Part 1 : defining the heating and cooling needs of a building

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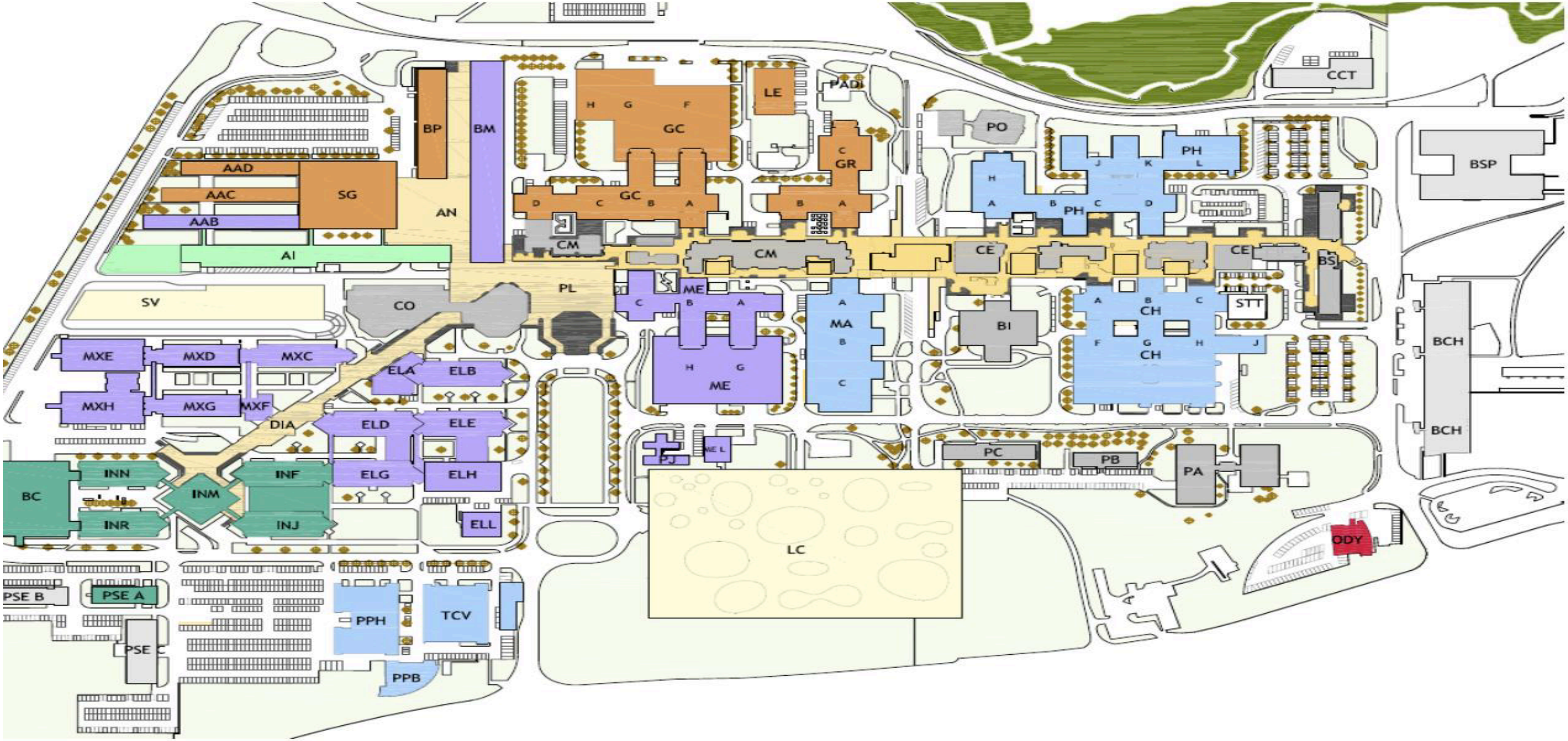
IPESE
Industrial Process and Energy Systems Engineering

Part1 : defining the building needs

EPFL Buildings stock



Steps in the course

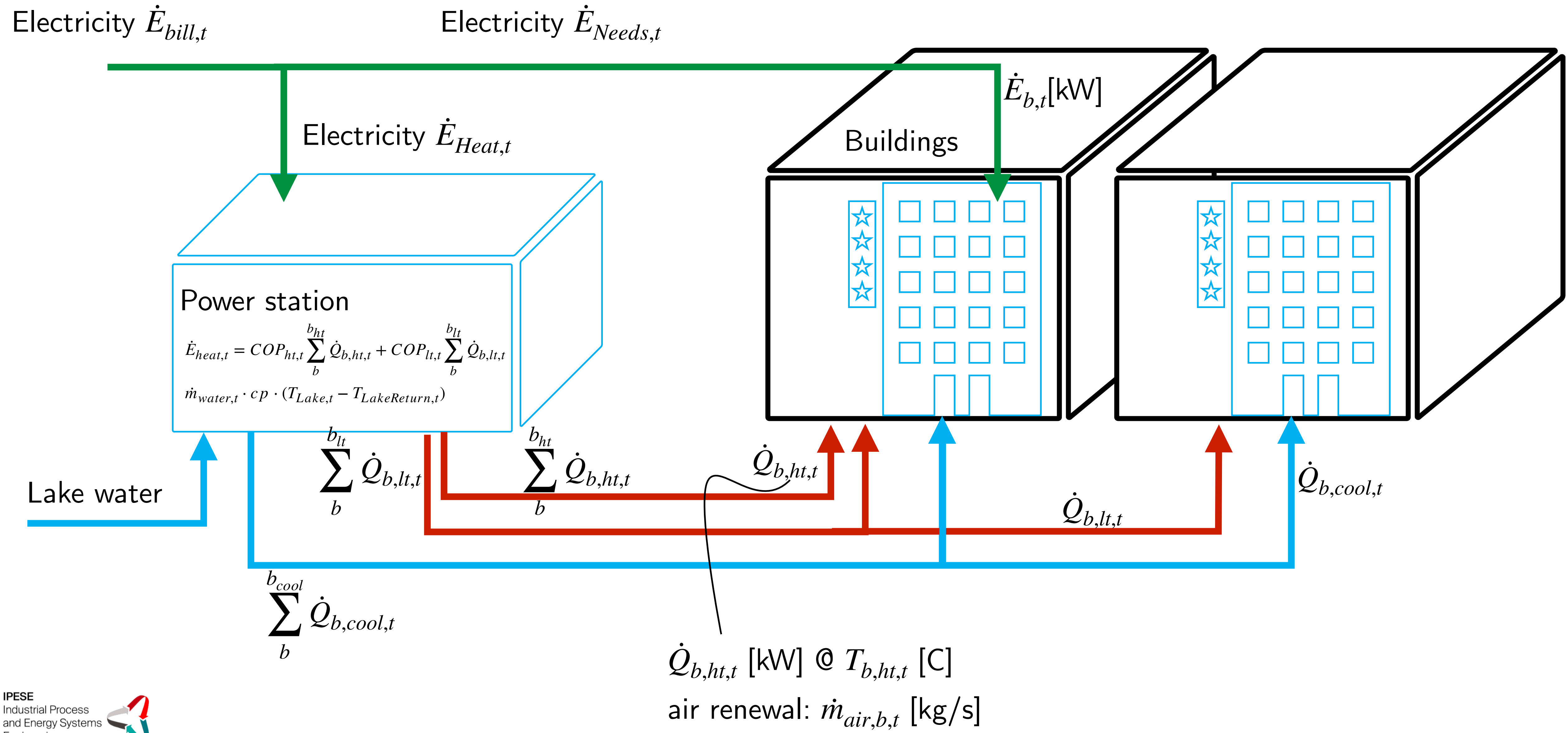
The goal is to design the energy system of an international university campus with the goal of minimising its environmental impact.

- **Task 1 : Defining the energy demand of a campus building**
  - What are the heat loads to be supplied to each building
  - Define the temperature levels of the demand
  - Define the energy bill
- **Task 2 : Model the building energy system and heat recovery options**
  - Define the building energy system flowsheet
  - Calculate the system configuration states
  - Estimate the related investment
- **Task 3 : Optimise the investment of heat recovery options for a building**
  - define the size of the investments on an objective function
  - model heat pumps and to choose the best working fluids and operating conditions of heat pumping cycles
  - Integrate the data center heat recovery
  - generate building's retrofit options
- **Task 4 : Propose and compare options for a more sustainable campus energy system**
  - integrate the buildings in the campus district heating and cooling system
  - define sustainability metrics for the decision support
  - Compare decentralised and centralised options with pro and cons for different options of the system design

Theory topics : Task 1

- **1. Energy demand models: building modelling**
- **2. Methods for solving a set of equations**
- **3.** Clustering : what are the most probable states to be realised by the energy system over its lifetime
- 4. Flowsheets and energy systems models
- 5. Key performance models of an energy system
- 6. Techno-economic optimisation of an energy system
- 7. Solving optimisation problems
- 8. Constitutive equations and thermodynamic properties of flows in flowsheets
- 9. Process units models
- 10. FlowSheet simulation
- 11. Data reconciliation and parameter identification
- 12. Energy system modelling with Linear programming techniques
- 13. Multi-objective optimization for energy system design

What are the needs ?



AGIR : the methodology of a task

Analyse

- **What we want ?**
  - define variables (x_i) : give a textual description
  - define physical units : e.g. $[kJ_e/kJ_{th}]$
  - define order of magnitude of expected value of x_i : $x_{i_{min}} \leq x_i \leq x_{i_{max}}$
- **What we know : Write equations defining your knowledge !**
  - write the knowledge as a set of equations $f_k(x_i, \pi_{k,j}) = 0$
  - $\pi_{k,j}$ are parameters of equation k
- **What we have : collect the data :**
  - values of $\pi_{k,j}$ => reference, [physical units], comments
  - add assumptions : $f_a(x_i, \pi_{a,j}) = 0$ so that $\#k + \#a = \#i$

Generate

- Find numerical value of x_i by solving the set of equations : $f_e(x_i, \pi_{e,j}) = 0$, with $x_{i_{min}} \leq x_i \leq x_{i_{max}}$ and $f_e = \{f_k, f_a\}$
  - define the solving method
  - define the convergence criteria

Interpret

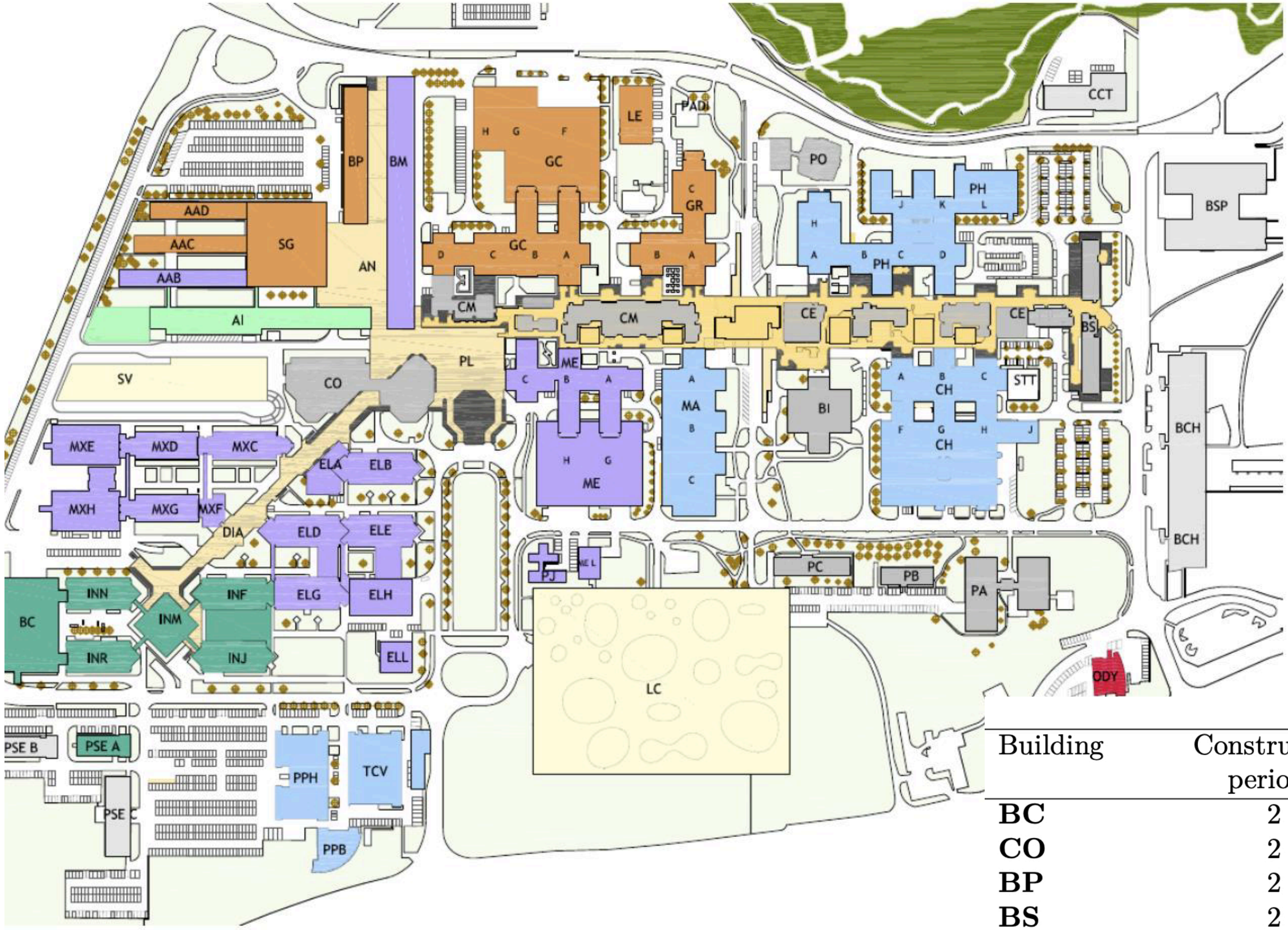
- Verify that the value of x_i is meaningful for the application

Report

- Report the values (plots, tables, validity check)

Part1 : defining the building needs

Buildings stock



Heating needs are defined by :

- $\dot{Q}_{b,t} \quad \forall b \in \{1..n_b\}$ [kW]

  heat required by building b

  at time t of the year
- $T^{supply}_{b,t} \quad \forall b \in \{1..n_b\}$ [°C]

  Minimum temperature

  of the heat supply of building b

  at time t of the year

Available :

Table 1.1: EPFL Buildings

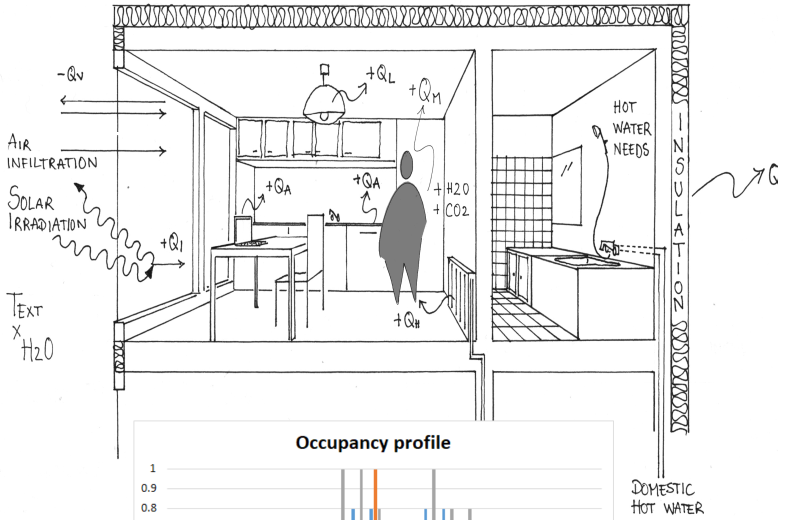
Building	Construction period[a]	Heated surface A_{th} [m^2]	Annual heat demand Q_{th} [kWh]	Annual electricity demand Q_{el} [kWh]
BC	2	17480	418,491	1,603,596
CO	2	11901	477,008	943,653
BP	2	10442	457,861	691,031
BS	2	10267	509,183	350,860
TCV	2	6095	318,209	2,067,675

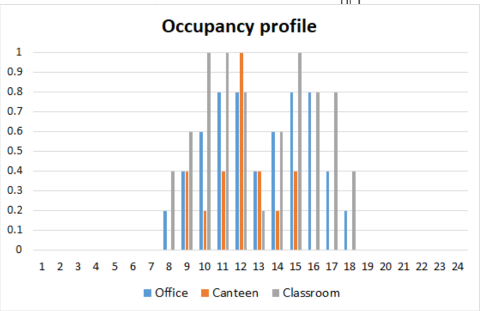
What do we have ?

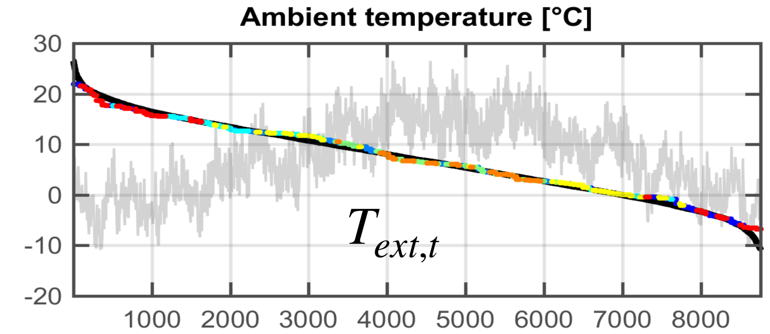
Building enveloppe

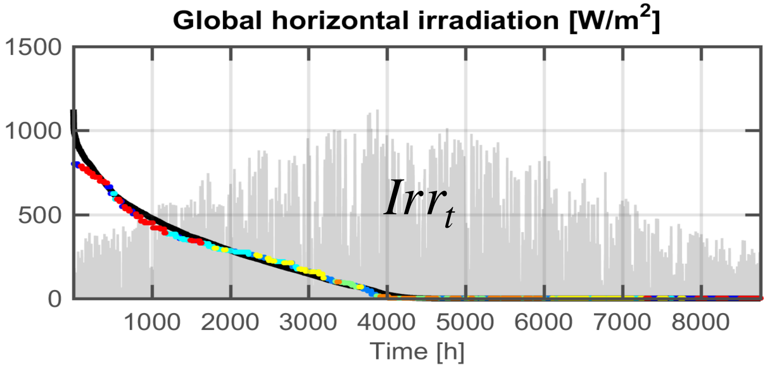
S [m2]

h [m]









People presence cap_t

Comfort Temperature $T_{comfort,t}$

Measurement

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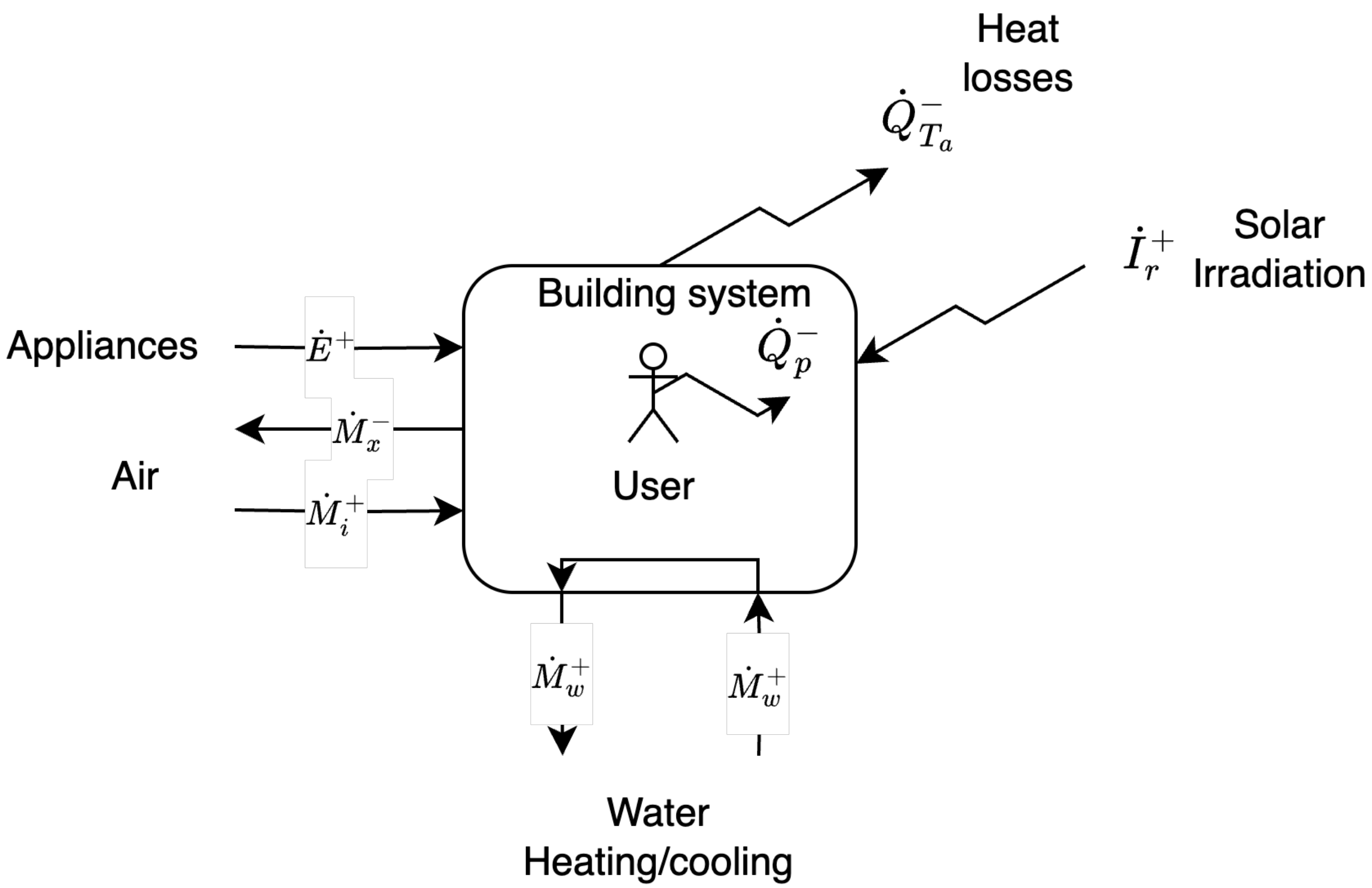
Building system flows



Generic form of balance equations

Accumulation = in - out + Generation - Consumption

Net accumulation in the control volume	=	+	Import in the control volume	-	Export from the control volume
		+	Generation in the control volume	-	Consumption in the control volume

Steady state model

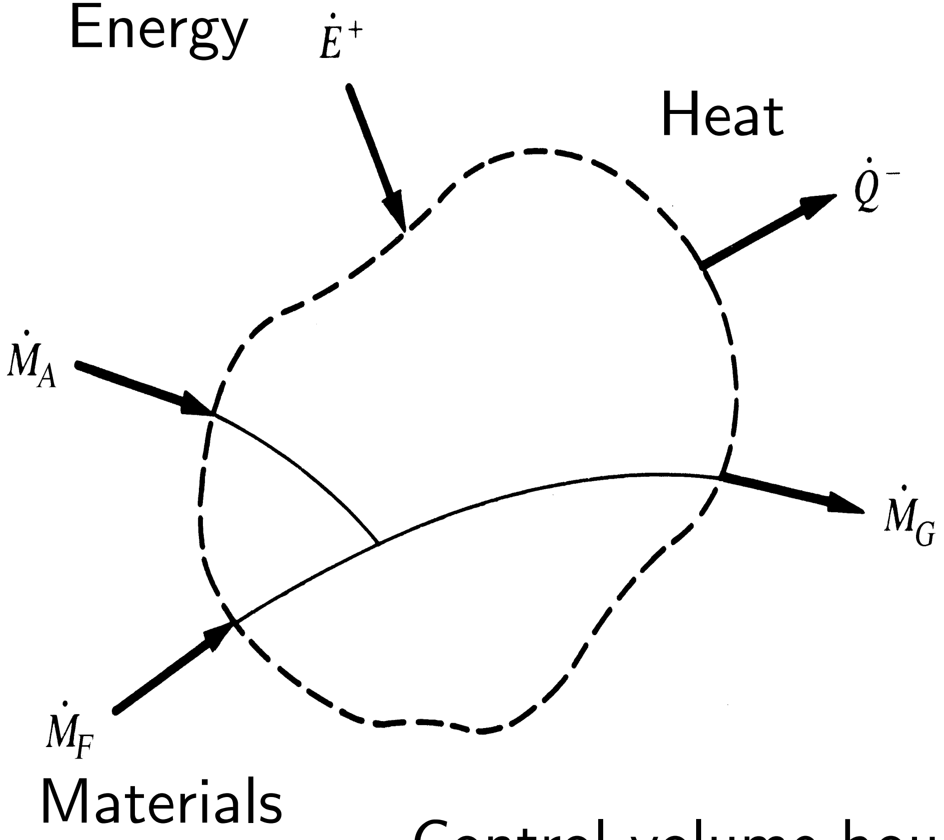
no Accumulation = 0 = in - out + Generation - Consumption

+	Import in the control volume	-	Export from the control volume

=

+	Generation in the control volume	-	Consumption in the control volume

For a given control volume with 1 network with N_c substances without chemical reactions



N_c mass balances per network*

1 energy balance

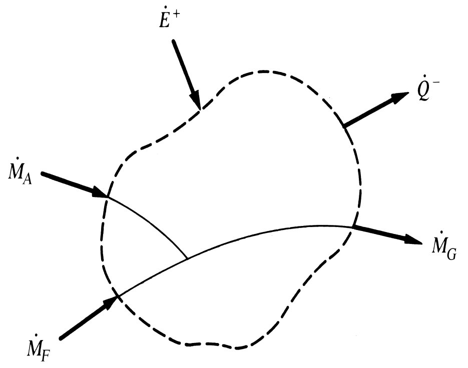
1 impulsion balance (P)

N_c+2 balance equations

*when chemical reactions occur the material balance is the atomic balance

Network or pipes : interconnected flows with mass exchange

For a given control volume with 1 network with N_c substances



Material balance

$$\sum_f \dot{m}^+_{c,f} = \frac{dM_c}{dt} = 0 \qquad \forall c$$

Accumulation

Energy balance

$$\sum_f \dot{m}^+_f \cdot h(T_f, P_f, x_f) + \sum_Q \dot{Q}^+ + \sum_E \dot{E}^+ = \frac{dQ}{dt} = 0$$

Accumulation

Subscript + means positive when entering

$h(T_f, P_f, x_f)$ enthalpy of flow f with temperature T_f, Pressure P_f and composition x_f

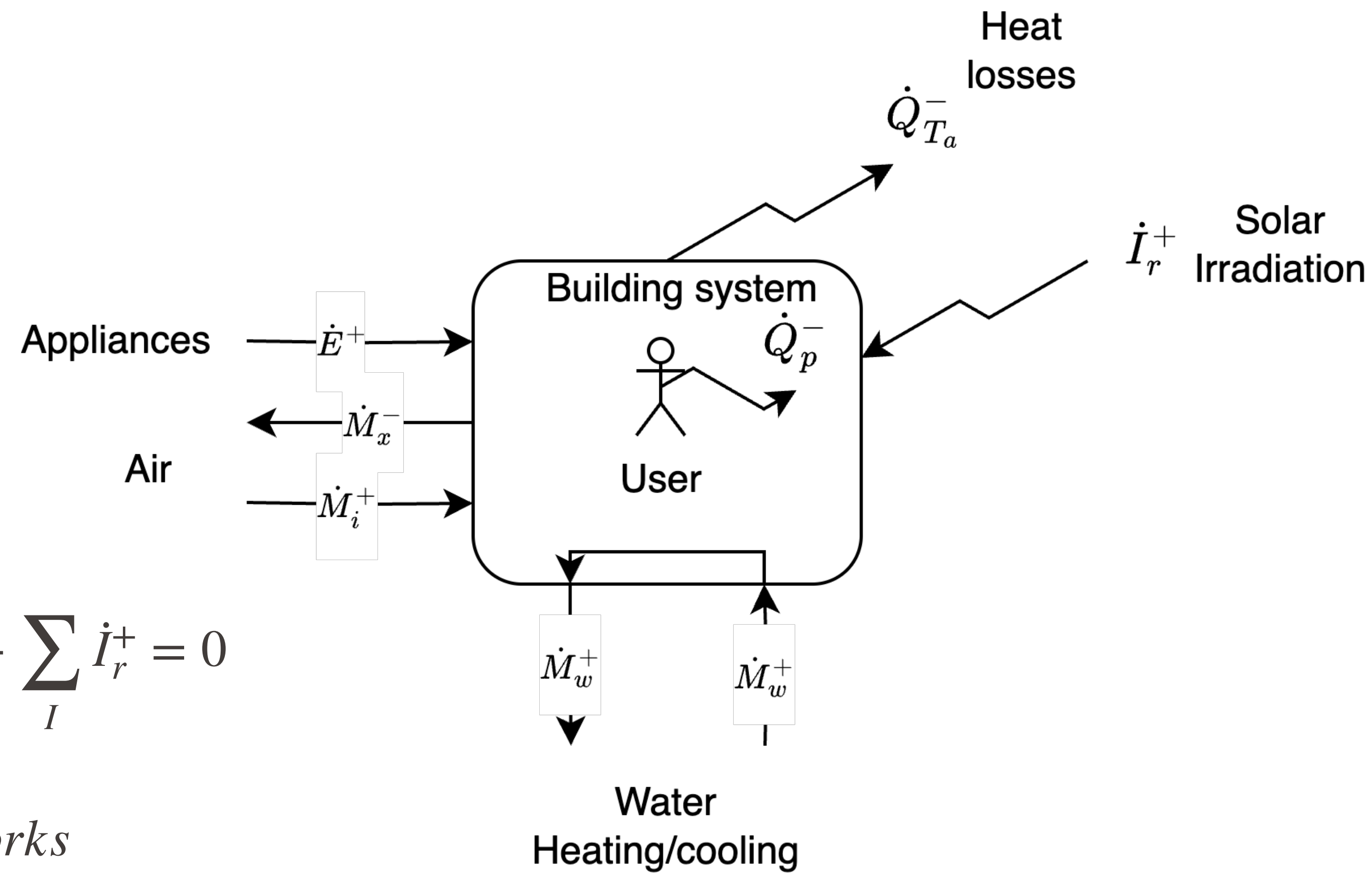
Non linear equations !

Building system flows

- Each flow x is characterized by
  - Mass flow: e.g. $\dot{M}_x^-$
  - Thermodynamic state: T_x, P_x, n_x
  - State variables : s_x e.g. $h(T_x, P_x, n_x)$
- Transfers are modeled by
  - $\dot{Q}_k^+ = f(\pi_k, \dot{M}_x^+, s_x)$
- Energy balance :

$$\sum_f \dot{M}_f^+ \cdot h(T_f, P_f, x_f) + \sum_Q \dot{Q}^+ + \sum_E \dot{E}^+ + \sum_I \dot{I}_r^+ = 0$$

- Mass balance : $\sum_f \dot{M}_{n,f}^+ = 0 \quad \forall n \in networks$



What we want ?

- We would like to know what is the heat load and the corresponding temperature of the heat supply for each state that the building will see in the future :

  $\dot{Q}_b^+$: Heating/cooling load to supply to building b at time t of its life time to maintain the comfort temperature when the peaople are in the building

$$\dot{Q}_b^+[kW] = \dot{M}_{w_b}^+ \cdot (h_w(T_s, P_s) - h_w(T_r, P_r))$$

with $\dot{M}_{w_b}^+$: flow of water heating of build b

$h_w(T_s, P_s)$: Enthalpy of water at T_s, P_s

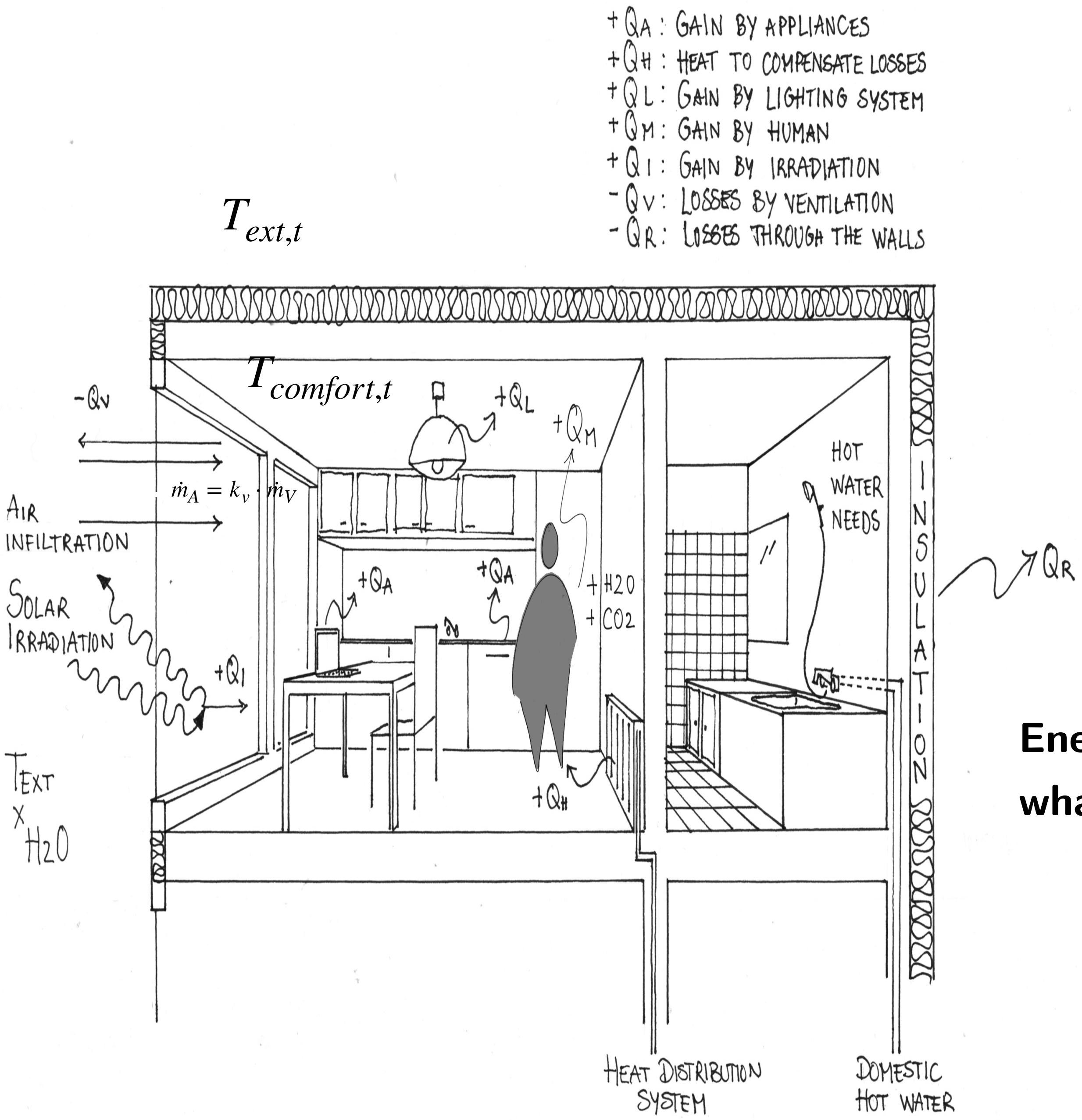
$$h_w(T_s, P_s) = \int_{T_0}^{T_s} cp_w(T) \cdot dT \approx \tilde{cp}_w(T_s - T_0)$$

T_s : the Supply Temperature of the heat distribution system to the building b at time t

T_r : the Return Temperature of the heat distribution system to the building b at time t

T_0: reference temperature for the calculation of enthalpies

What do we know ? : buildings energetics



Our knowledge :

The model of the building envelop heat balance

$$\dot{Q}_{A,t}[kW] = \dot{E}_{A,t}$$

$$\dot{Q}_{L,t}[kW] = \dot{E}_{L,t}$$

$$\dot{Q}_{M,t}[kW] = \dot{q}_{cap} \cdot \sum_{cap} cap_t$$

$\rightarrow \dot{Q}_{gain,t}$ **Gains**

$$\dot{Q}_{I,t}[kW] = \dot{Irr}_t \cdot k_{sun}$$

$$\dot{Q}_{V,t}[kW] = \dot{m}_V \cdot cp_{air} \cdot (T_{comfort,t} - T_{ext,t})$$

$$\dot{Q}_{R,t}[kW] = \sum_{wall} k_{wall} \cdot S_{wall} \cdot (T_{comfort,t} - T_{ext,t})$$

Losses

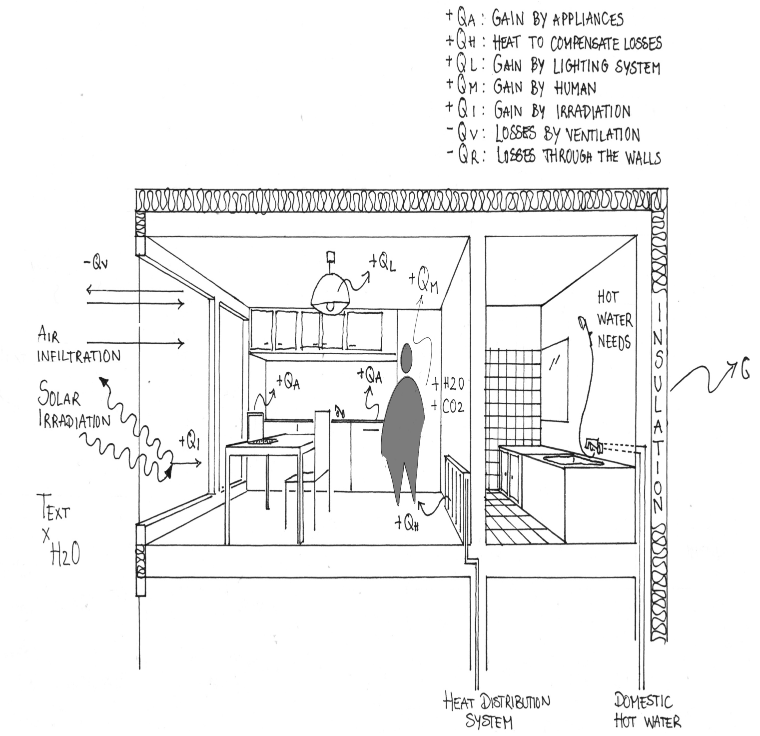
$$\dot{Q}_{V,t} + \dot{Q}_{R,t} = k_{th}(T_{comfort,t} - T_{ext,t})$$

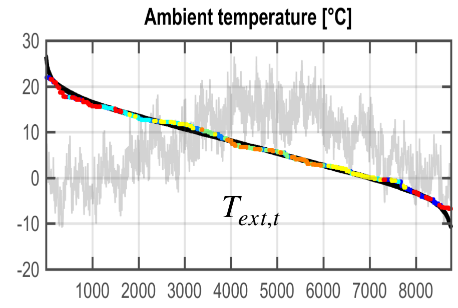
Energy balance :

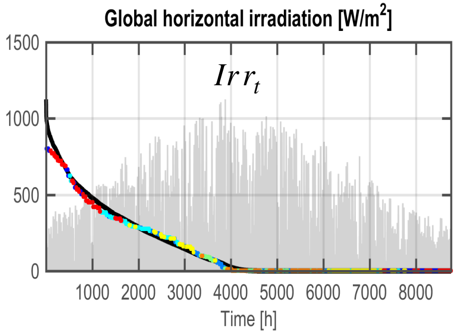
what is the heat load to maintain the comfort ?

$$\dot{Q}_{H,t}[kW] = max(0, \dot{Q}_{V,t} + \dot{Q}_{R,t} - (\dot{Q}_{A,t} + \dot{Q}_{L,t} + \dot{Q}_{M,t} + \dot{Q}_{I,t}))$$

What we want : $\dot{Q}_b(t)[kW]$







Heat gains :

Appliances : $\dot{Q}_{A_b,t} = \dot{E}_{A_b,t}$

Lightning : $\dot{Q}_{L_b,t} = \dot{E}_{L_b,t}$

People : $\dot{Q}_{M_b,t} = \dot{q}_{cap_b} \cdot \sum_{cap_b} cap_{b,t}$

Solar Irradiation : $\dot{Q}_{I_b,t} = \dot{Irr}_t \cdot k_{sun_b}$

Losses

Ventilation

$$\dot{Q}_{V_b,t} = \dot{m}_{V_b} \cdot cp_{air} \cdot (T_{comfort_b,t} - T_{ext,t})$$

Heat transfer through the walls

$$\dot{Q}_{R_b,t} = \sum_{wall_b} k_{wall_b} \cdot S_{wall_b} \cdot (T_{comfort_b,t} - T_{ext,t})$$

Balance : Heat to supply

$$\dot{Q}_{H,t} = \dot{Q}_{b,t} = max(0, \dot{Q}_{V_b,t} + \dot{Q}_{R_b,t} - (\dot{Q}_{A_b,t} + \dot{Q}_{L_b,t} + \dot{Q}_{M_b,t} + \dot{Q}_{I_b,t}))$$

Heat supply [kW] function :

$$\dot{Q}_b(t) = max(0, \mathbf{k_{th_b}} \cdot (T_{comfort_b,t} - T_{ext,t}) - \mathbf{k_{sun_b}} \cdot \dot{Irr}_t - \dot{Q}_{gain_b,t})$$

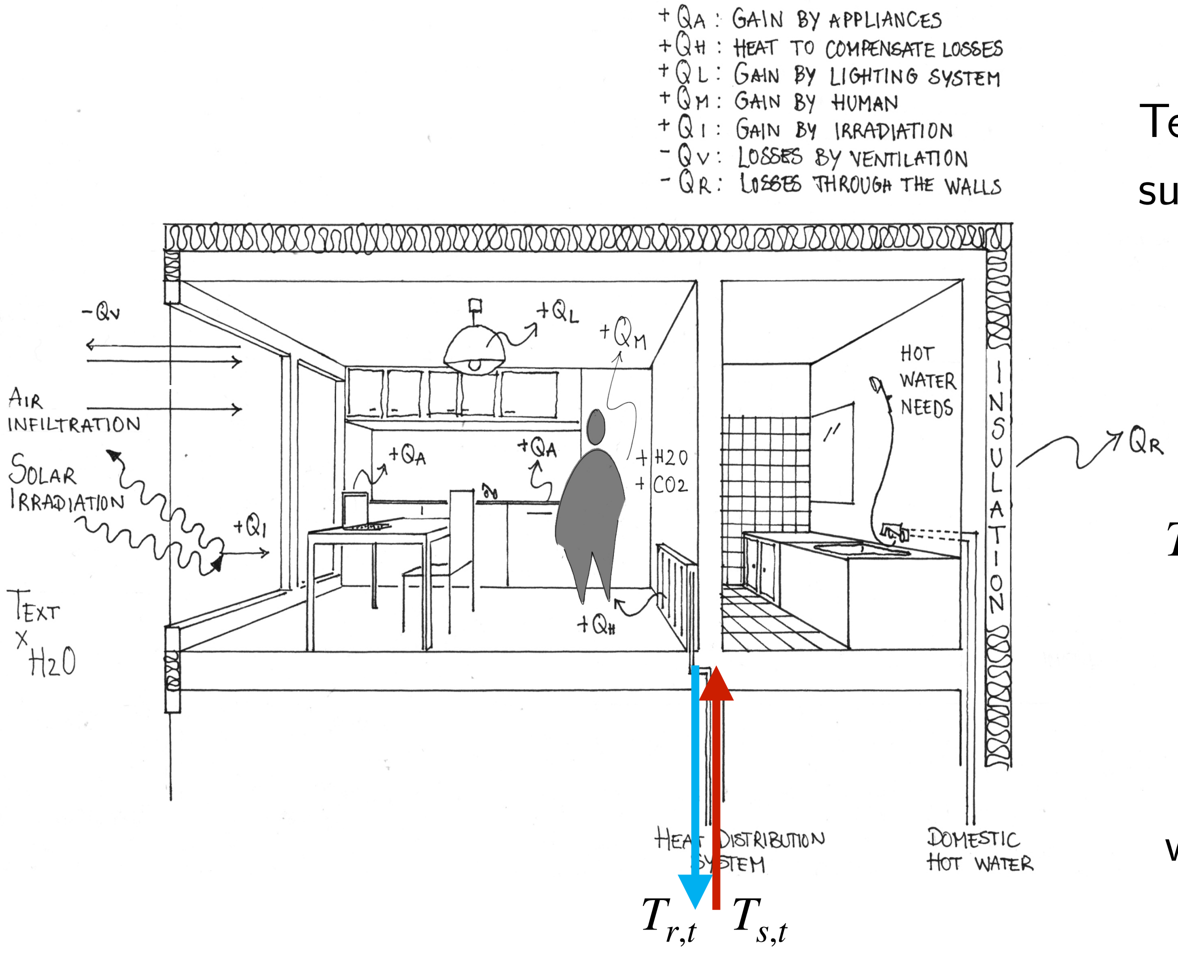
Heat energy [MJ/period] :

$$Q_b(t_0, t_{end}) = \int_{t_0}^{t_{end}} \dot{Q}_{b,t} \cdot dt = \int_{t_0}^{t_{end}} max(0, \mathbf{k_{th_b}} \cdot (T_{comfort_b,t} - T_{ext,t}) - \mathbf{k_{sun_b}} \cdot \dot{Irr}_t - \dot{Q}_{gain_b,t}) \cdot dt$$

Typical formulation of the needs

- $Need_{k,t} = f(\pi_k, x_{k,i,t})$
  - π_k : parameters characterising the need k
    - Assumptions & knowledge
      - Physical/Chemical phenomena
      - Typical values from engineering practice
    - Observations => parameter fitting
  - $x_{i,k,t}$: variables defining the environment applying to the need k in the future
    - Observations
    - Statistics
    - Models : e.g. future temperatures, future use of the building

Temperature of the heat supply



Temperatures of the heat distribution (hd) system: supply $T_{s,t}$ and return $T_{r,t}$ can be calculated

$$\dot{Q}_{b,t} = \dot{m}_{hd_b,t} \cdot cp_{hd_b} \cdot (T_{s_b,t} - T_{r_b,t}) \quad [1]$$

$$T_{r_b,t} = T_{s_b,t} - \frac{\dot{Q}_{b,t}}{\dot{m}_{hd_b,t} \cdot cp_{hd_b}} \quad [2]$$

$T_{s_b,t}$ is calculated by solving heat transfer equation

$$\dot{Q}_{b,t} = UA_{hd_b} \frac{(T_{s_b,t} - T_{r_b,t})}{ln(T_{s_b,t} - T_{comfort_b,t}) - ln(T_{r_b,t} - T_{comfort_b,t})} \quad [3]^*$$

with UA_{hd_b} calculated from the design conditions @ T_{ext}=-10 °C

$$UA_{hd_b} = \dot{Q}_{b,design} \cdot \frac{ln(T_{s_b,design} - T_{comfort_b,design}) - ln(T_{r_b,design} - T_{comfort_b,design})}{(T_{s_b,design} - T_{r_b,design})}$$

For each building and each time will obtain the minimum supply and return temperatures of the building.

* use [1] and [2] in [3] to have an explicit formula of $T_{s_b,t}$ as a function of $\dot{Q}_{b,t}$, $\dot{m}_{hd_b,t} \cdot cp_{hd_b}$ and UA_{hd_b}

State the problem to be solved : what needs to be calculated

$$Q_b(t_0, t_{end}) = \int_{t_0}^{t_{end}} \dot{Q}_{b,t} \cdot dt = \int_{t_0}^{t_{end}} max(0,\mathbf{k_{th_b}} \cdot (T_{comfort_b,t} - T_{ext,t}) - \mathbf{k_{sun_b}} \cdot \dot{Irr}_t - \dot{Q}_{gain_b,t}) \cdot dt$$

$\mathbf{k_{th_b}}$: thermal heat loss coefficient of the building b envelop

includes air renewable and convection losses via walls, windows roof and basement.

$\mathbf{k_{sun_b}}$: solar gains coefficient of building b envelop

includes orientation and windows

Calculate k_{sun_b} and k_{th_b} if

$$Q_b^1 = Q_b(January, December)$$

and

$$Q_b^2 = Q_b(February, March)$$

$$Q_b(January, December)(\mathbf{k_{sun_b}}, \mathbf{k_{th_b}}) - Q_b^1 = 0$$

$$Q_b(February, March)(\mathbf{k_{sun_b}}, \mathbf{k_{th_b}}) - Q_b^2 = 0$$

2 equations and 2 unknowns : $\mathbf{k_{sun_b}}, \mathbf{k_{th_b}}$

Activate your knowledge :

Solve a set of equations

$F(X,\pi)=0$