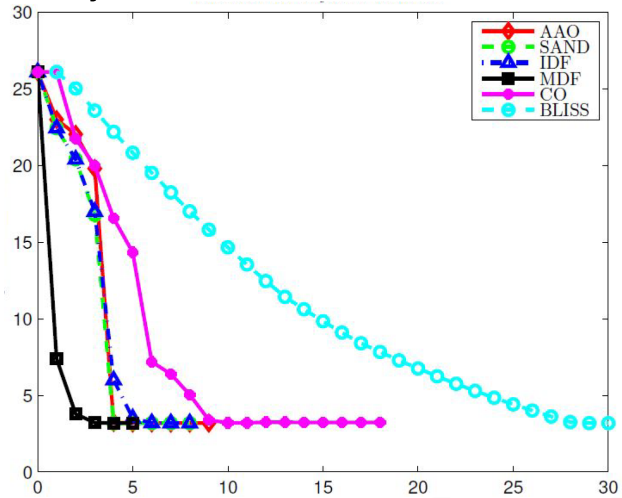
- MDA loop, system and discipline subproblems all in series with each other ➡ High convergence rate
- Thrust-region like behavior ➡ Poor robusteness

THE SELLAR PROBLEM
Architectures Comparison

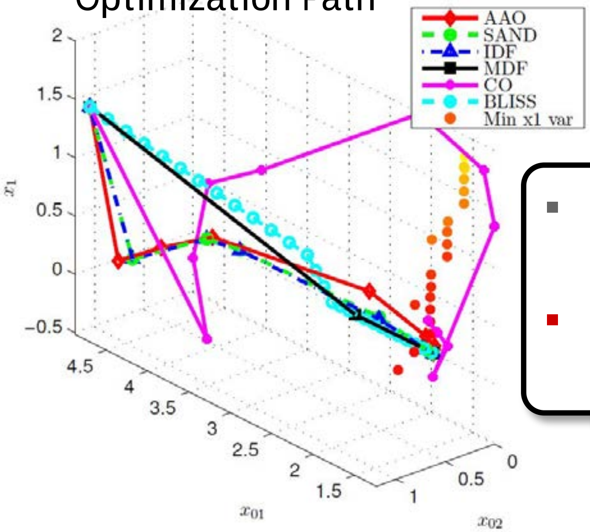
	AAO	SAND	IDF	MDF	CO	BLISS
Optimal obj.value	3.1834	3.1834	3.1834	3.1834	3.233	3.1834
Iterations	9	8	8	5	18	52
Obj.fun calls	80	72	72	48	176	243
Disc. 1 calls	0	0	72	152	2642	348
Disc. 2 calls	0	0	72	152	797	348

- High number of function calls for distributed architectures.
- MDF has the steepest descent.
- IDF has the lowest number of function calls.

Objective Function



Optimization Path



- Almost straight path for MDF.
- Heavily curvy optimization path for CO architecture.

MDO architectures: a comparison study of MDO platforms

THE SELLAR PROBLEM
Platforms Comparison

RCE

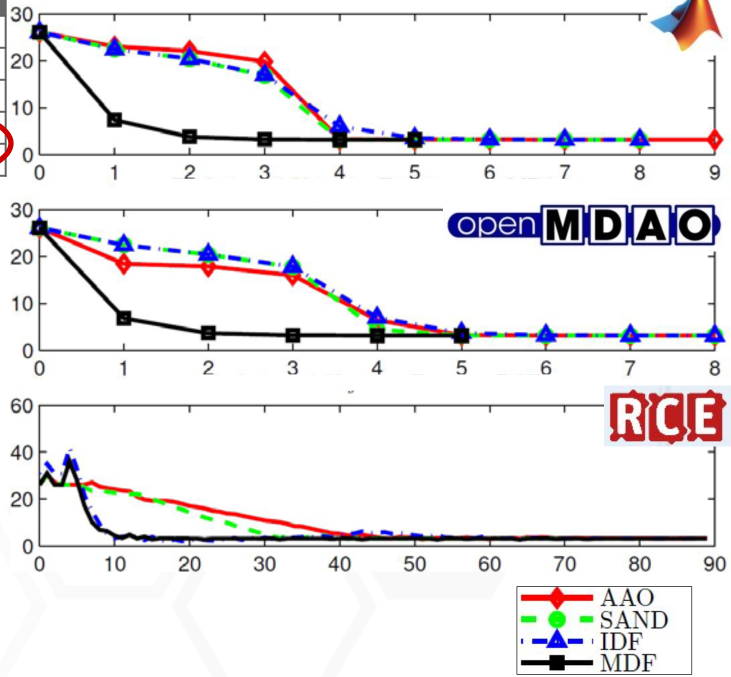
	AAO	SAND	IDF	MDF	CO	BLISS
Optimal obj.value	3.1834	3.1834	3.1834	3.1836	3.2191	3.1834
Iterations	169	72	118	113	118	61
Obj.fun calls	169	72	118	113	118	61
Disc. 1 calls	0	0	118	361	4720	408
Disc. 2 calls	0	0	118	361	1896	408

openMDAO

	AAO	SAND	IDF	MDF	CO
Optimal obj.value	3.1626	3.1834	3.1834	3.1834	3.1834
Iterations	9	8	9	7	138
Obj.fun calls	9	9	9	8	138
Disc. 1 calls	0	0	9	26	2071
Disc. 2 calls	0	0	9	26	624

Trends are confirmed by all the three implementations.

Objective Function



MDO architectures: a comparison study of MDO platforms

THE OAD PROBLEM

- The Sellar Problem
  - SAND
  - MDF
  - IDF
  - CO
  - BLISS

  Monolithic: SAND, MDF, IDF

  Distributed: CO, BLISS
- Architectures Comparison
- Platforms Comparison

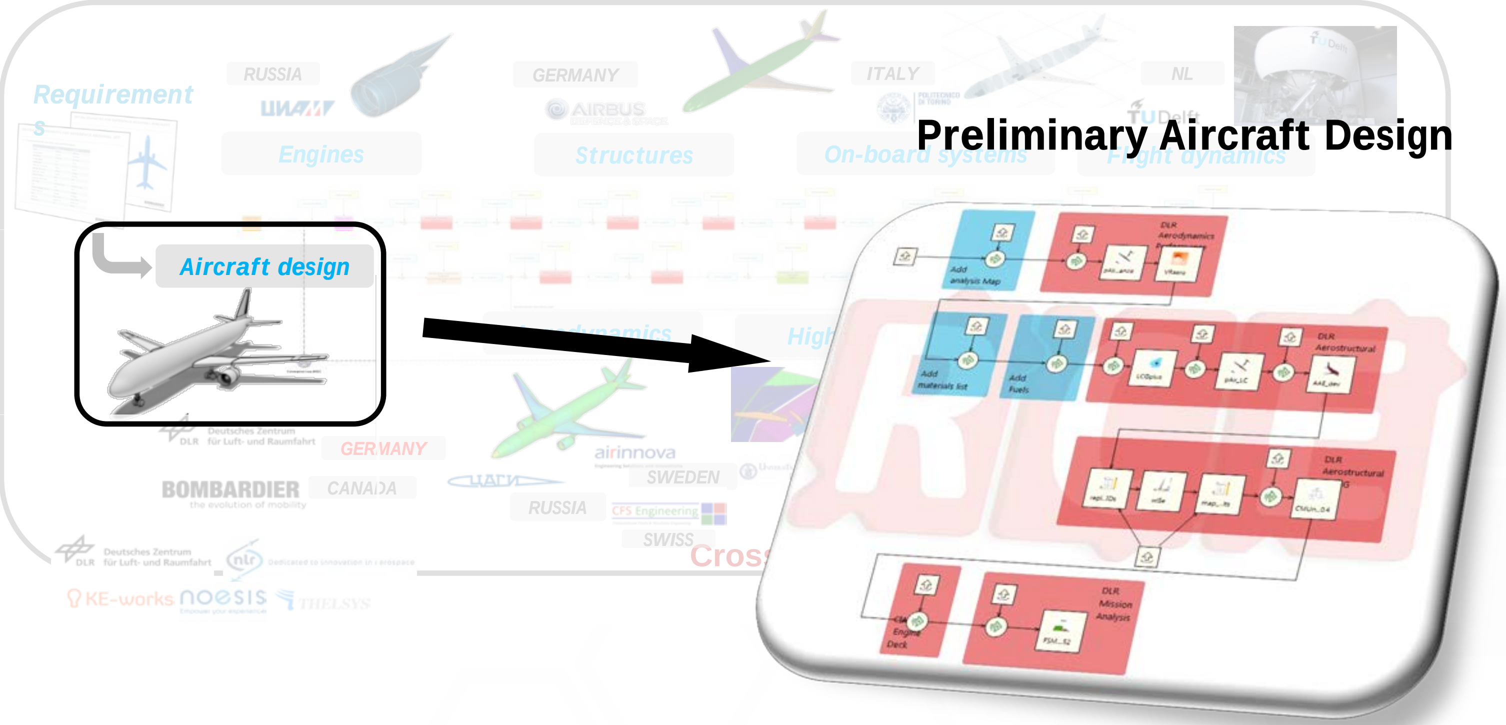
- The OAD Problem
  - MDF Gauss-Seidel
  - MDF Jacobi
  - IDF
  - CO

  Monolithic: MDF Gauss-Seidel, MDF Jacobi, IDF

  Distributed: CO
- Results

- The HYBRID PLATFORM

THE OAD PROBLEM
Framework: AGILE – Collaborative Process

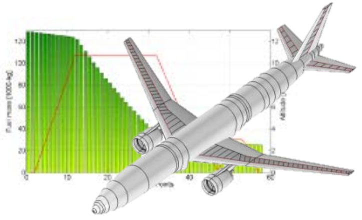


THE OAD PROBLEM
Definition

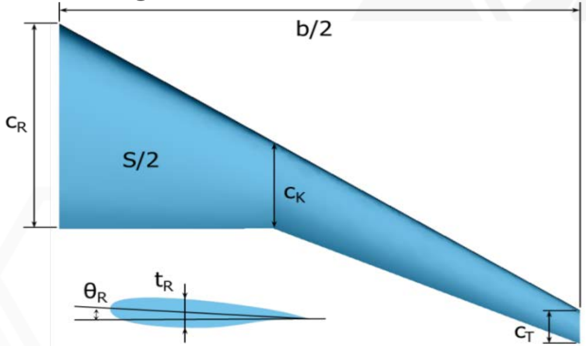
Objective	Constraints	Disciplinary eq.
$\min Fuel$ respect to $\boldsymbol{q}$	$span(\boldsymbol{q}) - span_{max} \leq 0$ $Fuel - Fuel_{max}(\boldsymbol{q}, Fuel) \leq 0$	$[OEM, Fuel_{max}] = \boldsymbol{D}_{struct}(\boldsymbol{q}, Fuel)$ $Fuel = D_{mission}(\boldsymbol{q}, OEM)$

- Shared design variables: **q** = wing parameters
  No local design variables
- Coupling state variables: Fuel, OEM
- Objective: minimize the Fuel
- Coupled disciplines: Structure & Mission

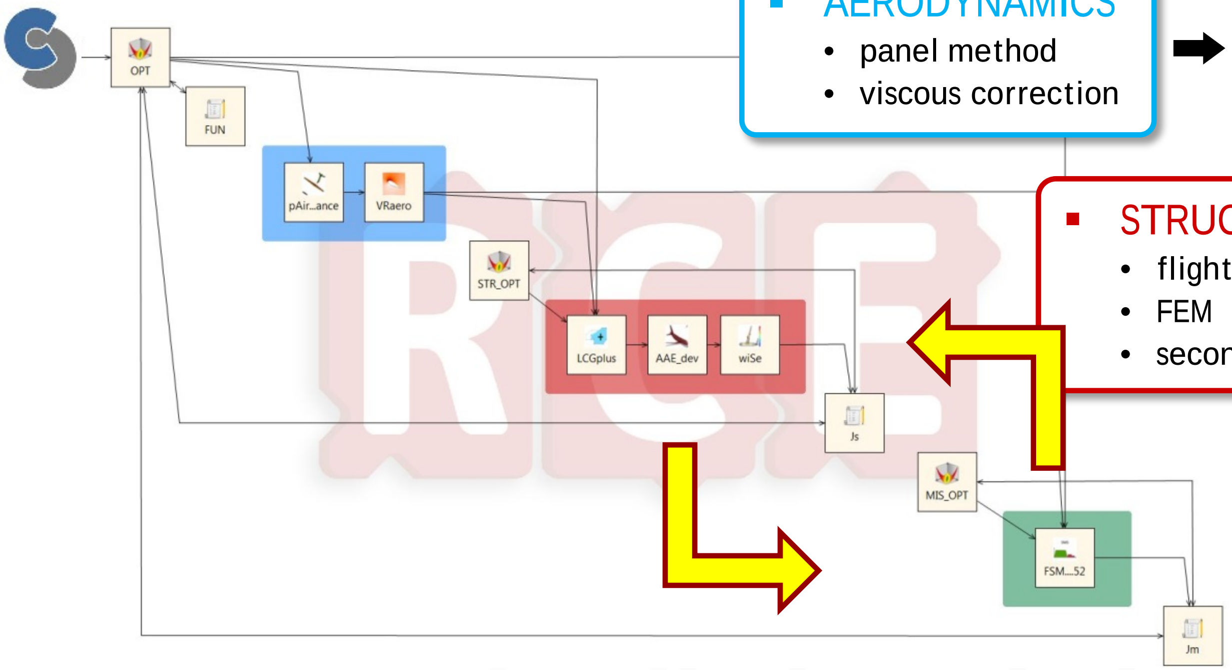
Reference Aircraft
Large Regional Jet
Pax:90
Range: 3500 km



Design variables



THE OAD PROBLEM
Physics Based Tools



- **AERODYNAMICS**
  - panel method
  - viscous correction

➡ Aircraft polars

- **STRUCTURE**
  - flight envelops
  - FEM
  - secondary mass

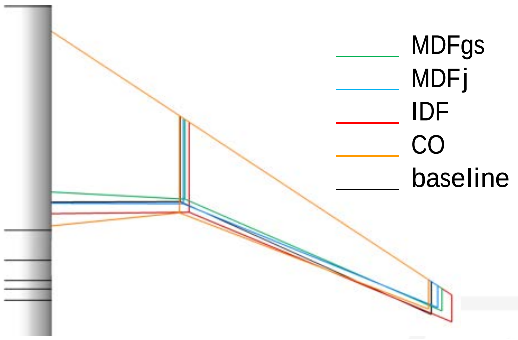
➡ Mass Breakdown

- **MISSION**

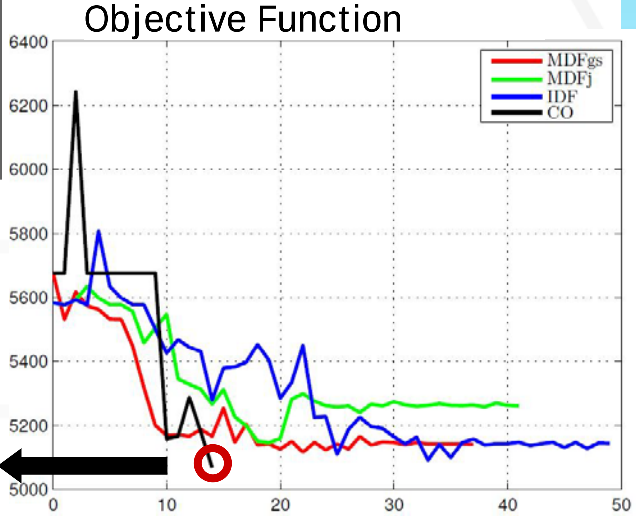
➡ Fuel

THE OAD PROBLEM
Results

	MDFgs	MDFj	IDF	CO (interrupted)
Optimal obj.value	5141 (-9.4%)	5260 (-7.3%)	5144 (-9.4%)	5068 (-10.7%)
AR	11.10	11.10	11.10	7.82
$S\ [m^2]$	69.66	69.66	69.66	91.56
τ	0.93	0.61	0.94	1.13
λ_{out}	0.25	0.27	0.26	0.31
$\theta_K\ [°]$	-0.0010	-0.0002	0.0005	0.0001
$\theta_T\ [°]$	-1.10	-0.92	-0.97	-1.02
Iterations	38	42	50	15
Obj.fun calls	76	84	50	15
Struct. tool calls	76	84	50	418
Miss. tool calls	76	84	50	423



Trends found for Sellar are confirmed also by the OAD problem.



consistency constraints equals $\mathbf{10^{-2}}$

THE HYBRID PLATFORM

- The Sellar Problem
  - SAND
  - MDF
  - IDF
  - CO
  - BLISS

  SAND, MDF, IDF: Monolithic

  CO, BLISS: Distributed

- Architectures Comparison
- Platforms Comparison

- The OAD Problem
  - MDF Gauss-Seidel
  - MDF Jacobi
  - IDF
  - CO

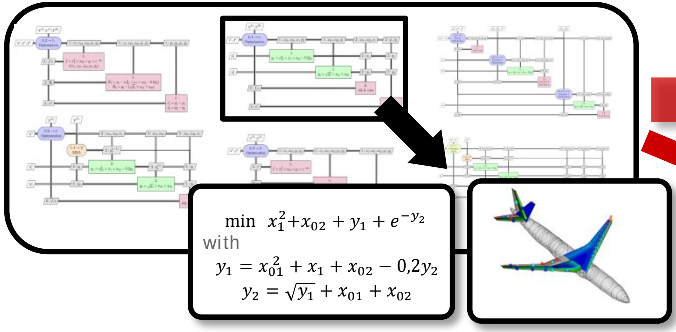
  MDF Gauss-Seidel, MDF Jacobi, IDF: Monolithic

  CO: Distributed

- Results

- The HYBRID PLATFORM

THE HYBRID PLATFORM
Motivations



RCE
openMDAO

HYBRID PLATFORM

CMDOWS

Storage the MDO problems in a neutral format.

RCE

Integration of remotely located tools.

openMDAO

Implementation of MDO architectures.

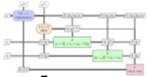
- Calculation of automatic analytic multidisciplinary derivatives
- Parallel programming feature.

- REDUCTION of SETUP TIME
- INCREASE of RELIABILITY

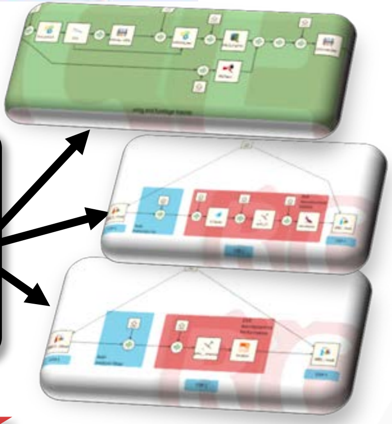
for LARGE SCALE MDO PROBLEM

THE HYBRID PLATFORM
Motivations

XDSM

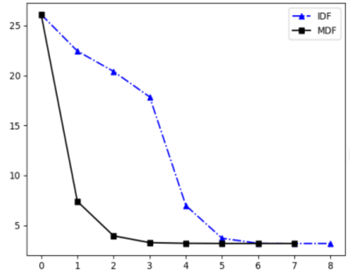


```
Problem()
     Group()
      Component()
       solve_nonlinear()
setup()
run()
```

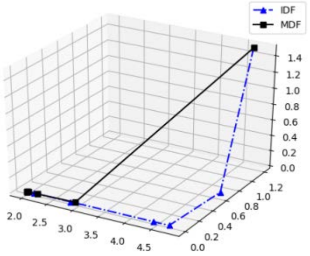


SELLAR PROBLEM

Objective Function



Optimization Path



MDO DEFINTION

- Architecture
- Obj. fun.
- Cons. fun.
- Des. var.
- Stat. var.

- Tools input
- Tools output

PARSER

CMDOWS xml

python Class()

openMDAO Problem()

HYBRID PLATFORM

- OPTIMIZATION: openMDAO
- DISCIPLINARY ANALYSIS: RCE

MDO architectures: a comparison study of MDO platforms

Thanks for the attention!

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