Introduction to the sizing of multi-rotor drones with Jupyter Notebooks

Marc BUDINGER
marc.budinger@insa-toulouse.fr

Scott DELBECQ
scott.delbecq@isae-supaero.fr

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Case study presentation: multi-rotor drones and eVTOL

Sizing Scenarios: Definition of scenarios corresponding to main design criteria of components

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Component level models: Establishment of estimation models from scaling laws or linear regression

Sizing procedure definition: under-constraint, over-constraint and algebraic loops

Design space exploration & optimization: effect of increase of drone size

<u>2nd part: Discussions and exchanges</u>

marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

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Case study

Electric Vertical Takeoff And Landing (eVTOL)

Joby S4

Ehang 184

marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr
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Winged eVTOLs

Kittyhawk Cora

Kitty Hawk, a California-based corporation, operated by Zephyr Airworks in New Zealand.

Joby S2 & S4

Joby Aviation, a Santa Cruz, CA, USA based company.

Vahana

A^3 technological development arm of Airbus, located in Santa Clara, CA.

https://transportup.com/the-hangar/

marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

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Wingless eVTOLs

Ehang 184

Ehang, based in Guangzhou, China.

Volocopter 2X

Volocopter, based in Bruchsal, Germany.

Boeing Cargo Air Vehicle (CAV)

The Boeing Company, based in Chicago, IL, USA.

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marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

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Wingless eVTOLs Characteristics

Ehang 184

Technical Details
- Flight Endurance: 25min
- Aircraft Gross Weight: 260kg
- Flight Speed: 100km/h
- Cruising altitude: 500m (AGL)
- Charging Time: 1 hr
- Rated Payload: 100kg

Materials
- Main frame: Reinforced composite material with carbon fiber and epoxy
- Other components: aerial aluminum alloy

Geometry
- Length: 3.99m
- Height: 1.45m
- Width: 4m

Interior
- Seat Depth: 395mm
- Seatback Height: 860mm
- Seatback angle: 95 degrees
- Storage capacity: 18-inch backpack

Volocopter 2X

Technical Details
- Passenger Capacity: 2 pax
- Max. take off mass (MTOM): 450 kg
- Max. payload: 160 kg
- Operating weight empty (OWE): 290 kg
- Max. range (@ MTOM): 27 km (17 mi) at an optimal range cruise speed of 70 km/h (43 mph)
- Max. airspeed (limited time): 100 km/h
- Rate of climb (@ MTOM): 3 m/s

Structure/Geometry
- Fibre composites; lightweight construction
- Overall height: 2.15 m
- Diameter of the rotor rim incl. propellers: 9.15 m
- Diameter of a single propeller: 1.80 m
- Cockpit: 3.20 m length / 1.25 m width / 1.21 m height
- Skids: 3.02 m length / 2.06 m width

Power supply & battery
- Number of battery packs: 9 independent battery systems with quick release
- Battery type: Lithium-ion battery
- Motors & rotors
- Number of motors & rotors: 18 each
- Engine type: 3-phase PM synchronous motor, brushless DC electric motor (BLDC)

marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

Introduction: Objectives

Sizing code:

Sizing scenarios

Components

Models definition

Sizing procedure

Exploration & Optimization

Evaluation of the sizing code on multiple specifications:

marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

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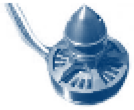
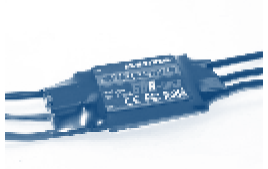
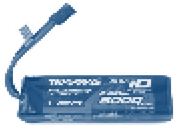
Sizing Scenarios and Design Drivers


System Components	Design Drivers (Function, Fast degradation, Slow degradation, Imperfection)	Hover	Take-off	Vertical & Horizontal flight
Propeller				
Motor				
ESC (Electronic Speed Controller)				
Battery				
Frame				

marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

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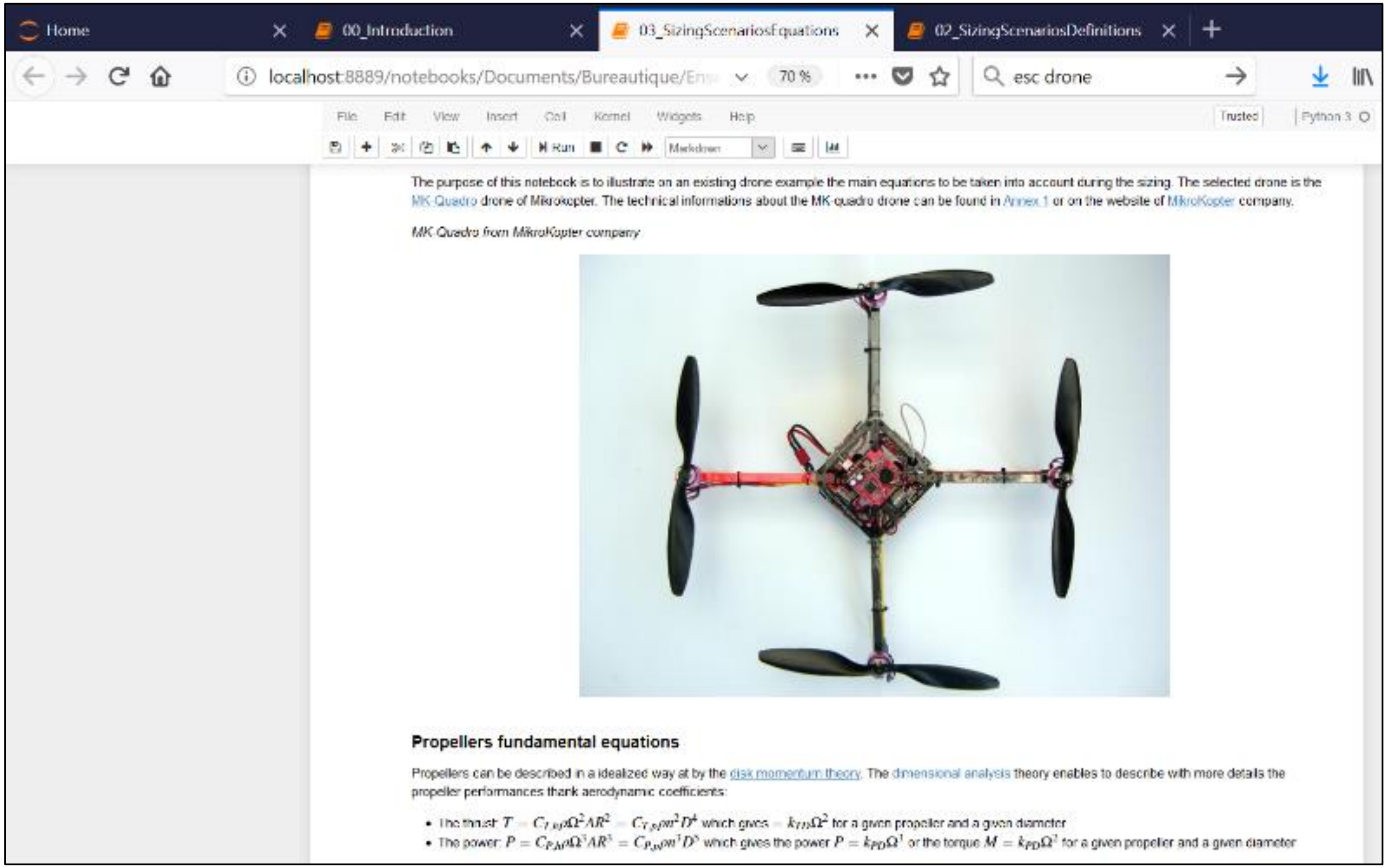
Sizing scenarios equations: Hover and Take-Off

Project (activity+report) :

A set of Jupyter Notebooks with active and usable python codes



marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

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Preliminary design and sizing of mechatronic systems

Estimation models - Scaling laws & Linear regression

marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

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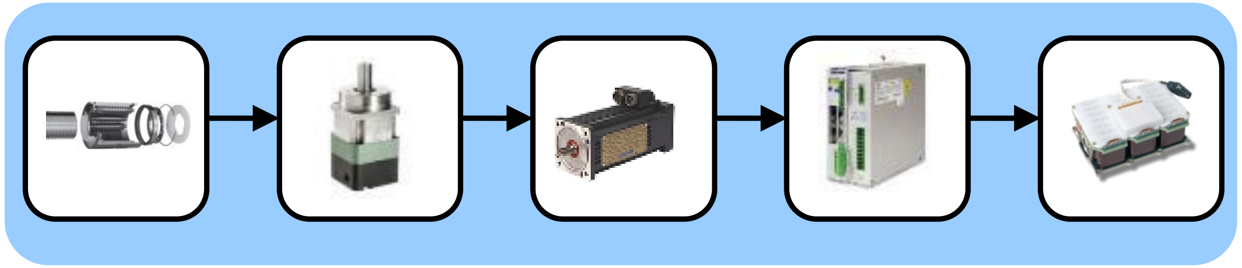
Components parameters estimation

During the preliminary design:



What are: *Volume, Mass, Inertia, Stiffness, Operational limits? …*

Catalogues — Regression models

Use of calculation sheets

Exchanges with experts or subcontractors

Use of light models — Scaling laws

marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

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Dimensional analysis & Estimation models

$$f\,(\underbrace{y, L, d_1, d_2, \ldots, p_1, p_2, \ldots}_{n}) = 0$$

$$\pi_y = g(\underbrace{\pi_1, \pi_2, \ldots, \pi_{p1}, \ldots}_{p=n\text{-}k\text{-}1})$$

Recall on the Buckingham theorem: if there is a physically meaningful equation involving a certain number n of physical variables, then the original equation can be rewritten in terms of a set of $p = n - k$ dimensionless parameters $\pi_1, \pi_2, \ldots, \pi_p$ where k is the number of independent physical dimensions involved

With: $$\pi_y = yL^{a_L} \prod p_i^{a_i}$$

$$\pi_i = \frac{d_i}{L}$$

$$\pi_{pi} = L^{a_{Lpi}} \prod p_j^{a_j}$$

π_i & π_{pi} constants ➔ Scaling laws $y = kL^a$

Budinger, M., Liscouët, J., Hospital, F., & Maré, J. C. (2012). Estimation models for the preliminary design of electromechanical actuators. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, 226(3), 243-259.

π_i & π_{pi} variables ➔ Regression models

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.

marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

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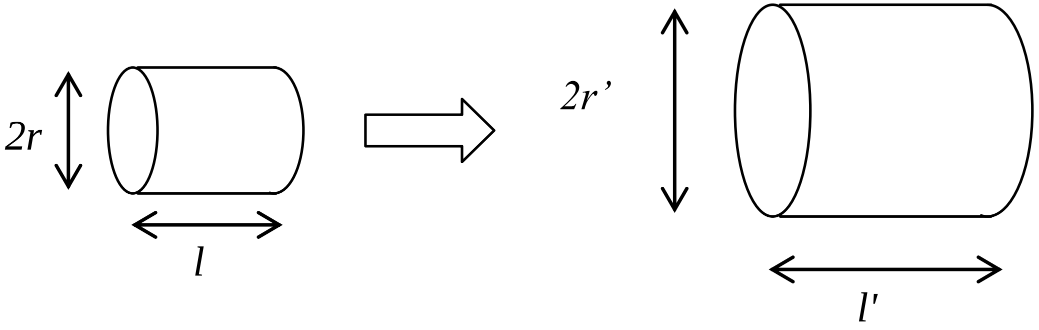
Scaling laws: principle and notation

Principle :



Scaling ratio :

$$l^* = \frac{l'}{l}$$

l' ← Studied component

l ← Reference component

Example :

Winding resistance
(Résistance d'un bobinage) :

$$R = \frac{\rho l}{S} = \rho \frac{l_{co} N}{S_{co}/N} \Rightarrow R^* = \frac{N^{*2}}{l^*}$$

with : l_{co} length of one turn (spire) of copper wire (fil de cuivre)
S_{co} total section of copper
N number of turns

marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr
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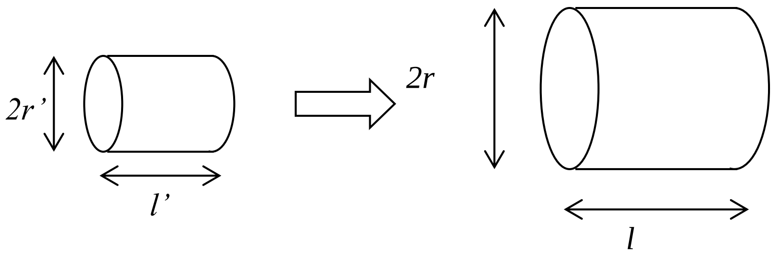
Geometric similitary

Example : Scaling law for the volume of a cylinder



What becomes of this relationship in the case of geometric similarity on all sizes :
r = l* = d* ?*

$$r^* = l^* \quad \Rightarrow \quad V^* = \frac{V'}{V} = \frac{\pi r'^2 l'}{\pi r^2 l} = r^{*2} l^* = l^{*3}$$

Determining scaling laws for the surface S, the mass M, the inertia J :

$$\begin{cases} M = \int \rho_m dV \Rightarrow M^* = l^{*3} \\ J = \int r^2 dM \Rightarrow J^* = l^{*5} \end{cases}$$

marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

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Different ways of finding the scaling laws

Example : Thermal time constant of an electric motor. It is assumed here that the motor temperature rise is uniform and is mainly due to convection between the stator and the air.

Direct approach :

$$\tau_{th} = R_{th}.C_{th}$$

$$R_{th} = 1/hS \Rightarrow R_{th}^* = l^{*-2}$$

$$C_{th} = c_m.M \Rightarrow C_{th}^* = l^{*3}$$

$$\tau_{th}^* = R_{th}^* C_{th}^* = l^{*1}$$

Buckingham theorem approach

$$f\left(\tau_{th}, d, l, h, c_v, \rho\right) = 0$$

$$F\left(\frac{c_v \rho l}{h \tau_{th}}, \cancel{\frac{l}{d}}\right) = 0$$

$$F'\left(\frac{c_v \rho l}{h \tau_{th}}\right) = 0$$

constant

$$\tau_{th}^* = l^{*1}$$

marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

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Scaling law adaptation

Which parameter :

- Limits motor torque ?

Maximal temperature of winding

T_{max}

- Gives mechanical structure or component size ?

Maximal stress

σ_{max}

The scale changes have to be done with X = Constant or X*=1

$T_{max}{}^{*}=1$ $\sigma_{max}{}^{*}=1$

marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

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Scaling with constant constraint (1)

Predicting the diameter of the leg of an elephant from a mouse :

⚠ No linear approximation !
⚠ No data fitting !

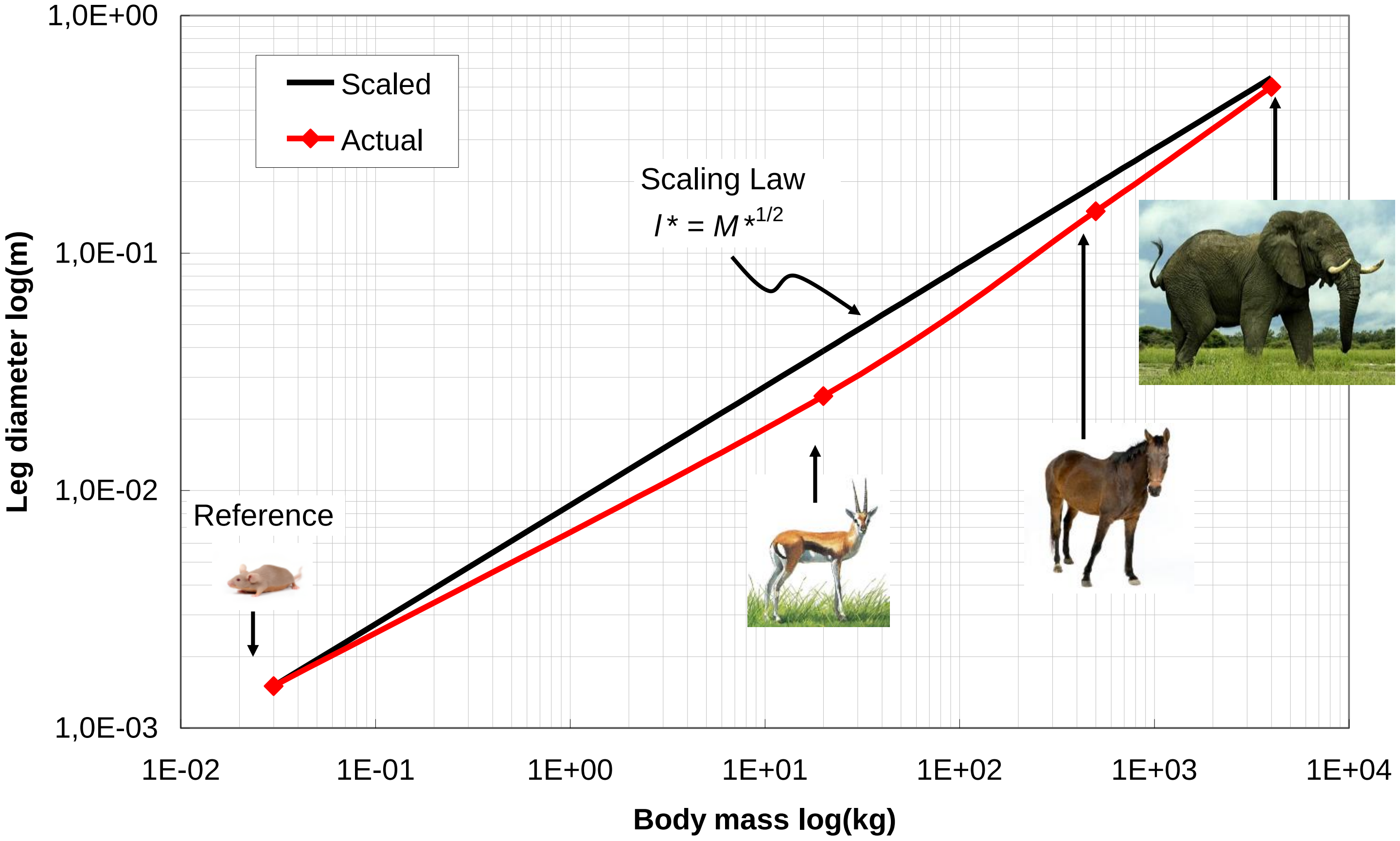
→ Reflects the physics of the sizing phenomena !

Hypothesis :
- During scale change, mechanical constraints in the leg remain constant.

$$\underbrace{\sigma_{max}^{*}}_{\text{Mech. constraint}} = 1 = \underbrace{F^{*}}_{\text{Weight}} / \underbrace{S^{*}}_{\text{Leg section}}$$

$$\begin{cases} F^{*} = M^{*} \\ S^{*} = d^{*2} \end{cases}$$

$$\Rightarrow \boxed{\underbrace{d^{*}}_{\text{Leg diameter}} = \underbrace{M^{*1/2}}_{\text{Body mass}}}$$



marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

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Scaling with constant constraint (2)

Scaling laws for the cyclo reducer :

Hypothesis :

- Geometrical similitude. $\Rightarrow S^* = l^{*2}$
- During scale change, mechanical constraints remain constant. $\Rightarrow \sigma_{max}{}^* = 1 = F^*/S^*$

$\Rightarrow F^* = l^{*2}$

Definition parameter	$T_{rated}{}^* = l^{*3}$
Integration parameters	$d^* = l^* = T_{rated}{}^{*1/3}$ $\quad M^* = l^{*3} = T_{rated}{}^*$
Simulation parameters	$J^* = l^{*5} = T_{rated}{}^{*5/3}$
Operational limit parameters Absolute maximum torque	$T_{max}{}^* = l^{*3} = T_{rated}{}^*$
Absolute maximum speed	$\omega_{max}{}^* = l^{*-1} = T_{rated}{}^{*-1/3}$

marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

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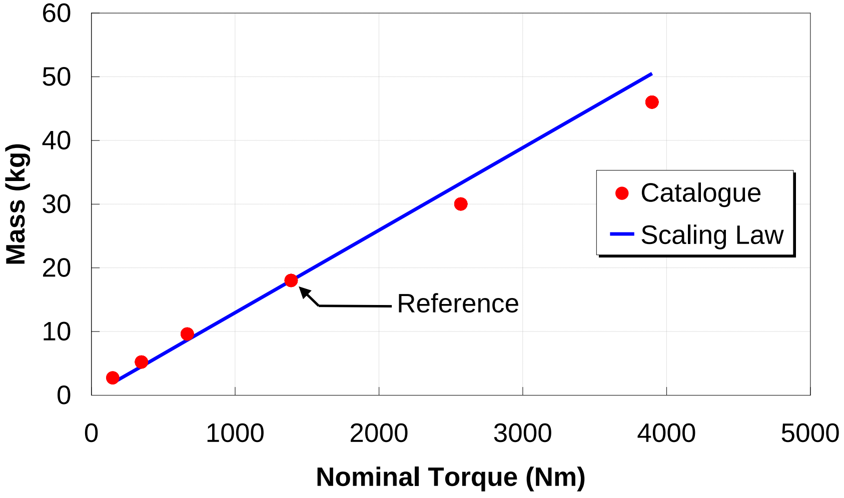
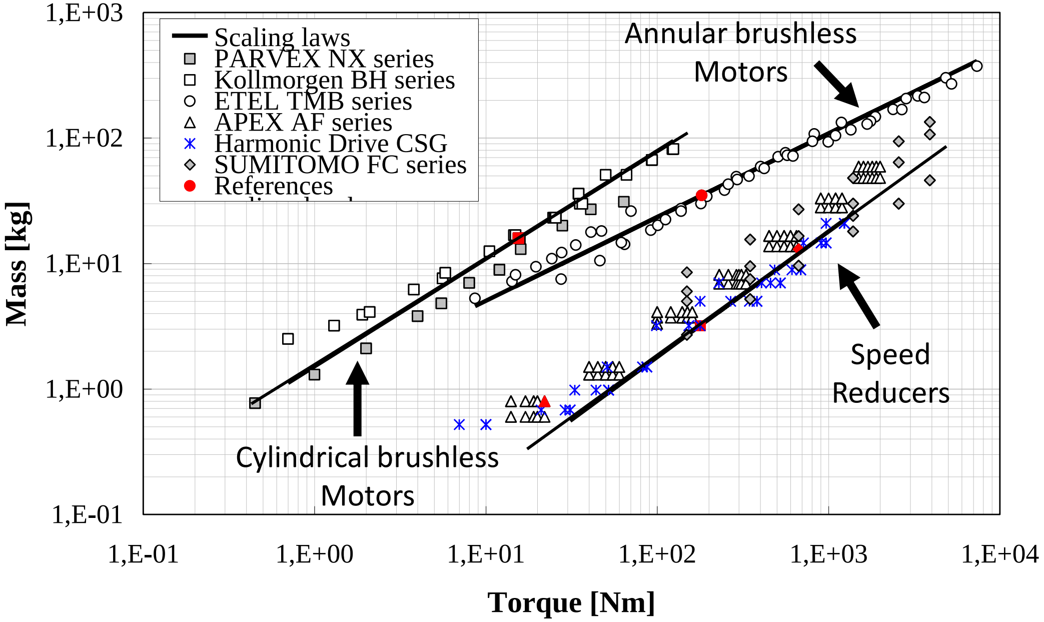
Comparison with catalogue data

Estimated and real (catalogue data) mass as function of nominal torque for a given type of cycloidal reducers
(FA series of Sumitomo).





Brushless motor and speed reducer masses as a function of the nominal torque.

Log-Log graphs : $Y = a.X^{\alpha} \rightarrow \log(Y) = \log(a) + \alpha.\log(X)$

marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

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Least square linear regression principle

Model form:

$$\underbrace{y}_{\text{dependent (response) parameter}} = \underbrace{a + b.\overset{\text{independent (explanatory) parameter}}{x} + c.x^2}_{\text{Non random or systematic component}} + \underbrace{\varepsilon}_{\text{Random component}}$$

Matrix representation:

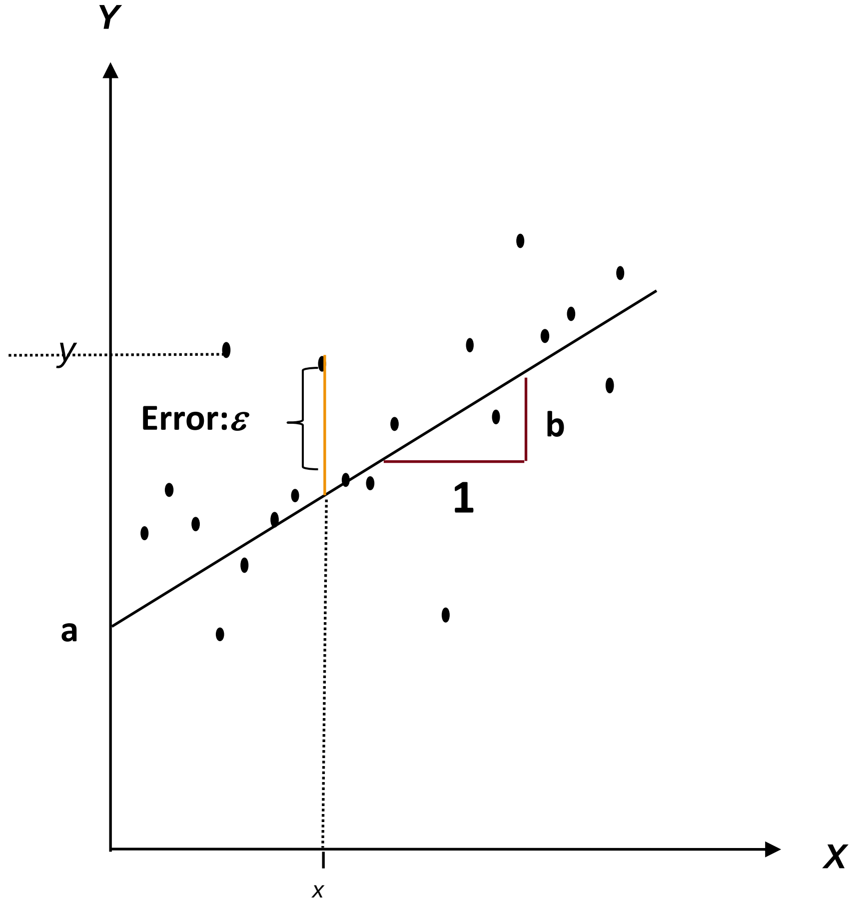
$$\begin{pmatrix} y_1 \\ \dots \\ y_p \end{pmatrix} = \begin{pmatrix} 1 & x_1 & x_1{}^2 \\ \dots & \dots & \dots \\ 1 & x_p & x_p{}^2 \end{pmatrix} \begin{pmatrix} a \\ b \\ c \end{pmatrix} + \begin{pmatrix} \varepsilon_1 \\ \dots \\ \varepsilon_p \end{pmatrix}$$

$$Y = X.\tilde{\beta} + \tilde{\varepsilon}$$

Square error:

$$L(\beta) = \tilde{\varepsilon}^t.\tilde{\varepsilon} = (Y - X.\tilde{\beta})^t (Y - X.\tilde{\beta})$$

minimum for $\frac{\partial L(\beta)}{\partial \beta} = 0$ and $\tilde{\beta} = (X^t X)^{-1} X^t Y$

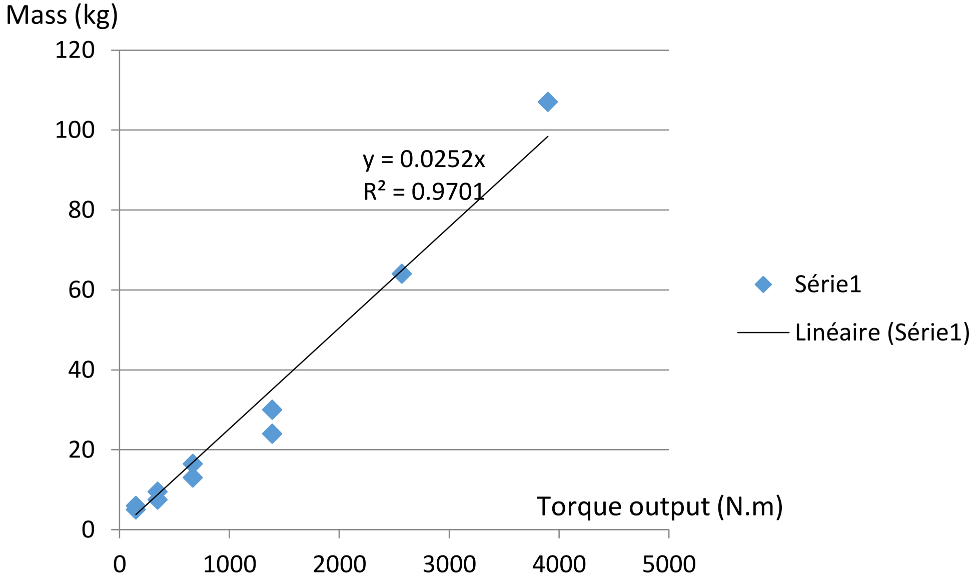


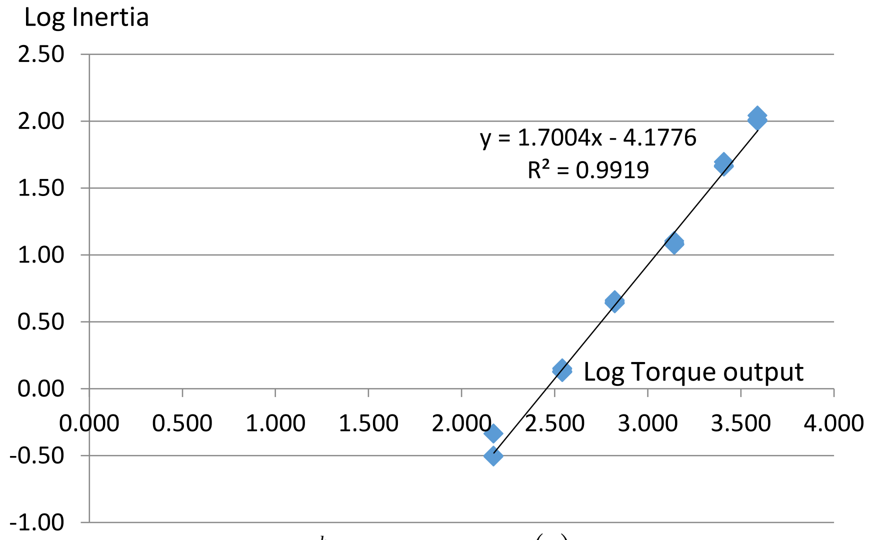
marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

Gear reducer: Simple linear regression

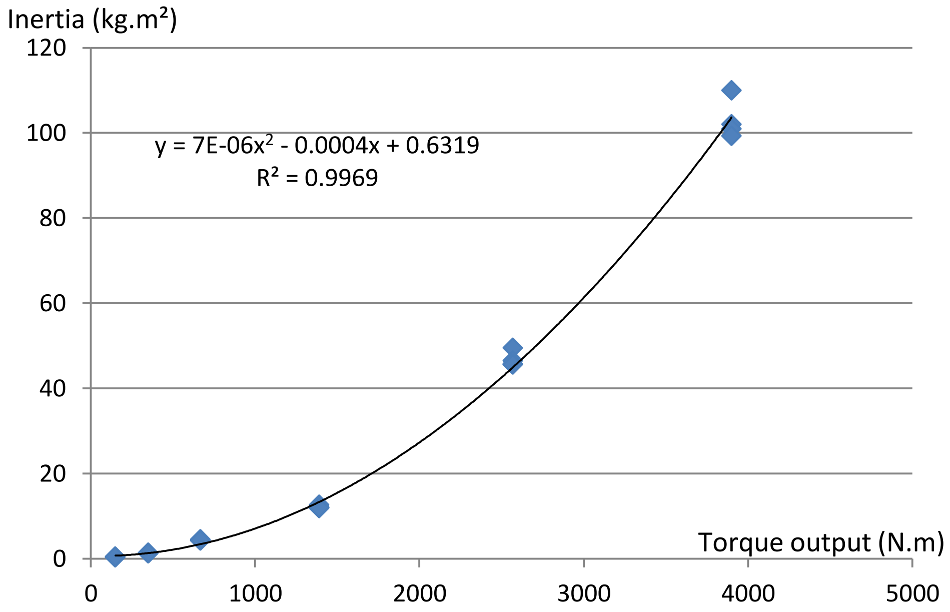
Mass and inertia with respect to output torque:

cyclo reducer





$$y = a.x^b \Rightarrow \log(y) = \log(a) + b.\log(x)$$



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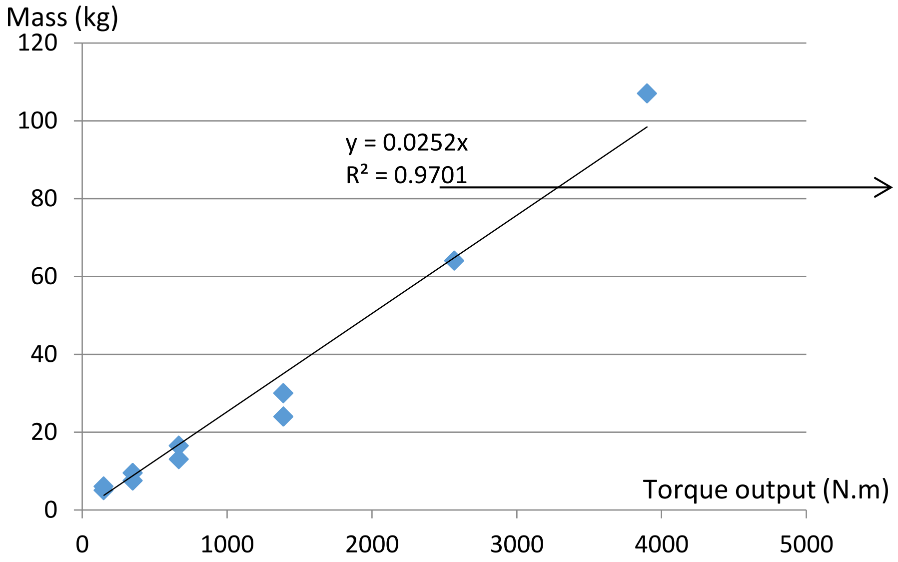
Verification



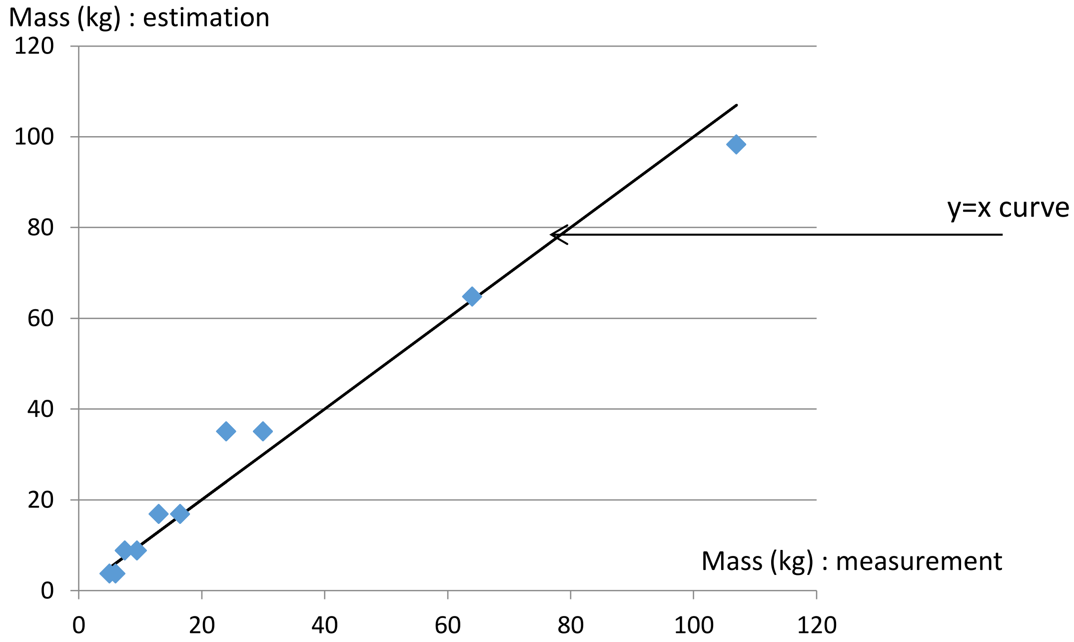
Coefficient of determination R^2:

Error variation

$$R^2 = 1 - \frac{\sum (y_i - \hat{y}_i)^2}{\sum (y_i - \bar{y}_i)^2}$$

Total variation

Percentage of total variation explained by the regression.



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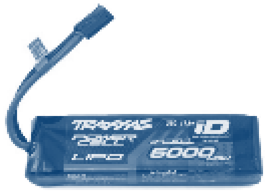
Case study application: Electrical components

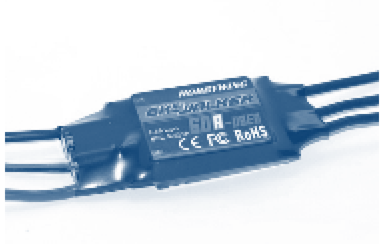
Scaling laws:

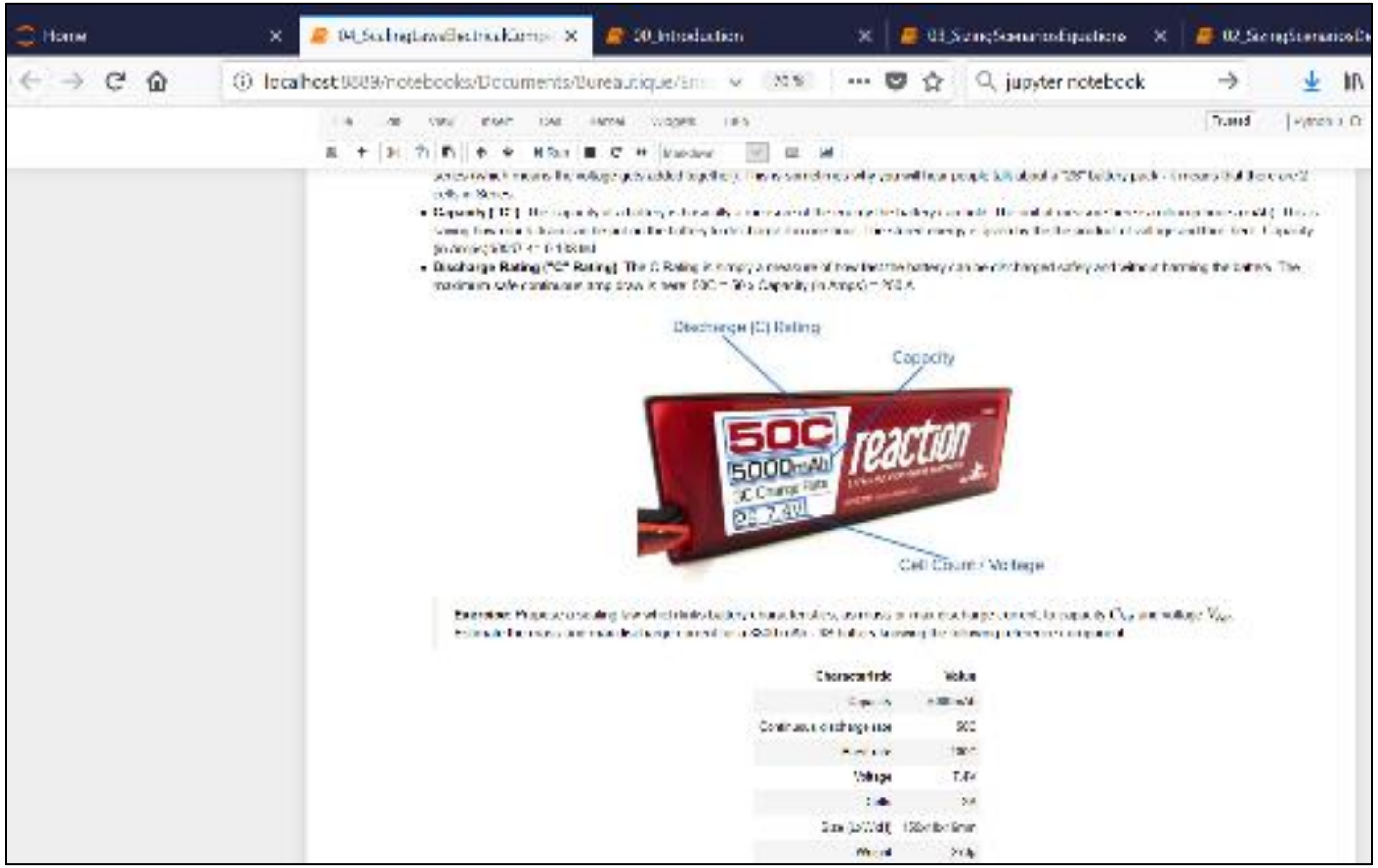
- Battery



- Brushless motor

- ESC





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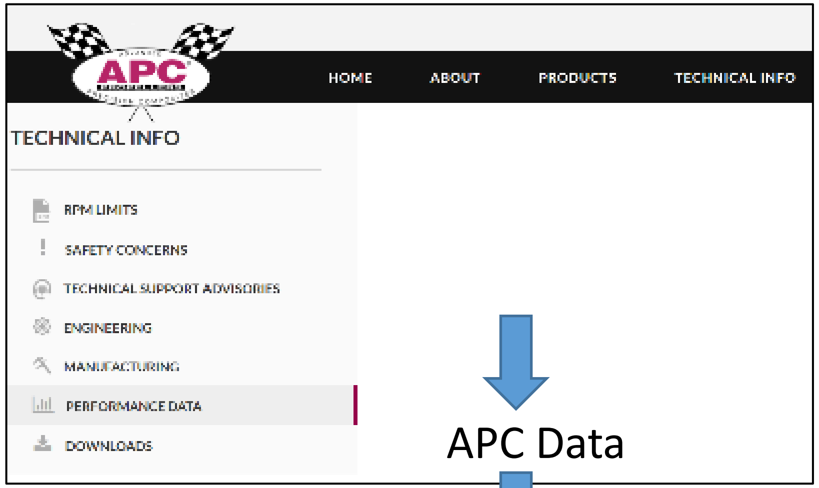
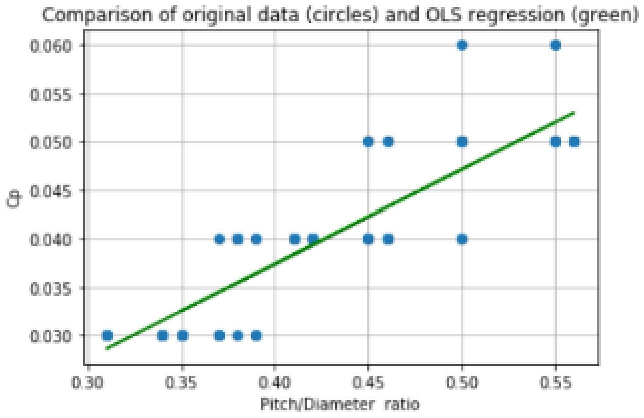
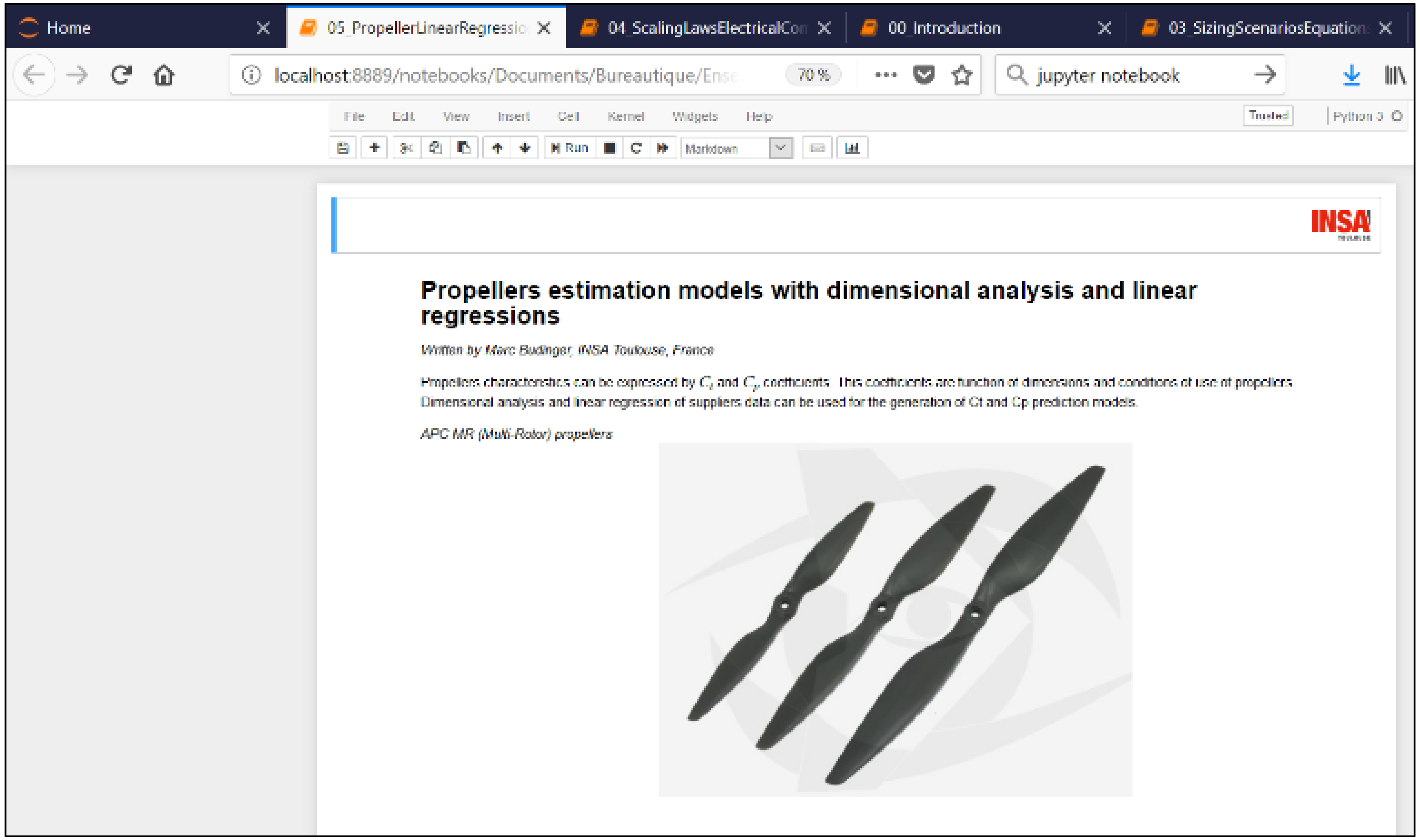
Case study application: Multi-Rotor propellers

Linear regression:



APC Data





marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

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Preliminary design and sizing of mechatronic systems

Sizing procedures and optimization problems definition

marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

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Sizing procedure and optimization

The preliminary design is an inverse problem :

What we want

Systems specifications → **Design model** → Components specifications

What we can have thanks modeling

Components characteristics → **Simulation model** → System performances

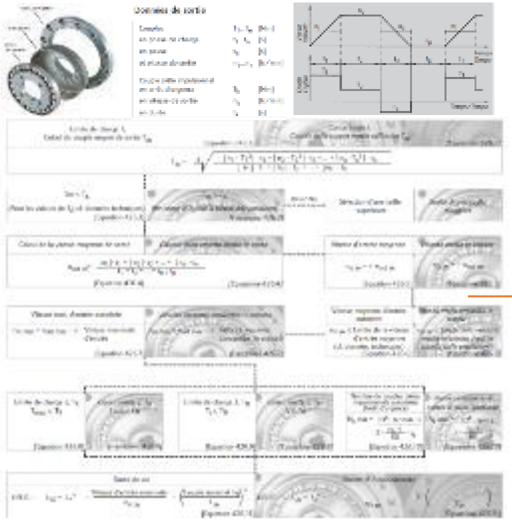
Inverse problem

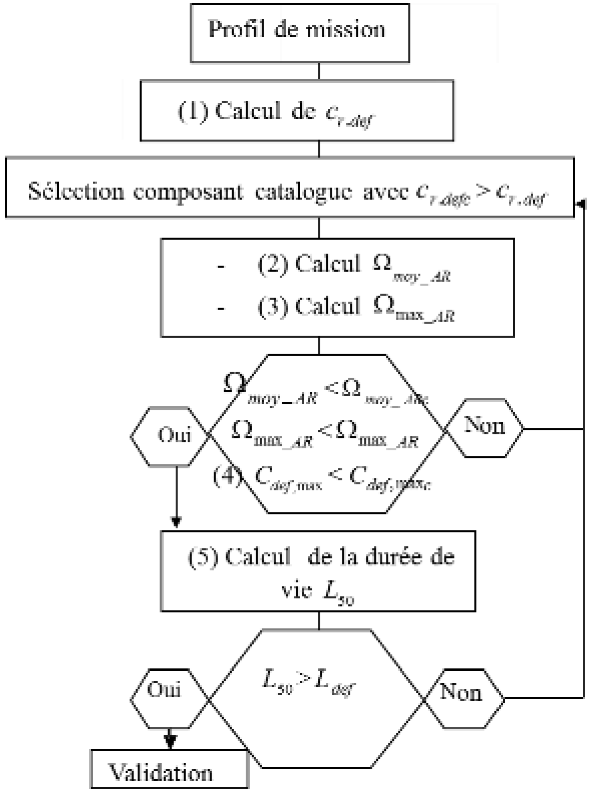
Two main solutions for this problem :

- **Sizing or selection procedure :**

Example :

Harmonic Drive reducer





- **Optimization algorithms :**

$$\text{Minimize} \quad f(\mathbf{x})$$

The goal is the objective function f

$$\text{Subject to} \quad \mathbf{h}(\mathbf{x}) = \mathbf{0}$$

$$\mathbf{g}(\mathbf{x}) < \mathbf{0}$$

Constraints (h & g) limit the number of alternatives to those that satisfy physical principles and design specifications, the feasible design

$$\mathbf{x}_{low} < \mathbf{x} < \mathbf{x}_{upp}$$

Design alternatives are expressed by a set of values assigned to the design variables (x)

marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

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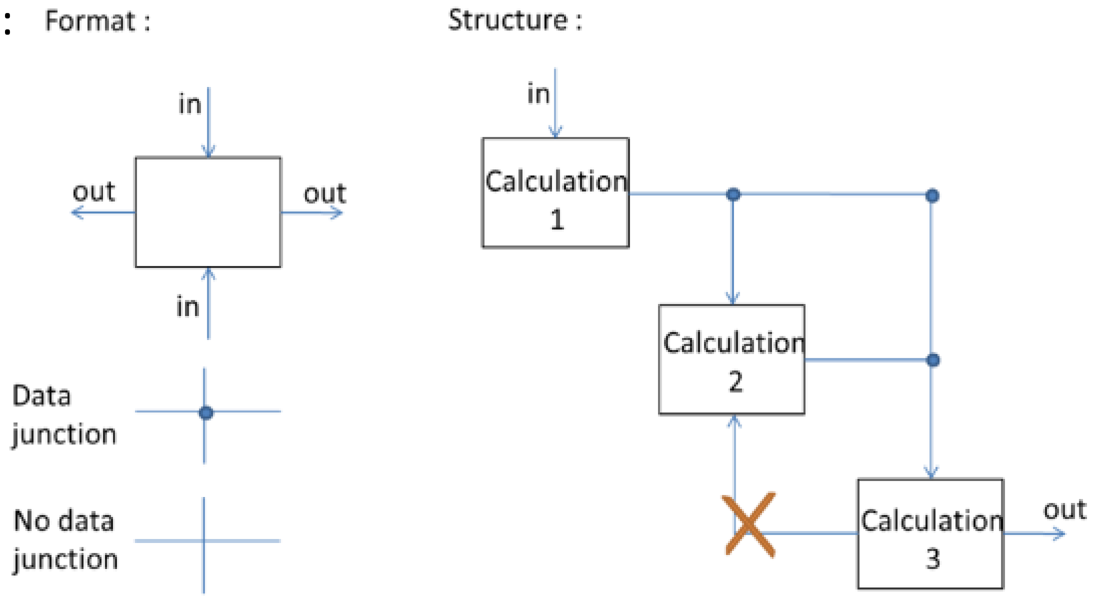
Sizing procedures / N² diagrams

The N² diagram :

- Causal diagram where the graphical entities (blocks) and interactions (arrows) are dictated by an organization convention
- The inputs of the blocks are represented by vertical arrows while the outputs must be horizontal arrows.

Organization convention :



➔ • quick visual summary of the organization of the studied system
• couplings and algebraic loops between blocks are easily identified

marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

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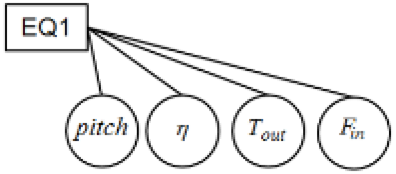
Sizing procedures / Graphs and dependency matrixes

- Sizing problem = a constraint network where sizing parameters represent variables and equalities/inequalities represent constraints.
- Constraint networks can be represented by graph and dependency matrixes

Graph representations of equation :

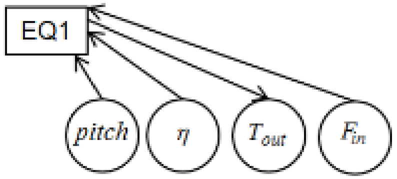
$$T_{out} - F_{in}.\frac{pitch}{\eta} = 0$$

Non-oriented graph and equation

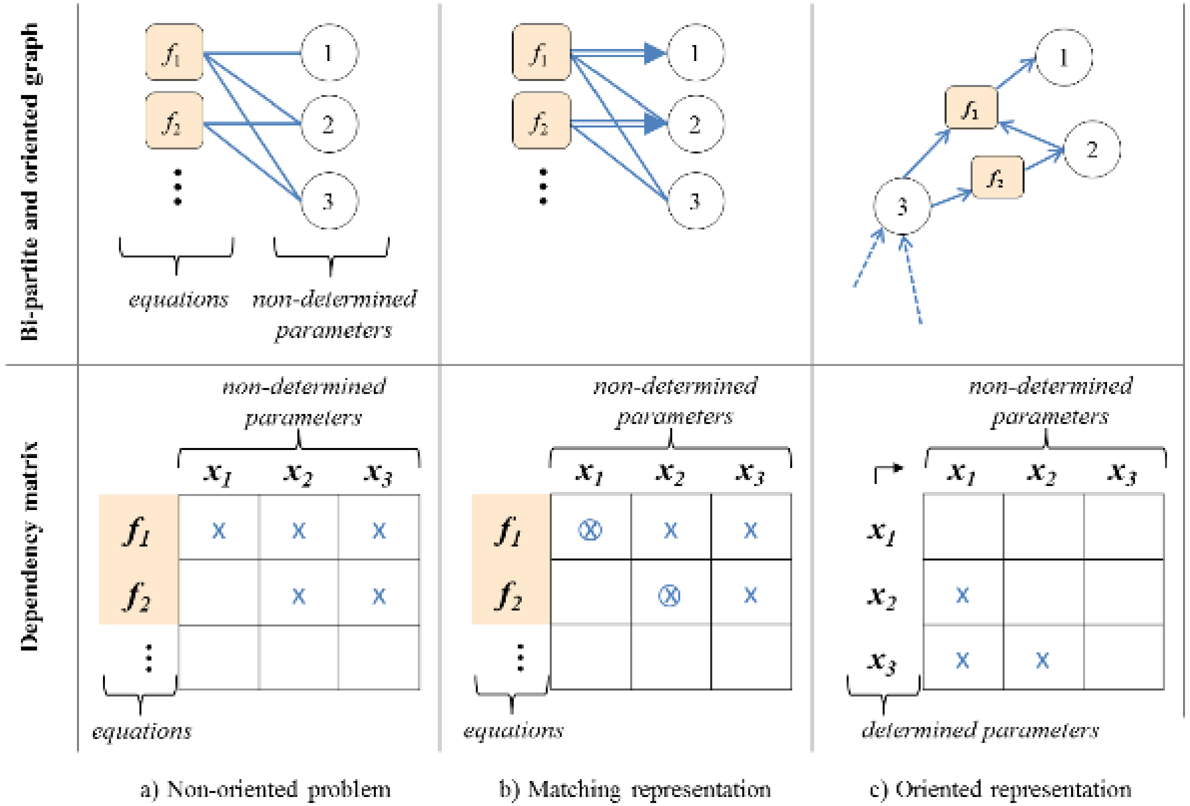


$$T_{out} = F_{in}.\frac{pitch}{\eta}$$

Oriented graph and equation



Matching of a 2x2 problem :



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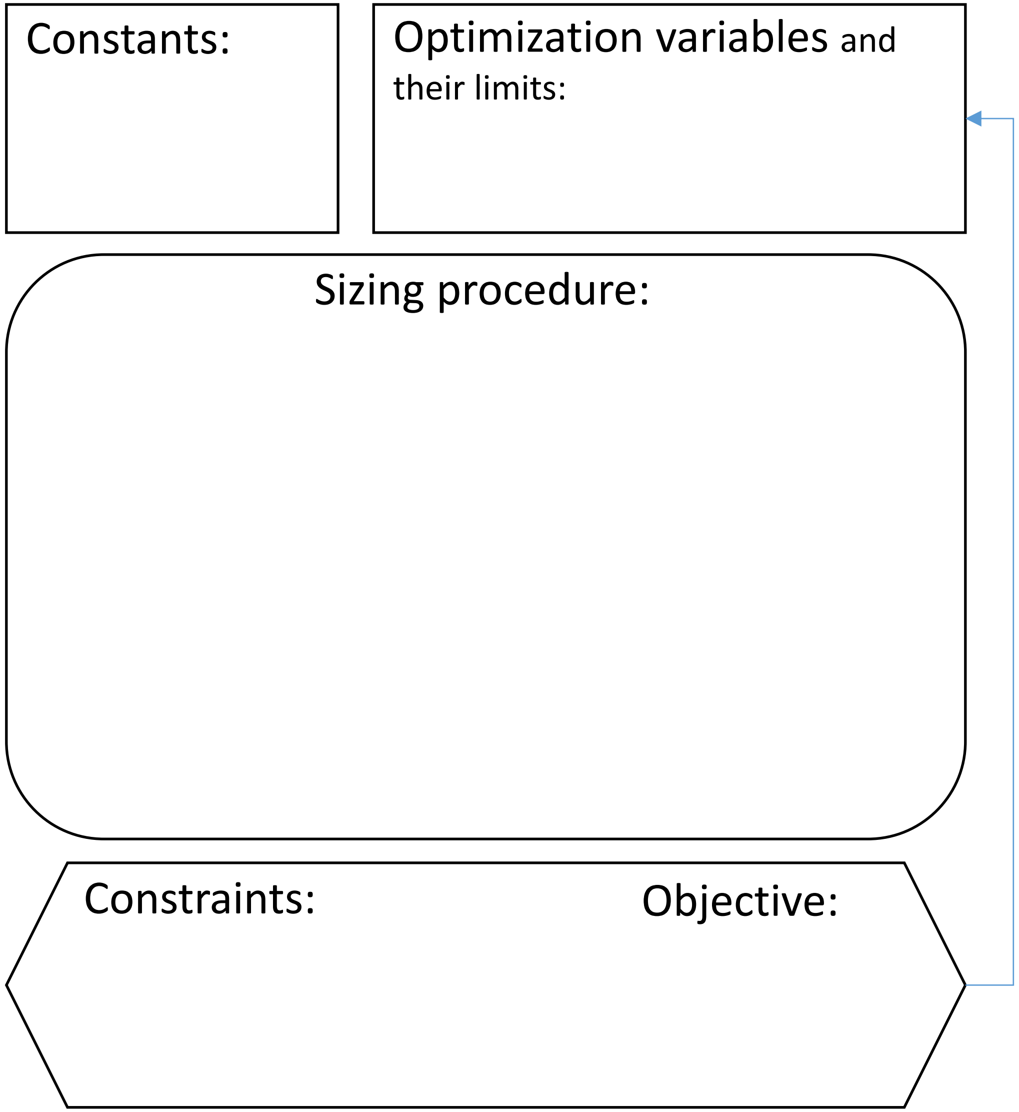
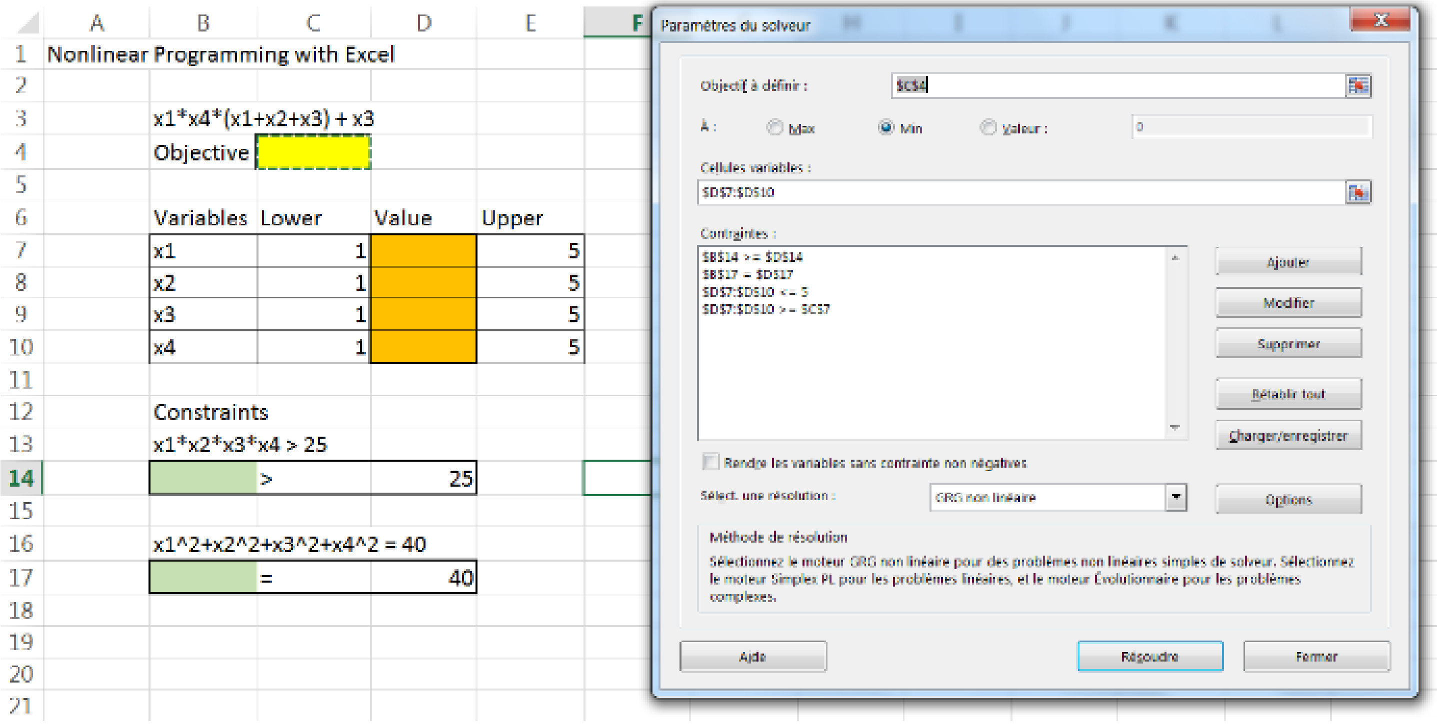
Optimization / Pseudo code representation

Pseudo-code skeleton of an optimization problem:



Excel solver:

- Add-in for Excel : /File/Options/Add-in
- Access : /Data/Solver



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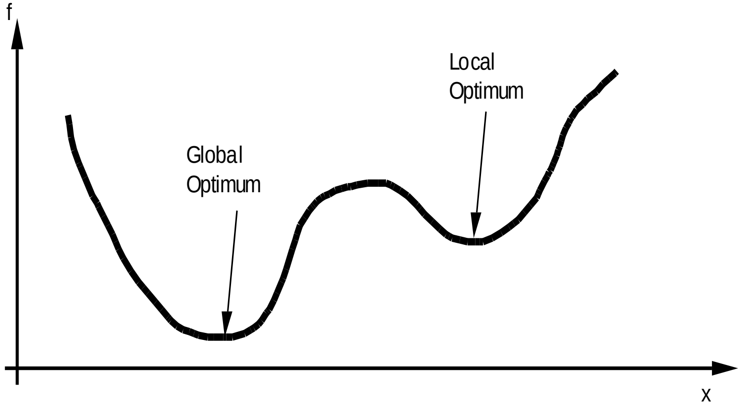
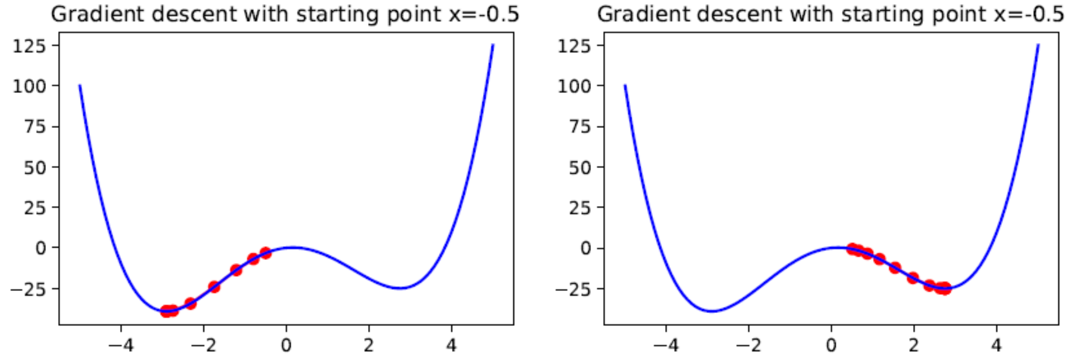
Local and global optima

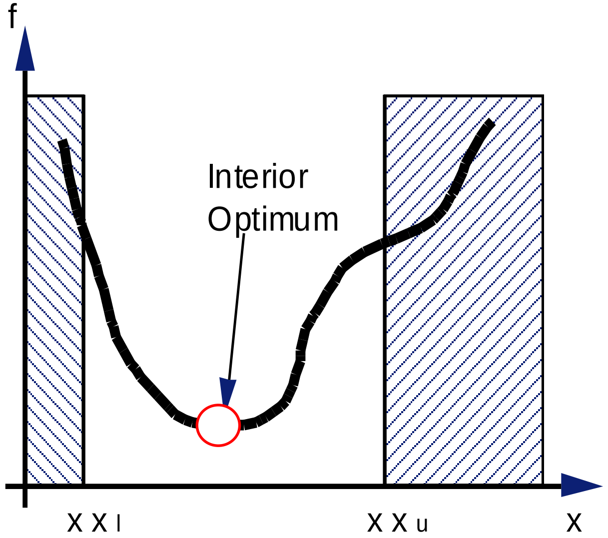


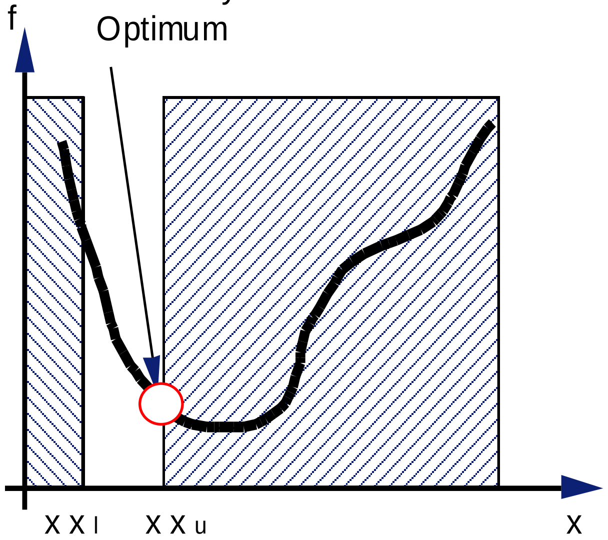


Gradient descent example

Interior and Boundary Optima

- An optimum is interior if all the constraints are inactive
- An optimum that is not interior is a boundary optimum

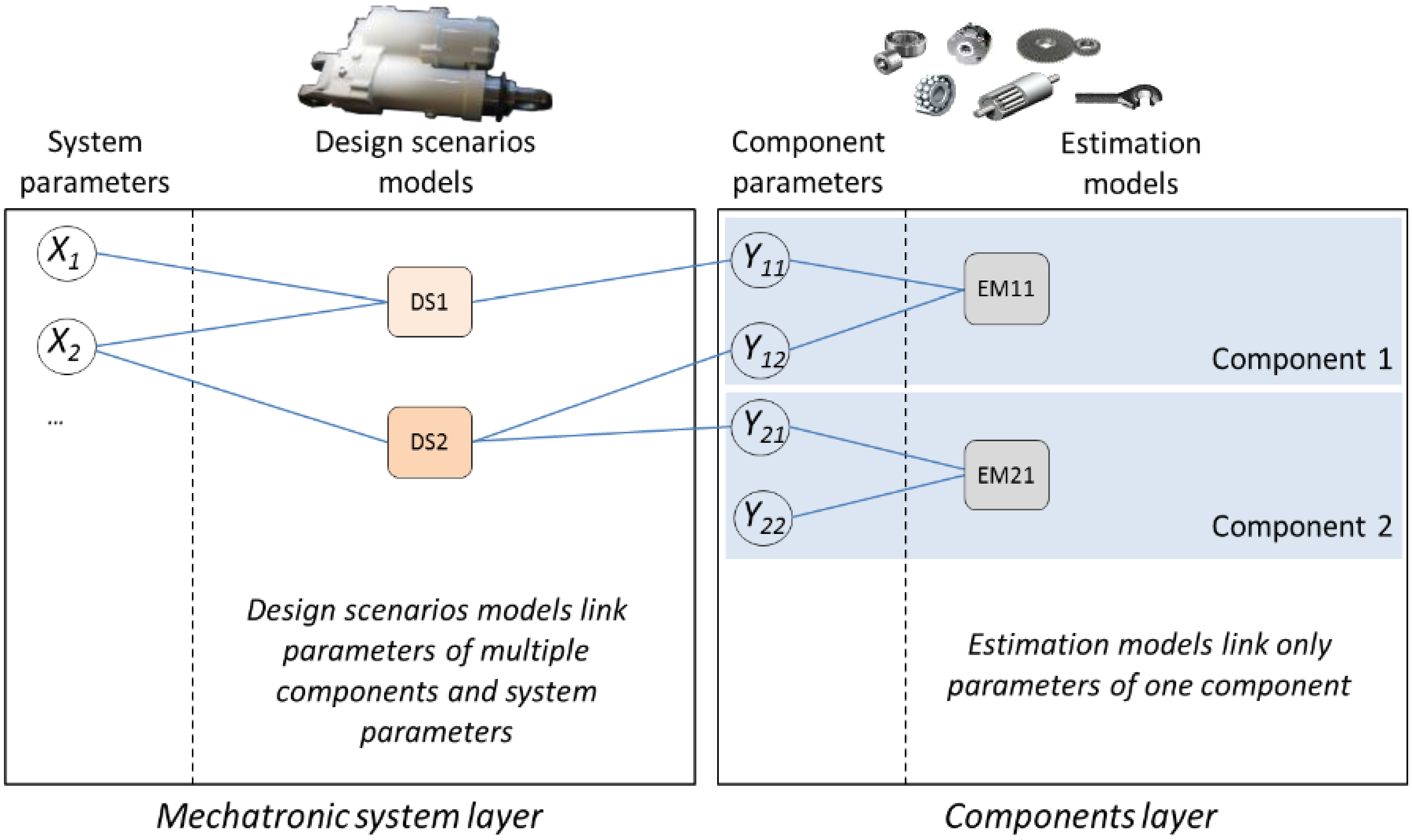




marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

SizingLab

Design graphs : representation of a set of sizing equations p31



➔
- Bipartite graph for each design layer
- Relationships between the parameters and equations are represented as non-oriented edges

marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

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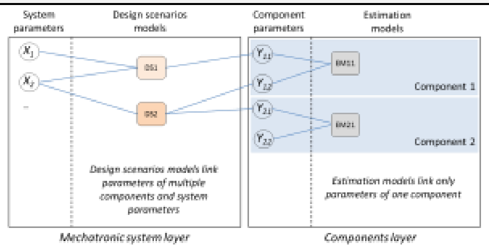
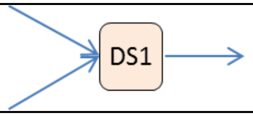
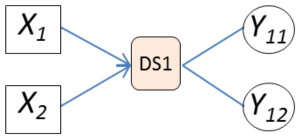
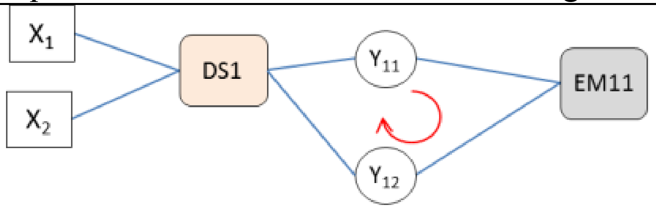
Design graphs: orientation and explicit formulation

Objectives:

- to order flows of information into a sizing procedure.
- a sizing procedure well posed and easy to use in any computing environment → this procedure must be explicit without internal numerical solver.

Proposed process :

	Process (« WHATs »)		Methods (« HOWs »)	Tools (implement the «HOWs ») : Design Graphs
1	Problem definition	1.1	Gather all the equations/inequalities describing the problem.	
2	Orientate the problem	2.1	Match equations/parameters	
		2.2	Identify and highlight over-constrained and under-constrained singularities	
		2.3	Errors are fixed by the designer manually modifying parameters status (to determined/input) or moving inequalities to constraint while introducing safety factors.	
3	Break problem calculation loops.	3.1	Identify and highlight algebraic loops	
		3.2	Identify and highlight the minimum set of parameters to be fixed to suppress loop.	
		3.3	Loops are displaced to upper layer manually by the designer.	

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scott.delbecq@isae-supaero.fr

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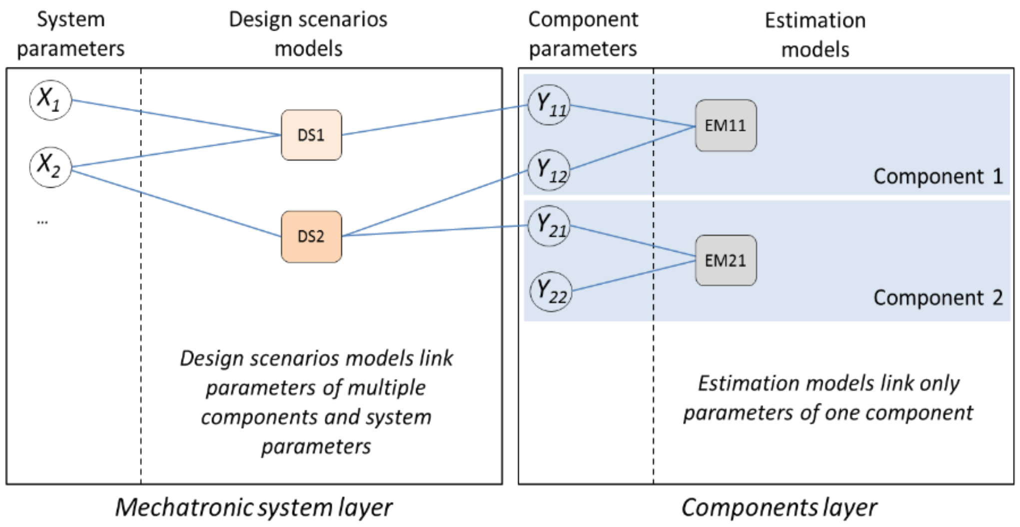
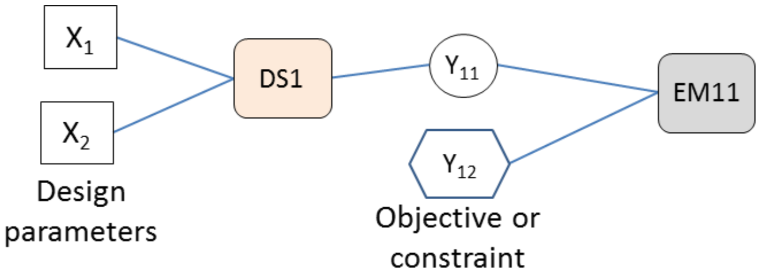
Design graphs: main steps and problems

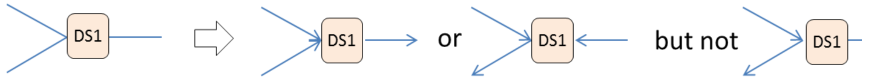
1/ Problem definition



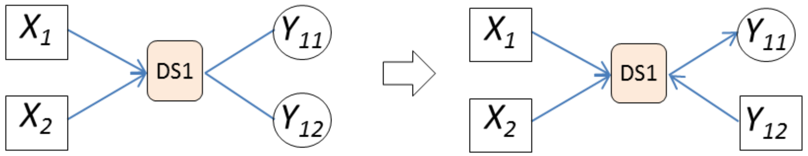
2/ Equations orientation



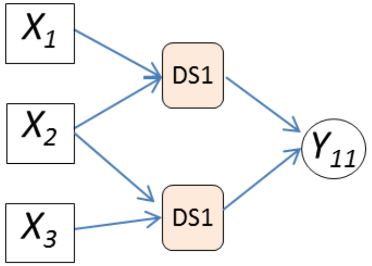
Inputs (design parameters) and outputs (objectives or constraint) representation



Equation orientation

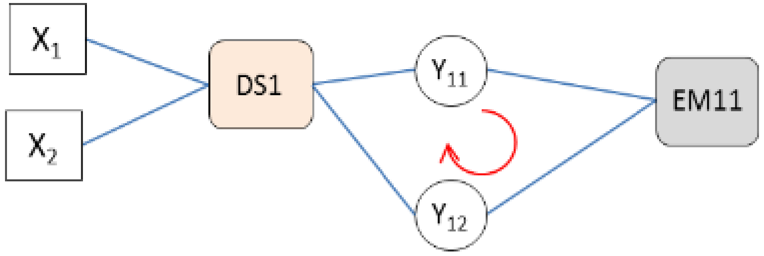


Under-constraint equation



Over-constraint equations

3/ Algebraic loops



➔ The optimization problem is defined (inputs, constraints, objective)

marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

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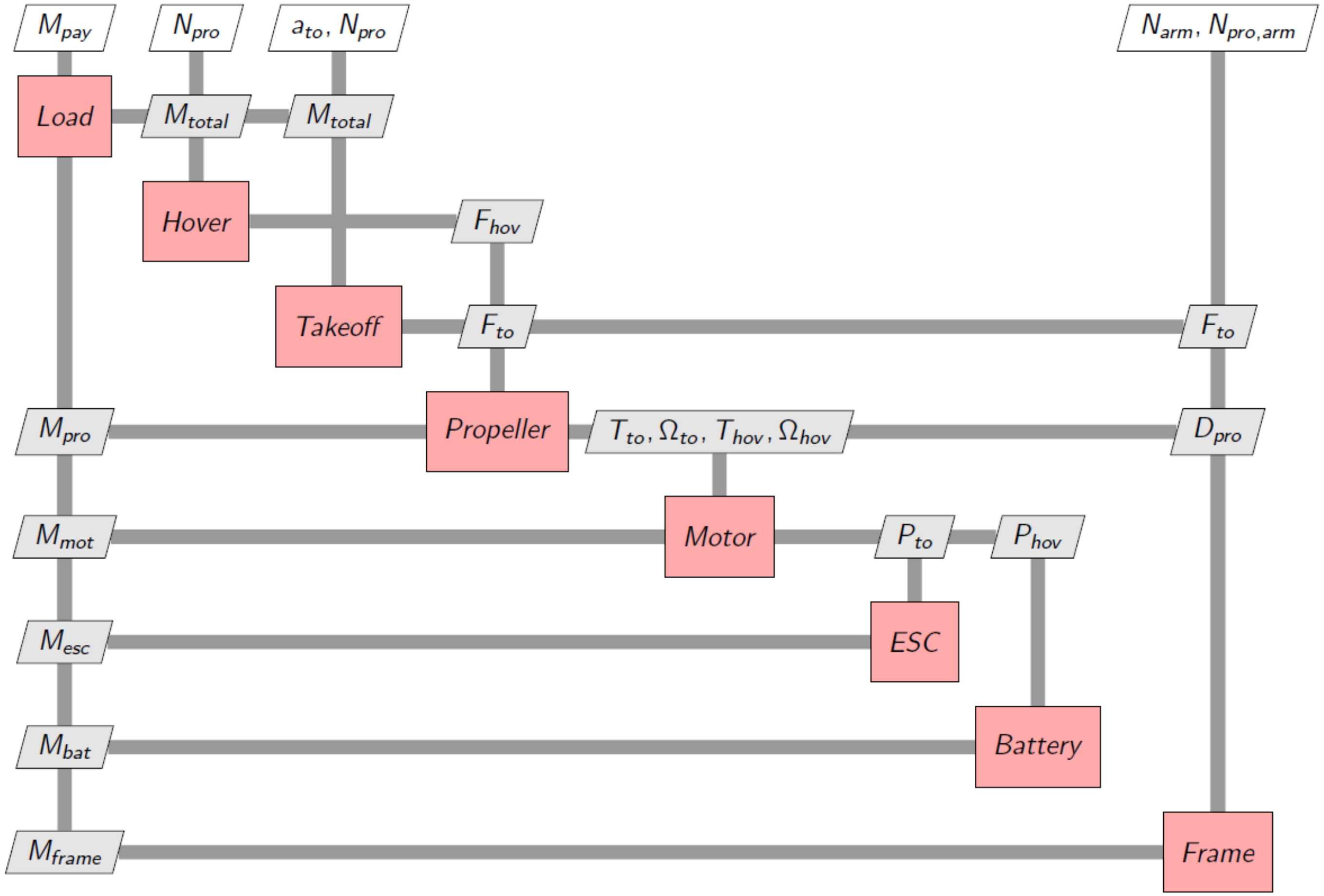
Case study, global sizing process

Multirotor sizing example



Question:

- Explain notation of N2 diagrams.
- Which classical sizing problem can be highlighted by this notation?
- Do you see a problem here? If yes, give a solution.

marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

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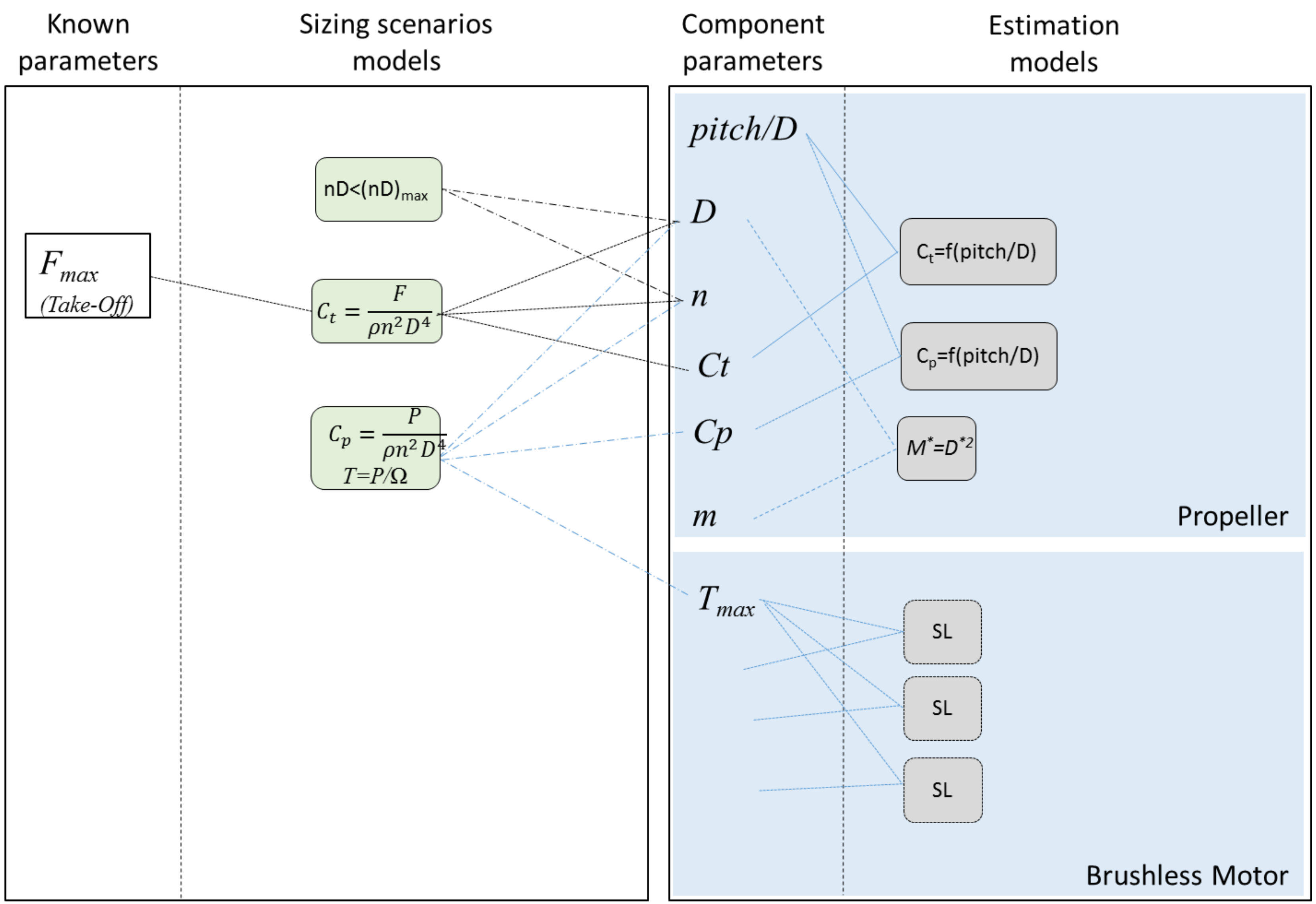
Case study, propeller selection



Questions:

- Give the main sizing problems you are able to detect.
- Propose one or multiple solutions (which can request equation manipulation, addition of design variables, addition of constraints)
- Orientate the arrows
- Give equations order, inputs/outputs at each step of this part of sizing procedure

marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

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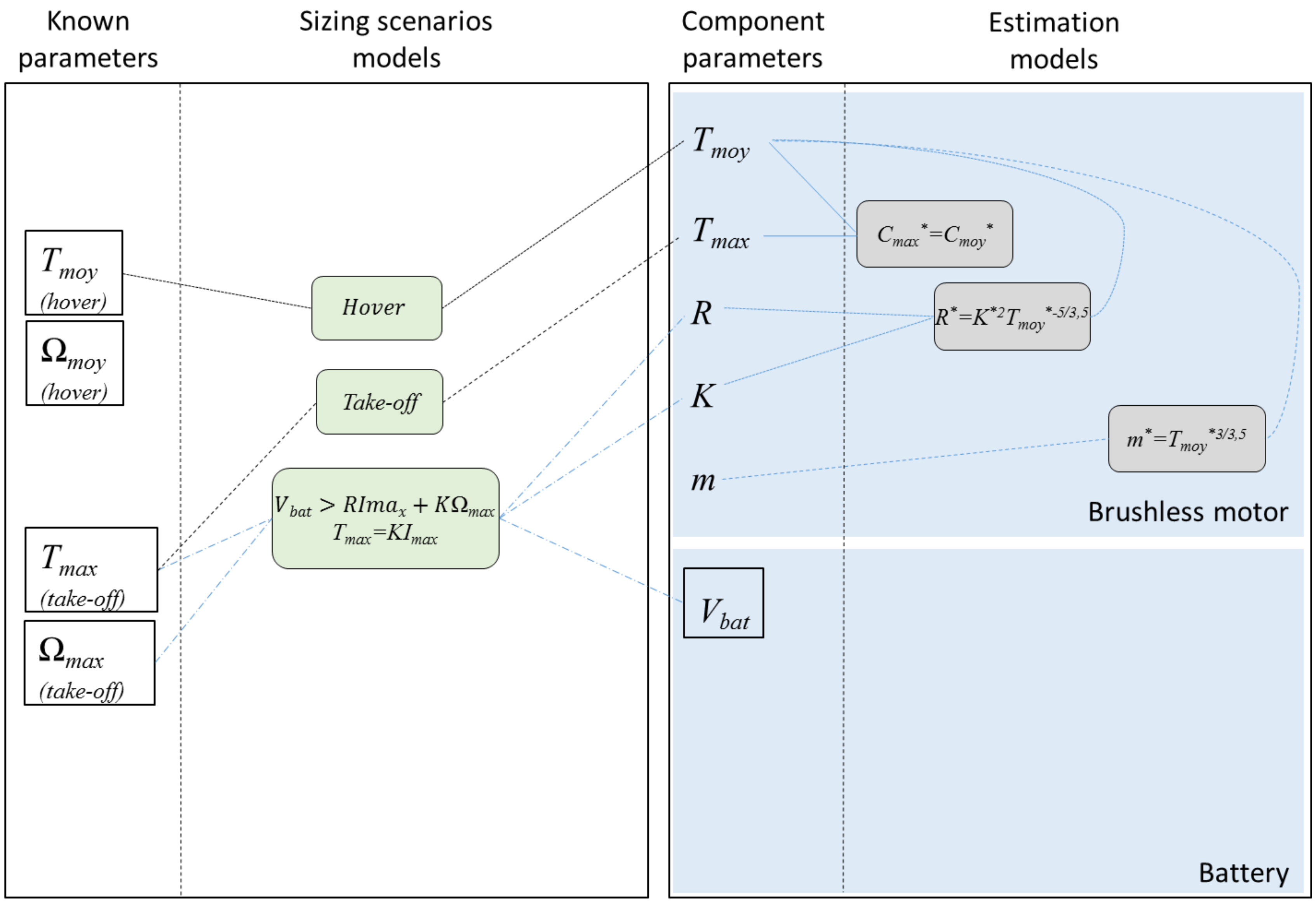
Case study, motor selection



The following diagram represents the design graph of the propeller's selection. The mean speed/thrust (Ωmoy & Tmoy), the max speed/thrust (Ωmax & Tmax) and the battery voltage are assumed to be known here.

Questions:

- Give the 2 main sizing problems you are able to detect here.
- Propose one or multiple solutions (which can request equation manipulation, addition of design variables, addition of constraints)
- Orientate the arrows and write equations order, inputs/outputs at each step of this part of sizing procedure, additional constraints

marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

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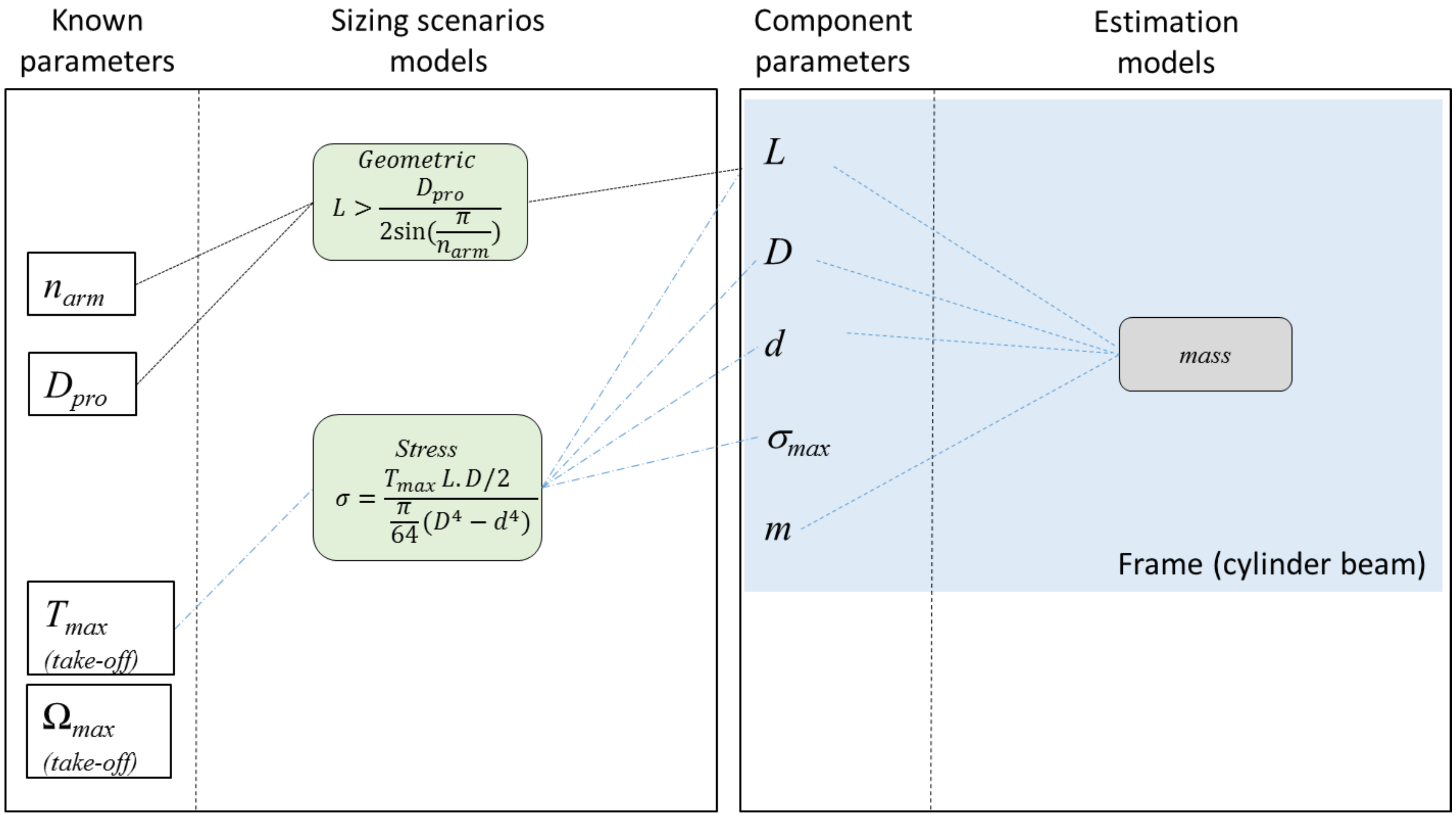
Case study, frame sizing



The following diagram represents the design graph of the frame sizing (round tube).

Questions:

- Give the main sizing problems you are able to detect here.
- Propose one or multiple solutions (which can request equation manipulation, addition of design variables, addition of constraints)
- Orientate the arrows and write equations order, inputs/outputs at each step of this part of sizing procedure, additional constraints

marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

Notebooks

Battery and ESC Sizing

Overall Multirotor Sizing

marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

Preliminary design and sizing of multi-rotor drones

Discussions and exchanges

marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

SizingLab

Increase the numbers of sizing criteria

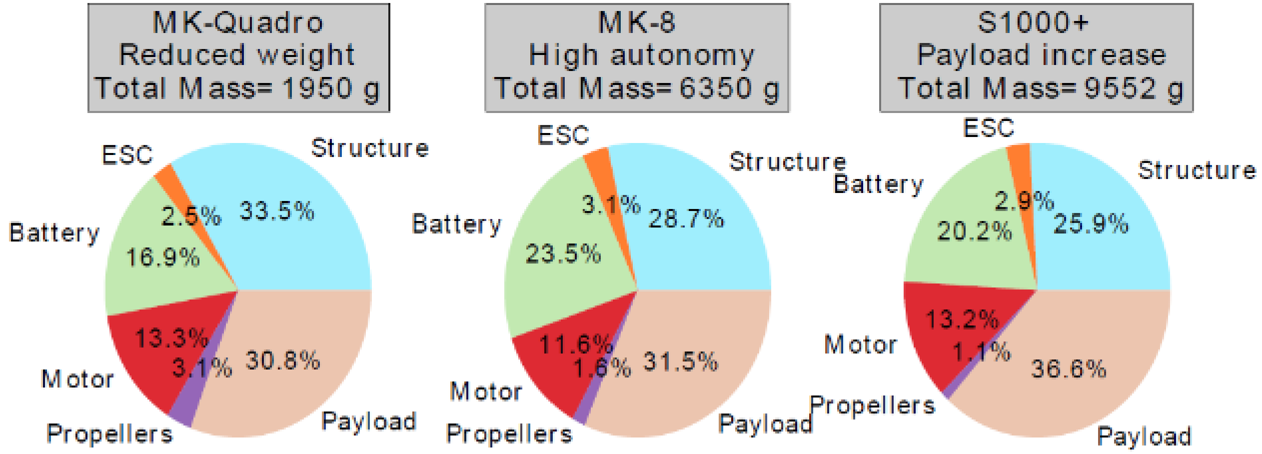
Sizing scenarios

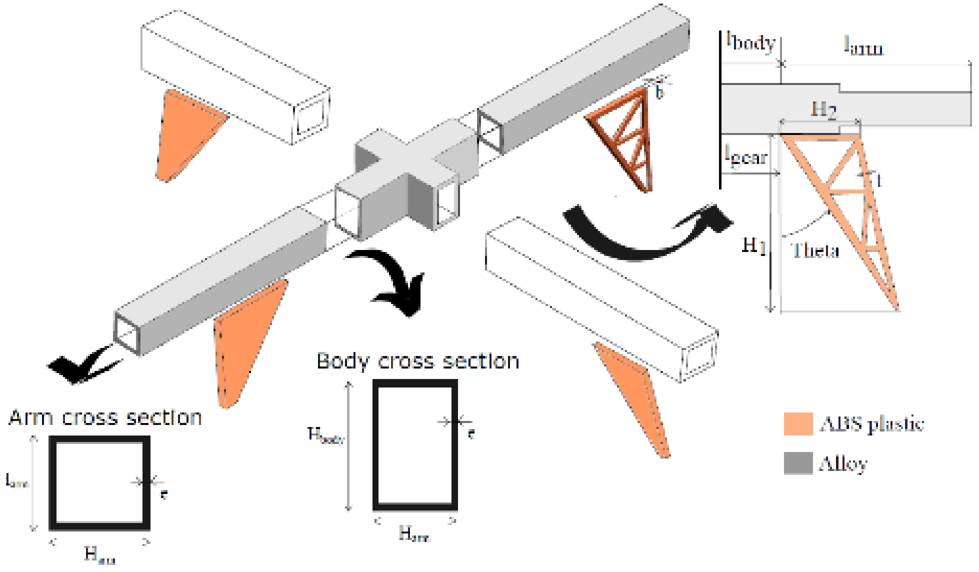
Vertical flight : calculation of drag force

Forward speed and : aerodynamic forces (lift ?, drag ?), propeller

Max forward speed and gust

Components





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scott.delbecq@isae-supaero.fr

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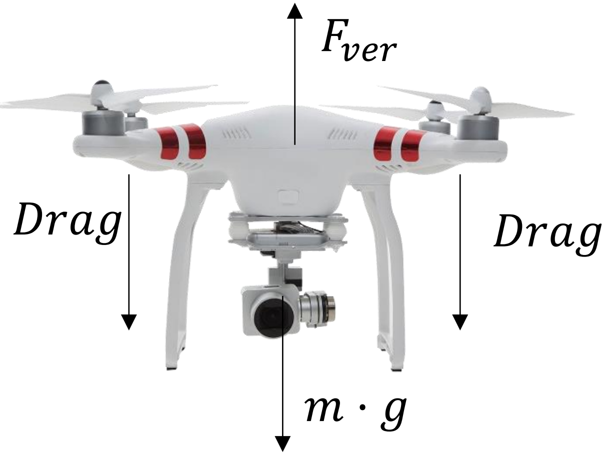
Maximum vertical speed

Vertical movement

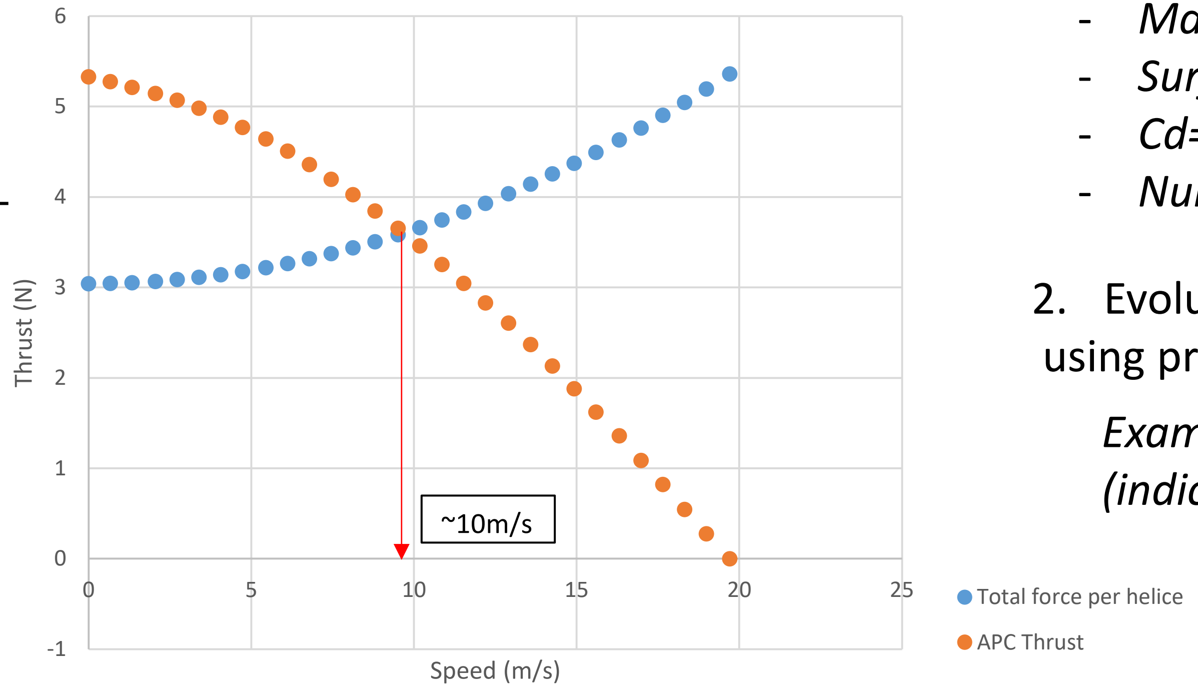


$$F_{ver,prop} = \frac{1}{N_{prop}} \cdot (m \cdot g + \frac{1}{2} \cdot \rho \cdot S \cdot C_d \cdot v^2)$$

Required thrust increases with the square of the speed

Propeller performance for speeds

Propeller thrust decreases as speed increases.



Need to find the maximum operating point for a certain speed v

HOW?

1. Calculation of vertical force w.r.t. speed (v)

Example: DJI Phantom 2 Vision+:

- *Mass: 1,24 kg*
- *Surface: 0,0306 m²*
- *Cd=1,3*
- *Number of propellers=4*

2. Evolution of thrust force w.r.t. speed (v) using propeller data catalog.

Example: APC MR for 7000 RPM (indicated by the manufacturer)

marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

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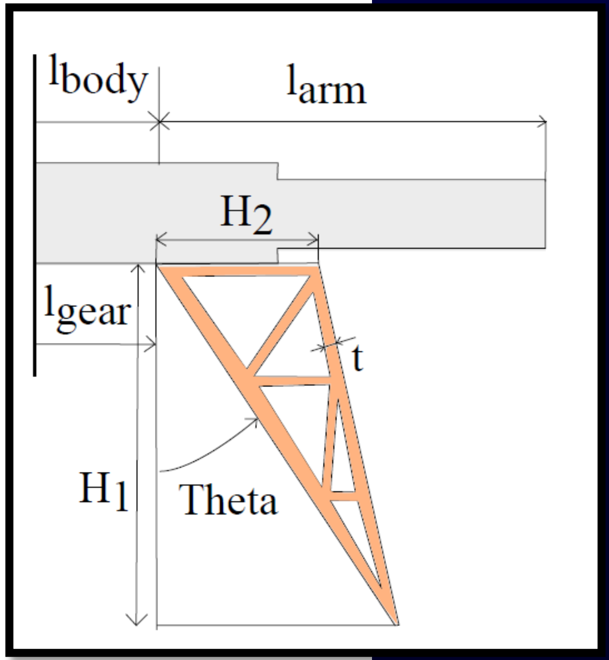
Increase model fidelity

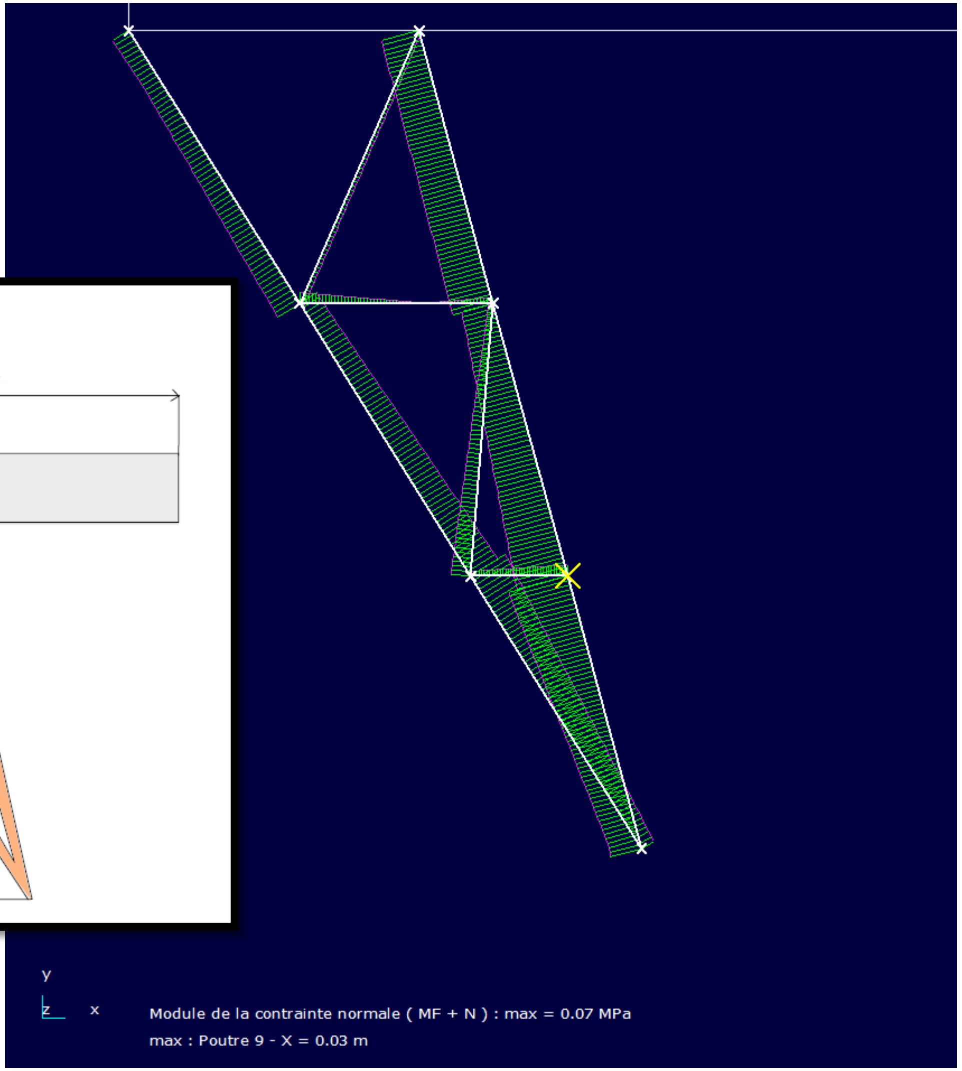
1. Sizing landing gears/body on crash scenario
    a) Evaluate landing gear stiffness
    b) Evaluate body stiffness
    c) Calculate max load (energy conversion)

$$F_{max} = \frac{1}{4}(k_{eq}.\delta x + M_{tot}.g) = \frac{1}{4}(V_{impact}.\sqrt{k_{eq}M_{tot}} + M_{tot}.g)$$

$$k_{eq} = 4.\frac{\tilde{k}_1.\tilde{k}_2}{\tilde{k}_1 + \tilde{k}_2}$$

    d) Evaluate mechanical constraint





marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

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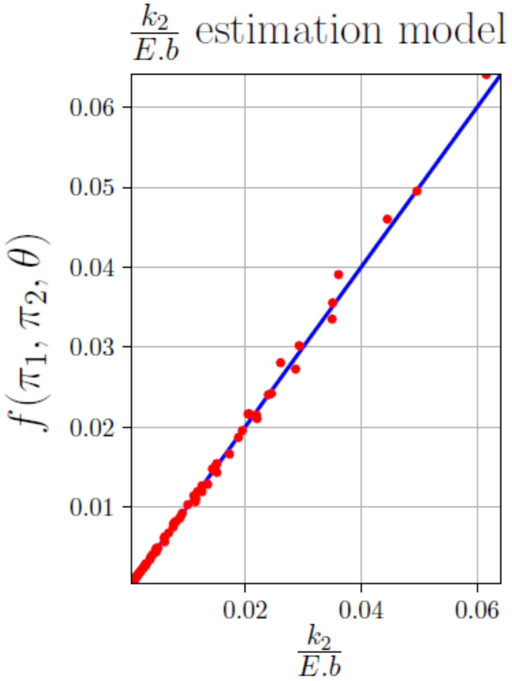
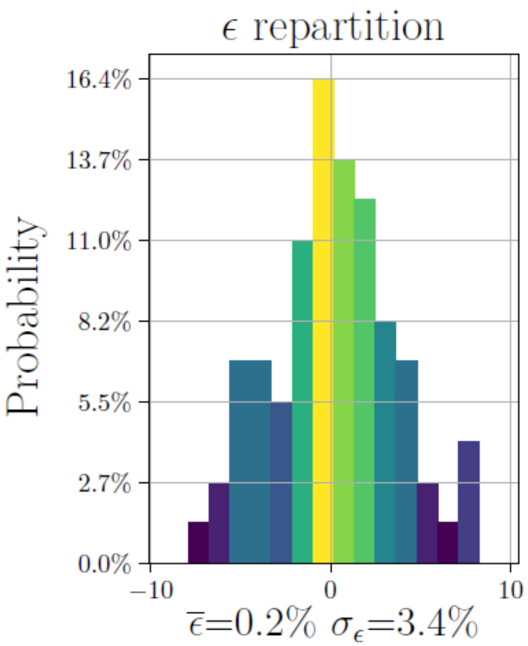
Increase model fidelity

a) Evaluate landing gear stiffness

$$\pi_{k_2} = \frac{k_2}{b.E} \approx f(\frac{H_1}{H_2}, \frac{t}{H_1}, \theta) = f(\pi_1, \pi_2, \theta) = \tilde{\pi}_{k_2}$$

$$\tilde{\pi}_{k_2} = 10^{-0.37053}.\pi_1^{-3.11170}.\pi_2^{1.10205}.\theta^{-6.61617-4.86580.log(\theta)}$$

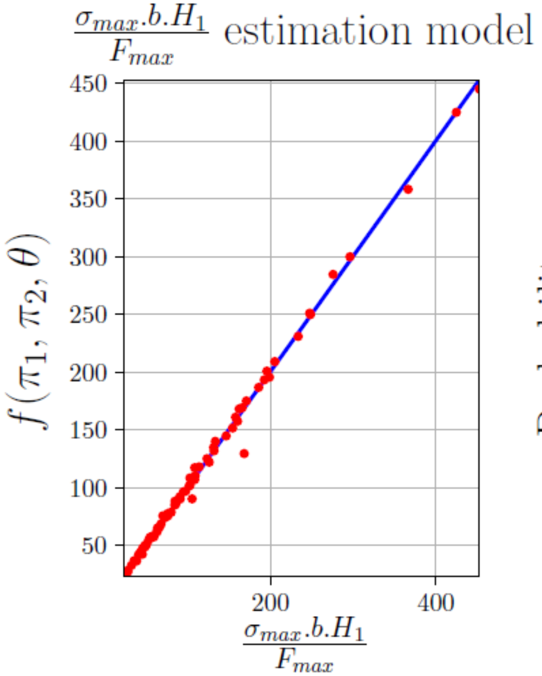


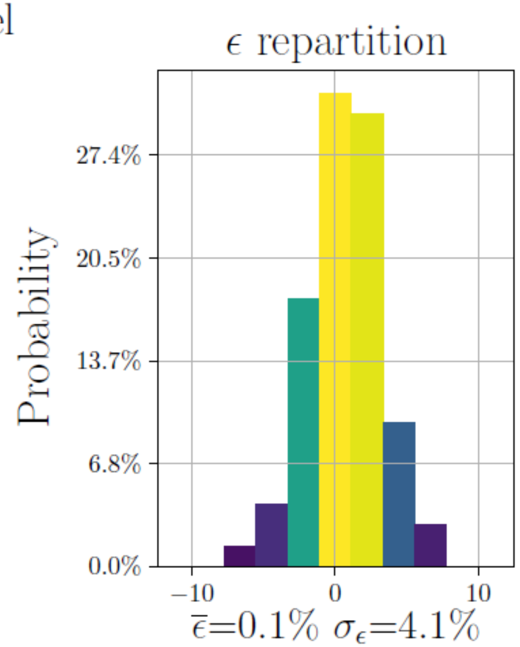


d) Evaluate mechanical constraint

$$\pi_{\sigma_{max}} = \frac{\sigma_{max}.b.H_1}{F} \approx f(\frac{H_1}{H_2}, \frac{t}{H_1}, \theta) = f(\pi_1, \pi_2, \theta) = \tilde{\pi}_{\sigma_{max}}$$

$$\tilde{\pi}_{\sigma_{max}} = 10^{0.14690}.\pi_1^{2.08982}.\pi_2^{-0.98108}.\theta^{3.38363+2.66468.log(\theta)}$$





marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

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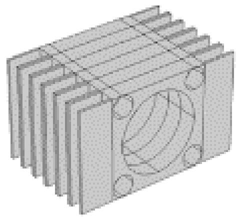
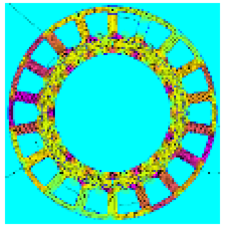
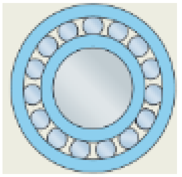
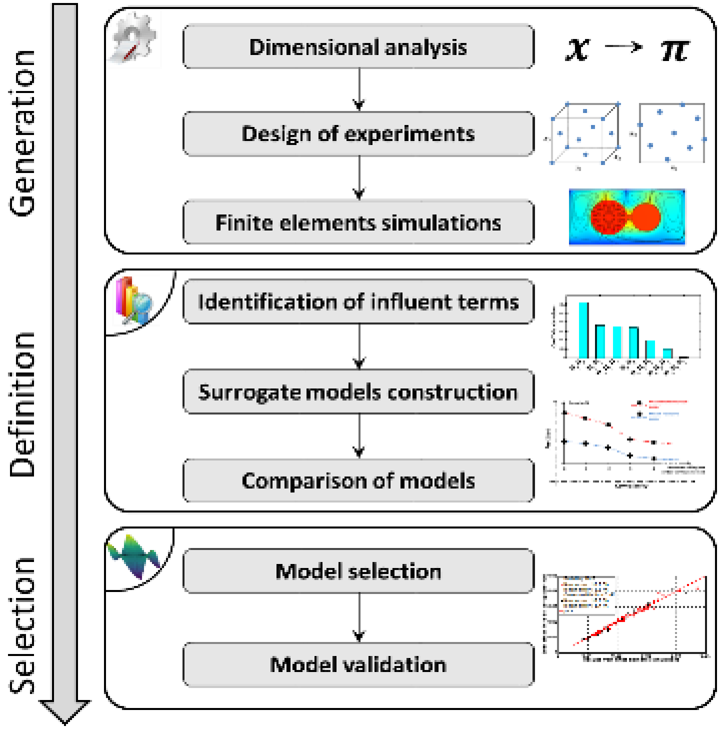
Increase model fidelity



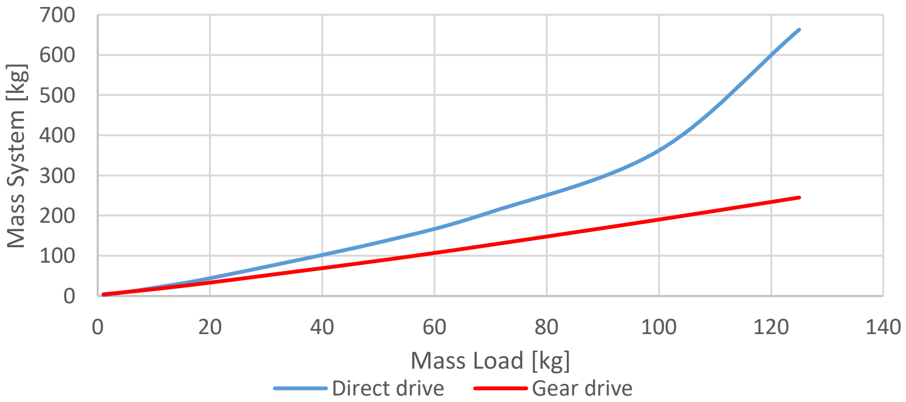


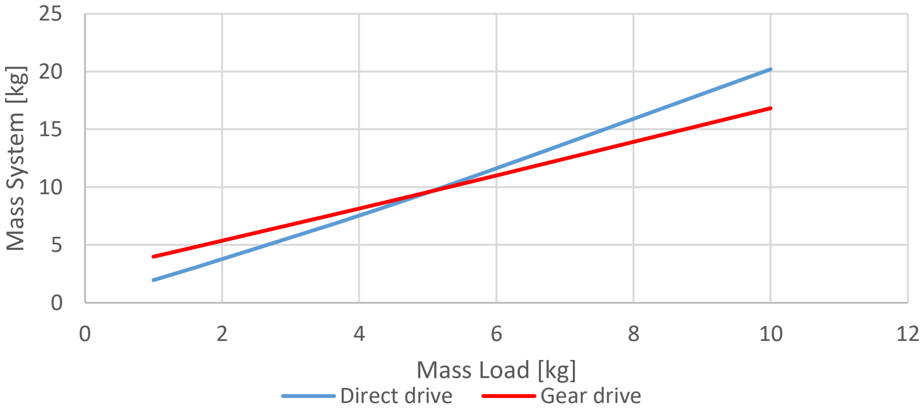


Joby Motor



Mass evolution at 30 min. of fixed autonomy





Marc Budinger, Francesco De Giorgi, François Defay. Surrogate models of PM brushless motor for the preliminary design of a multi-rotor drone. *AST 2019, Aircraft System Technologies,* Hamburg

marc.budinger@insa-toulouse.fr
scott.delbecq@isae-supaero.fr

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