OpenMDAO and the preliminary design of embedded mechatronic equipment

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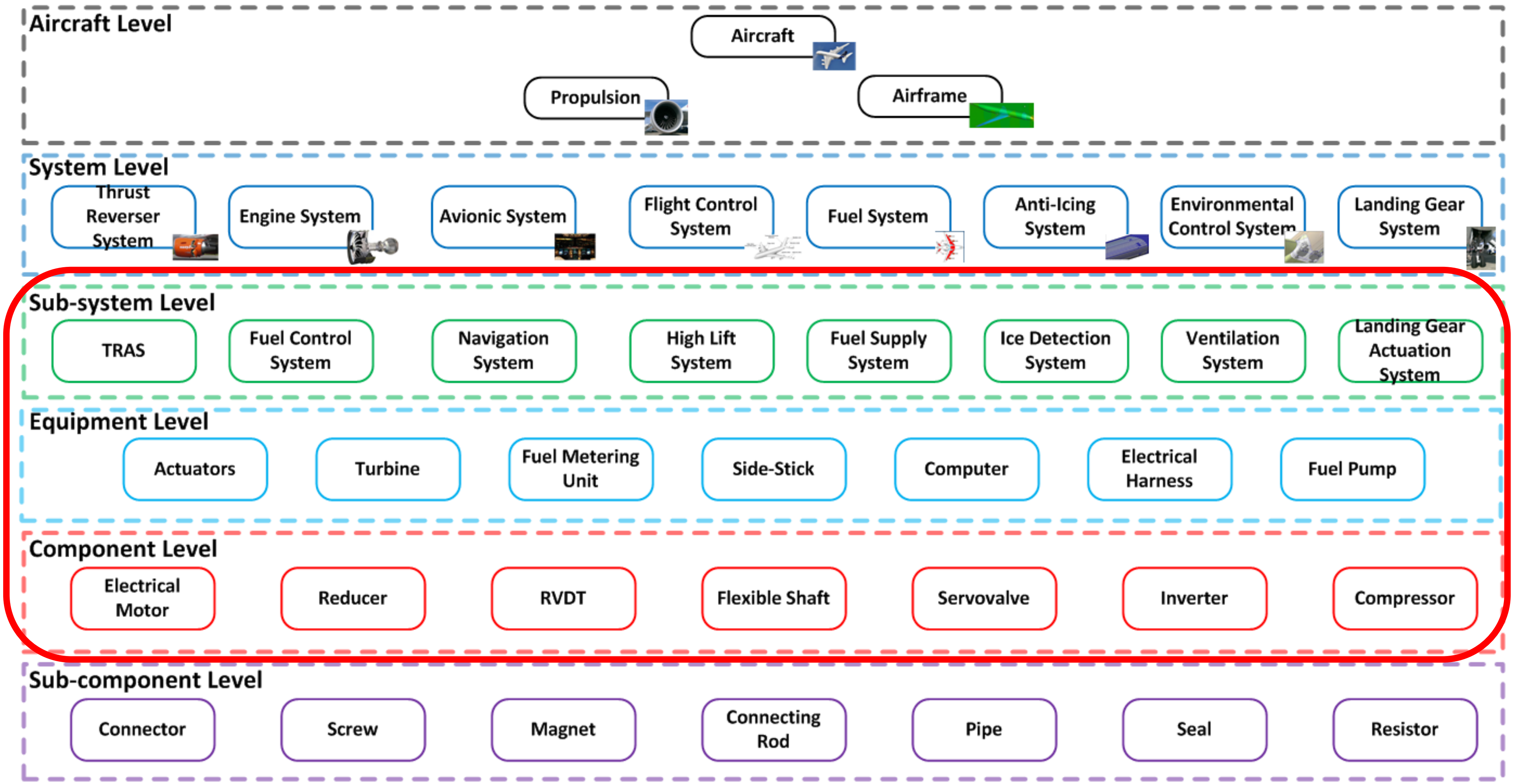
Summary

1. MDO and mechatronic equipment

Aircraft systems

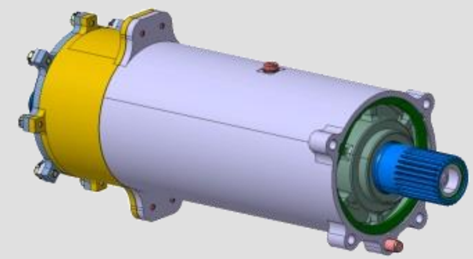


Multi-disciplinary systems

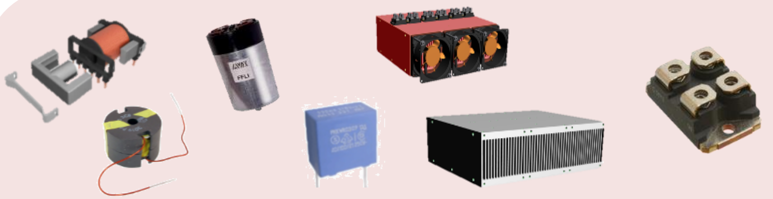
System level

DC/DC converter

EMA actuator



Component level



Inductor | **Capacitor** | **Heat sink** | **Transistor**

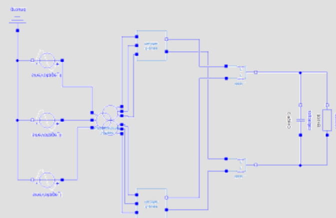
Brushless Motor | **Gear and bearings** | **Torsion bar**

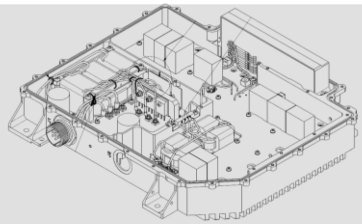
Embedded mechatronics equipment = complex multi-disciplinary systems

Models for design

System level

$$T_{bob}(t) = \frac{R_{th}C_F\left(P_J C_F - P_F C_B\right)}{(C_B + C_F)^2}\left(1 - e^{-\frac{C_B + C_F}{R_{th}C_B C_F}t}\right) + T_{bob0} + \frac{P_J + P_F}{C_B + C_F}t$$

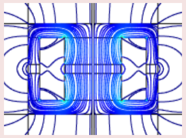


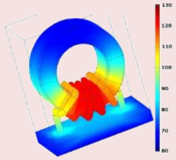


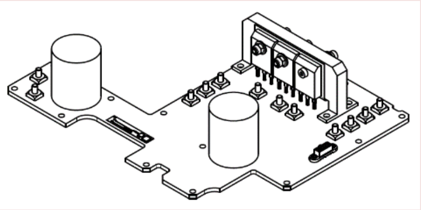
Analytical models	0D – 1D models	3D CAD models
Excel, python, MATLAB	MODELICA, PSIM	SOLIDWORKS, CATIA

Component level

$$P_{iron} = P_{ref}\left(\frac{f}{f_{ref}}\right)^{1.5}\left(\frac{\Delta B}{B_{ref}}\right)^{2.74}$$







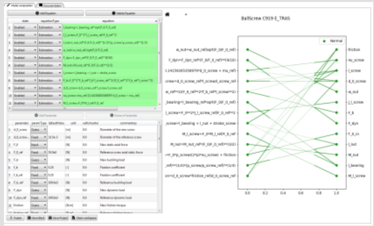
Analytical models	3D FEM models	3D CAD models
Excel, python, MATLAB	COMSOL, ANSYS FLUENT	SOLIDWORKS, CATIA

Design model = different physics , scales and tools

2. Preliminary design framework overview

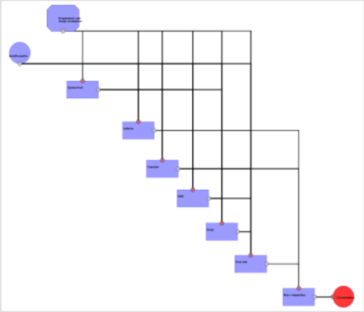
Design process

Block generation
- Acausal model library
- Model constructor
- Algorithms and graph for transforming an acausal model to a causal model



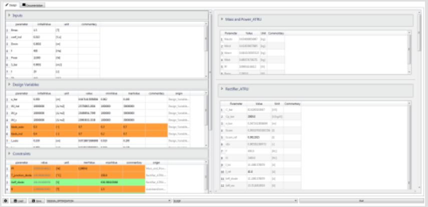
Knowledge capitalization through reusable models

Sizing procedure
- N^2 diagram formalism
- System/Component specification/sizing inputs



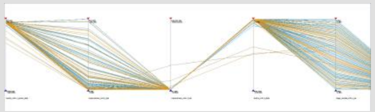
Structured association of different types of models

Design
- Sizing spreasheet
- Evaluate or optimize the sizing procedure **(openMDAO)**



Structured parametrization and result visualization

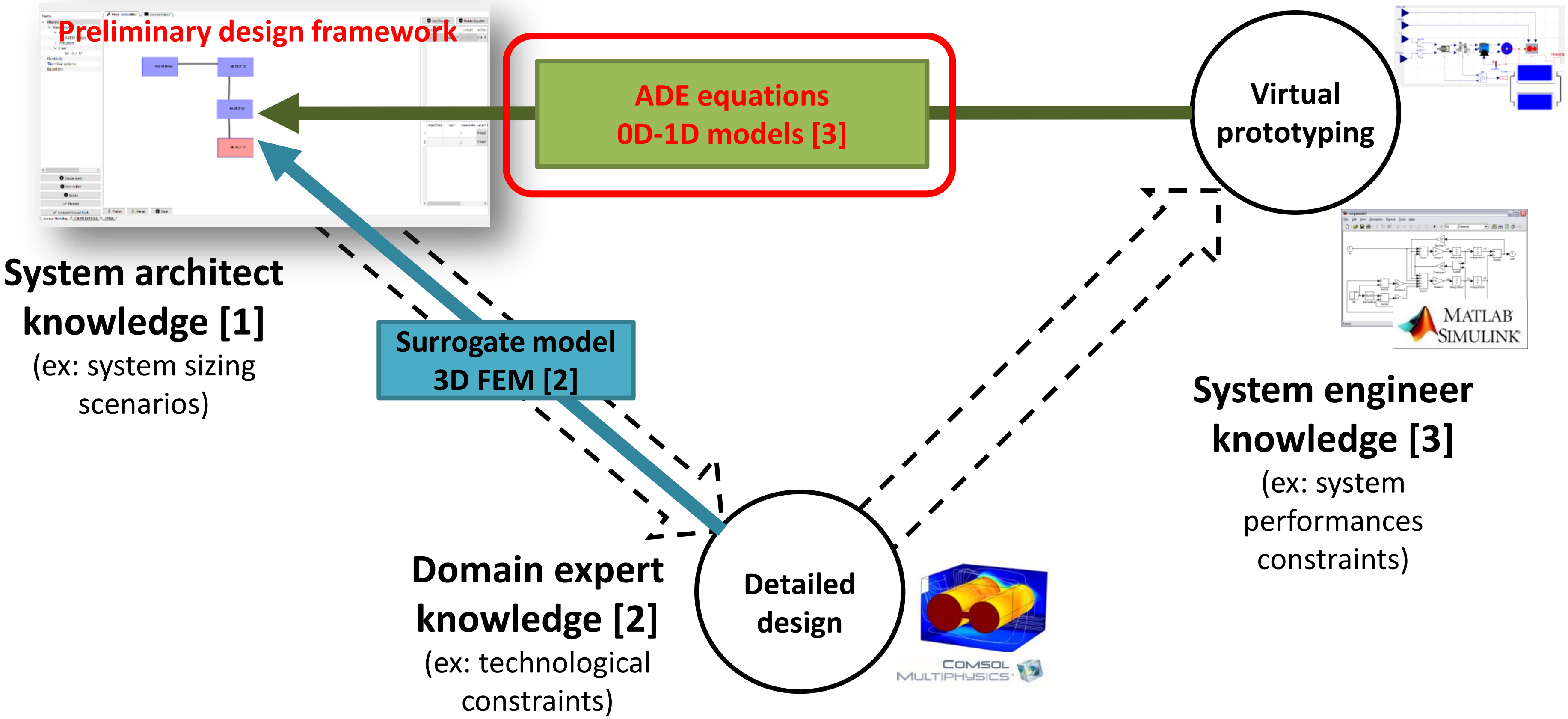
Explore
- DoE
- Parallel coordinates plot



Design space visualization

System level and component level models

- **Preliminary design methodology:**



[1] S. Delbecq, M. Budinger, I. Hazyuk, F. Sanchez, J. Piaton. A framework for sizing embedded mechatronic systems during preliminary design, *IFAC, 2017.*

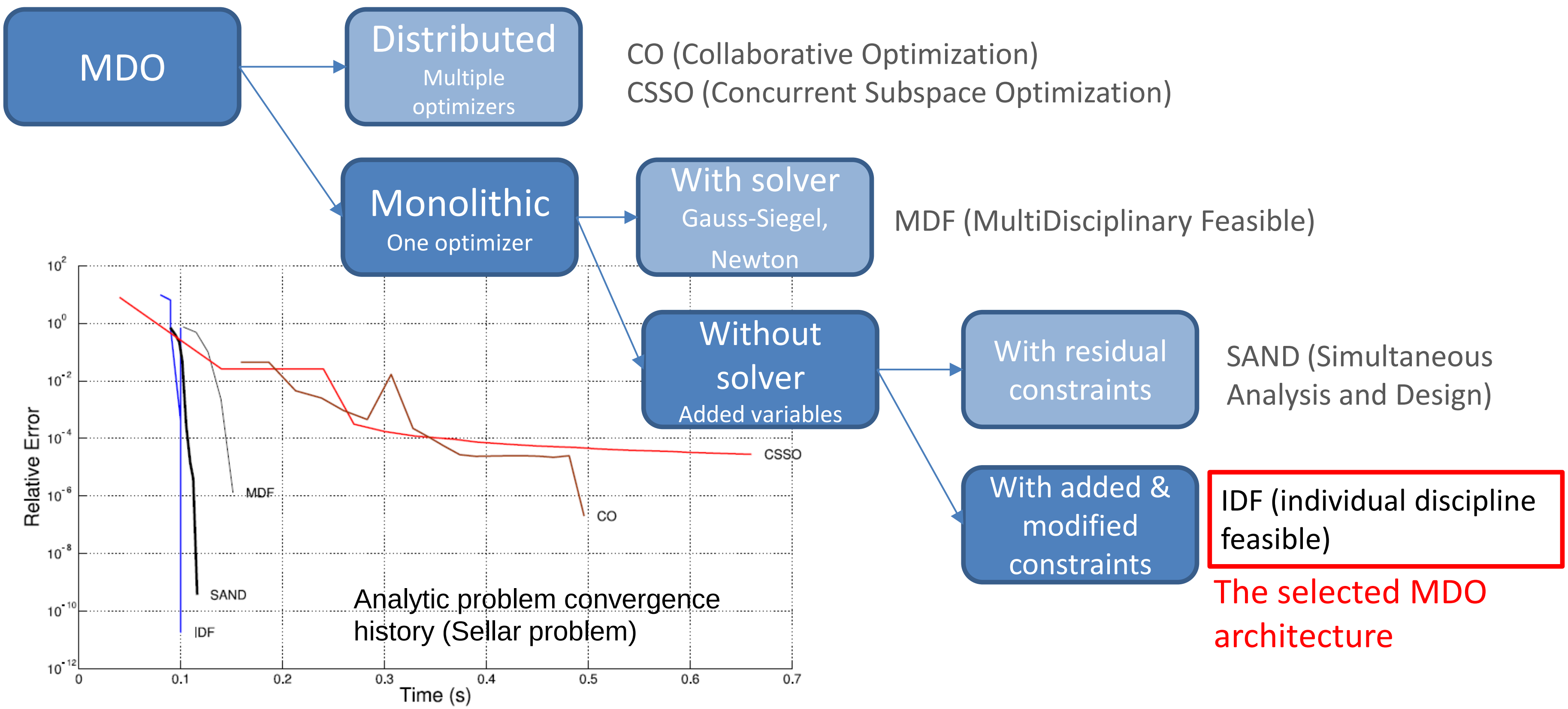
[2] F. Sanchez, S. Delbecq. Surrogate modeling technique for the conceptual and preliminary design of embedded systems and components, *International Council of Aeronautical Sciences*, 2016. (*John McCarthy award finalist 2016)*

[3] S. Delbecq, F. Tajan, M. Budinger, J-C Maré, F. Sanchez. A framework for the conceptual and preliminary design of embedded mechatronic systems, *International Workshop on aircraft System Technologies*, 2017

Institut Clément Ader

MDO Architecture of the Framework

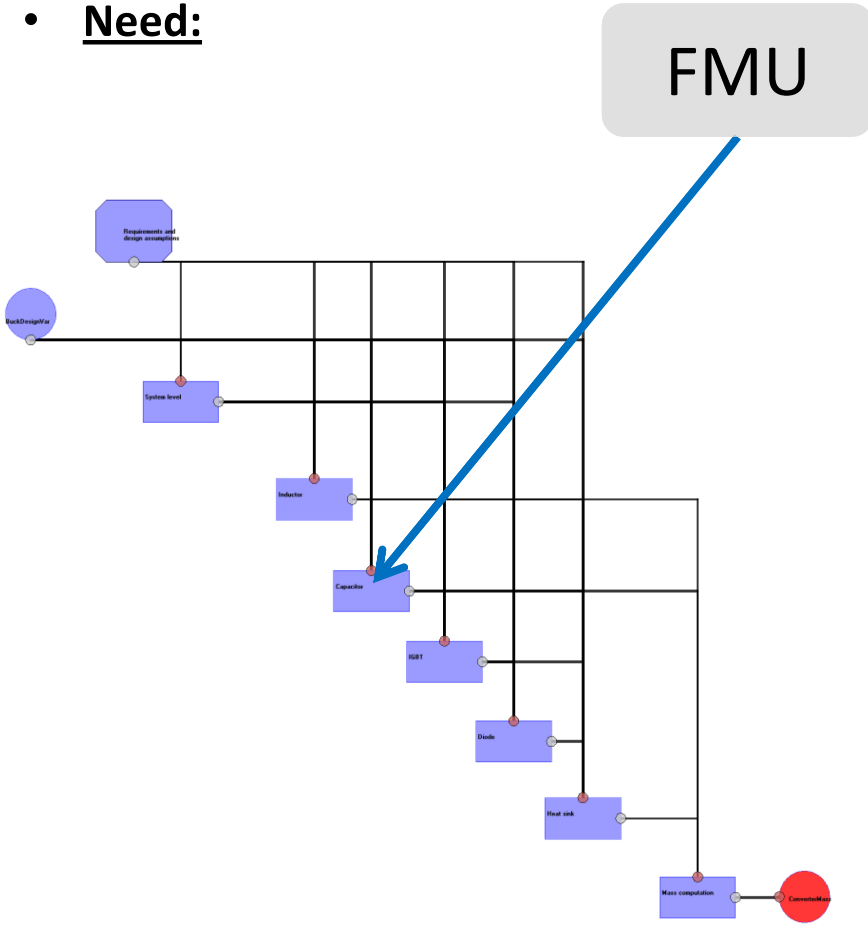
- **MDO Architectures :**



- Martins, Joaquim RRA, and Andrew B. Lambe. "Multidisciplinary design optimization: a survey of architectures." *AIAA journal* (2013).
- Yi, Sang-Il, Jung-Kyu Shin, and G. J. Park. "Comparison of MDO methods with mathematical examples." Structural and Multidisciplinary Optimization 35.5 (2008): 391-402.
- Tedford, Nathan P., and Joaquim RRA Martins. "Benchmarking multidisciplinary design optimization algorithms." *Optimization and Engineering* 11.1 (2010): 159-183.

3. FMI wrapper

- **Need:**



Why use Functional Mock-up Units during preliminary design of mechatronic systems?

To evaluate complex dynamic responses of the system or components for:
- Quantifying sizing scenarios
- Quantifying performances constraints
- Quantifying technological limits constraints

http://fmi-standard.org/

3. FMI wrapper

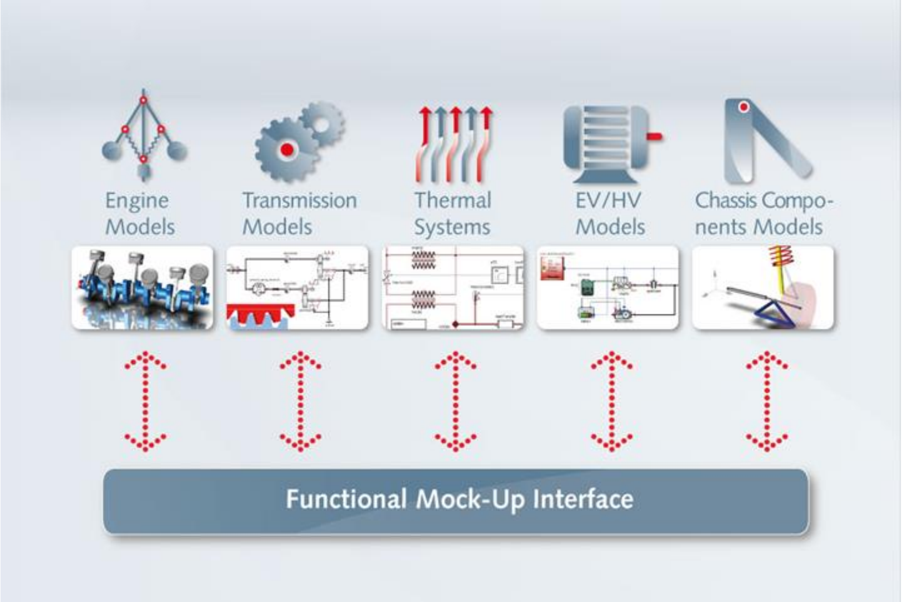
- **Concept:**

Standard developed in 2010 by DaimlerAG (German automotive corporation)

Aims to improve the exchange of simulation models

Supports both co-simulation (embedded solver) and model-exchange (only equations and parameters)

Efficient by the use of C programming language



3. FMI wrapper

- **Software compatibility (examples)**

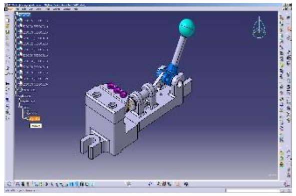
Mechanical:
- CATIA (CAD)
- Adams (Kinematic simulation)

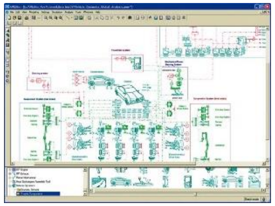
Multi-physical systems:
- Dymola (based on Modelica)
- Amesim

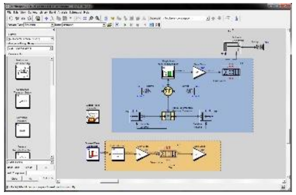
Hydraulic:
- Easy5

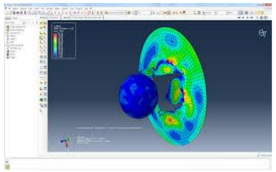
Finite element methods:
- Abaqus

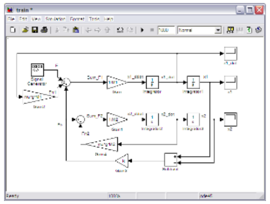
Others:
- Mworks
- Matlab/Simulink







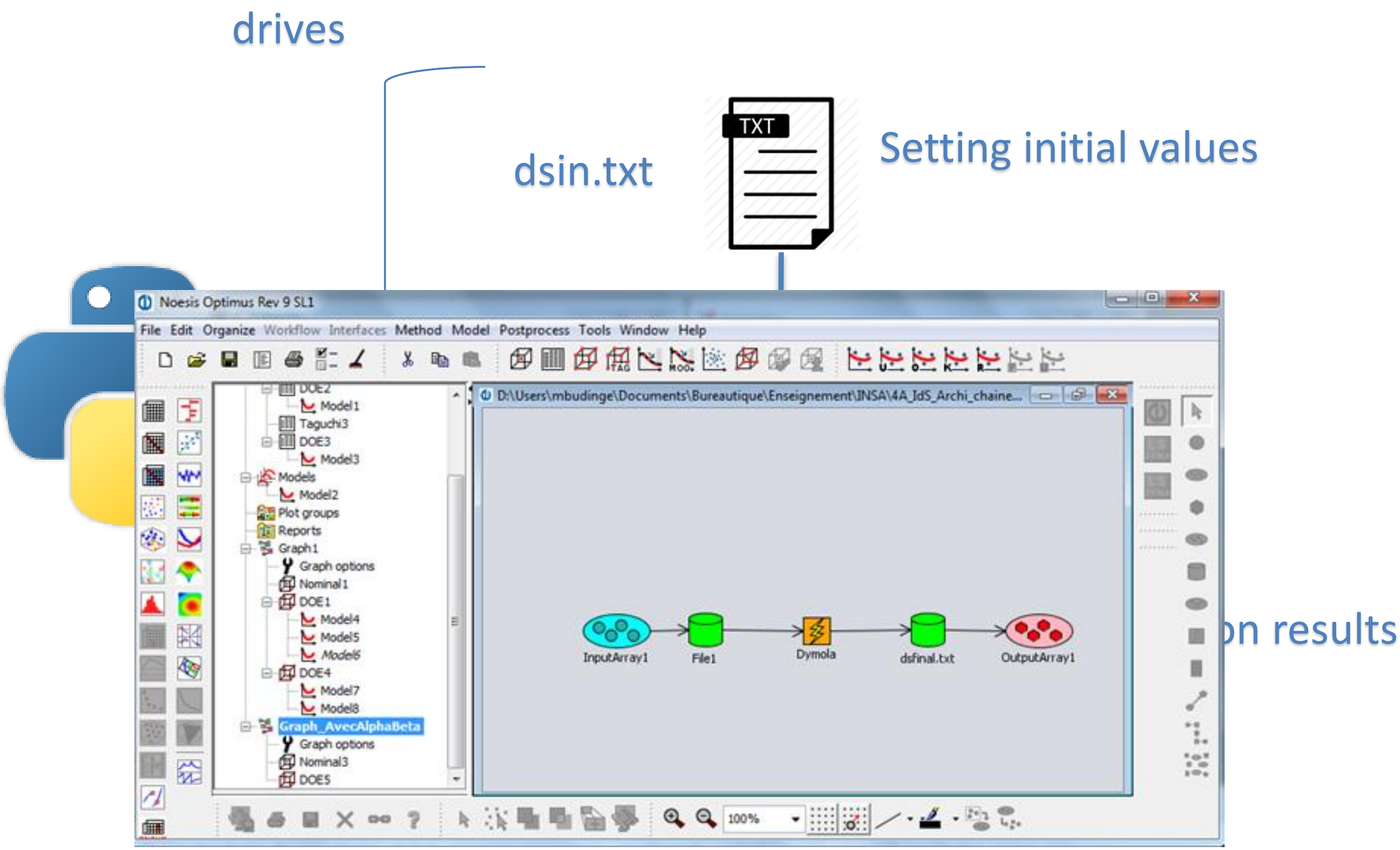




Today 28 softwares use FMI 1.0 standard and 16 FMI 2.0 standard

3. FMI wrapper

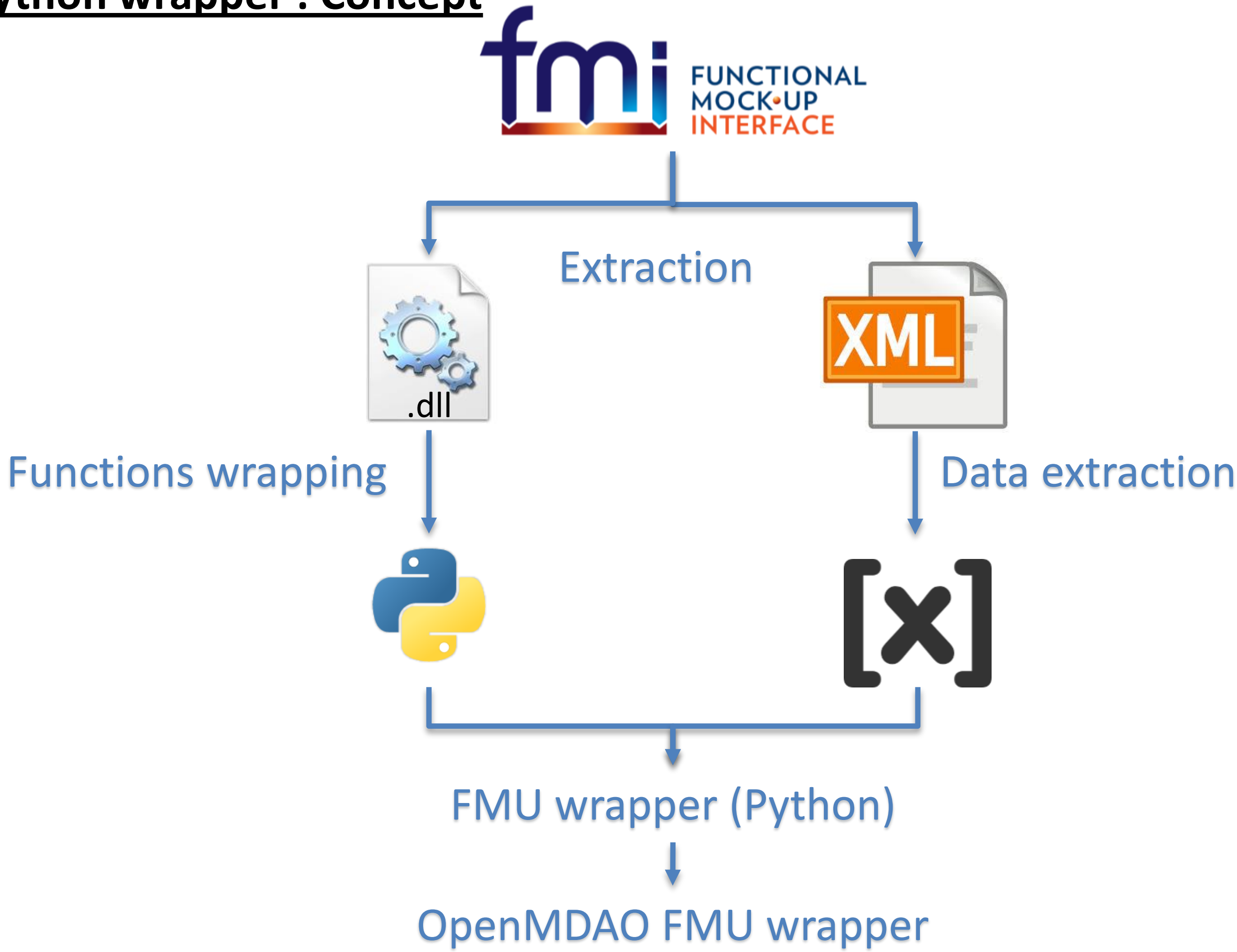
- **File dependant approach (dymosim)**



Generally used in commercial MDO softwares

3. FMI wrapper

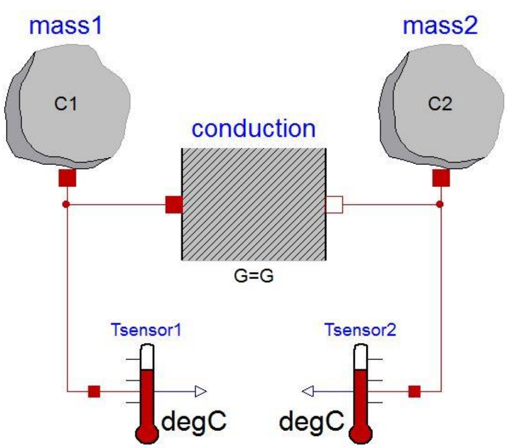
- **The Python wrapper : Concept**



Fast, resettable FMUs for optimization purposes

3. FMI wrapper

- **The Python wrapper : Benchmark**



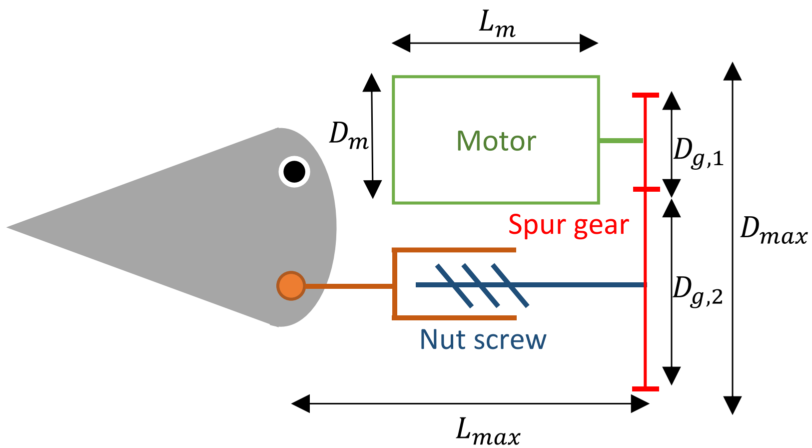
Components	File dependant approach (cf. dymosim [Dymola])	DLL linking approach (cf. FMU)	Comparison
Insentivity to file concurrency issues	No	Yes	-
Access to all functions	No	Yes	-
Execute without license	No	Yes	-
Total simulation time [50 samples]	135 s	9 s	15 times quicker

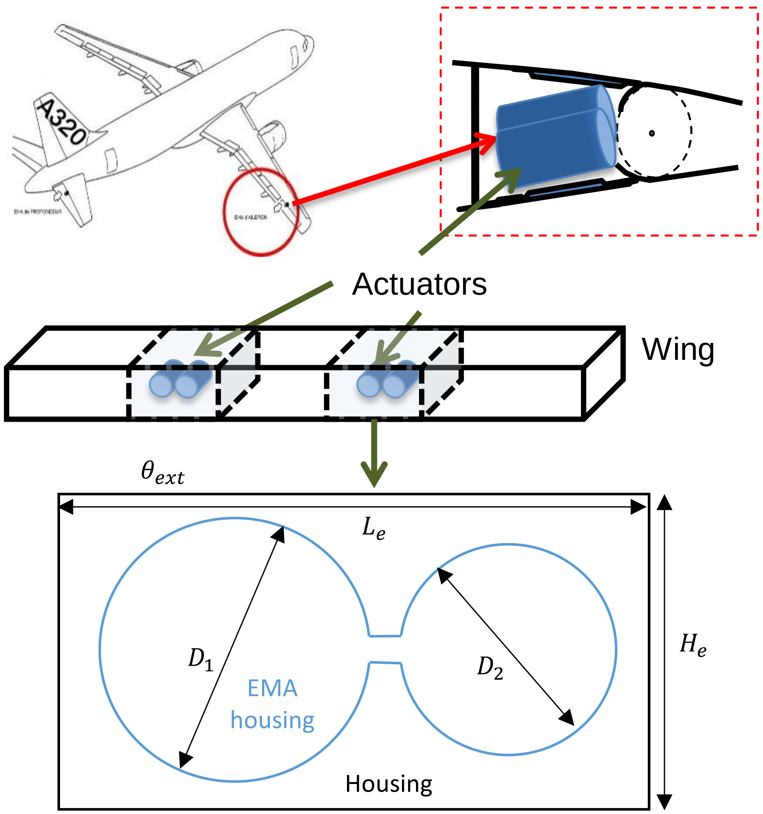
DLL linking is more adapted to MDO (multiple simulations)

4. Case study

- **Design of an EMA for aileron**

Linear geared drive with parallel axis



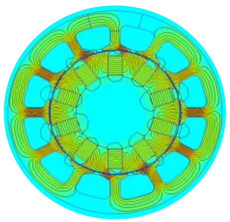


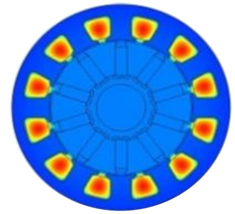
Natural convection in a confined space

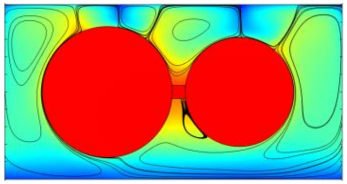
Objectives:
- Test the EMA design applying an entire flight profile on the dynamic model
- Control if the thermal behavior meets the requirements

4. Case study

- **Surrogate models of components [1][2]:**





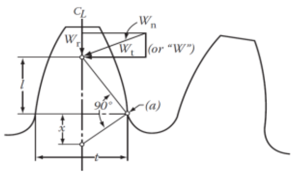


Linear torque
$T/L_m = f(D_{Se}, L_c, J, \dots)$

Thermal resistance winding/housing:
$R_{th,co} = f(D_m, L_m, e_N, \dots)$

Thermal resistance housing/ambient :
$R_{th,conv} = g(D_1, D_2, L_e, H_e, z, \dots)$

- **Scaling laws and analytical models of components :**



Gear teeth bending stress

$$\sigma_t{}^* = K_t^* U_l^* K_d^* = \frac{T^*}{b^* \cdot m^* \cdot d^*}$$

Ball screw nut scaling ratio

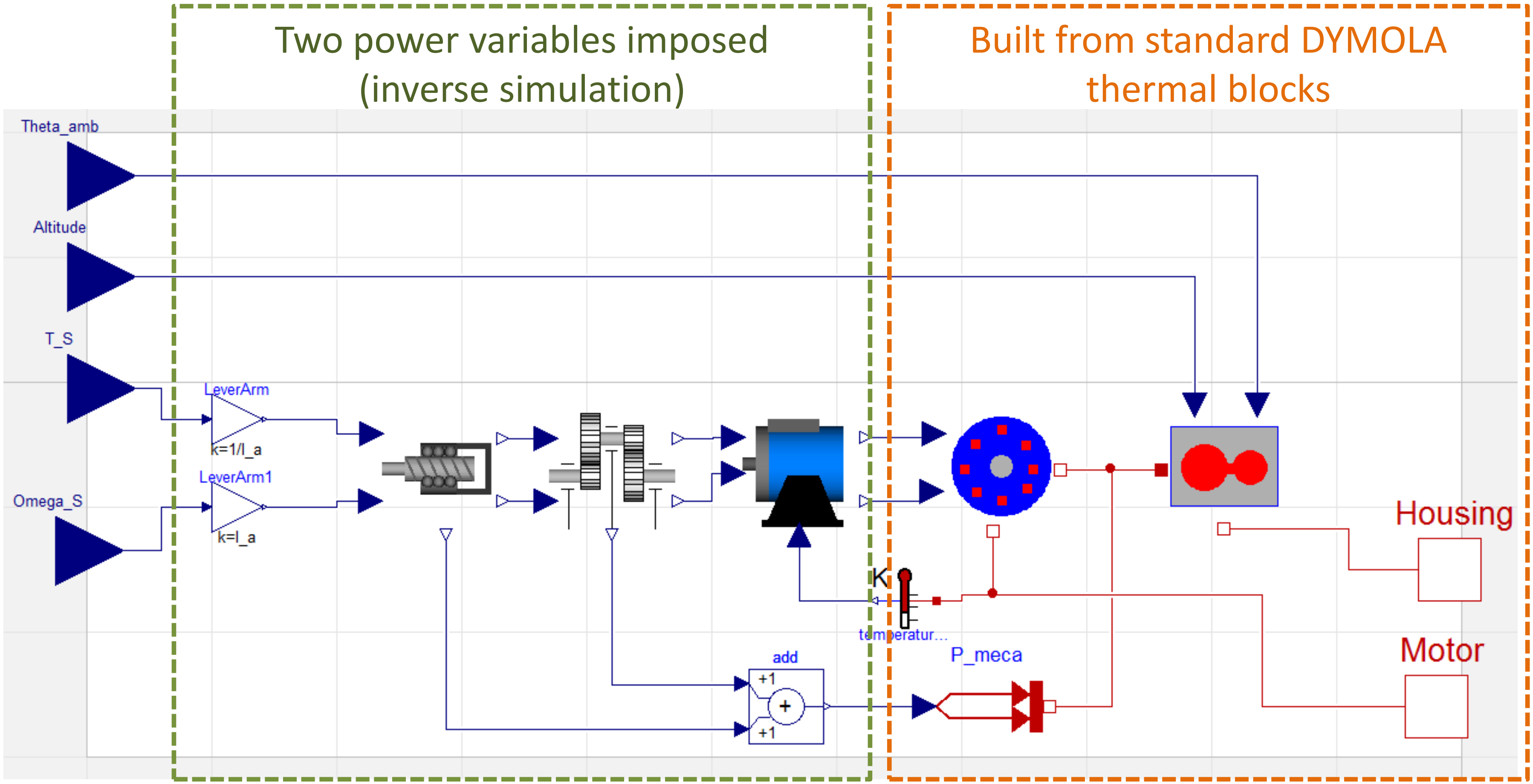
$$l_{nut}{}^* = F_0{}^{*\frac{1}{3}} \cdot p^{*\frac{1}{3}}$$

[1] Sanchez, F., Budinger, M., & Hazyuk, I. (2017). Dimensional analysis and surrogate models for the thermal modeling of Multiphysics systems. *Applied Thermal Engineering*, *110*, 758-771.

[2] Hazyuk, I., Budinger, M., Sanchez, F., & Gogu, C. (2017). Optimal design of computer experiments for surrogate models with dimensionless variables. *Structural and Multidisciplinary Optimization*, 1-17.

4. Case study

- **System model:**



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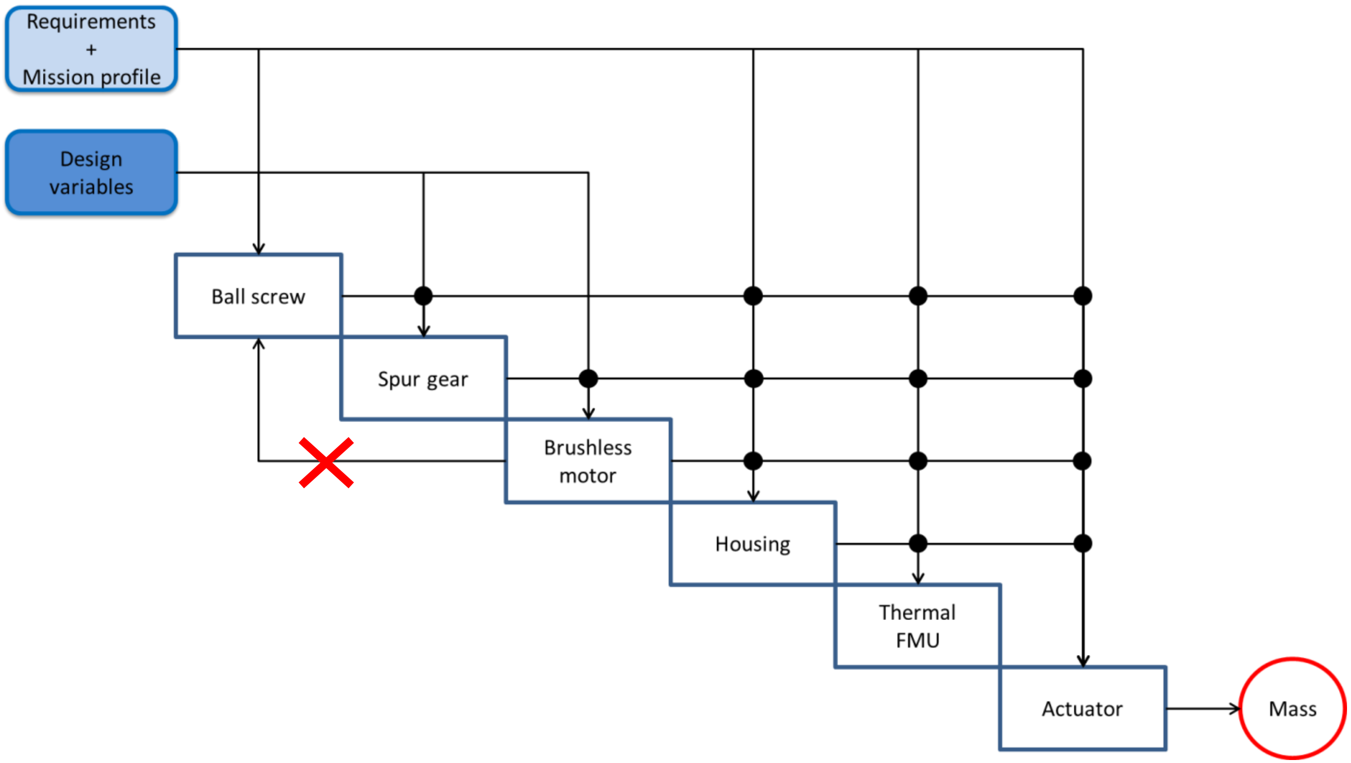
4. Case study

- **Optimization problem:**

Design variables: ball screw (pitch), gear (ratio + form factor), motor (current density, diameter, yoke) , over sizing factor

Constraints: geometry (3), gear (bending, contact stresses), **thermal FMU (motor hot spot and actuator skin temperature)** , maximum torque/force

Objective: minimize actuator overall mass



4. Case study

- **Selected approach:** 3 different sizing scenarios for the evaluation of thermal criteria

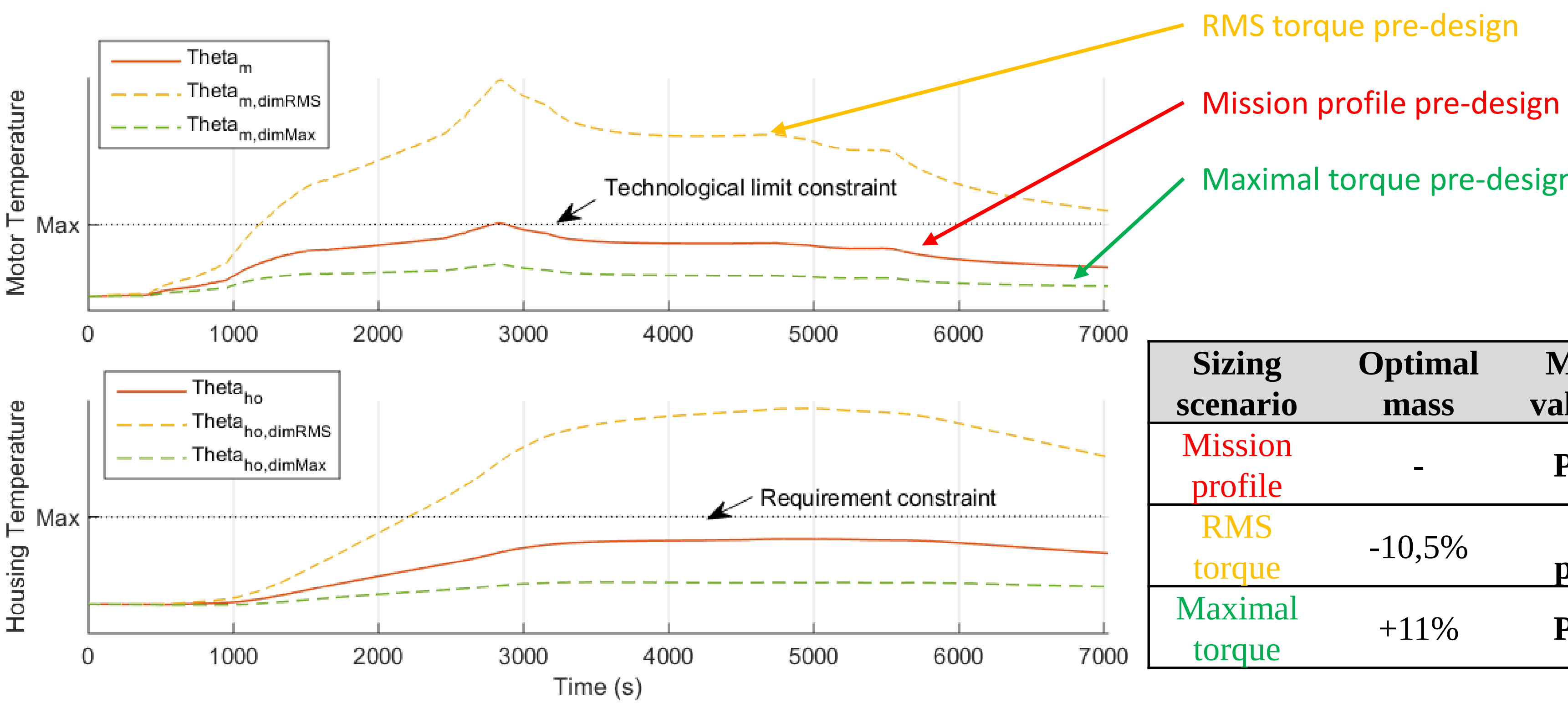
Sizing for the mission profile:
- Model: FMU of the global actuator dynamic model
- Input: Mission profile (Hinge moment, Steering rate, Altitude, external temperature)

Sizing for the RMS torque of mission profile:
- Model: Steady state
- Input: RMS torque of the mission profile

Sizing for the maximum torque of mission profile:
- Model: Steady state
- Input: Maximum torque of the mission profile

4. Case study

- **Results:** 3 different sizing scenario → 3 designs → comparison of their mass and their thermal behavior during the flight profile



Sizing scenario	Optimal mass	Mission validation
Mission profile	-	**Passed**
RMS torque	-10,5%	**Not passed**
Maximal torque	+11%	**Passed**

Thermal response of pre-designs over the entire mission

5. Conclusion and perspectives

Mechatronic equipments are multi-domain, multi-scale an multi-physical → MDO approach is necessary

Main features of the associated preliminary design framework have been underlined

FMUs are an interesting tool for evaluating complex dynamic responses

The use of FMU during preliminary design of a mechatronic equipment based on a MDO approach has been illustrated in the design problematic of an aileron EMA

Christophe is seeking an internship opportunity for summer 2018 in abroad research laboratories → *corsi@etud.insa-toulouse.fr*