Bond Graph for Modelling, Analysis, Control Design, Fault Diagnosis

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Bond Graph Research Group

Laboratoire d'Automatique et d'Informatique Industrielle de Lille

Ecole Centrale de Lille

- 6 academics (2 Profs, 2 associate profs, 2 assistant profs)
- 10 PhD students

Application areas : power systems (electrical machines, photovoltaic systems, fuel cells), thermofluid process, car industry

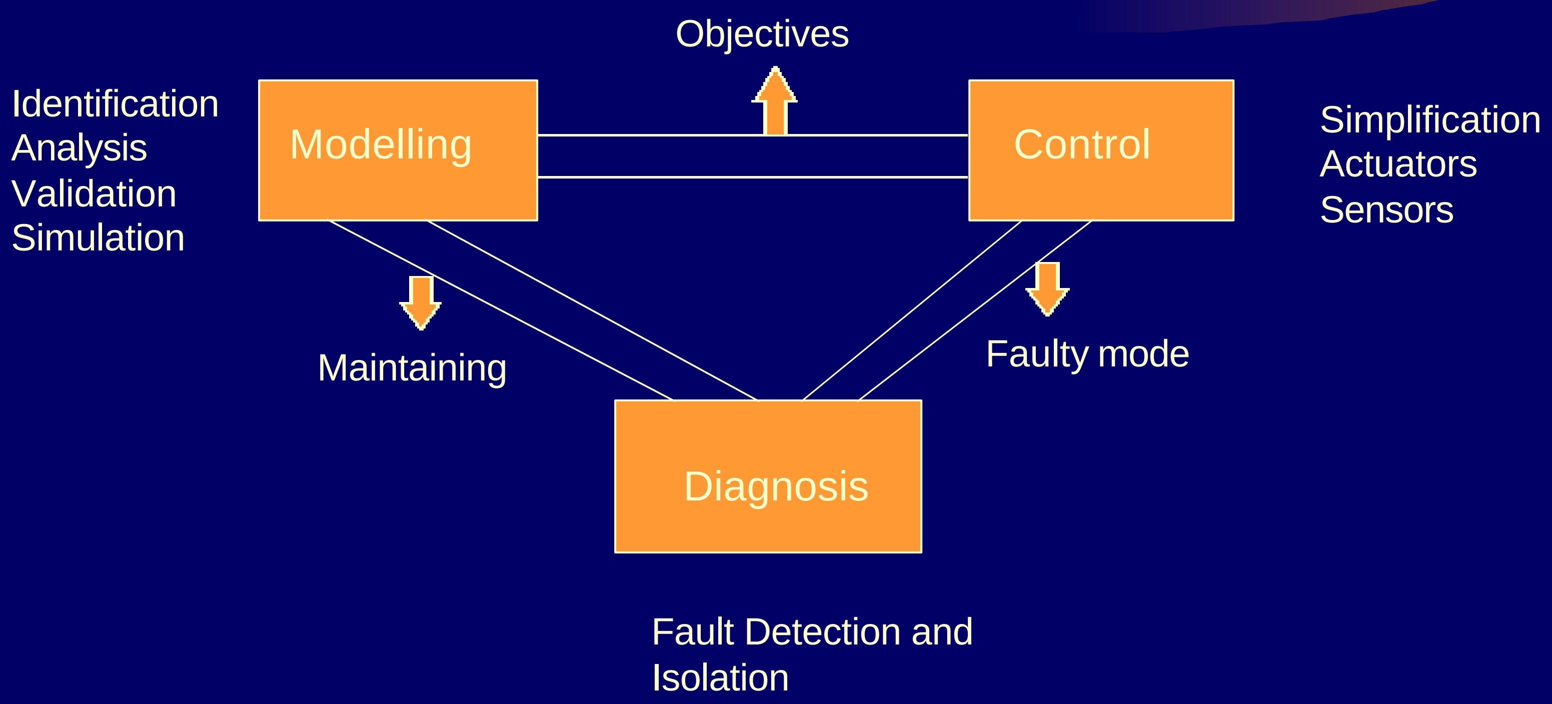
Studies performed in collaboration with Peugeot -Citroën

- Mechatronic design of an automatic gear box
- Clutch management and drive comfort
- Mechatronic design of an active hydraulic suspension
- Thermal comfort regulation in a car interior
- Modelling and simulation of a fuel cell system
- Analysis of structural properties of bond graph models
- Robustness of control laws for systems with parametric uncertainties
- …..

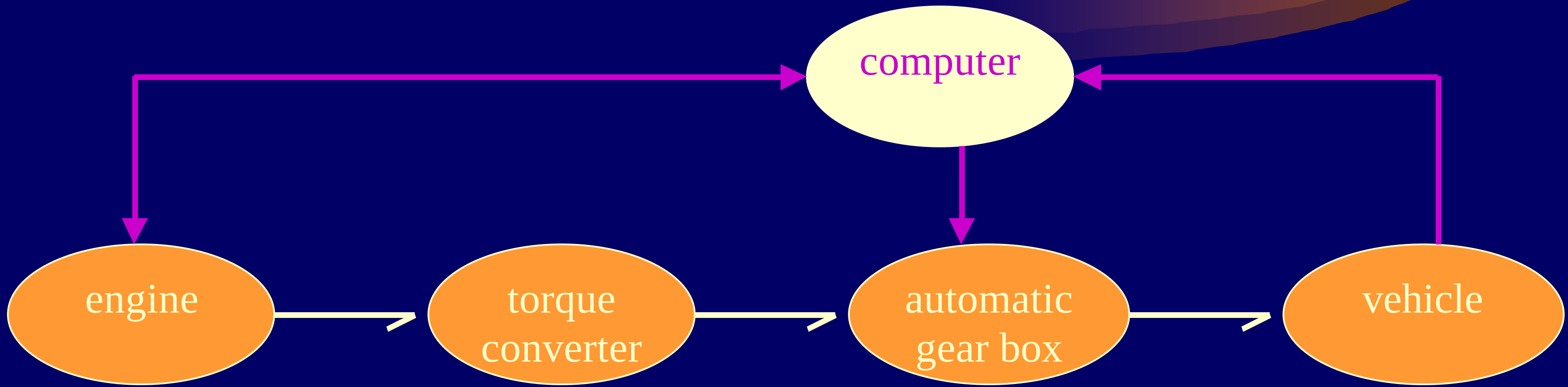
Why a bond graph approach ?

- Multidisciplinary systems → need for a communication language between people from different physical domains
- Need for models with physical insight (virtual testing facility)
- Unified modelling methodology for knowledge storage in model libraries
- Integrated (« mechatronic ») design of controlled systems

Mechatronic design



1 - Mechatronic design of an automatic gear box



Differential,
Transmission shaft
Wheels,
Vehicle mass,
air resistance,
road friction

Complete driveline

1 - Mechatronic design of an automatic gear box

Problem statement

- Design control laws for the driving of an automatic gear box by a computer with the following objectives:
  - Complete satisfaction of the customer corresponding to a variation of the engine torque as continue as possible

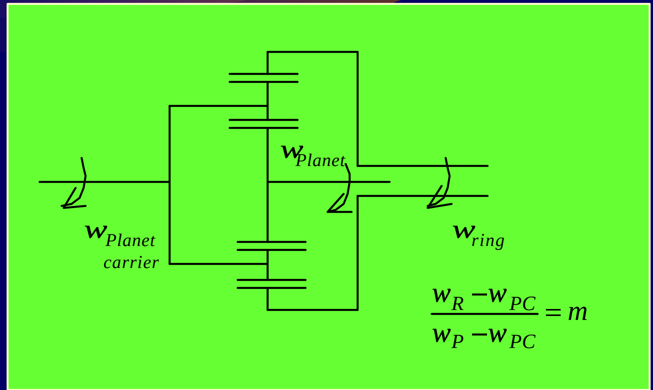
    (no jerk in acceleration during a shift)
  - Respect of technological constraints (actuator response duration, minimization of the energy dissipated in the clutchs)

When to shift ? How to shift ?

1 - Mechatronic design of an automatic gear box

Automatic gear box : physical scheme

Arrangement of 2 epicyclic gear trains
which allows 3 ratios plus one reverse

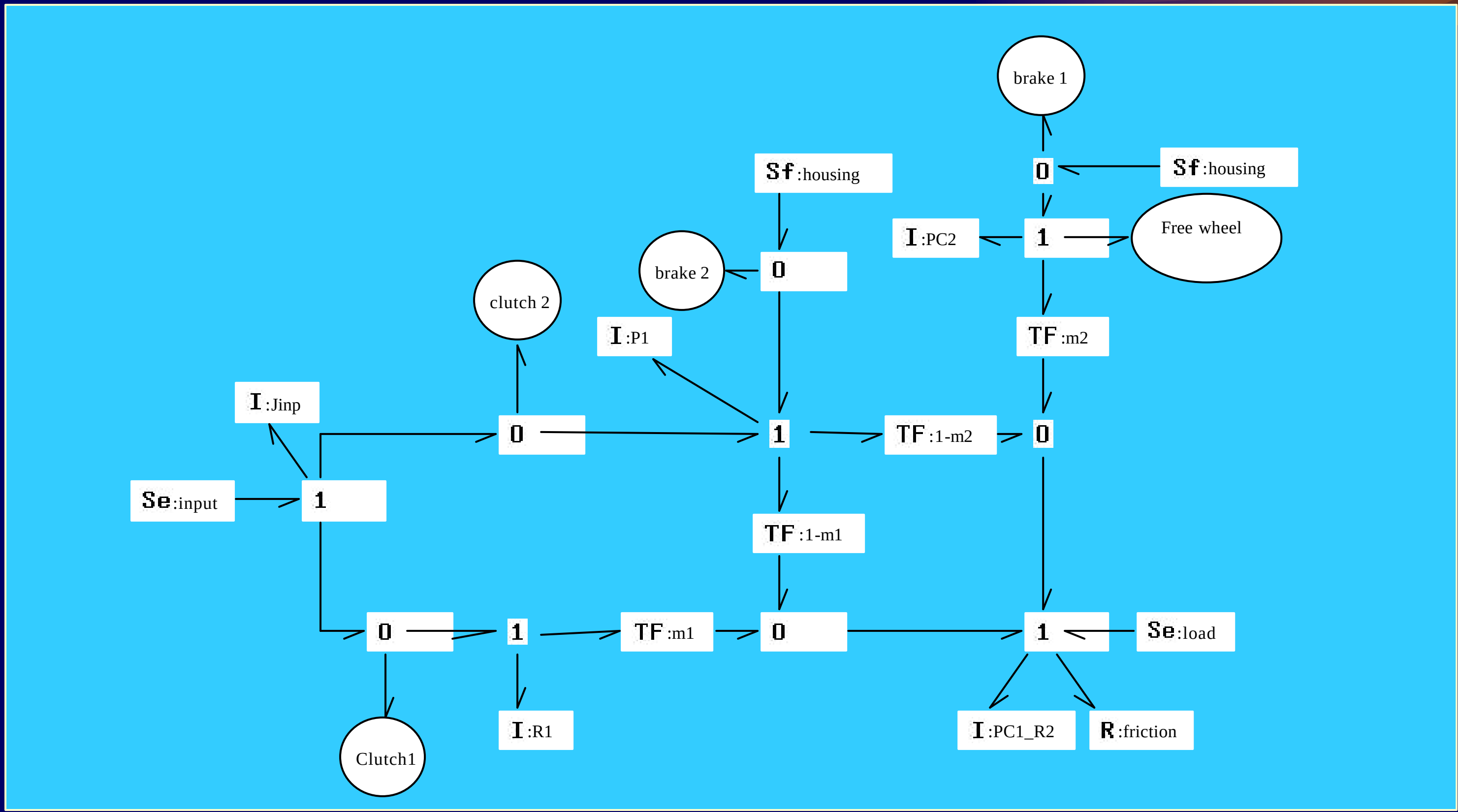


Different ratios : one element blocked
or 2 elements maintained at the same speed

Clutches between 2 rotating elements
Brakes between one element and the housing block

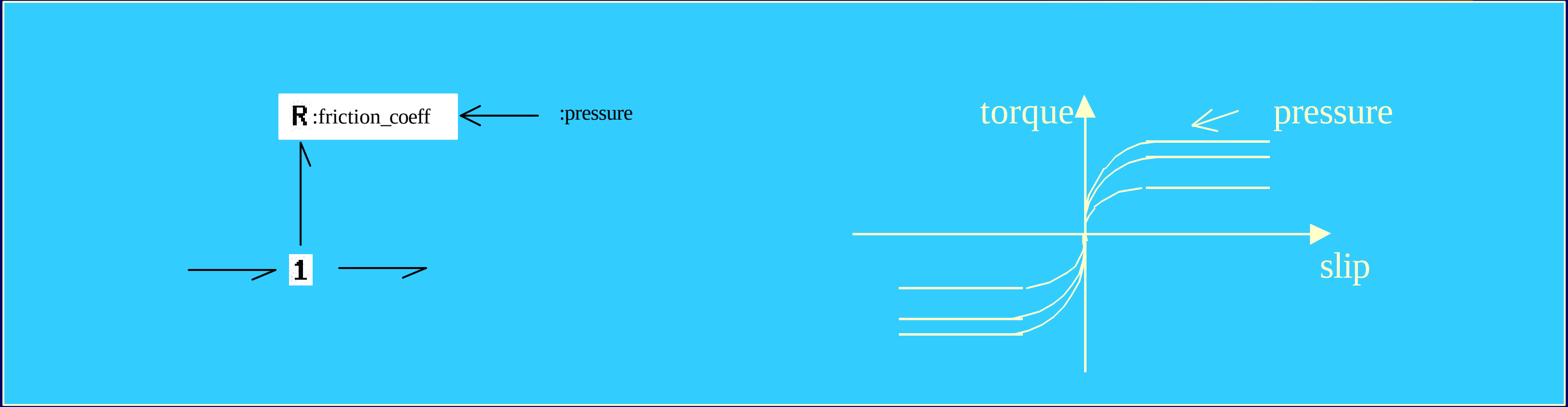
1 - Mechatronic design of an automatic gear box

Bond graph model of the automatic gear box



1 - Mechatronic design of an automatic gear box

Bond graph model of a clutch or a brake



Coulomb friction depending on the pressure applied on the clutch disks, defining the « limited torque »

If clutch torque < limited torque → clutch closed, all the torque transmitted
If clutch torque = limited torque → clutch opened, slipping velocity

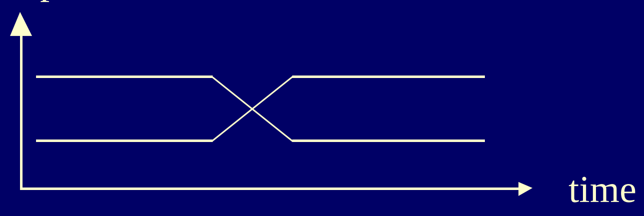
1 - Mechatronic design of an automatic gear box

Decision block

Contains the schift schedule (diagram throttle position vs vehicle speed) which permits to know *« when to shift »*

Different programs: economical, sport, snow

When a shift is decided, the different pressures in the clutches are controlled

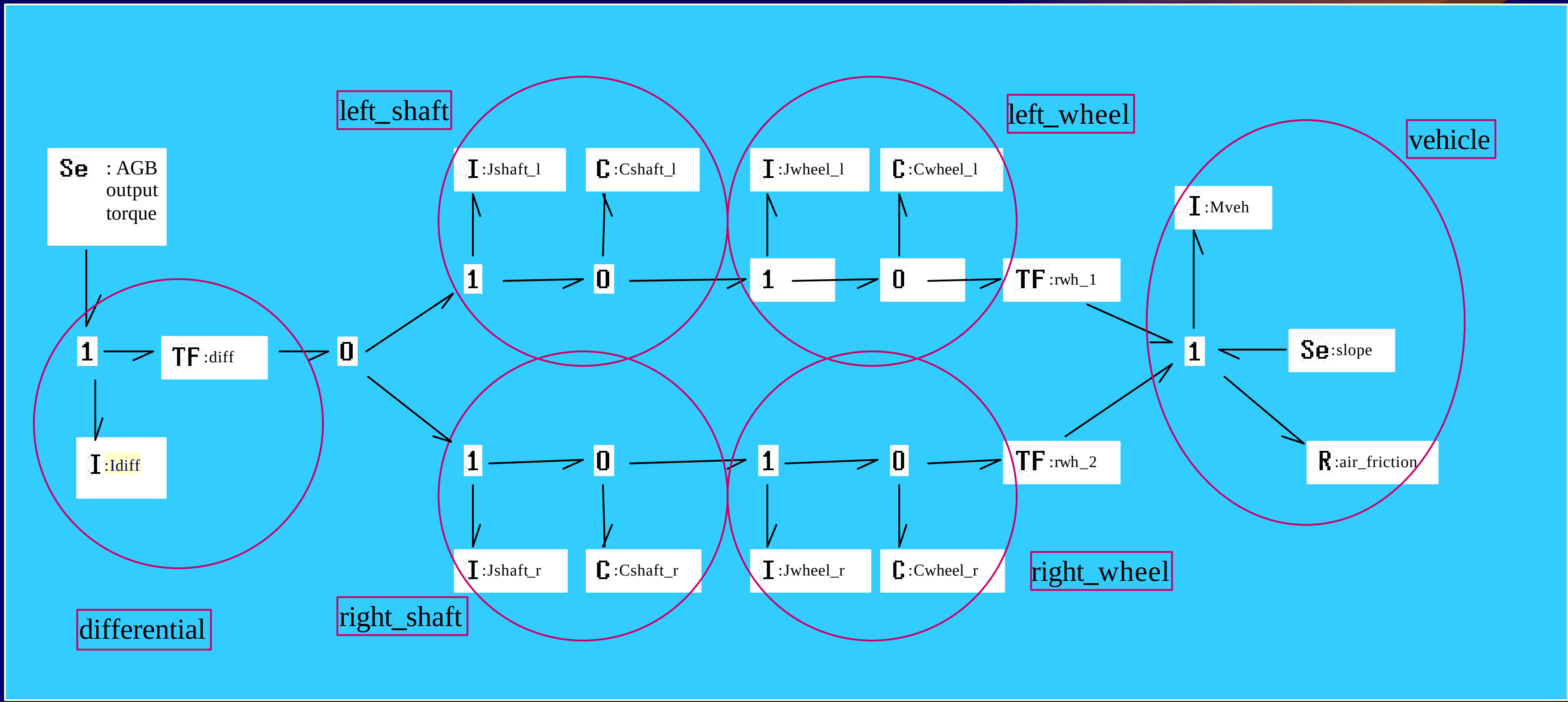


« How to shift » :

- action on only 2 clutches or 2 brakes at the same time,
- control of the pressure to have a smooth shift and no jerk in acceleration

1 - Mechatronic design of an automatic gear box

Bond graph model of the vehicle



2- Clutch management and drive comfort

- Ojectives:
  - Reduce the well-known fore and aft oscillation of a vehicle occuring when a sudden torque variation takes place in the transmission (throttle step sollicitation)
  - Satisfy comfort and driving pleasure

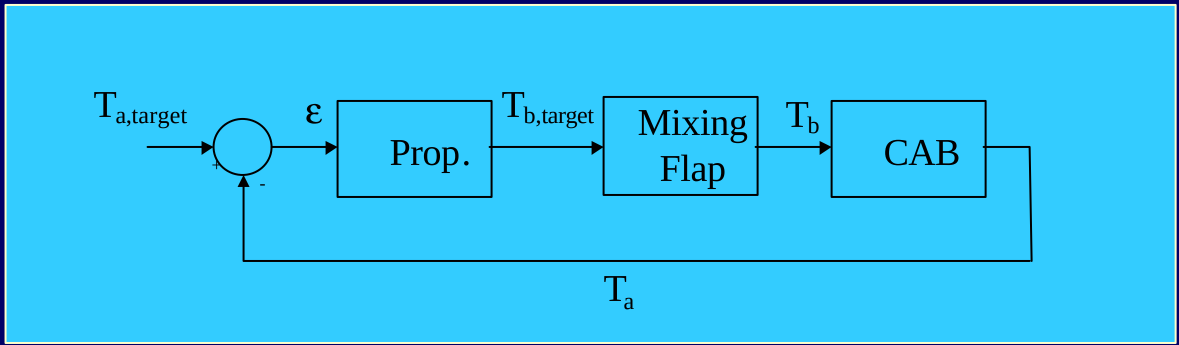
- Means:
  - Define an hydraulic-electronic-mechanical actuator transforming the numerical output into pressure on the plates of the clutch
  - Design control laws for this electrohydraulic servovalve

3 - Thermal comfort regulation in a car interior

<u>Usual climate control</u>

- Try to reach and maintain the passenger compartment temperature to a specified target temperature.

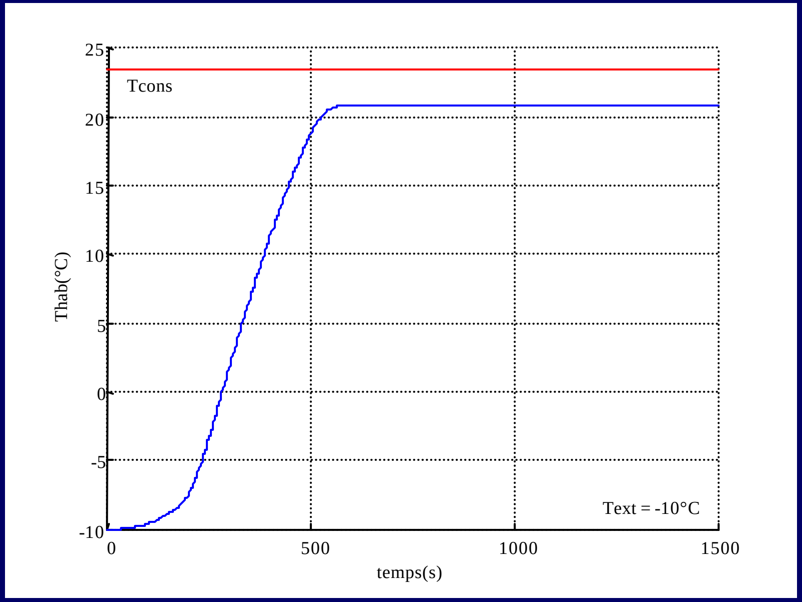
→ The regulator acts on the mixing flap to increase or decrease the blown air temperature. Usually, a proportional strategy is used to control the mixing flap



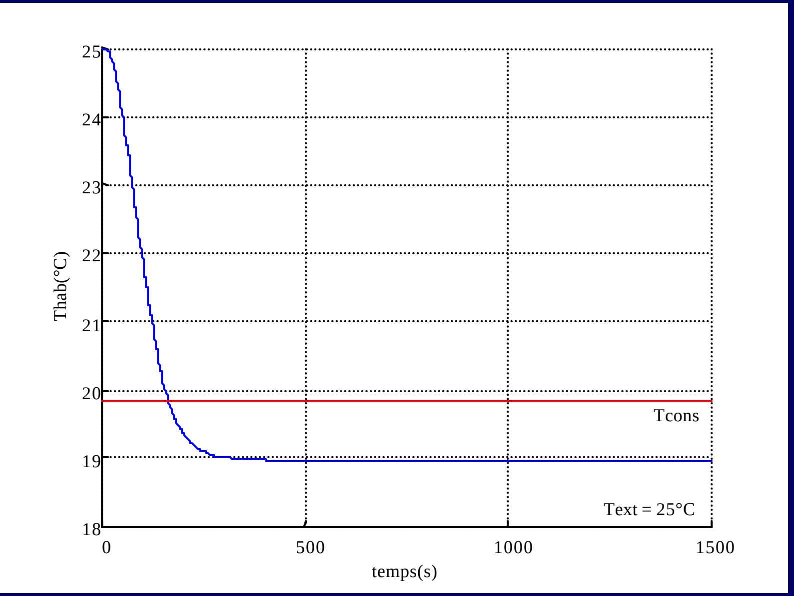
3 - Thermal comfort regulation in a car interior

Usual climate control

! Usually the air temperature in the compartment does not reach the target temperature.



heating



cooling

3 - Thermal comfort regulation in a car interior
Comfort strategy

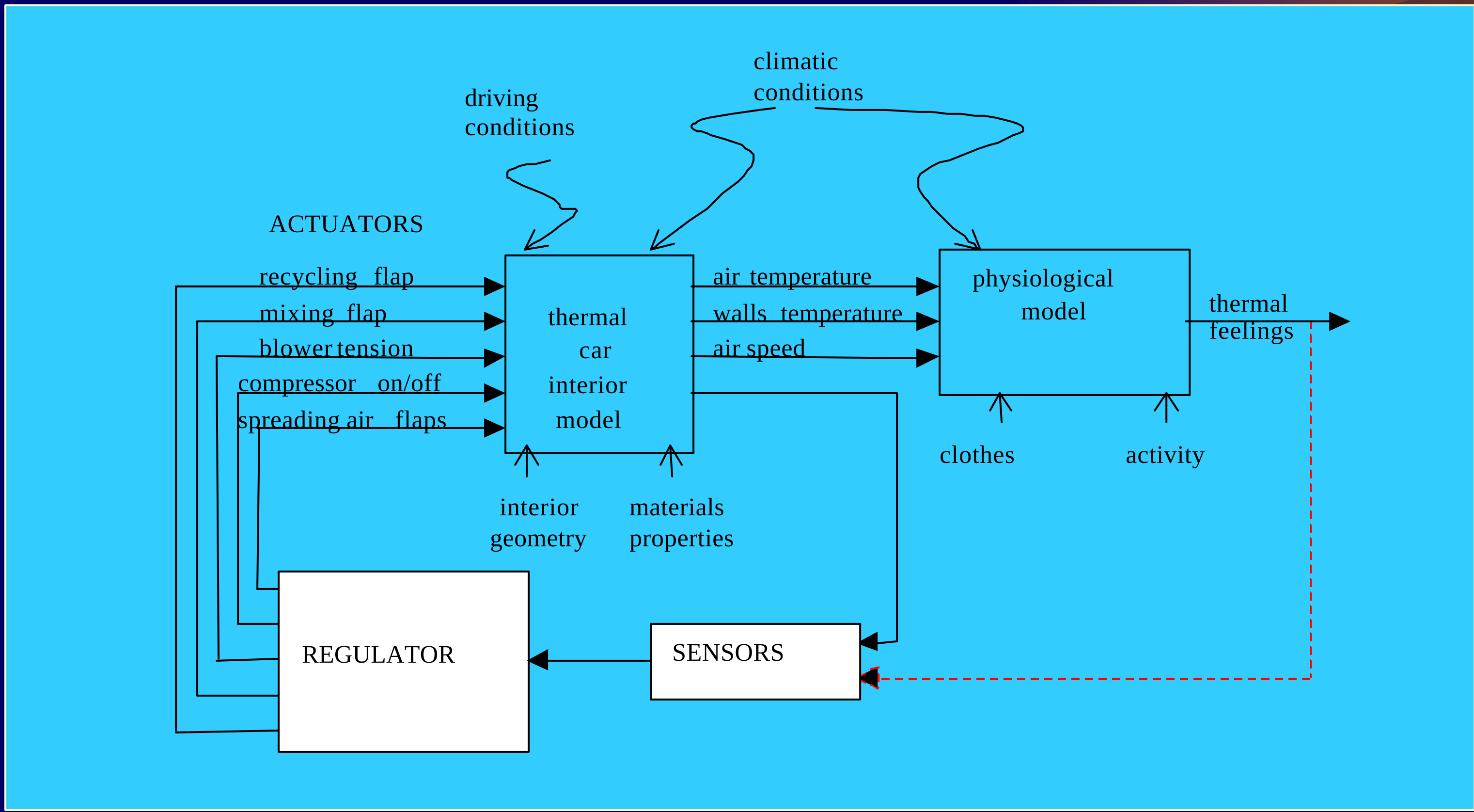
- comfort : much more than only thermal comfort. Our five senses, our cerebral state, our thermal state have an influence on our comfort estimating.
- thermal sensations rather than thermal comfort - a very subjective notion.
- in PSA Peugeot-Citroën, quantitative scale to evaluate a thermal sensation : an integer between 1 (very cold) and 9 (very hot) sensation.

Objectives:

define a regulation strategy for a climate controller for car interior, taking into account the car passenger's thermal sensations.

3 - Thermal comfort regulation in a car interior

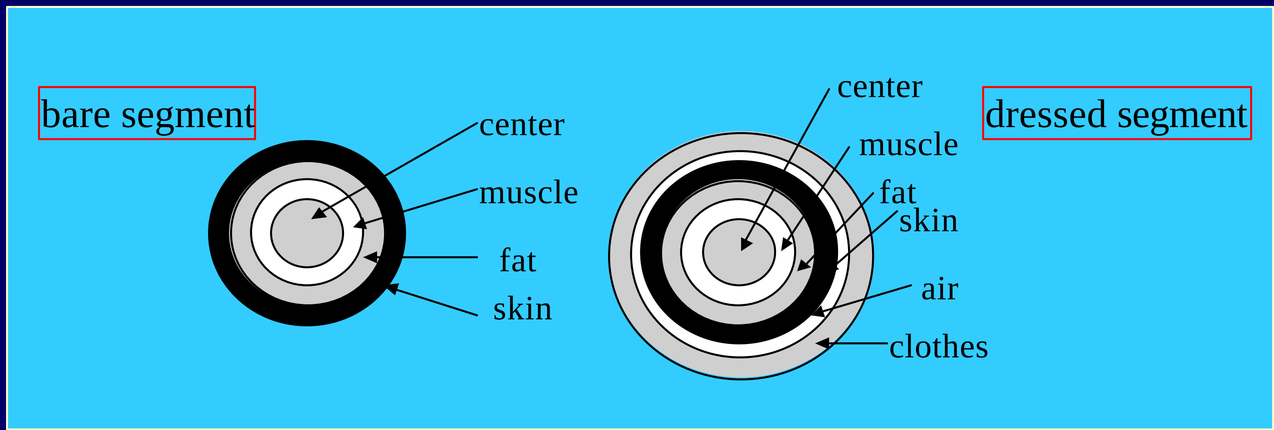
Block representation of the model



3 - Thermal comfort regulation in a car interior
Physiological model

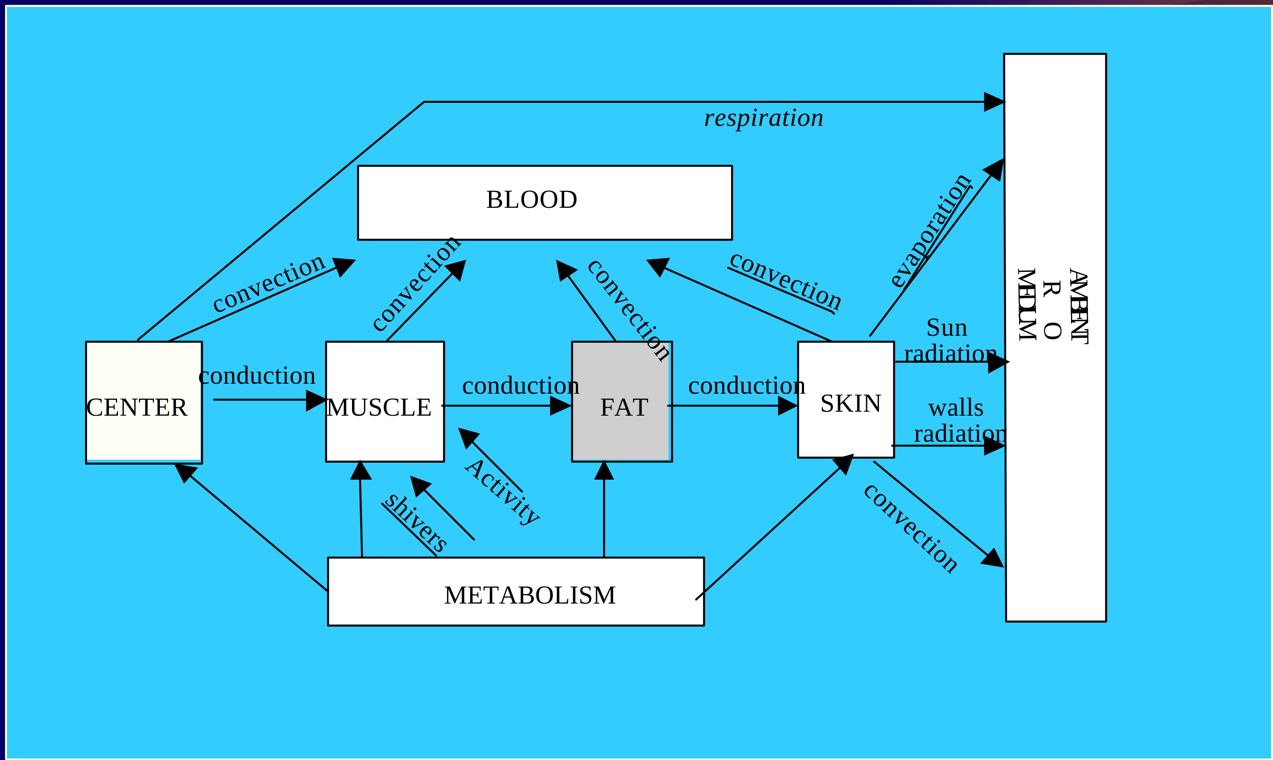
→ *human body divided into seven parts called **segments:***
the head, the trunk, the left arm, the right arm, the hands, the legs and the feet.

→ head and hands segments are bare.

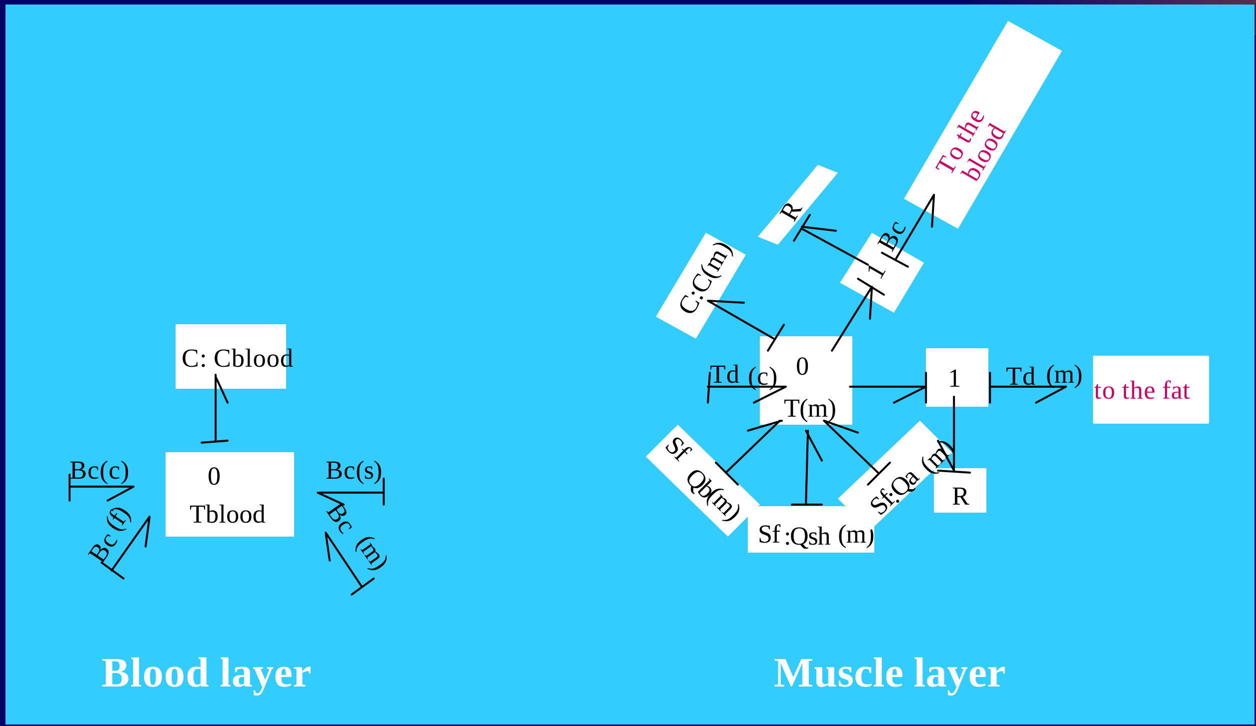


3 - Thermal comfort regulation in a car interior

Physiological model



3 - Thermal comfort regulation in a car interior
Physiological model



For each segment

3 - Thermal comfort regulation in a car interior

Physiological mathematical model

- ***x*** state vector (order = 57) : temperature, water mass, sudation production and water partial pressure of the layers.
- ***u*** input vector (size = 14) : air temperature and air speed of the ambient air close to the 7 segments.
- ***d*** disturbance vector (size = 35) : ambient air humidity, sun and wall radiation on clothes and skin layers.
- ***y*** output vector (size = 7) : thermal feelings of the 7 segments.

$$\begin{cases} \dot{x} = f(x,u,d) \\ y = g(x,u,d) \end{cases}$$

3 - Thermal comfort regulation in a car interior
Linearized physiological mathematical model

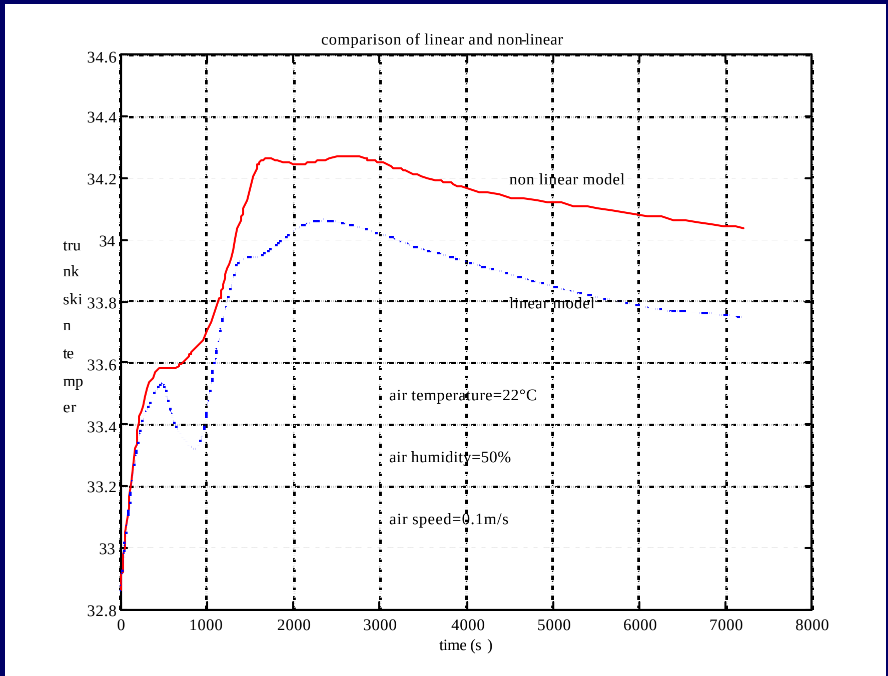
- A nominal functioning point defined as a comfortable situation for the human (air temperature=299K, air speed=0.5m/s and humidity=50%).
- Two linear models containing saturations, because heat transfers are different whether the body is warm or cold.

$$\begin{cases} \dot{x} = (bA_c + \bar{b}A_w)x + B \cdot u + E \cdot d + F \\ y = C \cdot x + D \cdot u \\ m < K \cdot x < M \end{cases}$$

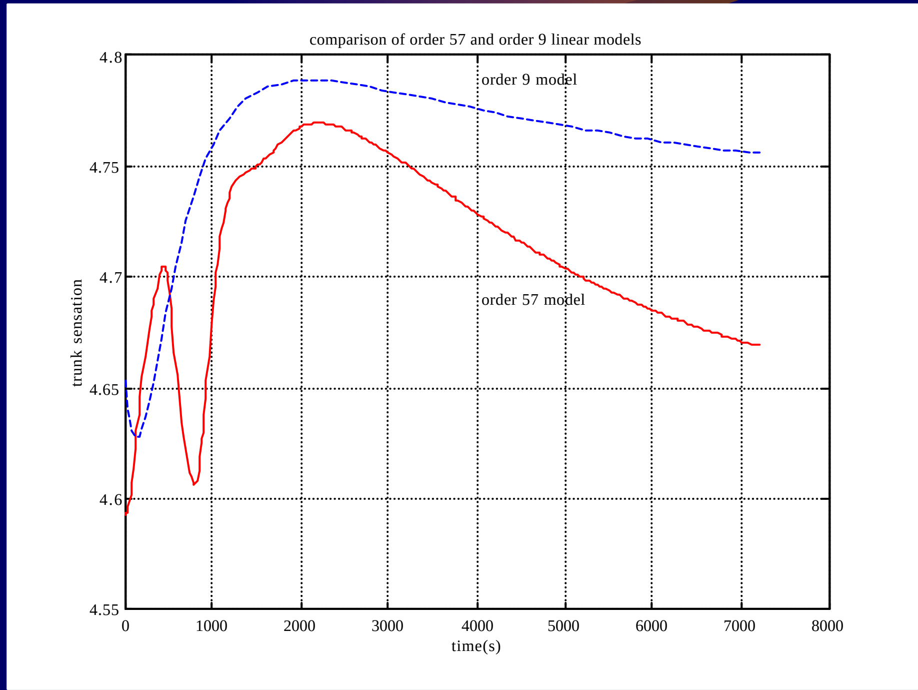
  - **b** = 1 if the body is cold, and 0 if not.
  - ***F*** vector that results from constant thresholds due to saturations.
  - **K** matrix selecting the x components concerning the saturations.

3 - Thermal comfort regulation in a car interior

Physiological model : simplifications



Trunk skin temperature



Trunk sensations

3 - Thermal comfort regulation in a car interior
Proposed comfort strategy

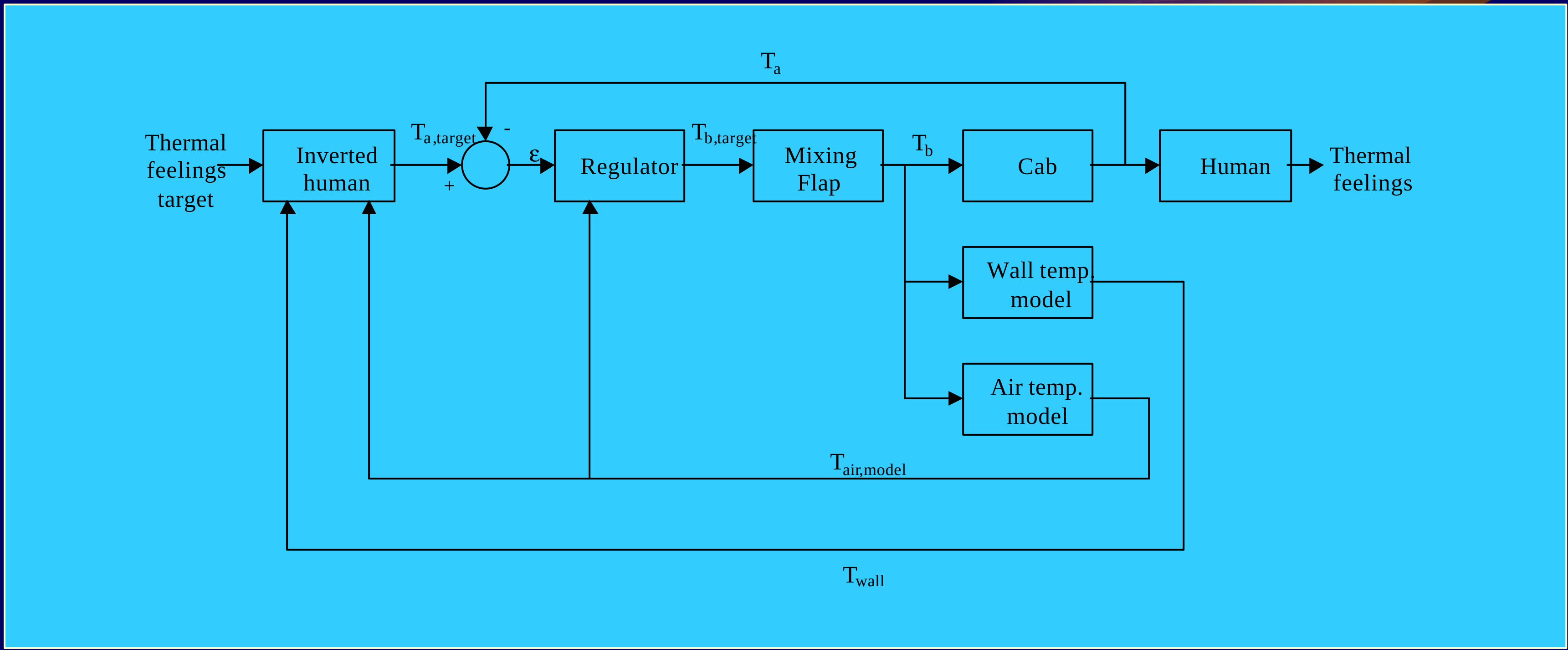
Control strategy based on the thermal feelings :

- Determine the air temperature close to the head driver to ensure him a comfortable thermal feeling (level 5 in PSA scale)
- Take into account the wall temperatures and the air flows in the compartment.
- Compute the best air temperature target for the driver to be comfortable by using the inverted human model

In case of chilly driver, a target sensation superior to 5 can be asked for

3 - Thermal comfort regulation in a car interior

Proposed comfort strategy



Predictive control (GPC)

3 - Thermal comfort regulation in a car interior

Comfort strategy - Air temperature model

linear convex formulation:

$$T_a = \left(\frac{a}{1+t_1 s} + \frac{1-a}{1+t_2 s}\right)(l_a T_{out} + (1-l_a)T_b)$$

- T_a air temperature,
- T_{out} outside air temperature,
- T_b blown air temperature,
- ✞ convex parameter depending essentially of the blown air flow and the vehicle speed.

There are two dynamic modes : a fast mode caused by the mass transfer and a slow mode caused by the thermal transfers with the outside.

3 - Thermal comfort regulation in a car interior
Comfort strategy - Wall temperature model

first order model:

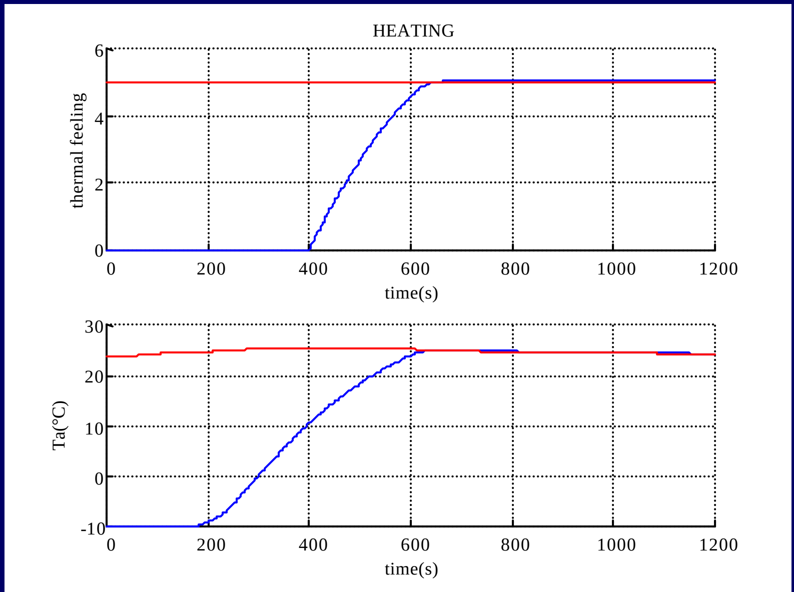
$$T_w = (\frac{1}{1+t_w s})(l_w T_{out} + (1-l_w)T_a)$$

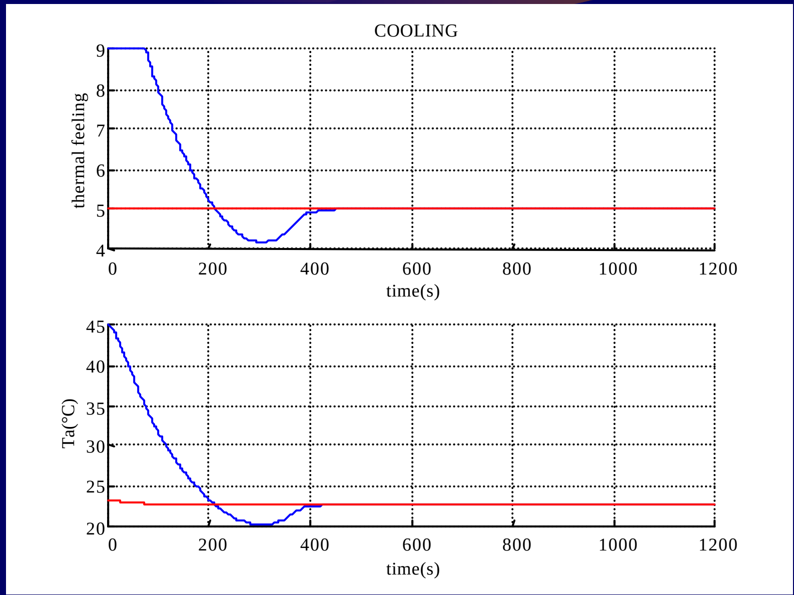
- T_w the surface temperature,
- T_a the air compartment temperature close to the surface.

Experiments in a wind tunnel to identify the parameters of each air temperature model and wall temperature model :
several wind-tunnel air flows (for the air flow due to the vehicle speed), several outside temperatures, several blown air temperatures and flows

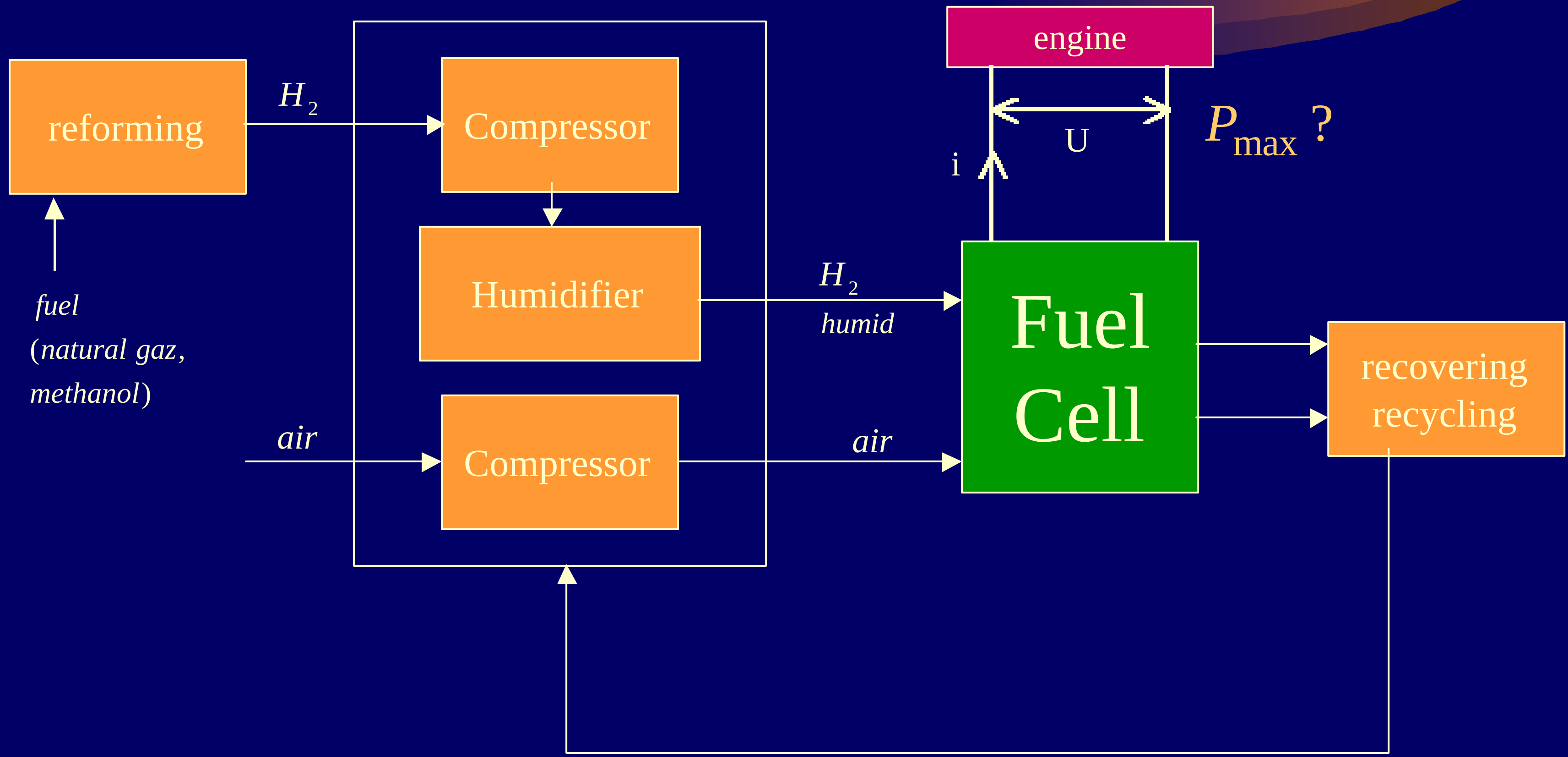
3 - Thermal comfort regulation in a car interior

Comfort strategy



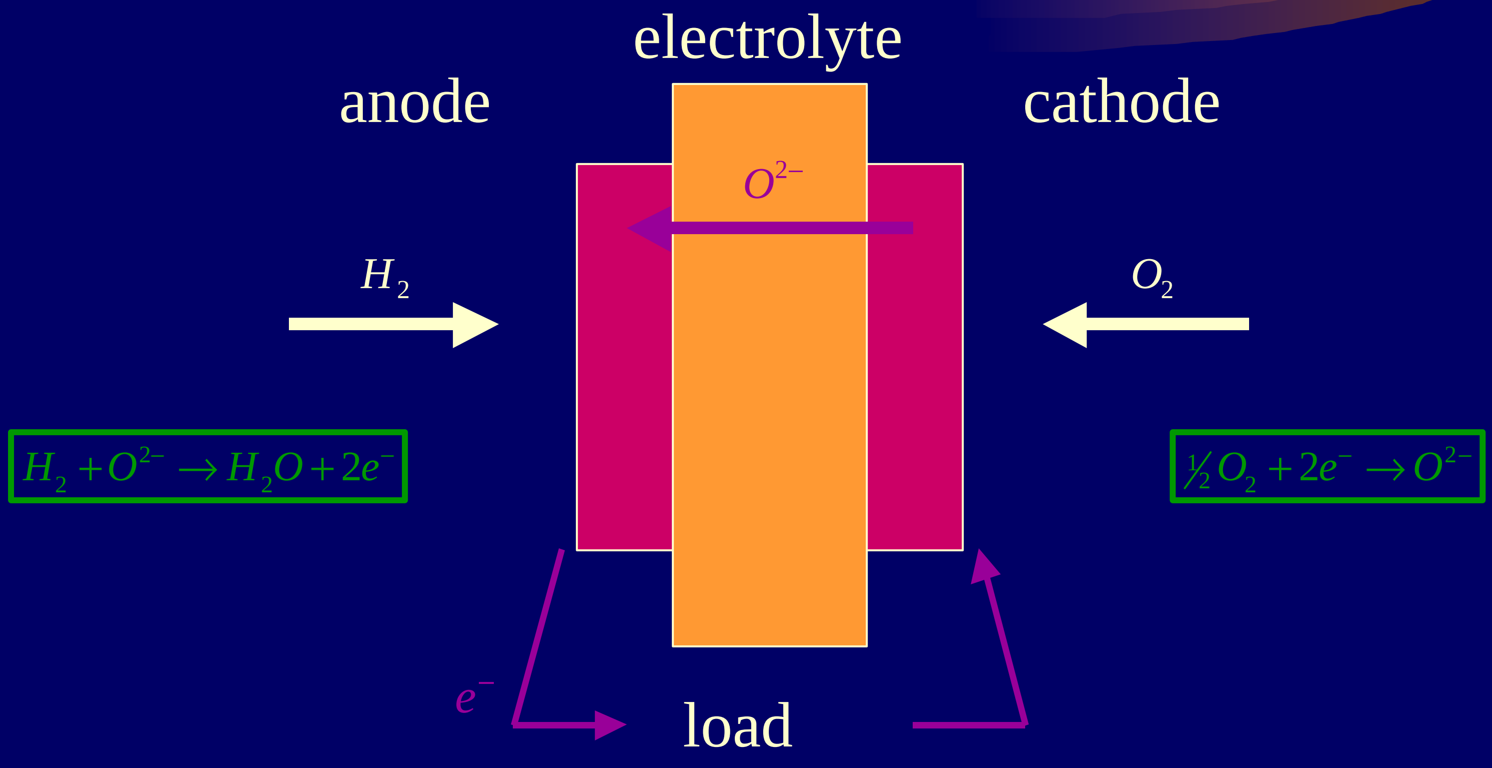


4 – Modelling of a fuel cell system



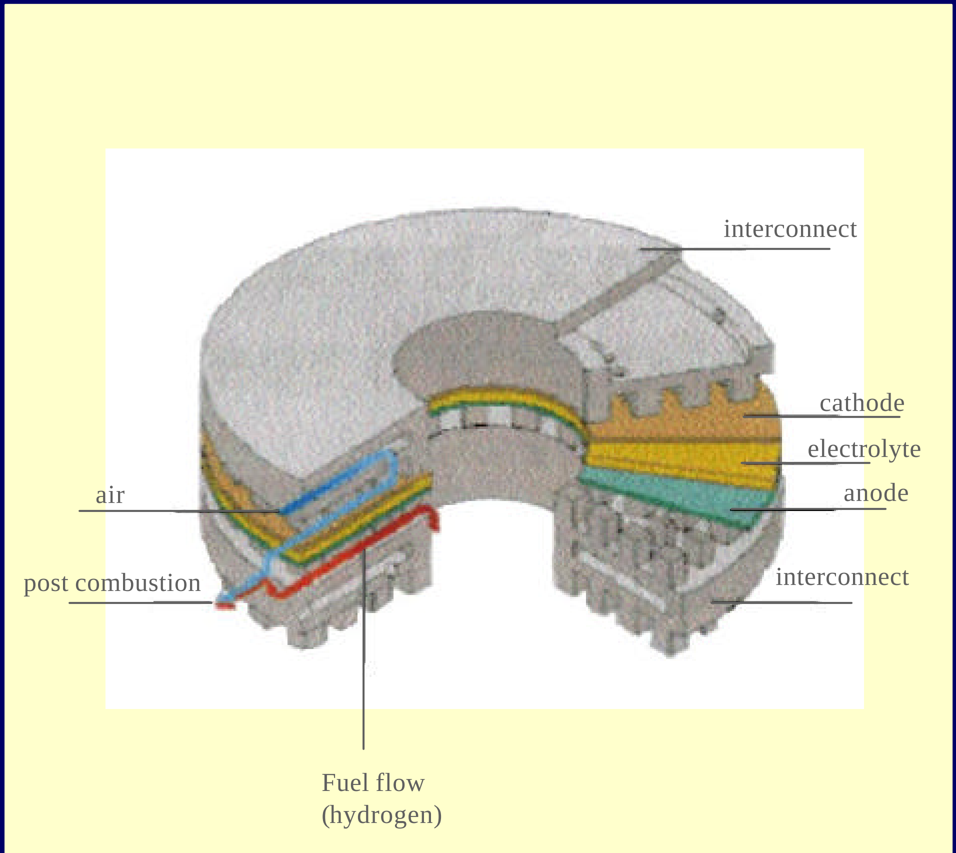
4 – Modelling of a fuel cell

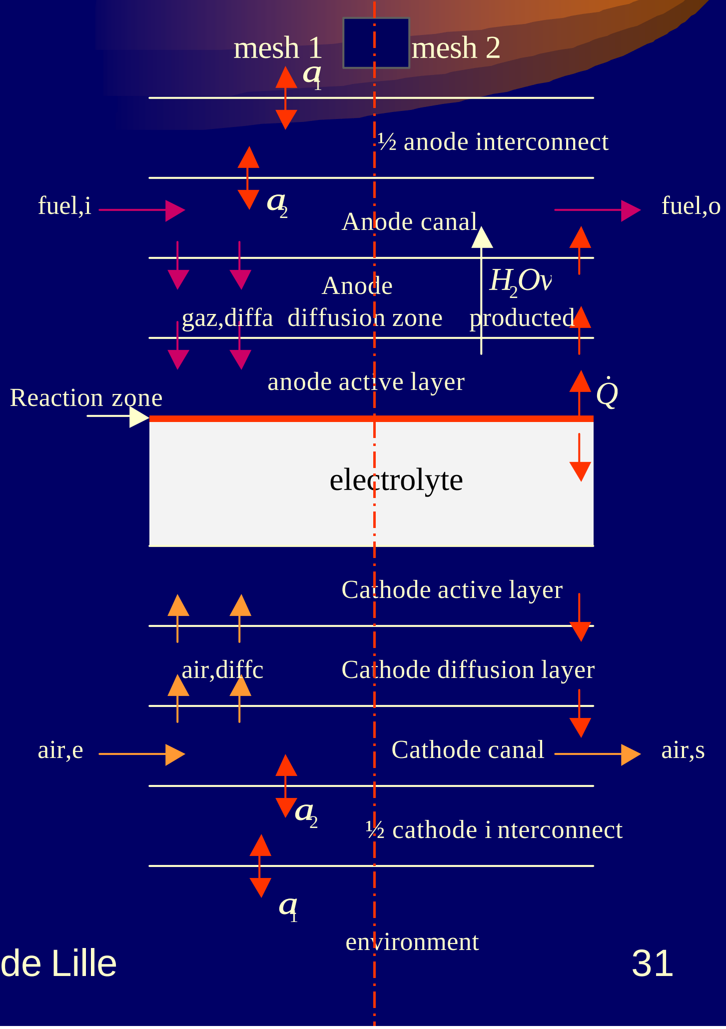
Fuel cell : principle



4 – Modelling of a fuel cell

Fuel cell : tubular design



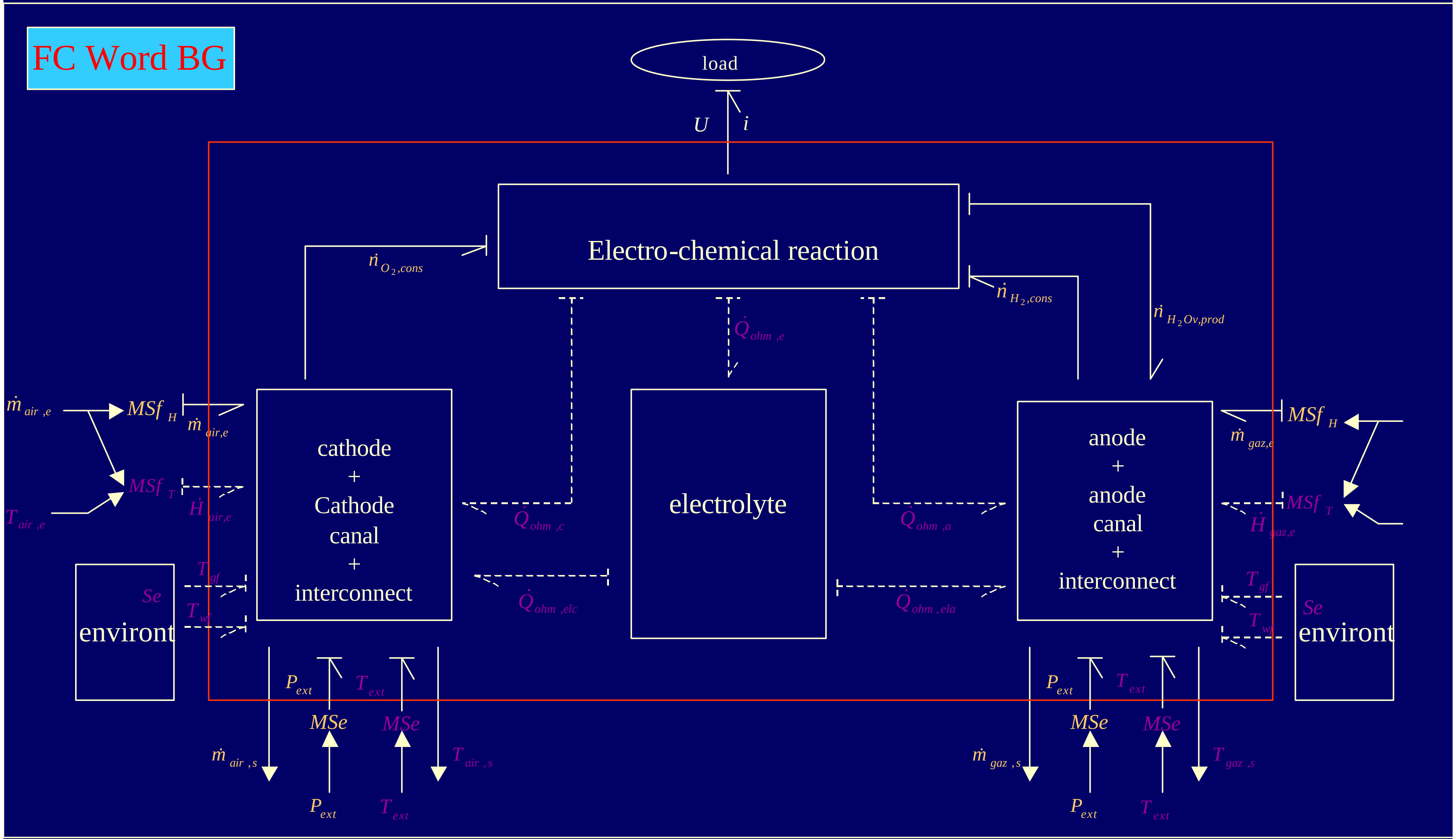


4 – Modelling of a fuel cell
Variables

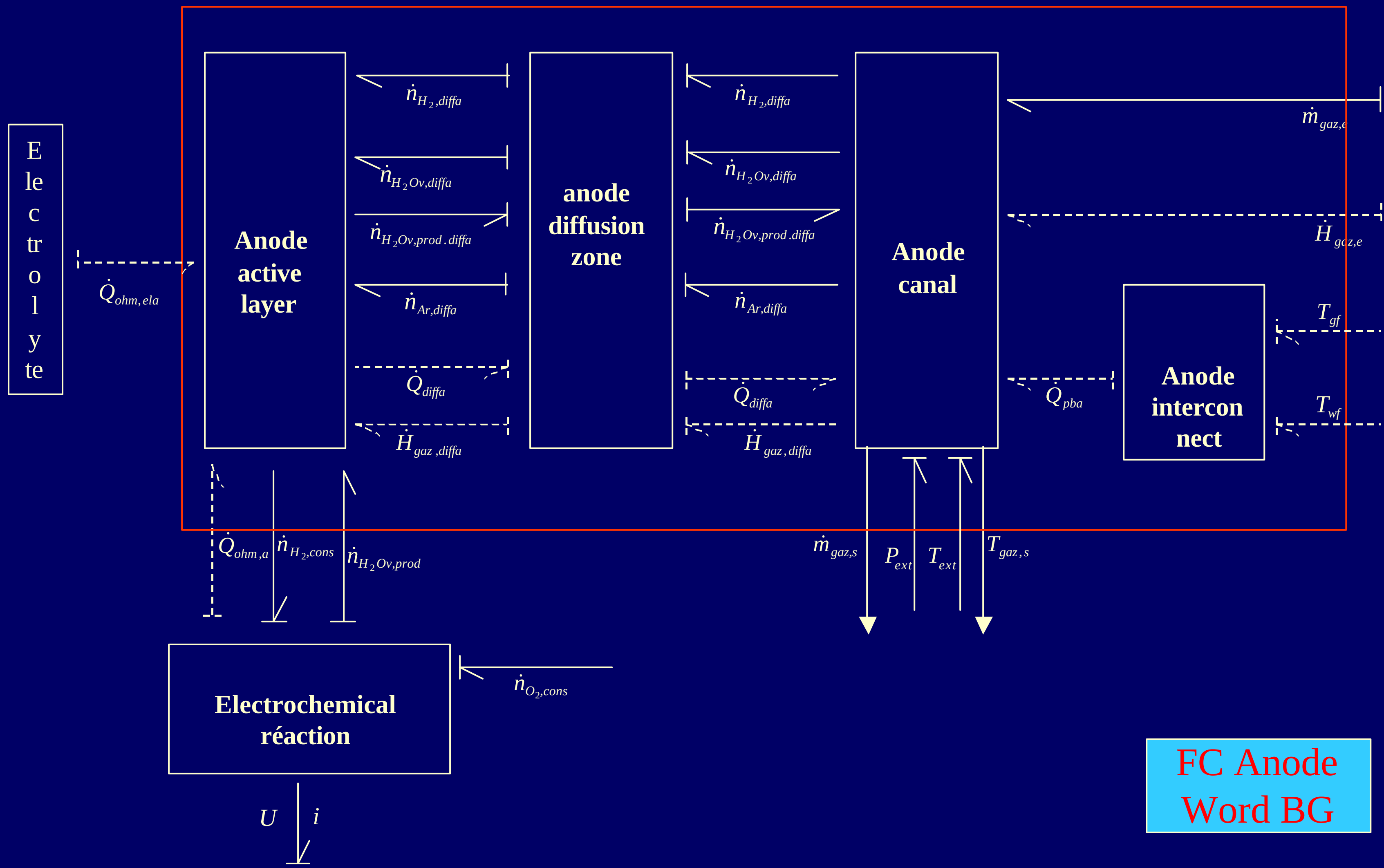
Fluid
- Pressure: P
- Temperature: T
- Mass or molar flow rate: $\dot{m}$ or $\dot{n}$
- Enthalpy flow $\dot{H} = \dot{m}.c_p.T$

Chemical reaction
- Molar flow rate: $\dot{n}$
- Chemical potential : m

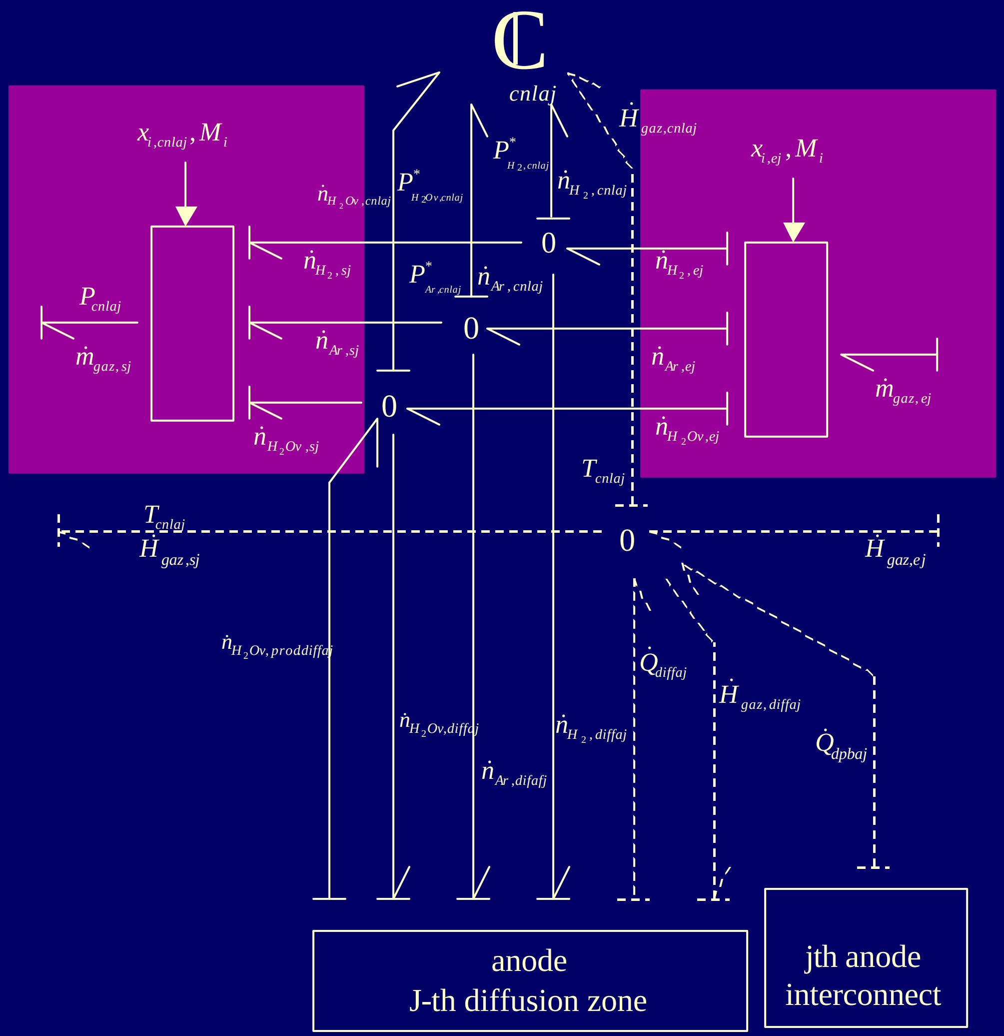
Electrical
- Current: i
- Voltage: U



FC Word BG
load
U
i
Electro-chemical reaction
cathode
+
Cathode
canal
+
interconnect
electrolyte
anode
+
anode
canal
+
interconnect
environt
Se
environt
Se
MSf
MSf
MSe
MSe
MSe
MSe



FC Anode Word BG

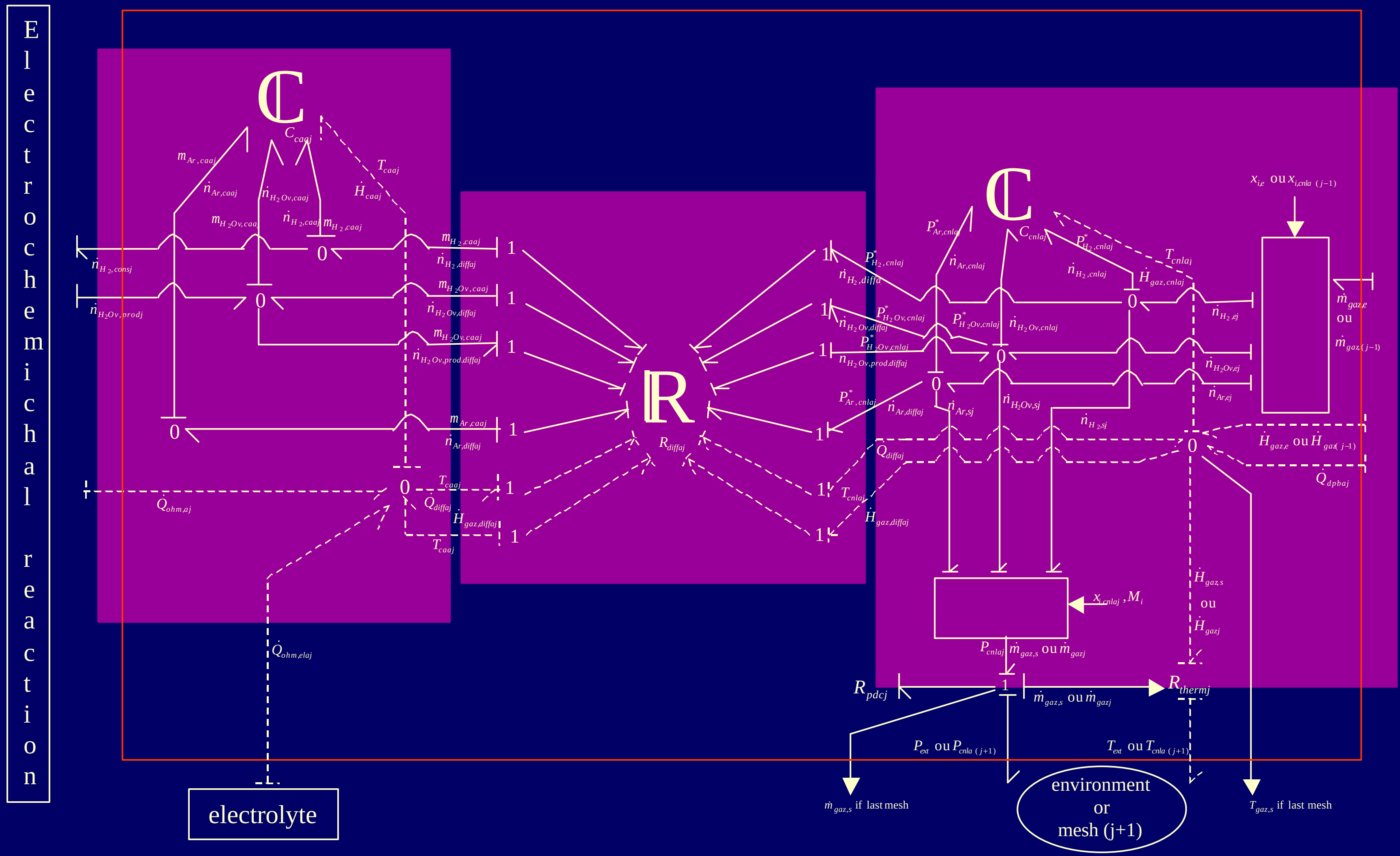


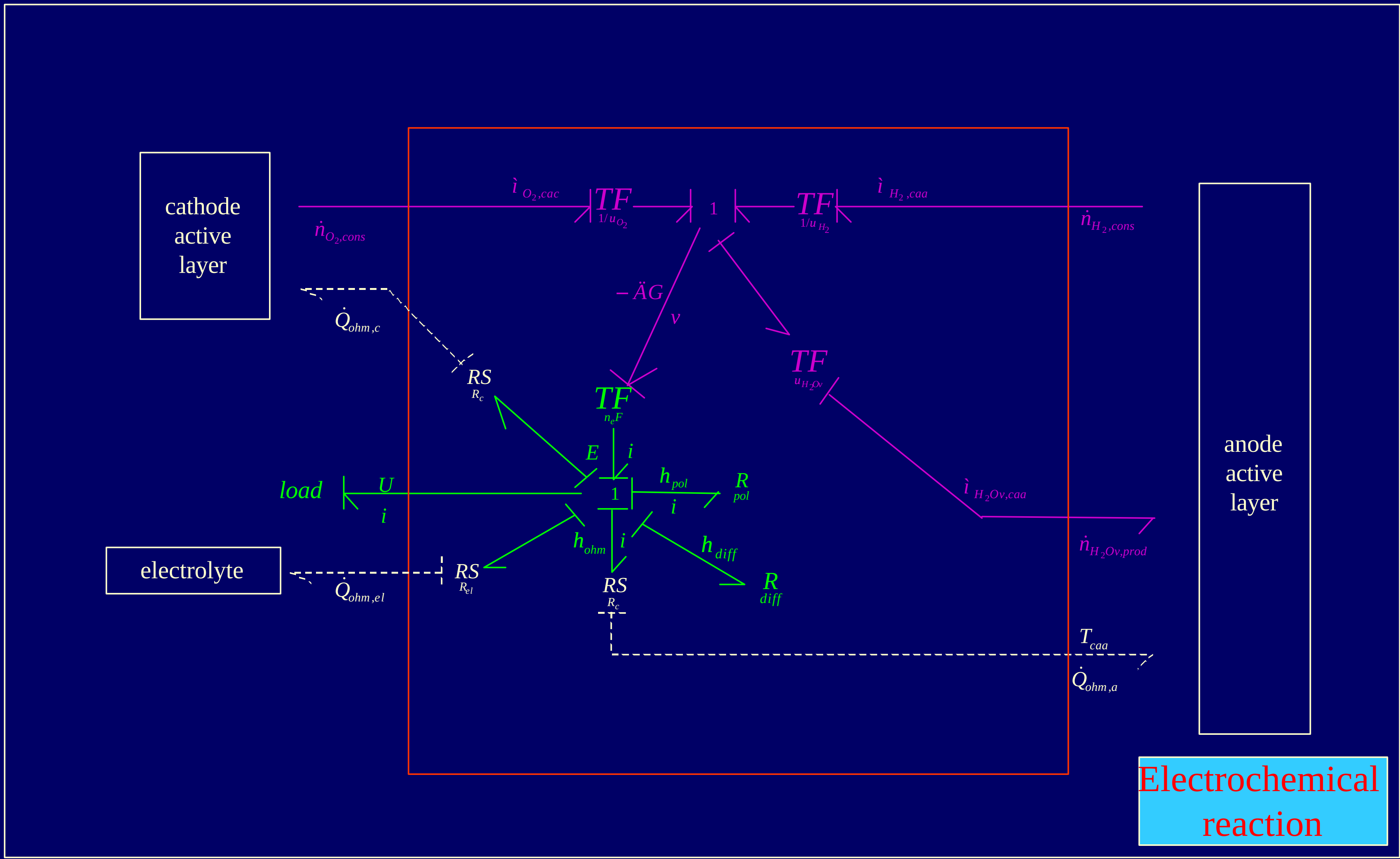
Fuel supply

$\dot{m}_{gaz,ej}$

$$\dot{n}_{H_2,ej} = \dot{m}_{gaz,ej} \,.\, x_{H_2,ej} \,.\, M_{H_2}$$

Anode canal BG


Electrochemical reaction
electrolyte
environment
or
mesh (j+1)
if last mesh
if last mesh



cathode
active
layer
electrolyte
anode
active
layer
TF
1
TF
TF
TF
1
RS
RS
RS
R
pol
R
diff
load
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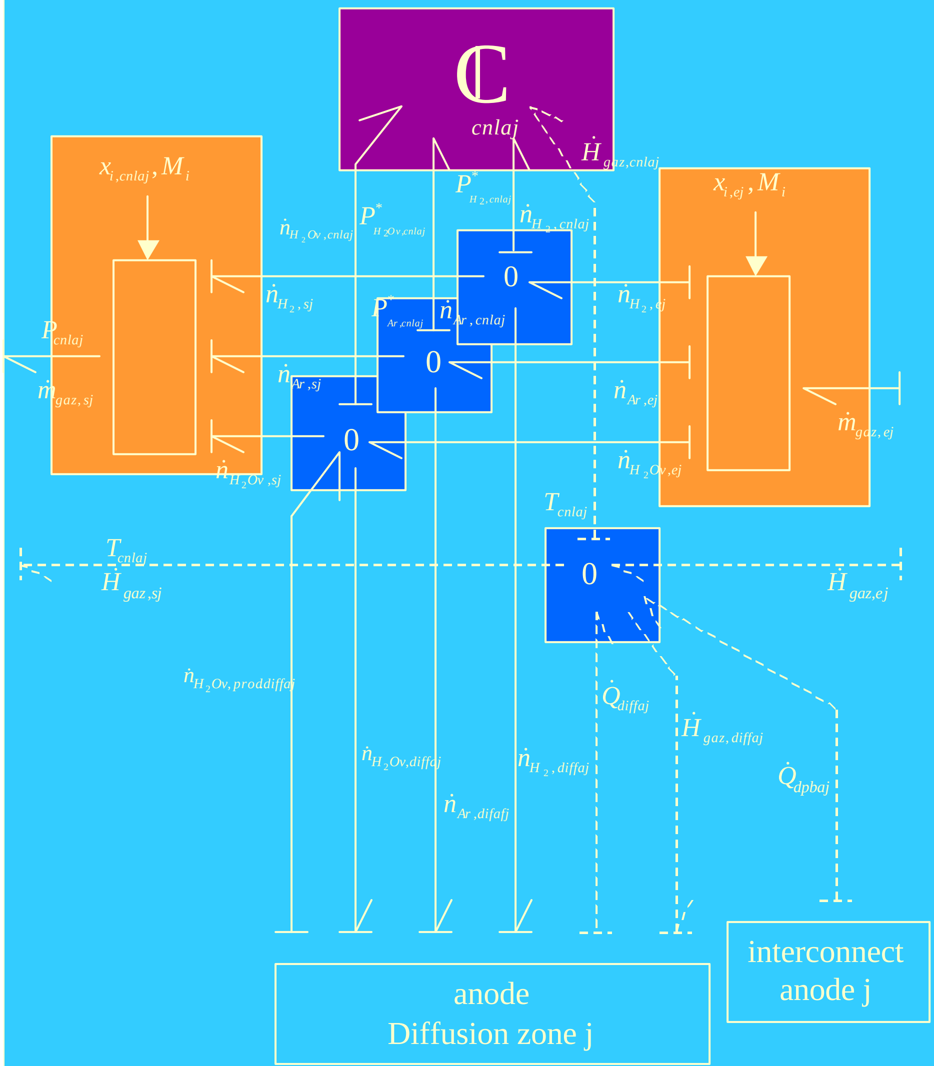
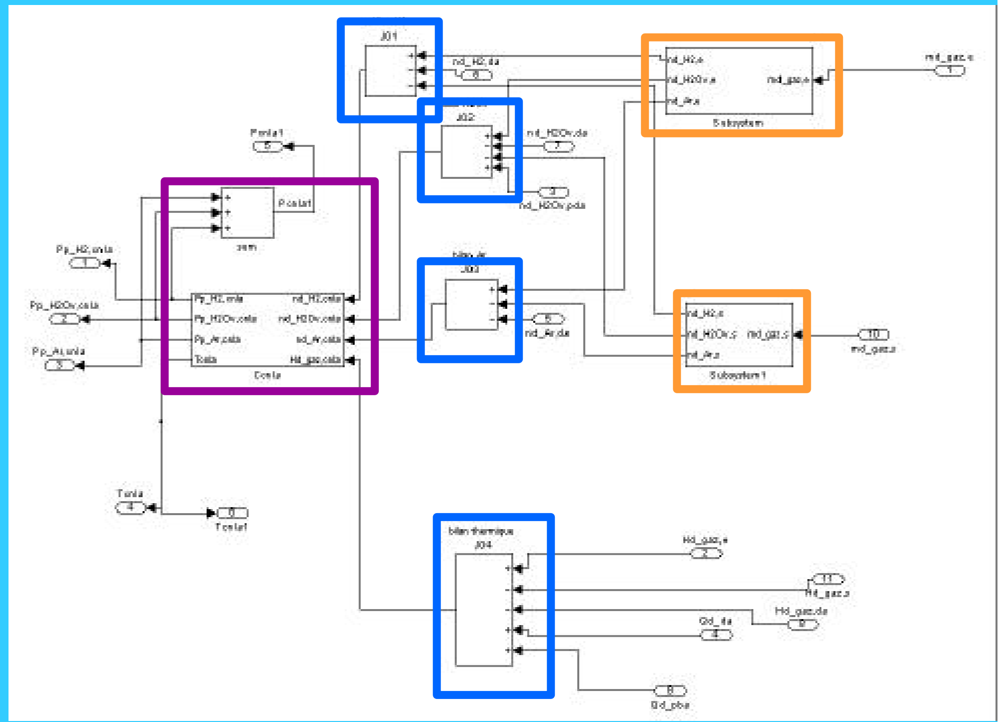
i
E
i
−ÄG
v
Electrochemical
reaction



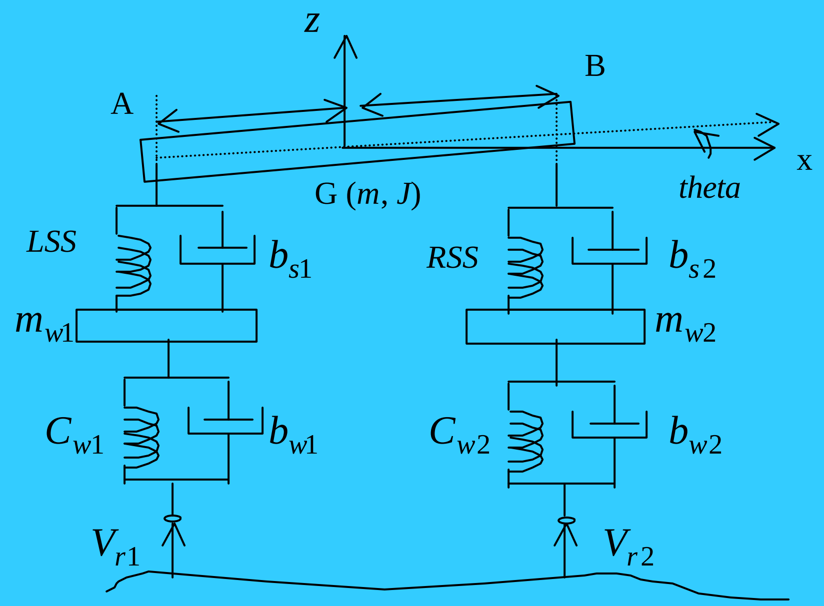


BG to Simulink

4 – Modelling of a fuel cell
Results

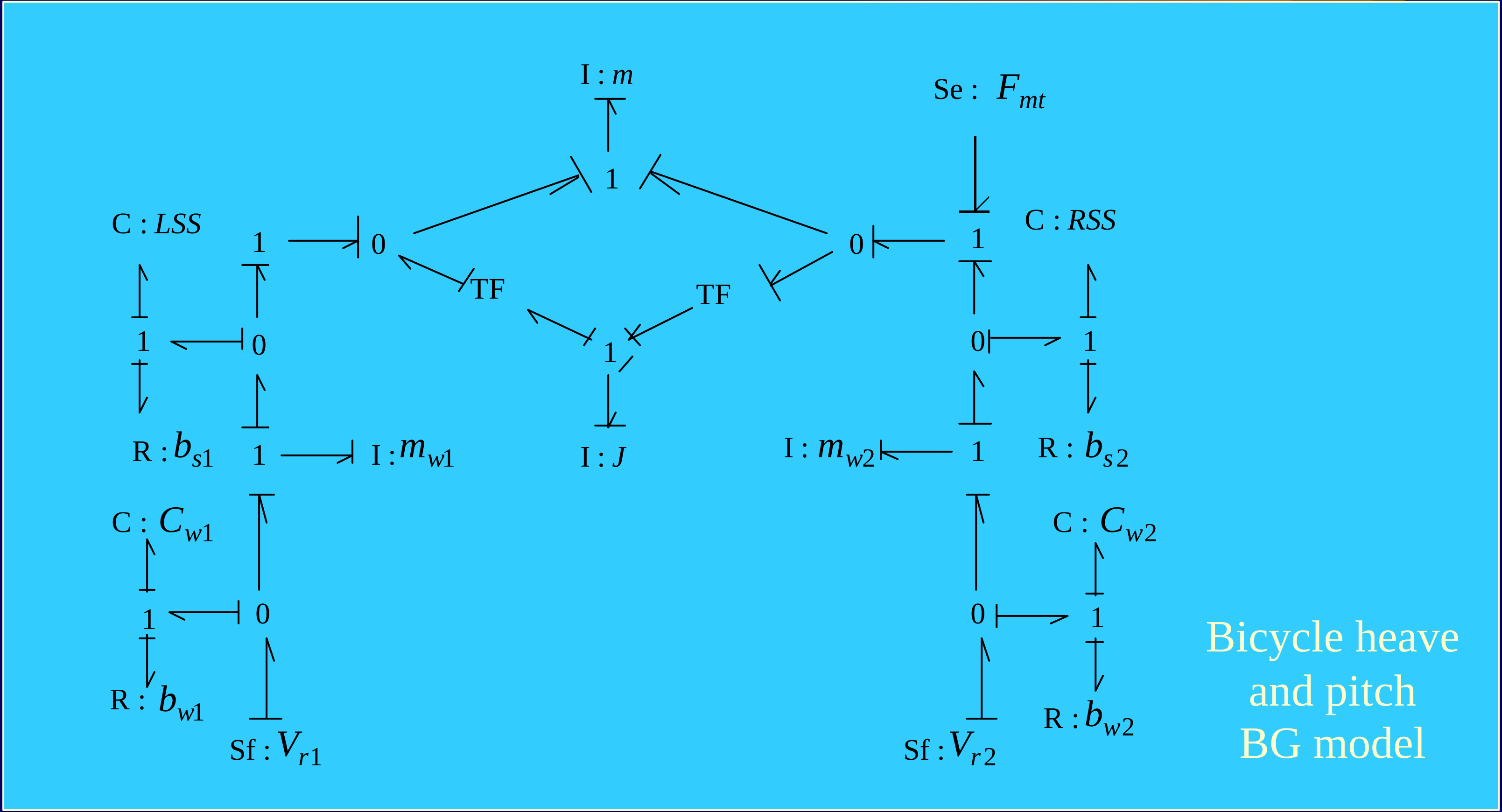
- → Complete dynamic model of the fuel cell system (no similar result in the literature, only static models)
- → Simulation results validated by comparison with experimental data
- → Work with PSA is running for:
  - → Control designing : how to maximize the power delivered by the fuel cell system
  - → Fault diagnosis

5 - Structural properties of bond graph models



Bicycle heave and pitch physical model

5 - Structural properties of bond graph models



5 - Structural properties of bond graph models

Passive model

- State equation

$$\dot{x} = Ax + Ed$$

$$x = \begin{pmatrix} p_I \\ q_C \end{pmatrix} = \begin{pmatrix} \text{inertia impulses} \\ \text{spring displacements} \end{pmatrix}$$

$$d = \begin{bmatrix} d_1 \\ d_2 \end{bmatrix} \qquad d_1 = \begin{bmatrix} F_{masstransfer} \end{bmatrix} \qquad d_2 = \begin{bmatrix} V_{road1} \\ V_{road2} \end{bmatrix}$$

5 - Structural properties of bond graph models

Passive model

- State equation $\dot{x} = Ax + Ed$

- order n of a model : number of I and C elements in integral causality when a preferred integral causality is assigned to the bond graph model

- BG-rank q of the state space matrix A : number of I and C elements in derivative causality when a preferred derivative causality is assigned to the bond graph model.

- number of structurally null modes of A-matrix : number of I and C elements which have to stay in integral causality when a preferred derivative causality is assigned to the bond graph model

5 - Structural properties of bond graph models

Passive model

- State equation $\dot{x} = Ax + Ed$

- minimum number of actuators for the model to be controllable :
  - If BG-rank $A = n$, the model is controllable with a single actuator
  - If BG-rank $A = n\text{-}k$, for the model to be controllable, k well-located actuators are needed

- minimum number of sensors for the model to be observable :
  - idem

5 - Structural properties of bond graph models

Design of the measurement and control architecture for the active system

- <u>definition of the control objectives</u>
  - what variables to be controlled?
  - for what performances (dynamical or frequential criteria)?
  - with what strategy (pole placement, disturbance rejection, …)?

- <u>what type of control law?</u>
  - state feedback?
    - Is the state measurable?
  - output feedback?

5 - Structural properties of bond graph models

Design of the measurement and control architecture for the active system

Choice here

State feedback for pole placement and rejection of the disturbance corresponding to the mass transfer due to driver actions (braking or accelerating) on the 2 velocity variables (heave and pitch)

! the 2 variables (absolute velocities) to be controlled are not measurable

→ an observer is needed

! We want to perform input/output decoupling

→ 2 control inputs are needed

5 - Structural properties of bond graph models

Design of the measurement and control architecture for the active system

§
- → 2 outputs to be controlled : not measurable $y = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} V_m \\ w_J \end{bmatrix}$ (Df*)
- → measurement vector $z = \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \begin{bmatrix} V_{rel1} \\ V_{rel2} \end{bmatrix}$ (Df)

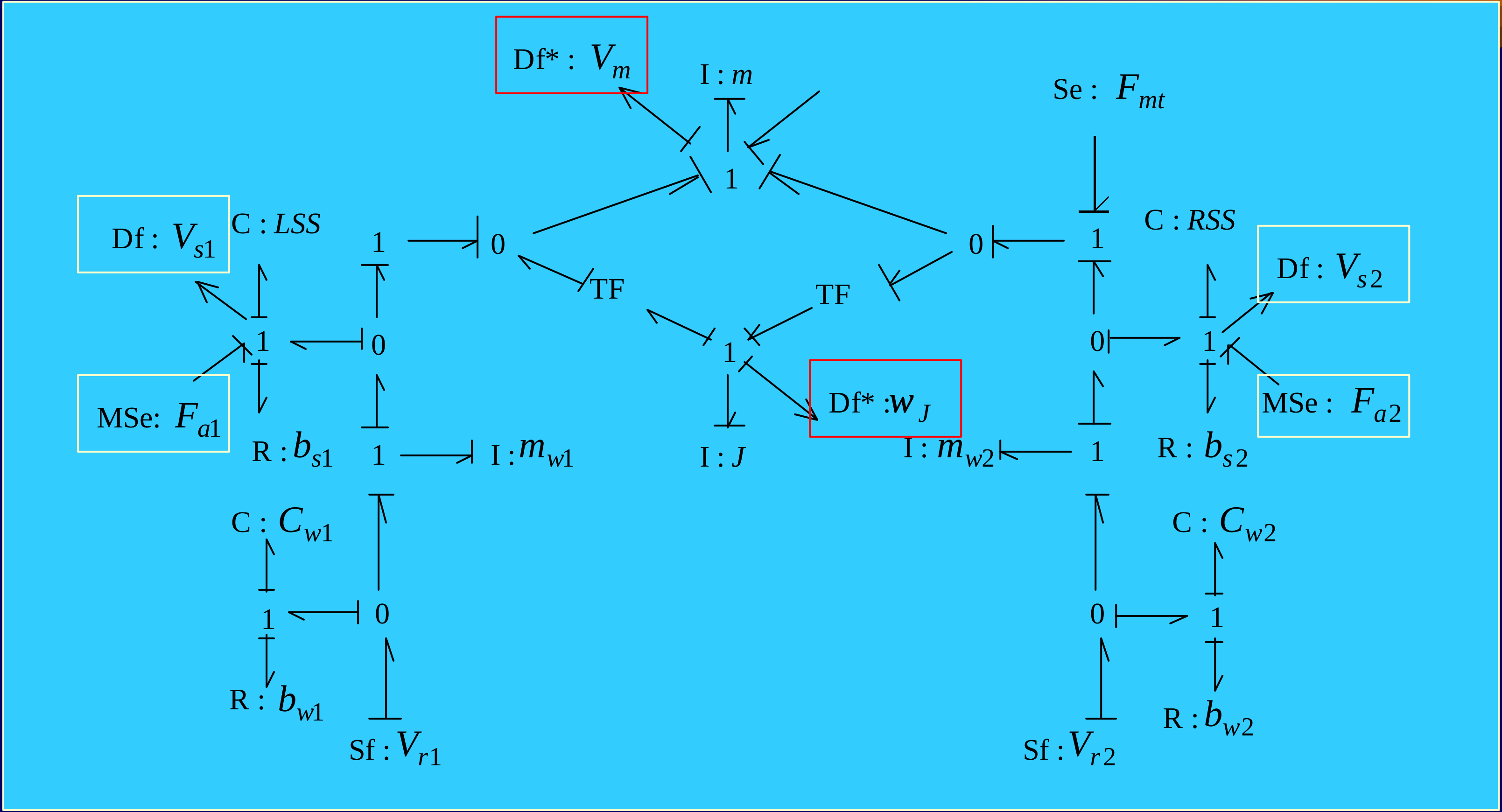
§
- → 2 control inputs $u = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} F_{act1} \\ F_{act2} \end{bmatrix}$ (MSe)
- → disturbance vector

measurable to be rejected $d_1 = \begin{bmatrix} F_{masstransfer} \end{bmatrix}$ (Se)

non- measurable $d_2 = \begin{bmatrix} V_{road1} \\ V_{road2} \end{bmatrix}$ (Sf)

5 - Structural properties of bond graph models

Design of the measurement and control architecture for the active system



Conclusion

* bond graph : language quite « strange » which needs a learning time

* Could appear difficult to implement, but

what is difficult is PHYSICS

* more and more introduced in the industrial world in France (better than in the academic world!)