Modeling for Designing –

An essential Stage

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Outline

- Introduction
- Bond Graph methodology
- Industrial applications
- Conclusion

Designing new technological engineering systems : a complex task

Difficulties linked to the system:
→ Multiphysics, multienergy (mechanical, hydraulic, electrical, thermal …)
→Mixing power and information
→ Constraints : Energy consumption, safety and reliability

→ Teams with specialists of different physical domains

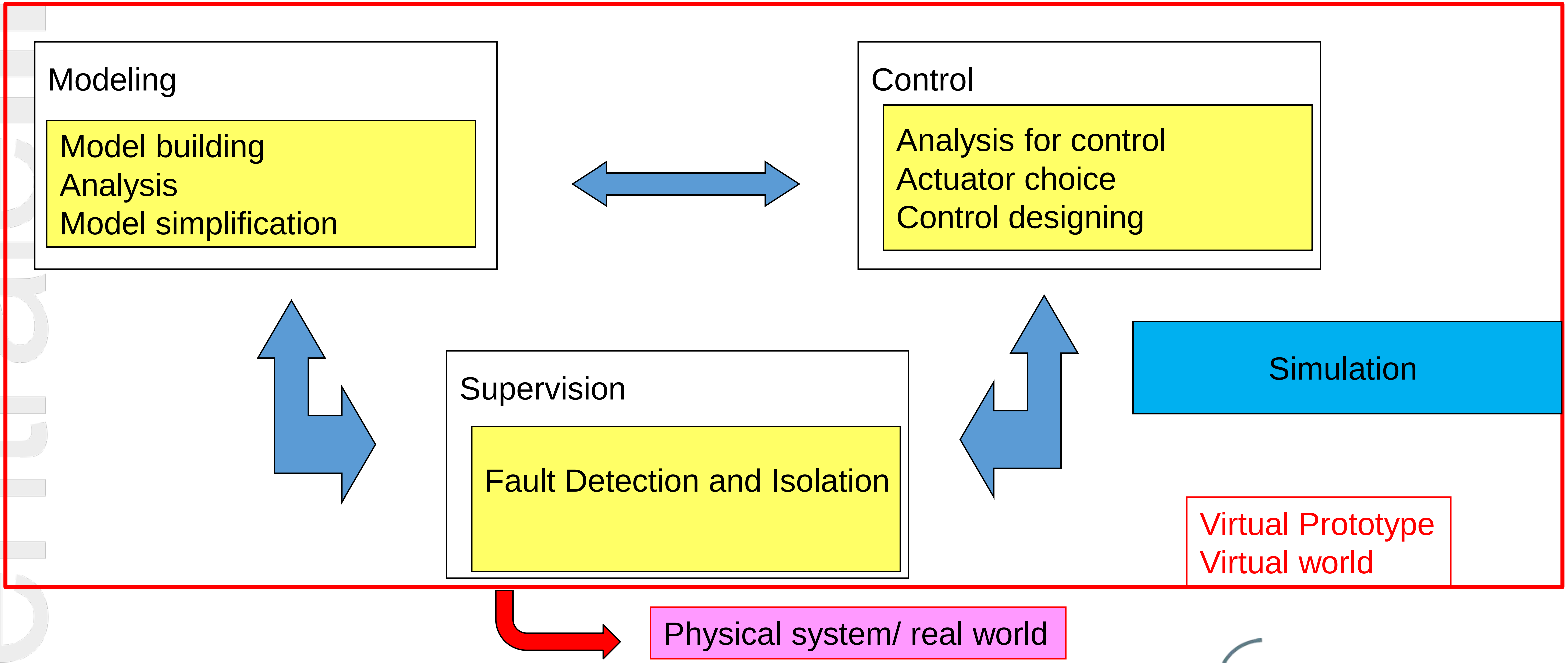
→ « Mechatronic approach »

→ « Integrated design »

Difficulties linked to the industrial context:
→Economical constraints: Costs for research, production
→ Industrial strategy :
→To be the first
→To guarantee the « just necessary » quality asked for by the market

→ Study on virtual prototypes first

Integrated design



Objective : choice of a model usable during all the steps of this design procedure

- a knowledge model

  * with real physical insight
  * for all the domains of physics
  * for dynamic study and analysis
  * for energetic approach

- a representation model for controller designing.

→ **the bond graph tool is well adapted for that purpose**

Bond Graph Modeling Procedure

1) Functional Analysis : Decomposition in sub-systems exchanging power

→ ***Word bond graph***

2) Phenomena Analysis : Identification of physical components and phenomena transforming the supplied power into stored or dissipated energy

→ ***Detailed bond graph***

3) Causal Analysis : Visualisation of cause-to-effect relations and analysis of causality

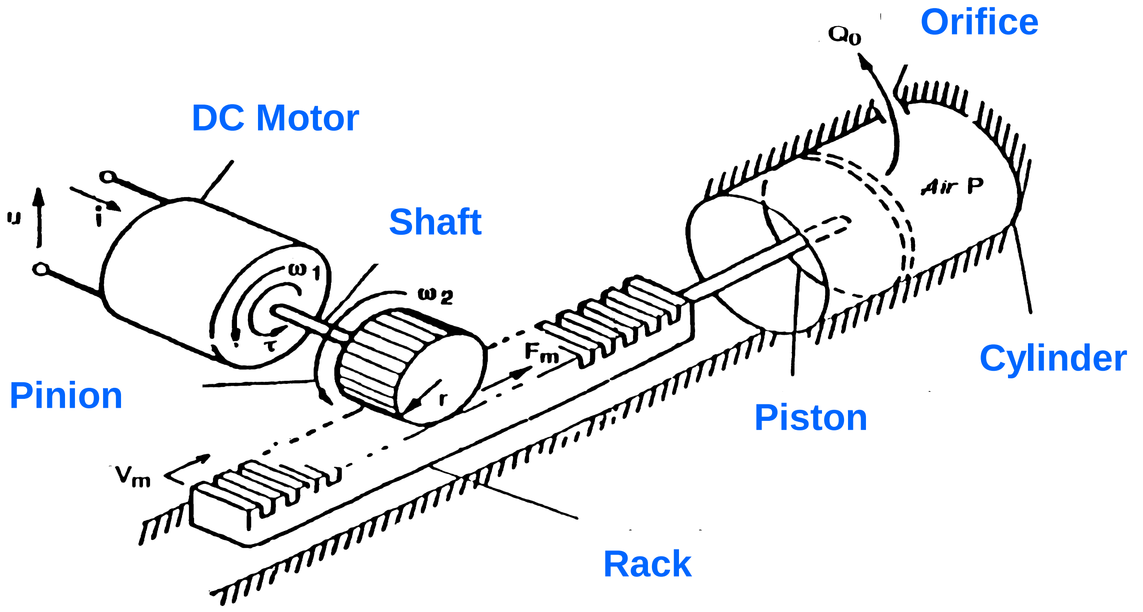
→ ***Causal bond graph***

4) Structural Analysis : Causal paths, causal loops

→ ***Model reduction, Designing of actuator and sensor architecture***

5) Writing of associated mathematical models : Differential equations , state equation, transfer function

1) Functional Analysis



Word bond graph

$$\xrightarrow[f]{e}$$

$$Power = e.f$$

$\xrightarrow[i]{u}$ **DC Motor** $\xrightarrow[\omega_1]{T_1}$ **Shaft** $\xrightarrow[\omega_2]{T_2}$ **Pinion + Rack** $\xrightarrow[V]{F}$ **Piston** $\xrightarrow[q_v]{P}$ **Cylinder + Orifice** $\xrightarrow[q_{vo}]{P_{env}}$

- DC Motor: Electrical +Mechanical rotation
- Shaft: Mechanical rotation
- Pinion + Rack: Mechanical rotation+ Translation
- Piston: Mechanical translation+ Pneumatic
- Cylinder + Orifice: Pneumatic

Generalized Variables

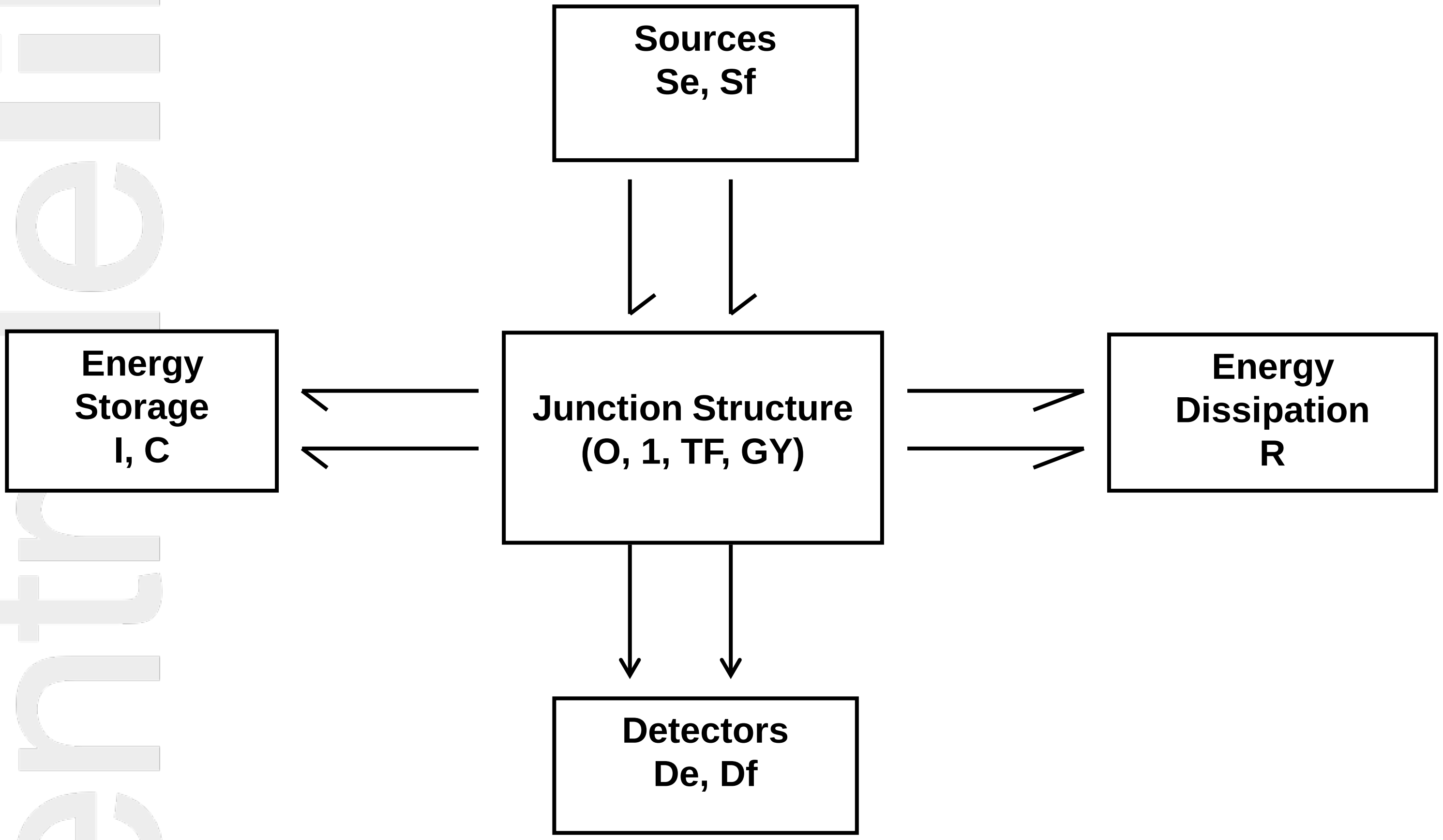
Power Variables

Energy Variables

Domain	Effort e	Flow f	Momentum $p(t)=\int e(\tau)d\tau$	Displacement $q(t)=\int f(\tau)d\tau$
Mechanical Translation Rotation	force torque	velocity ang. velocity	momentum ang. moment.	displacement angle
Electrical	voltage	current	flux linkage	charge
Hydraulic	pressure	volume flow rate	pressure momentum	volume
Chemical	chemical potential	molar flow rate		mole number
Thermodynamic	temperature	entropy flow		entropy

2) Phenomena Analysis

Basic Elements



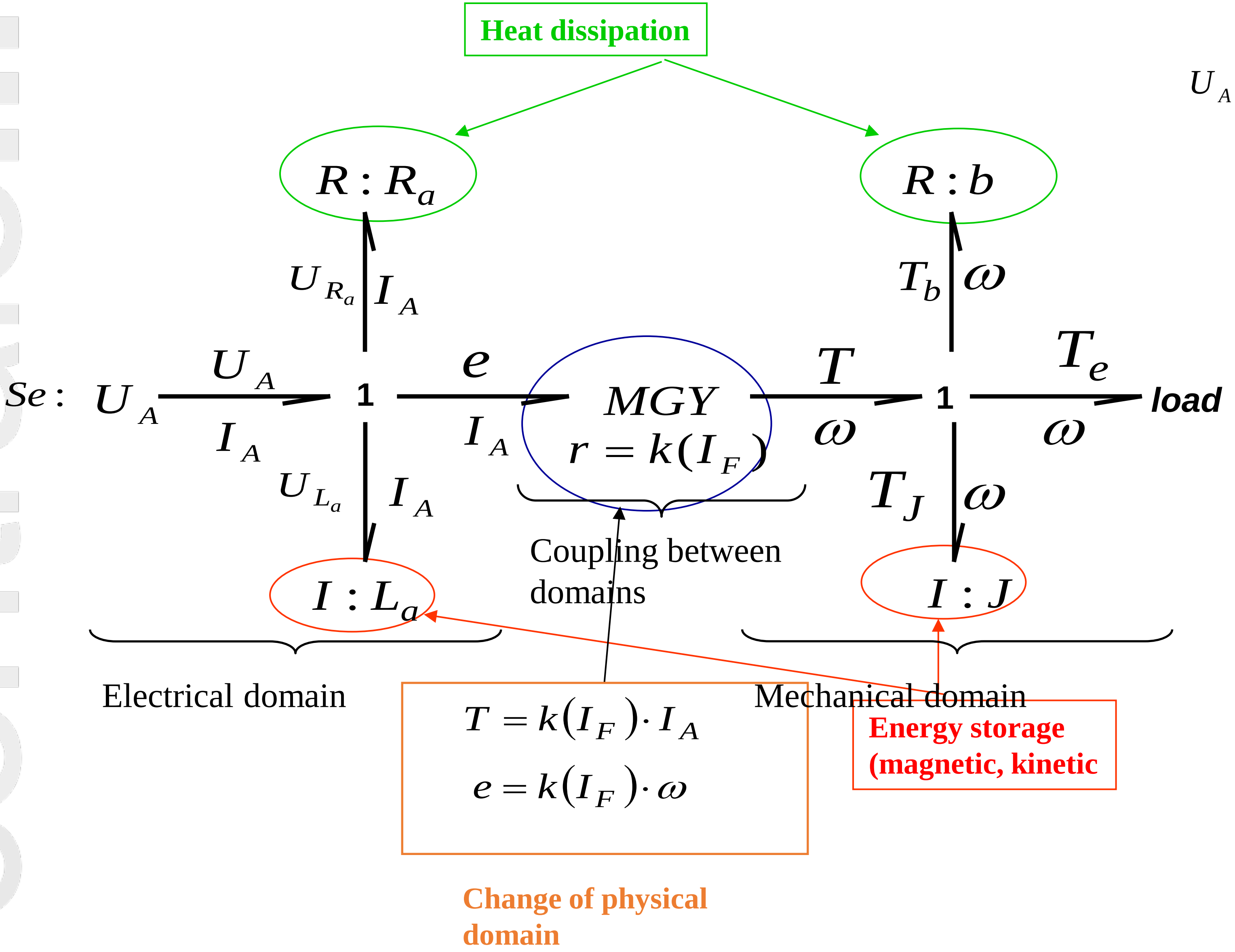
3 passive elements (receive power)
- R : energy dissipation
- C , I : energy storage

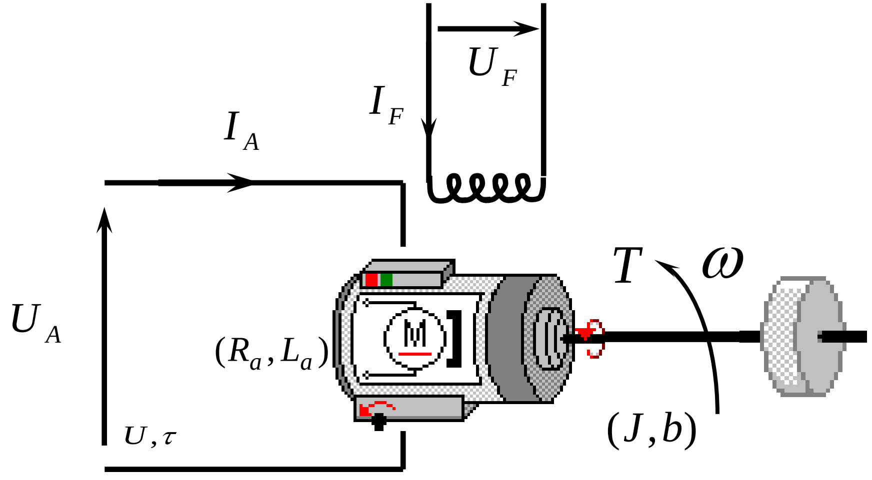
2 active elements (supply power)
- Se , Sf : effort source, flow source

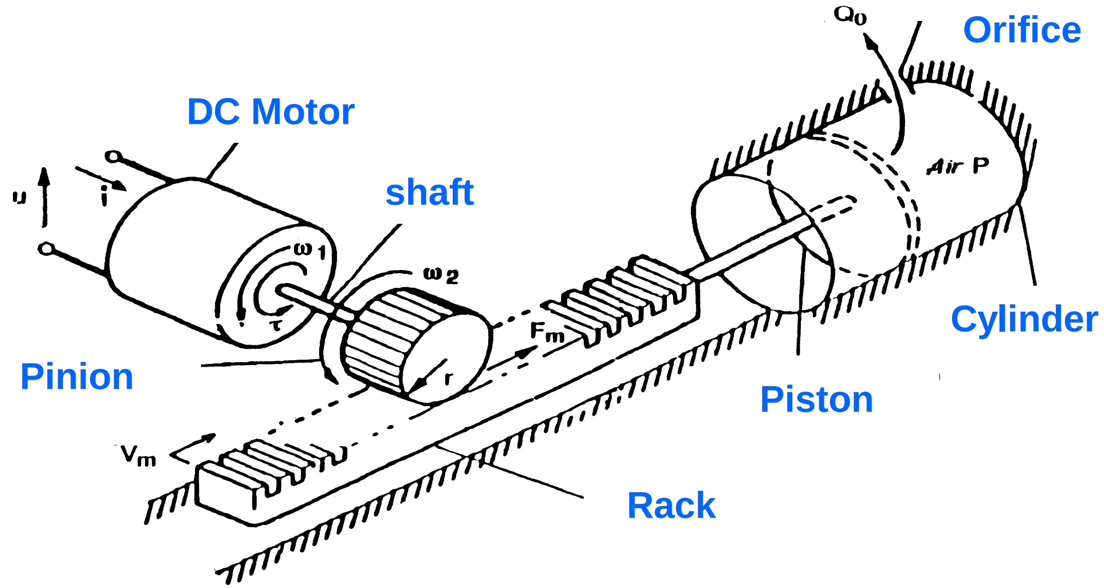
4 junction elements (power conservative)
- 0, 1, TF, GY

2 sensors supposed ideal
De, Df

Example : DC motor

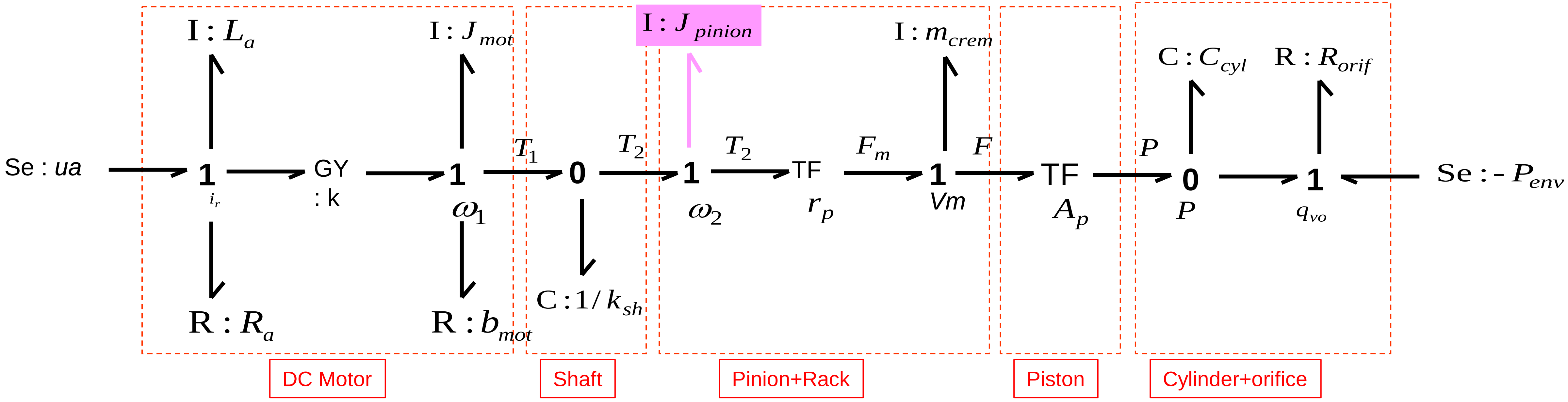






Hypothesis : J_{pinion} neglected

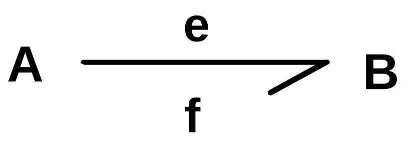
J_{pinion}



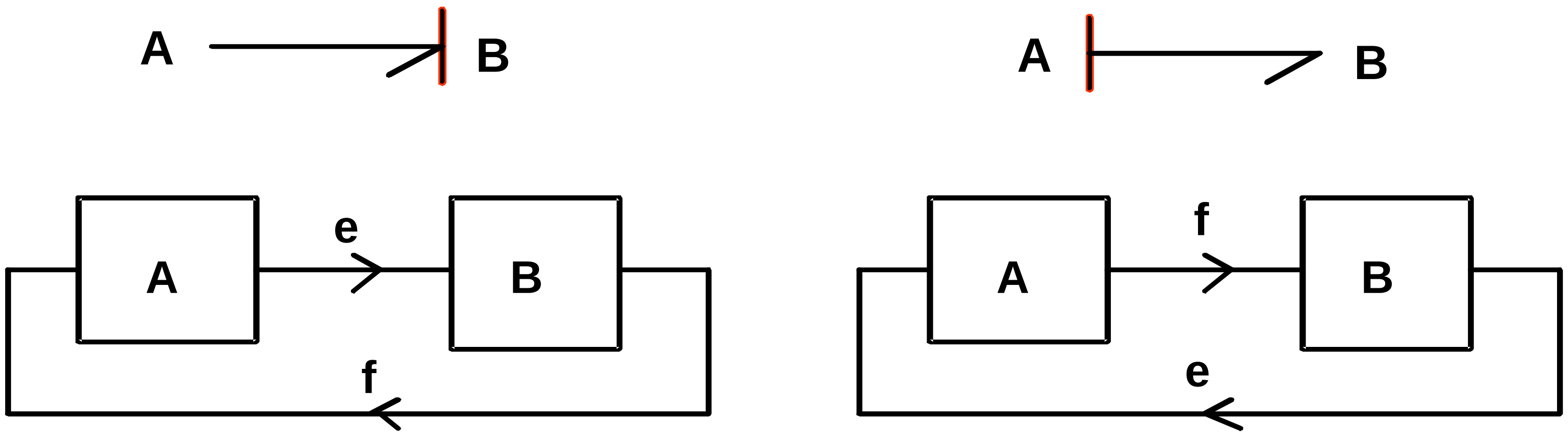
2) Causal Analysis

Causality Convention

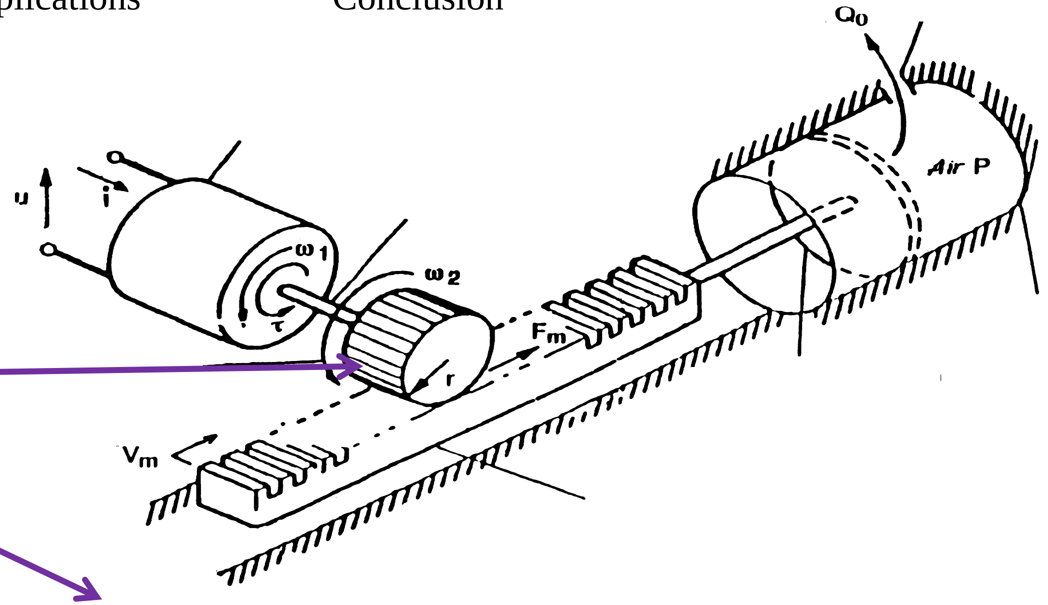
The causal stroke is placed CLOSE to (FAR from) the element
for which the EFFORT (FLOW) is known



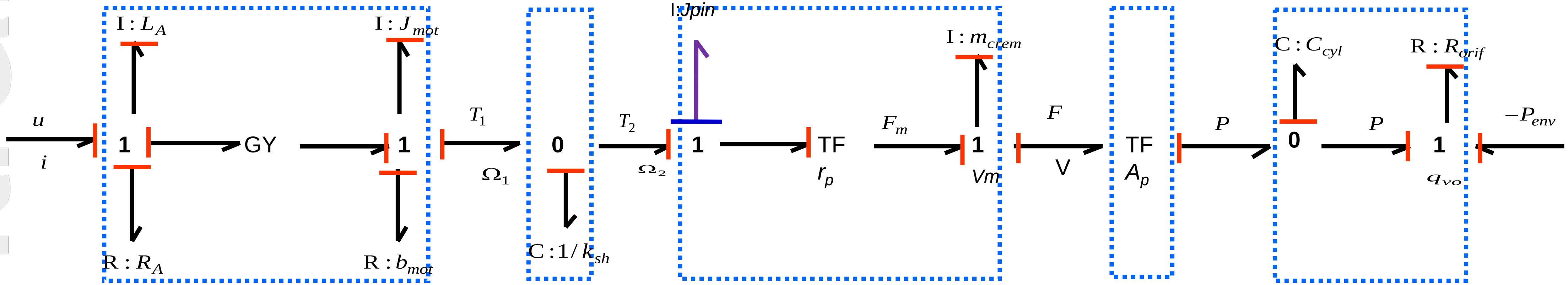
$P = e \cdot f$



→ Rules for assigning causality to elements
→ Integral causality in storage elements I and C should be preferred



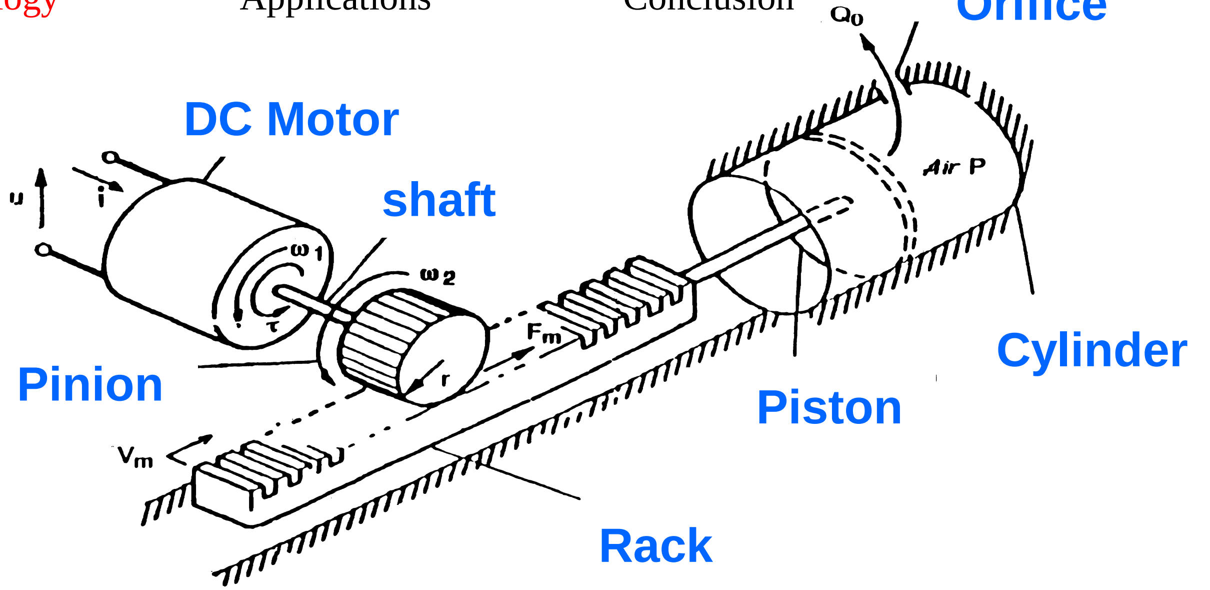
Jpinion

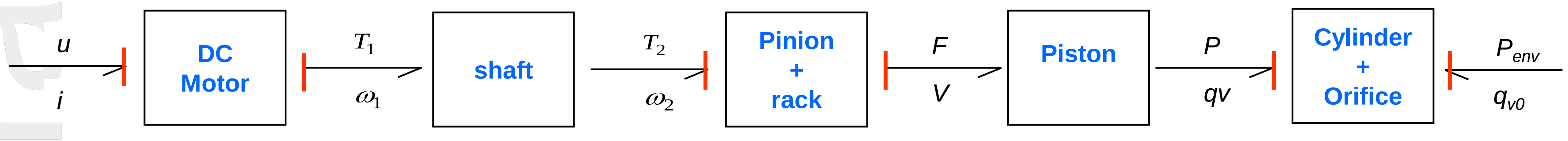


No causal singularity

If the pinion inertia taken into account

Derivative Causality!





Model libraries: Sub-models with

- → **a defined energetic environment**
- → **a coherent choice of coupling variables**
- → **a systematic determination of I/O variables**

Singularities in causality assignment

- Non determinist causality (possibility of choice on R -elements)
- Derivative causality on a I- or C-element

! Implicit Equations

$$x_i = ax_i + by_j + cz_k$$

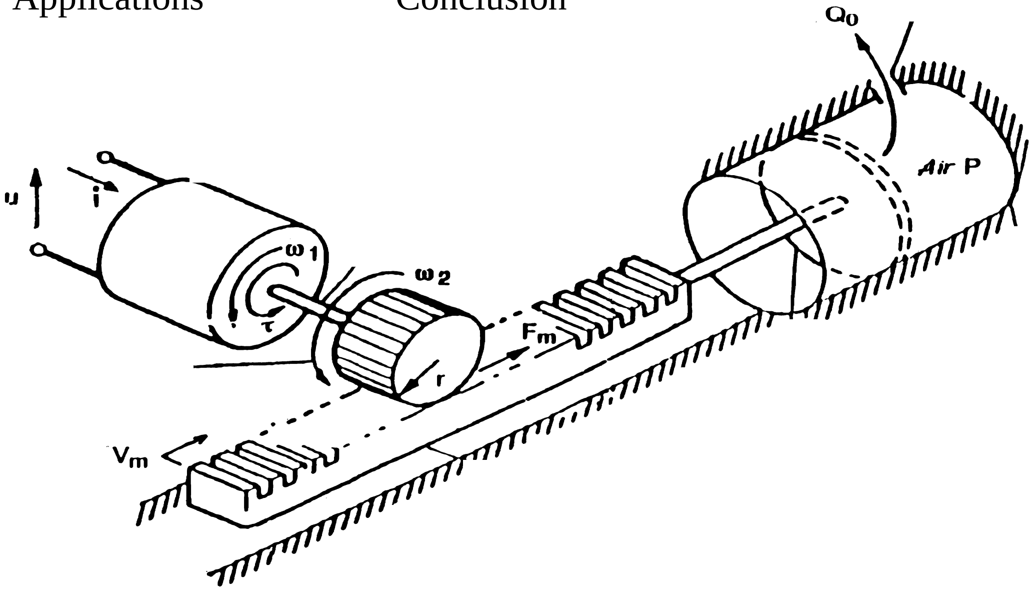
or

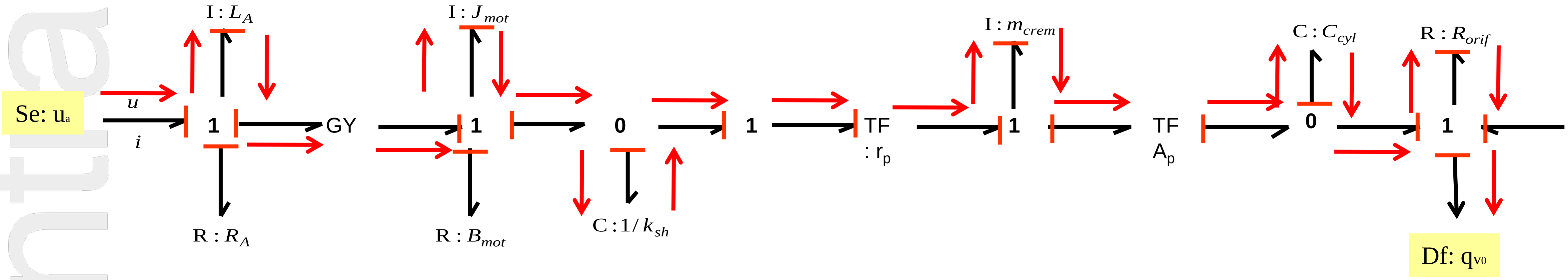
$$x_i = f_i(x_i, y_j, z_k)$$

⇒detected before writing equations

⇒What to do? Treate them by hand? Use an adequate software? Solve the problem physically by going back to the BG model and modify some hypothesis?

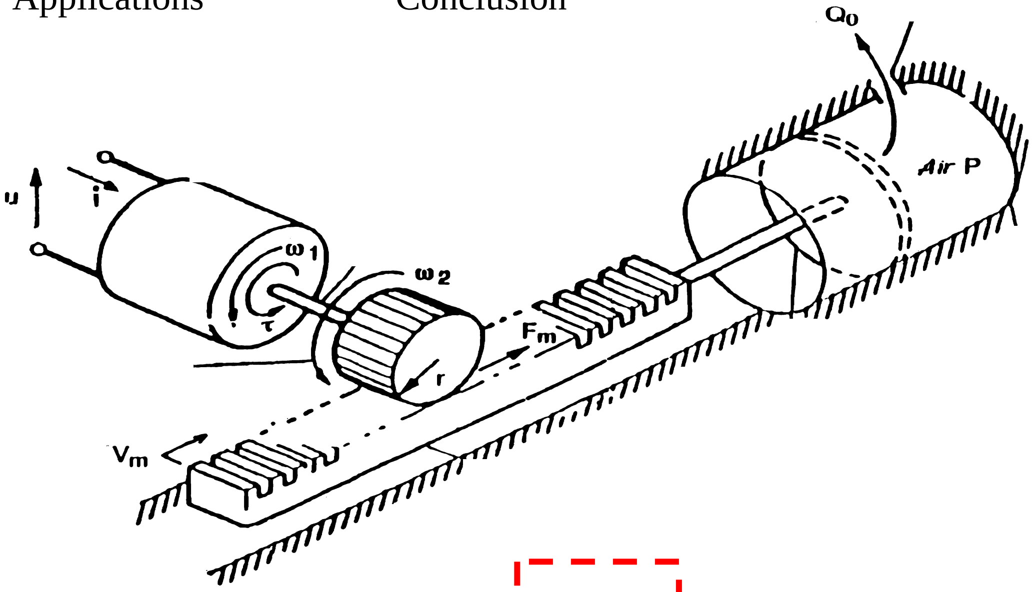
4) Structural Analysis

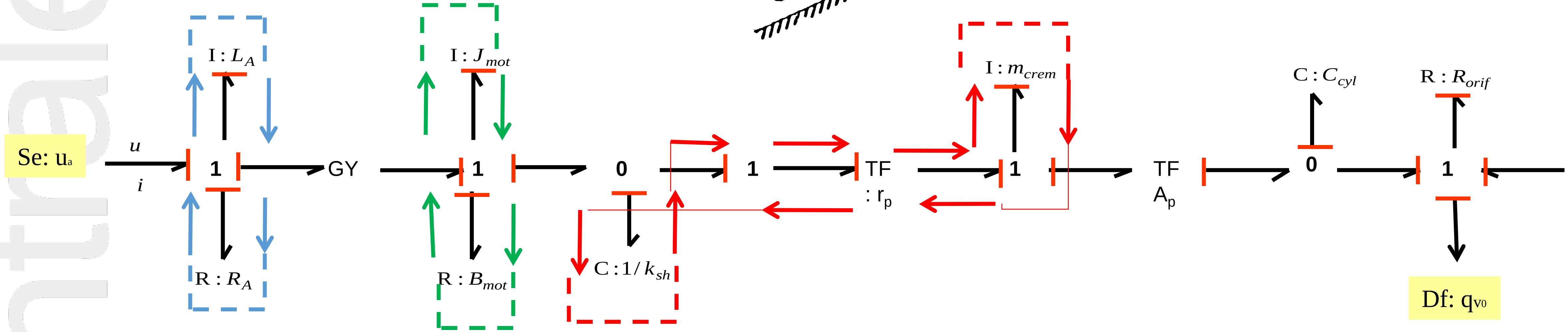




Input/Output causal path

4) Structural Analysis





Causal loops between R, I, C elements

→Gains give an approximation of time constants and natural periods

$$-\frac{R_A}{L_A s} \rightarrow \frac{1}{\tau_{elect}} \qquad -\frac{B_{mot}}{J_{mot} s} \rightarrow \frac{1}{\tau_{mec}} \qquad -\frac{k_{sh}}{m_{crank} s^2} \rightarrow \omega_n^2 \rightarrow T_n = \frac{2\pi}{\omega_n}$$

4) Structural Analysis

- Structural Controllability
- Structural Observability
- Structural Invertibility
- Structural I/O decouplability
- Structural monitoriability

Important for

*building the actuator and sensor architecture

*designing control laws

* designing FDI and FTC systems

Only using graphical procedures on the BG:
causal paths, causal loops and causality assignment

Simulation

✓ BG dedicated software

(20Sim, CAMPG+Matlab, Symbols, MTT, Dymola Bond Graph library for Modelica….)

! No need to write global mathematical models

Only the relations for elements

✓ Classical simulation software

(Matlab/Simulink, Modelica, Scicos …)

- Transformation of the BG into block-diagram
- Mathematical models derived from the BG
  - Transfer function
  - State equation
  - Differential equations

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Industrial applications

3 industrial studies where modeling was an essential stage and BG methodology a true advantage

- RAT for Airbus A380
- High speed train
- EHA for Airbus A320

Application 1 : RAT on Airbus 380 (1/6)

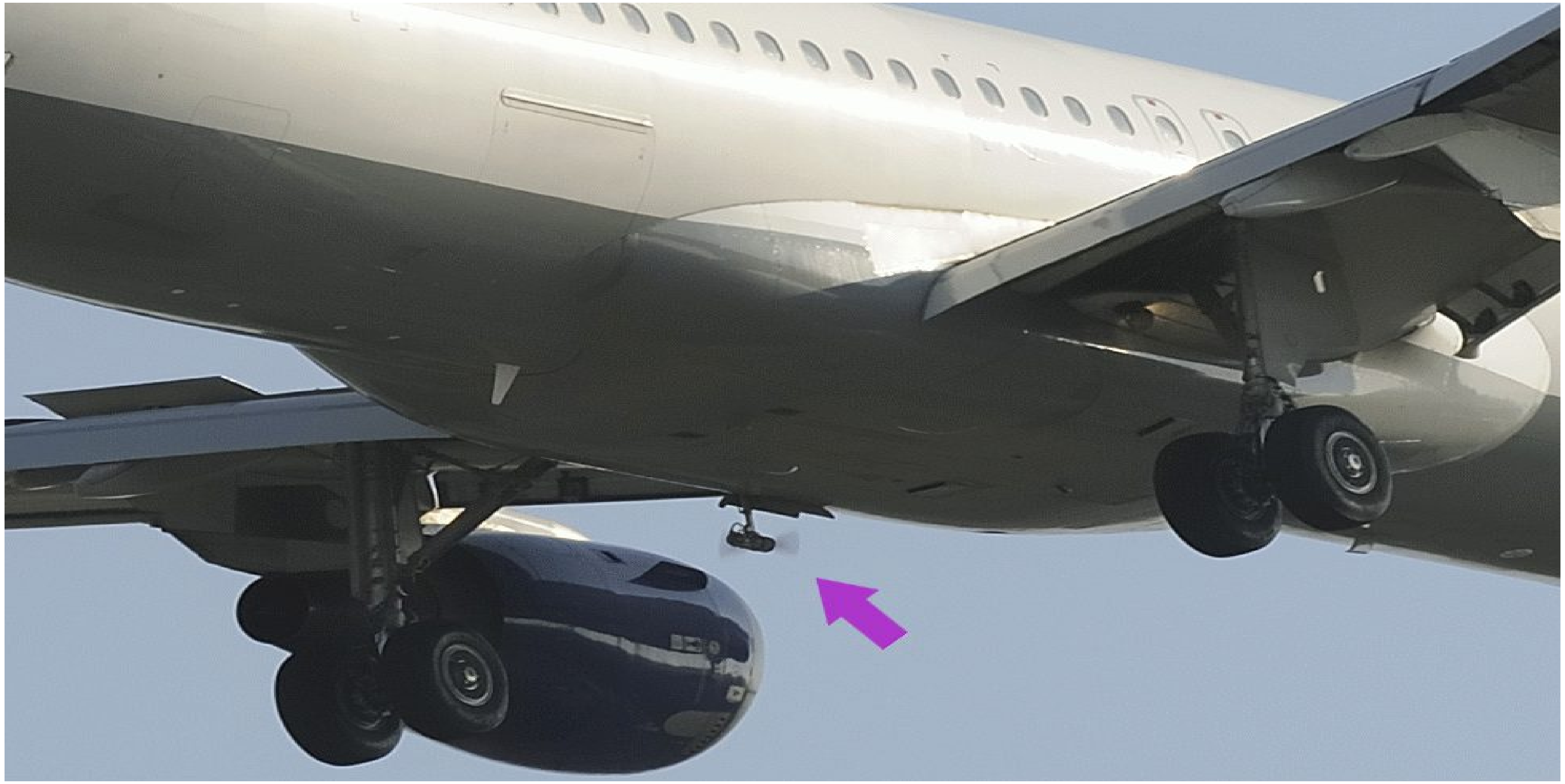
- Crash of the US Airways Airbus A320 on January 15th, 2009 on Hudson River, New York (bird strike resulted in an immediate and complete loss of thrust from both engines).

"European Aeronautic Defence and Space" company

Airbus planes are equipped with a ram air turbine (RAT), a type of wind turbine that can be deployed into the airstream to provide backup hydraulic pressure and electrical power at certain speeds

Application 1 : RAT on Airbus 380 (2/6)

Application 1 : RAT on Airbus 380 (3/6)



Application 1 : Ram Air Turbine on Airbus 380 (4/6)

Problem: Sizing of Ram Air Turbine on Airbus A380, the biggest of Airbus planes with the greatest number of electrical devices (Fly by wire)

Application 1 : Ram Air Turbine on Airbus 380 (5/6)

Methology used :

- BG modeling of all the devices using electrical power
- Calculation of the instantaneous power and global energy consumed by the electrical devices
- Sizing of the RAT

Application 1 : Ram Air Turbine on Airbus 380 (6/6)

- Great advantages in using BG tool for modeling
  - Decomposition in sub-systems exchanging power
  - Energy consumption estimation directly from the BG model

Application 2 : High Speed Train (TGV) (1/8)

Application 2 : High Speed Train (TGV) (2/8)

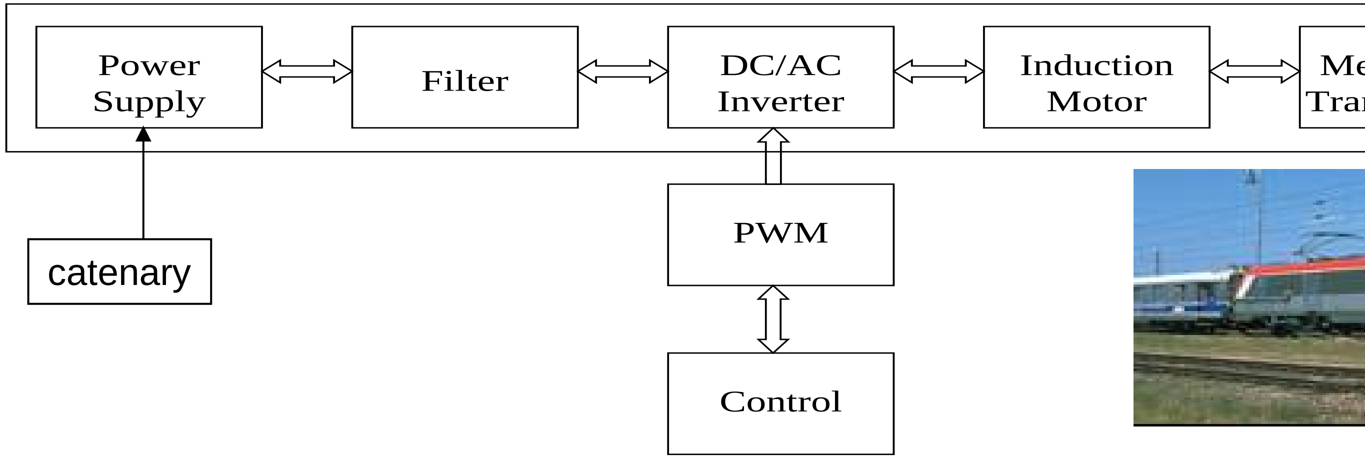
catenary : system of overhead wires used to supply electricity to the locomotive equipped with a pantograph

pantograph

Application 2 : High Speed Train (TGV) (3/8)

Problem : the break down of the catenary

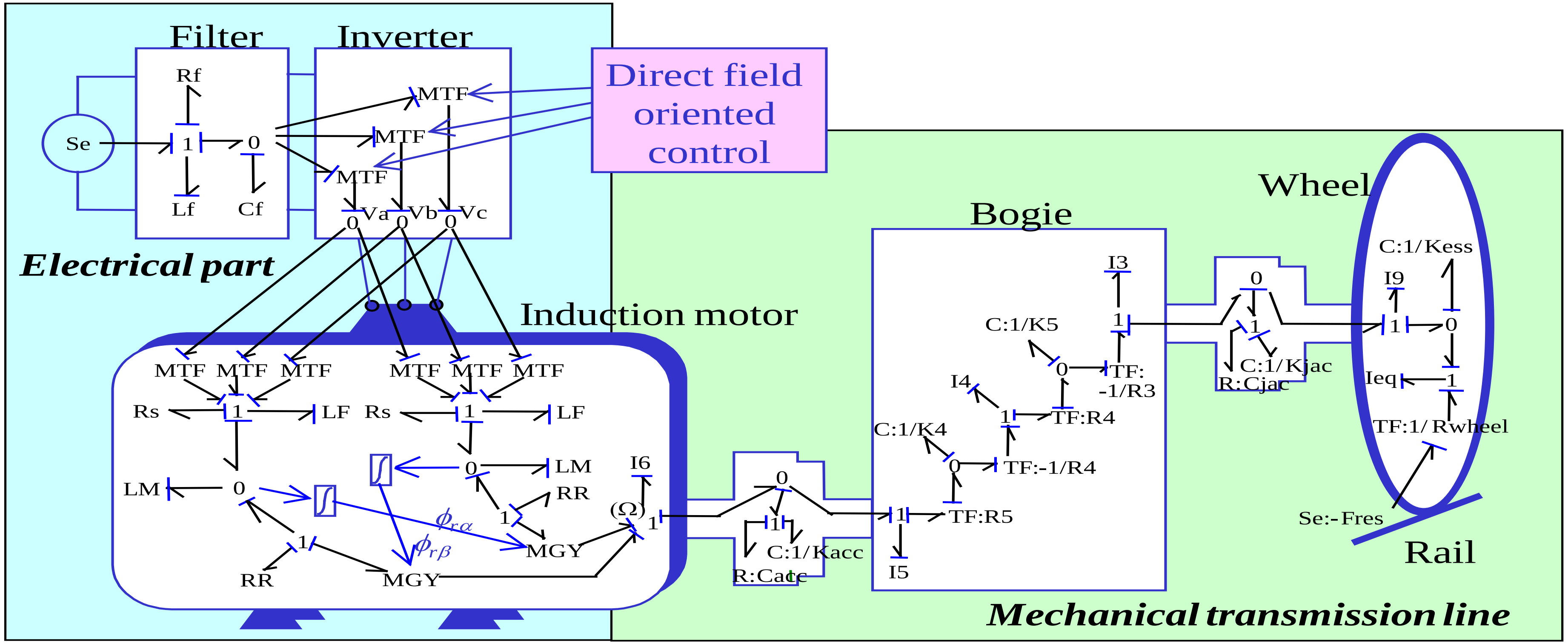
Railway traction device



BB36000

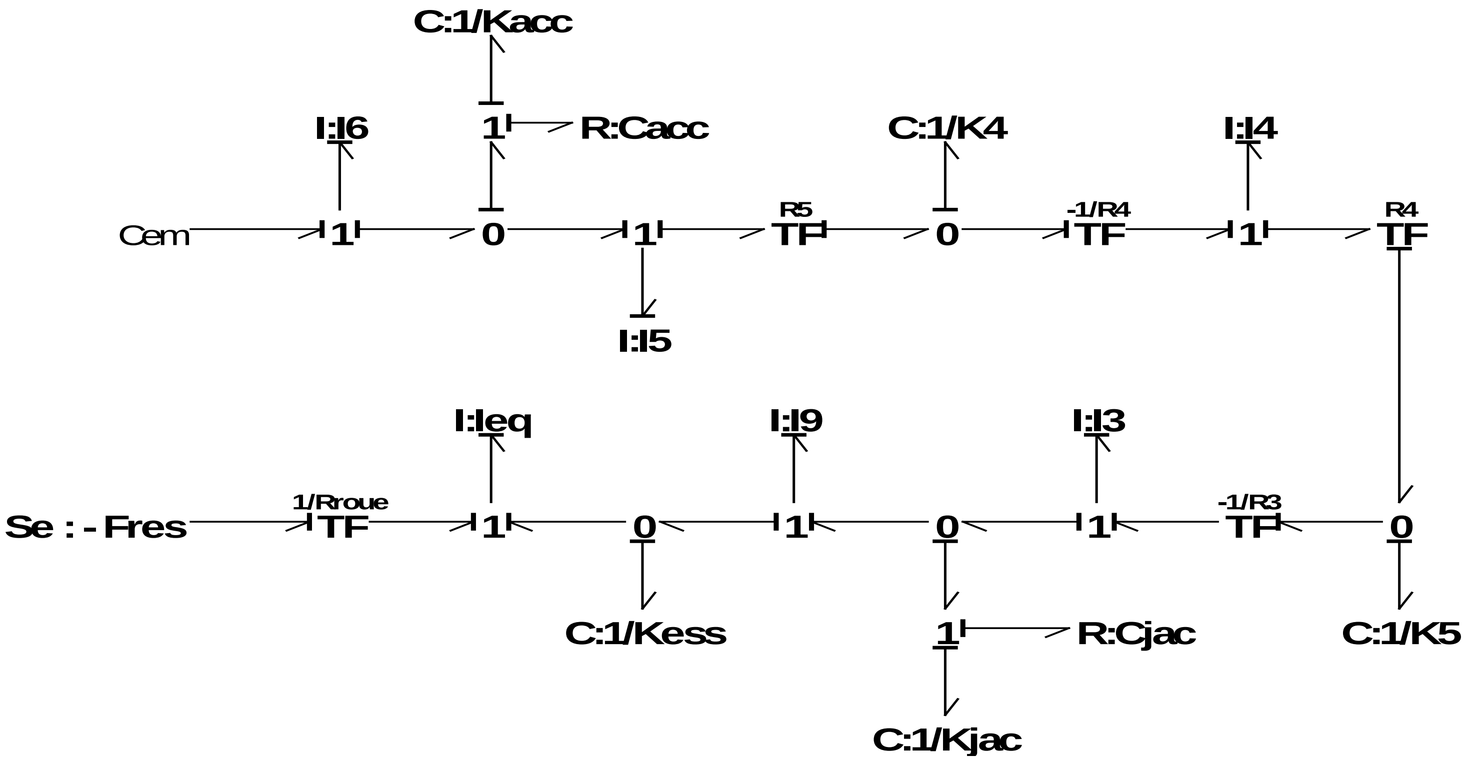
Application 2 : High Speed Train (TGV) (4/8)

BG of Railway traction device



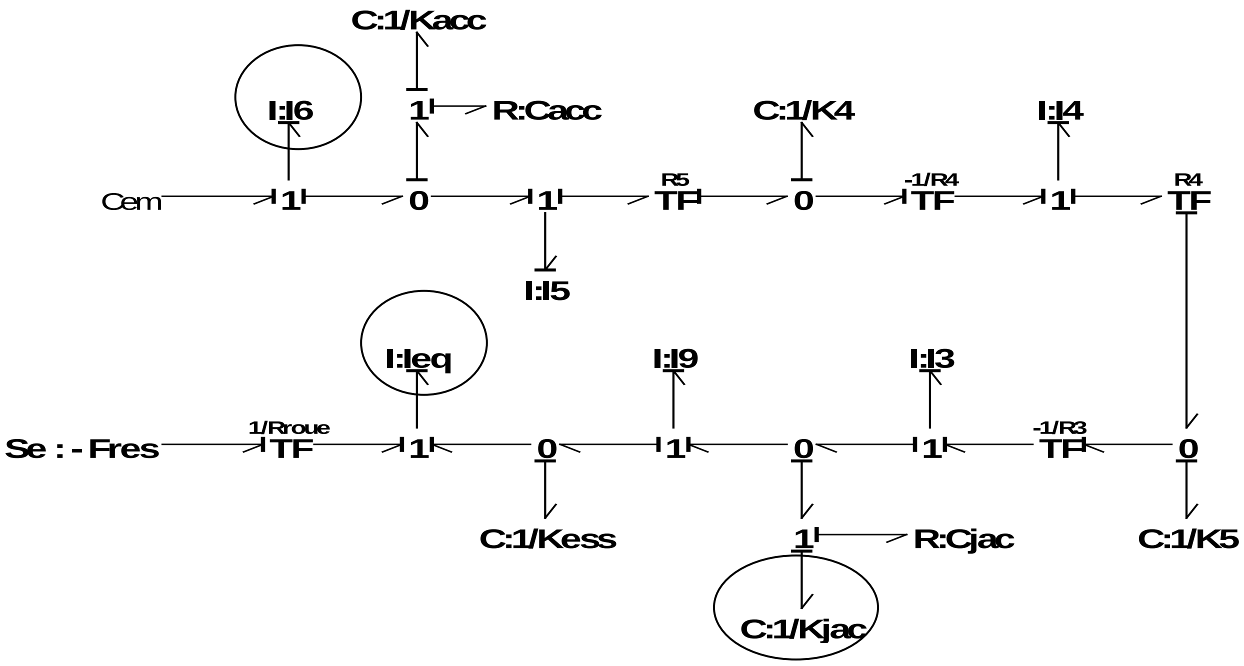
Application 2 : High Speed Train (TGV) (5/8)

Mechanical transmission line model.



11th order

Application 2 : High Speed Train (TGV) (6/8)



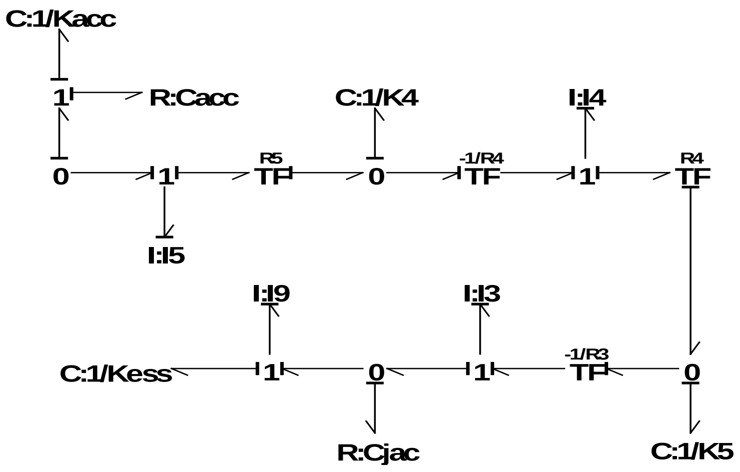


Fig. 1. SPM : fast model.

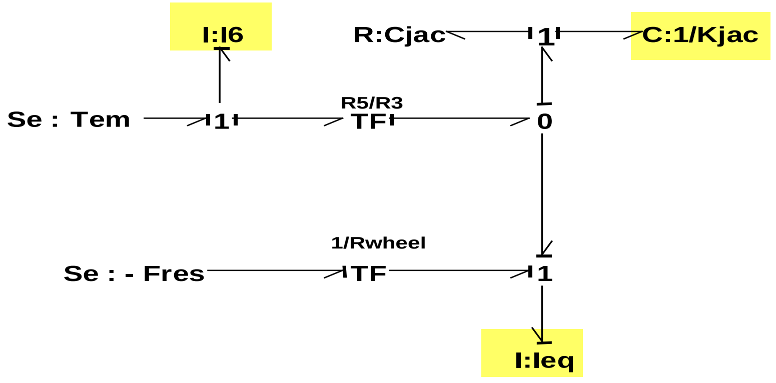
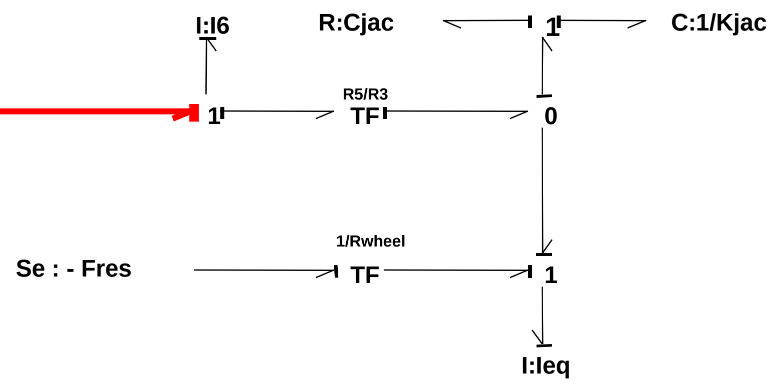


Fig. 2. SPM : slow model.

Application 2 : High Speed Train (TGV) (7/8)

BG model of the electrical part



Slow BG model of the mechanical part.

→ Resonance Mode of the train at 18.6 Hz due to the coupling between the I:L of the filter and the C of the mechanical part

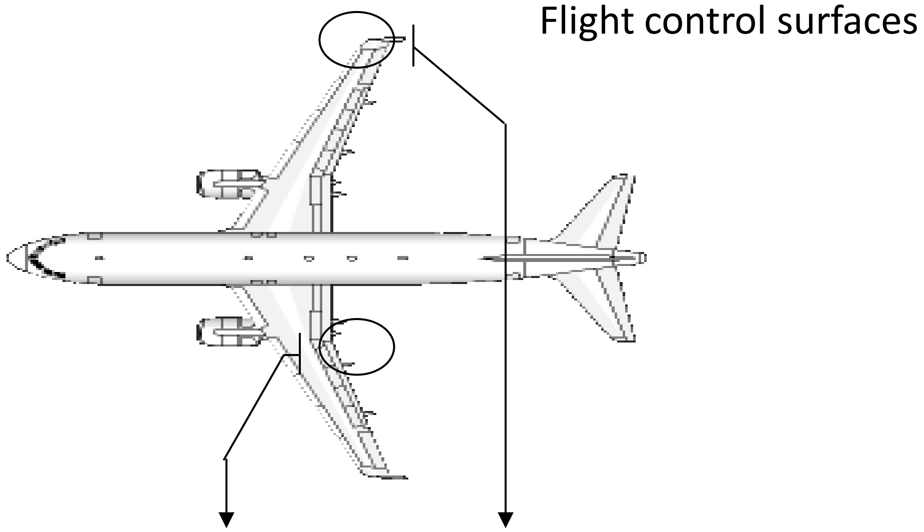
= resonance frequency of the catenary!

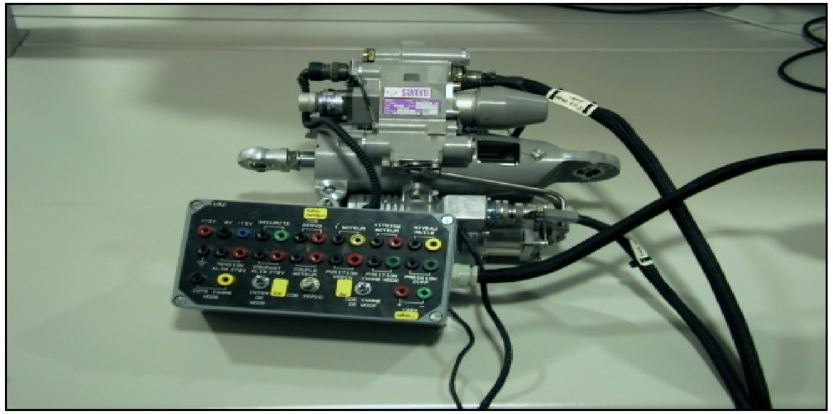
! Solution: modify the value of the filter inductance L

Application 2 : High Speed Train (TGV) (8/8)

- No means to do in an other way than using BG models
- Unique way to
  - determine the causal links between components,
  - estimate the resonance frequencies and identify the corresponding elements

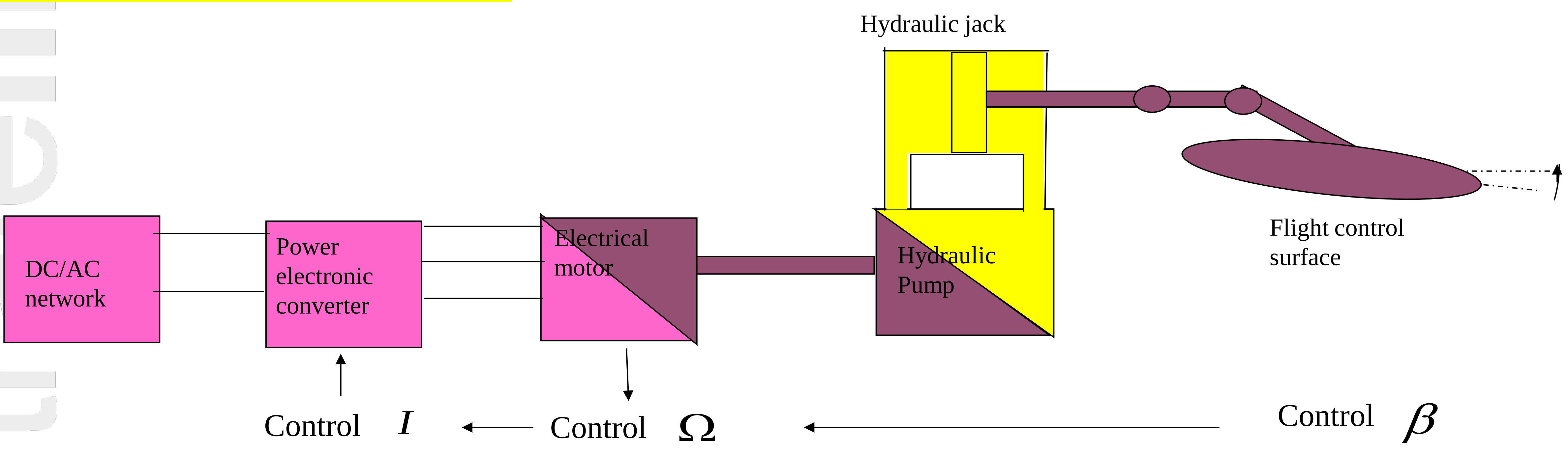
Application 3 : EHA for Airbus A320 (1/8)





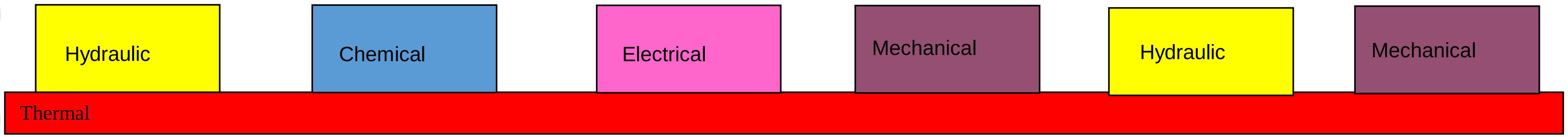
Application 3: EHA for Airbus A320 (2/8)

Problem : Sizing of EHA components



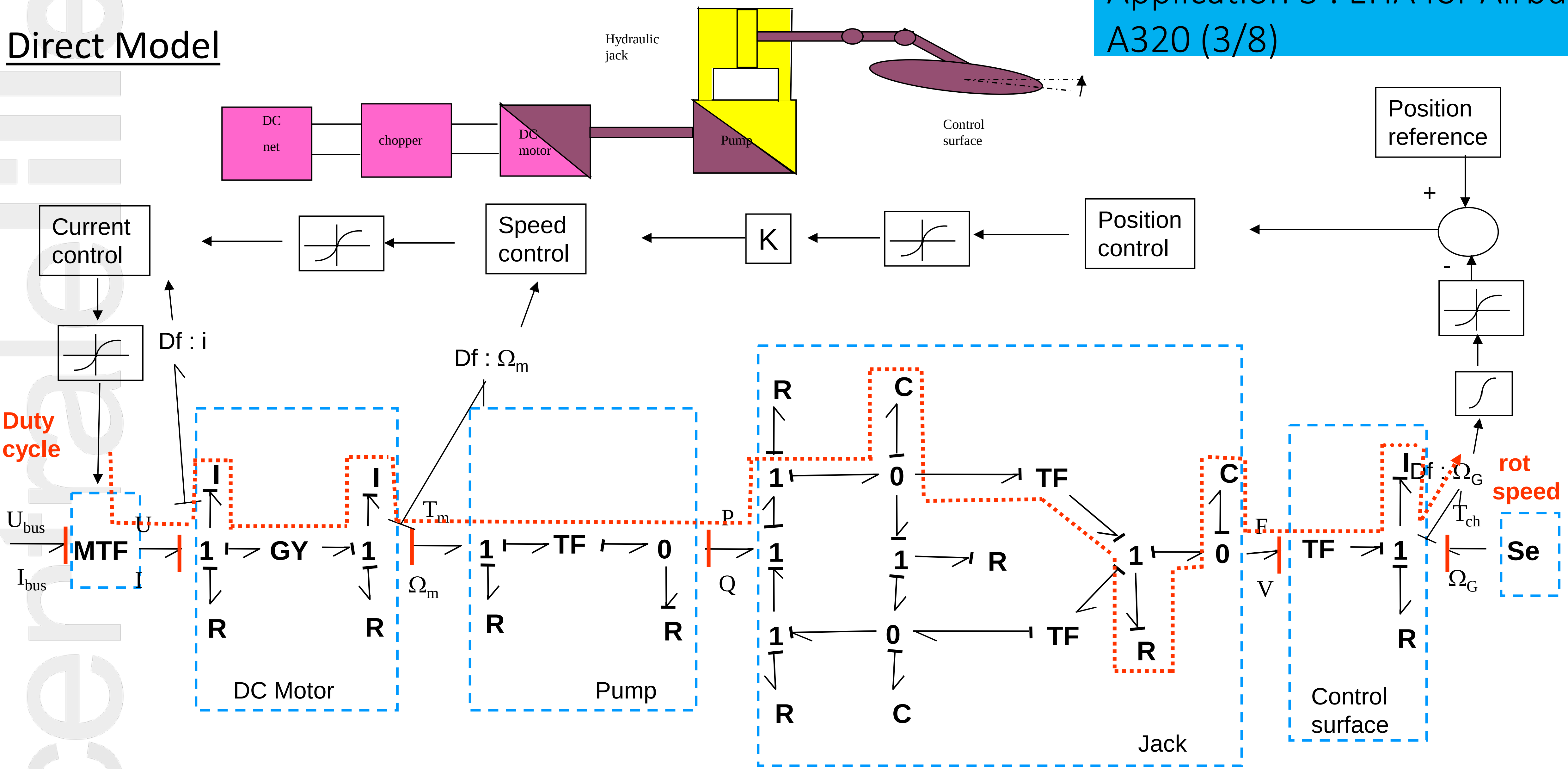
6 different physical domains

<u>Example « fiction » : APU with Fuel Cell</u>



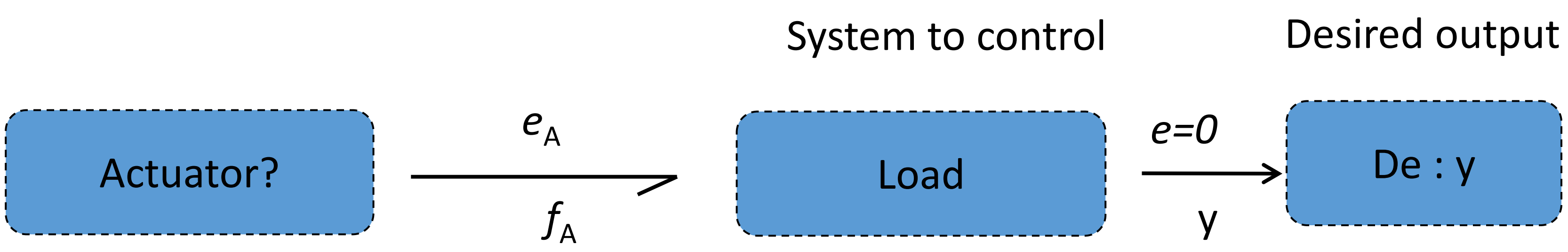
Application 3 : EHA for Airbus A320 (3/8)

Direct Model

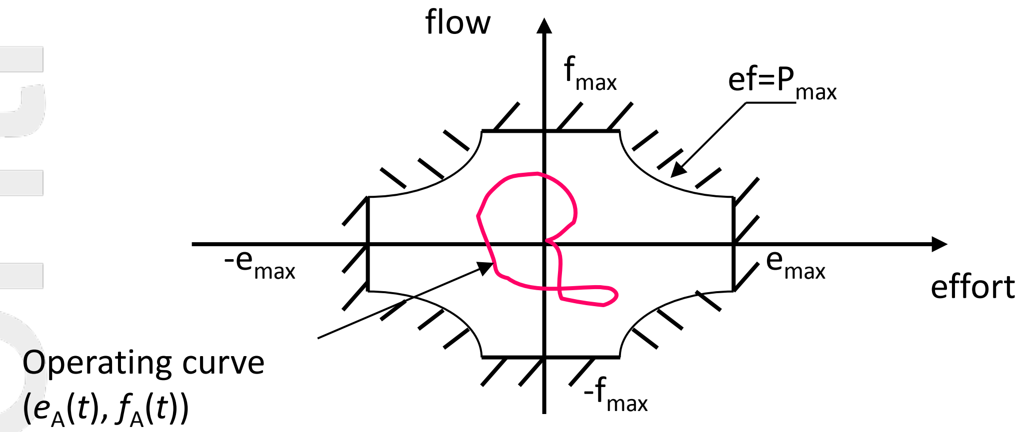


Application 3 : EHA for Airbus A320 (6/8)

Sizing of actuators



Determine the requirements for the actuator in terms of the power variables e_A and f_A and the prescribed output specifications

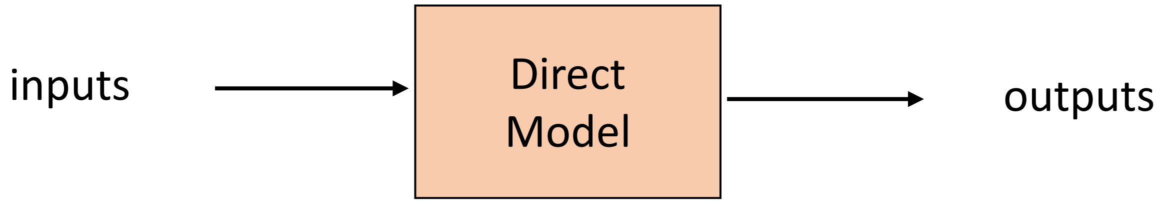


Admissible operating domain of a chosen actuator

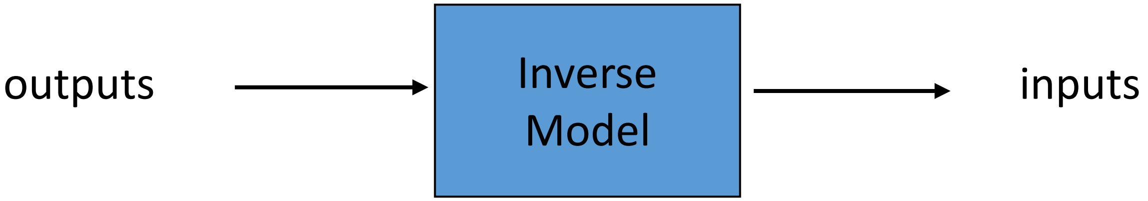
The chosen actuator is sized, oversized or inadequate?

Inverse model

Application 3 : EHA for Airbus A320 (5/8)

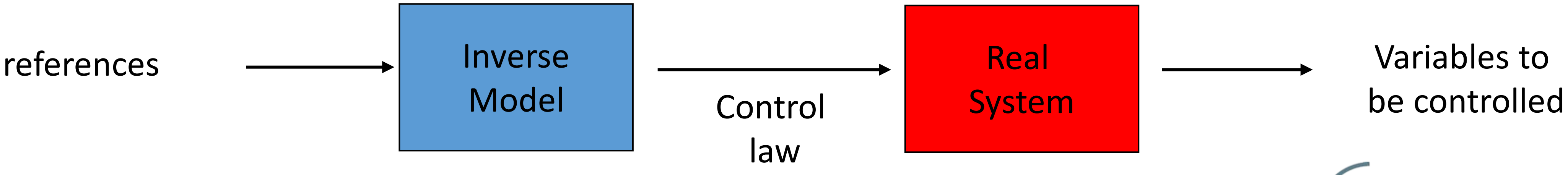


Model inversion using bicausality (invertibility condition to be verified)



<u>Applications:</u>

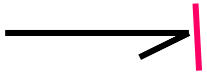
- Designing of control laws (open loop → closed loop)



- Actuator sizing

Application 3 : EHA for Airbus A320 (4/8)

« Classical » Causality



B

e data for B

$$f_B = \Psi_B(e_B)$$

B

f data for B

$$e_B = \Psi_B^{-1}(f_B)$$

Bicausality

B

e data for B (e.g. imposed)
f data for B (e.g. measured)

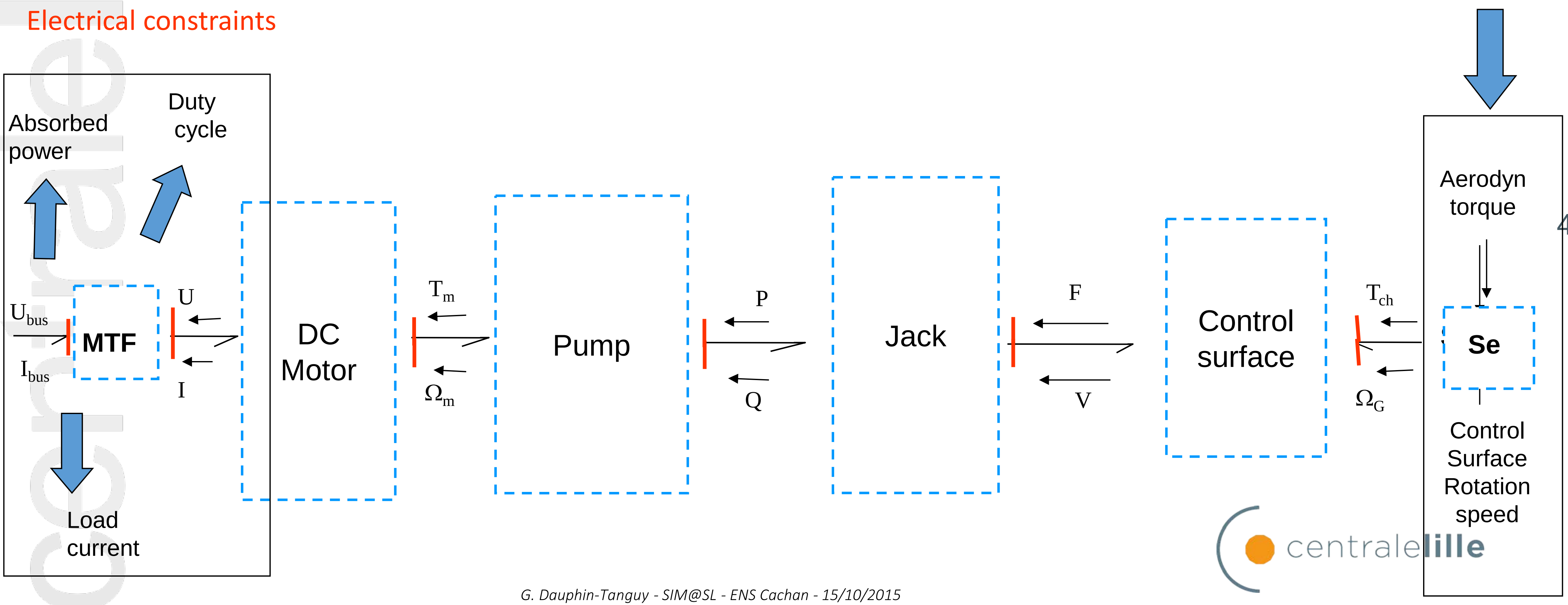
→ Possible to estimate Ψ_B

Application 4 : EHA for Airbus A320 (7/8)

Inverse model

Flight Cycles

Electrical constraints



Application 3 : EHA for Airbus A320 (8/8)

- No means to determine inverse dynamic models without using BG tool
  - Bicausality : specific to BG tool
  - Graphical analysis of the model structural invertibility property
  - Systematic determination of the inverse mathematical model

Bond Graph Modeling for

«Integrated Design», « System Approach», « Mechatronic Approach»
+
Virtual test benchs

- Graphical representation of power exchanges
- Generic approach for all physical domains (analogy)
- Easy to implement bottom-up or top-down modeling procedures
- Causality for analysis

Thank you for your attention

Any question?