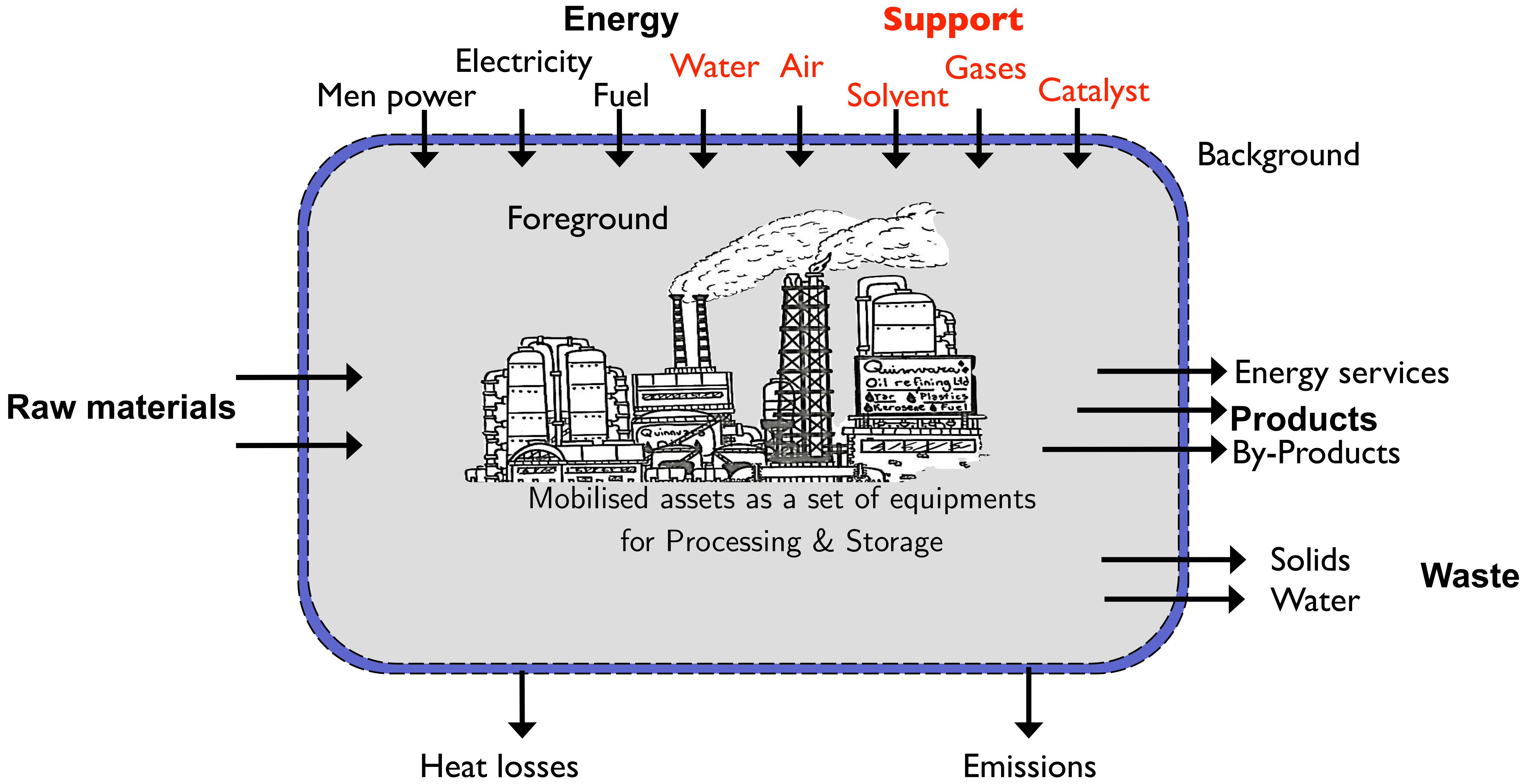
Process flows balances

An industrial process system



Energy

Electricity

Men power

Fuel

Support

Water

Air

Solvent

Gases

Catalyst

Background

Foreground

Mobilised assets as a set of equipments for Processing & Storage

Raw materials

Energy services

Products

By-Products

Solids

Water

Waste

Heat losses

Emissions

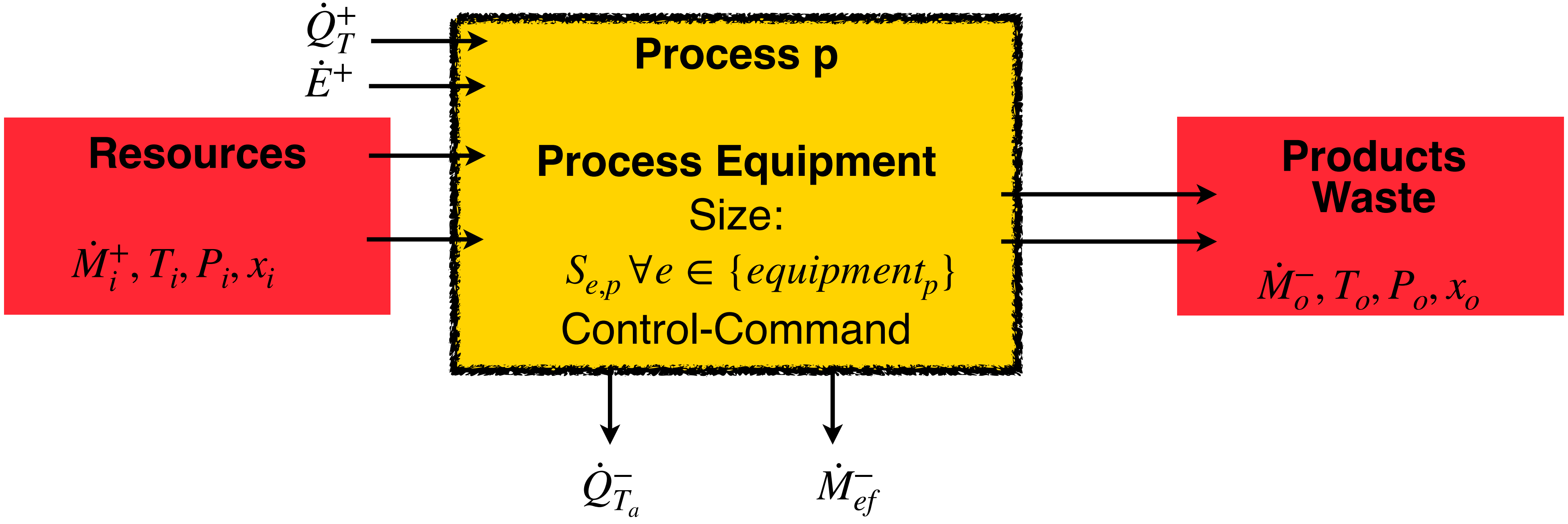
Characterizing the flows with the technosphere

- Material and energy flows : $\dot{M}_f^+$ $[kg/s, l/s, Nm^3/h]$ or $kW]$
  - Thermodynamic state: $T, P, x_{m_{(C_cH_hO_oN_nS_sCl_{cl})}}, h, s, k, \delta, e$

Thermodynamic state of process flows

- Thermodynamic :
  - Thermodynamic state : T, P, α_{S-L-V}
    - $x_{m,f}$: concentration of molecule m in flow f
    - $c_{a,f}$: Ultimate composition in atom a in flow f. Molecule $m = C_cH_hO_oN_nS_sCl_{cl}$
  - Energy content [e.g. kJ/kg or kWh/l]
    - ex: Lower Heating Value
    - Enthalpy (h) incl. Δh^0 enthalpy of formation
    - specific cinetic energy $c = \frac{1}{2}v^2 \quad [\frac{m^2/s^2}{kg/s}]$
    - relative altitude $g\Delta z \quad [kJ/kg]$

First principle of thermodynamics System flows balances



$\dot{Q}^+_T$

$\dot{E}^+$

Resources

$\dot{M}^+_i, T_i, P_i, x_i$

Process p

Process Equipment

Size:

$S_{e,p} \forall e \in \{equipment_p\}$

Control-Command

Products
Waste

$\dot{M}^-_o, T_o, P_o, x_o$

$\dot{Q}^-_{T_a}$

$\dot{M}^-_{ef}$

$\dot{Q}^-_{T_a}$: heat released in the environment

$\dot{M}^-_{ef}$: elementary flows released in the environment

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 operation

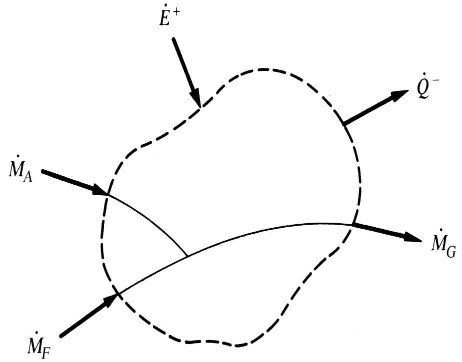
no Accumulation:
0= in - out
+ Generation - Consumption

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

=

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

Process unit control volume: Mass and Energy Balance equations



Material balance:

$$\sum_{f}^{flows} \dot{m}^+_{c,f} + \sum_{r}^{reactions} \dot{\nu}^+_{c,r} = \frac{dM_c}{dt} = 0 \quad \forall c \in compunds$$

with $\dot{m}^+_{c,f}$ flow of compound c in flow f

$\dot{\nu}^+_{c,r}$: production of compound c by reaction r

Reactions stoechiometry:

$$\sum_{c}^{compounds} \dot{\nu}^+_{c,r} \,.\, n_{a,c} = 0 \qquad \forall \quad a \in atoms, \quad \forall r \in reactions$$

with $n_{a,c}$ number of atom a in compound c

Energy Balance

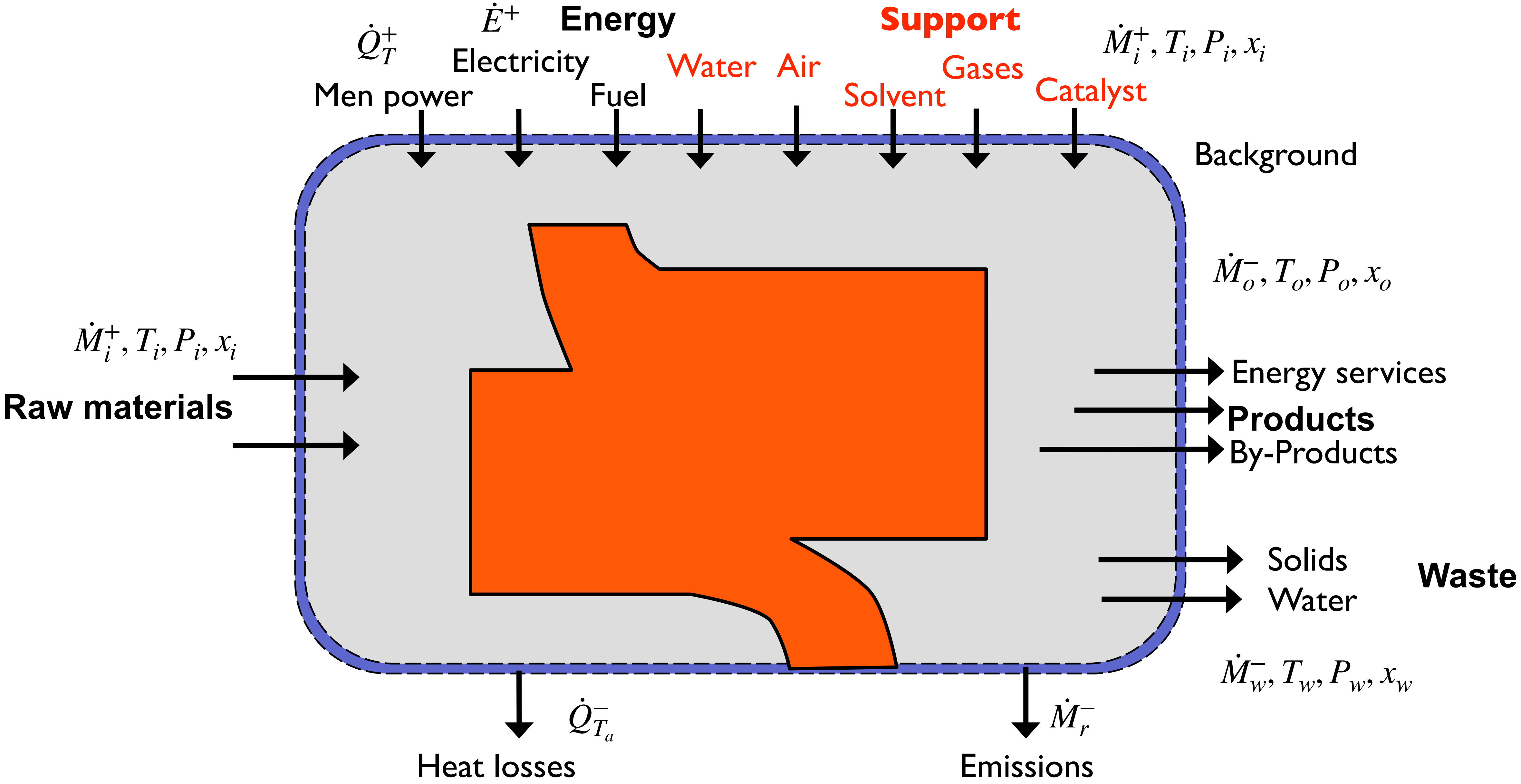
Non linear equations !

$$\sum_{f}^{flows} \dot{m}^+_f \cdot h(T_f, P_f, x_{c,f}) + \sum_{q}^{heat} \dot{Q}^+_{T_q} + \sum_{e}^{energy} \dot{E}^+_e - \frac{dU}{dt} = \dot{Q}^-_{T_a}$$

with $h(T_f, P_f, x_{c,f})$ enthalpy of flow f including the enthalpy of formation

Subscript $^+$ means positive when entering or when produced

Mass and energy balances



$\dot{Q}_T^+$ $\dot{E}^+$ **Energy**

Men power Electricity Fuel

Support

Water Air Solvent Gases Catalyst

$\dot{M}_i^+, T_i, P_i, x_i$

Background

$\dot{M}_o^-, T_o, P_o, x_o$

$\dot{M}_i^+, T_i, P_i, x_i$

Raw materials

Energy services

Products

By-Products

Solids

Water

Waste

$\dot{M}_w^-, T_w, P_w, x_w$

$\dot{Q}_{T_a}^-$

Heat losses

$\dot{M}_r^-$

Emissions

Heat losses is not ignorance

- Process energy balance:

$$\sum_{f}^{flows} \dot{m}_f^{+} \cdot h(T_f, P_f, x_{c,f}) + \sum_{q}^{heat} \dot{Q}^{+}_{T_q} + \sum_{e}^{energy} \dot{E}^{+}_{e} - \frac{dU}{dt} = \dot{Q}^{-}_{T_a} + \dot{E}^{-}_{unexplained}$$

$\dot{Q}^{-}_{T_a}$ is the heat released in the environment by explained reasons,

this identifies source of efficiency gains

$\dot{E}^{-}_{unexplained}$ is closing of the energy balance,

the goal is to have this value as small as possible as it expresses how good we are mastering the system’s mass and energy balances

inefficiency is released as heat to the environment

$$\dot{Q}^{-}_{T_a} = \dot{Q}^{-}_{T_a,conv} + \dot{Q}^{-}_{T_a,rad} + \dot{Q}^{-}_{T_a,emissions} + \dot{Q}^{-}_{T_a,products}$$

- $\dot{Q}^{-}_{T_a,conv}$: losses by conduction and convection heat transfer
- $\dot{Q}^{-}_{T_a,rad}$: losses by radiative heat transfer
- $\dot{Q}^{-}_{T_a,emissions}$: losses in the emissions in the environment
- $\dot{Q}^{-}_{T_a,products}$: losses to the supply chain

Heat losses emissions to ecosphere

- Conductive or radiative losses
  - based on physical principles

- $\dot{Q}^{-}_{T_a,conv} = \sum_{s}^{sources} U_s \,.\, A_s \,.\, (T_s - T_a)$

- $\dot{Q}^{-}_{T_a,rad} = \sum_{s}^{sources} G_s \,.\, A_s \,.\, (T_s^4 - T_a^4)$

T_s is the temperature of the source of the heat transfer with environment

- Comfort temperature of building
- Temperature of a pipe

- Exergy destruction: $\dot{L} = \dot{Q}^{-}_{T_a} \,.\, (1 - \frac{T_a}{\tilde{T}_r})$

Heat losses emissions to ecosphere

- Heat content of the emissions to the environment

$$\dot{Q}^{-}_{T_a,emissions} = \sum_{r}^{emissions} \dot{M}^{-}_{r} \,.\, (h(T_r, P_r, x_r) - h(T_a, P_a, x_r))$$

    - r : conditions of the emissions at exhaust to the environment
    - a: ambient conditions
    - Can also be the heat lost by evaporation of a water surface
  - Exergy destruction

$$\dot{L}_r = \dot{M}^{-}_{r} \,.\, (h(T_r, P_r, x_r) - T_a \,.\, s(T_r, P_r, x_r) - (h(T_a, P_a, x_r) - T_a \,.\, s(T_a, P_a, x_a)))$$

Heat losses Products to Technosphere

- Heat content of the products to the supply chain

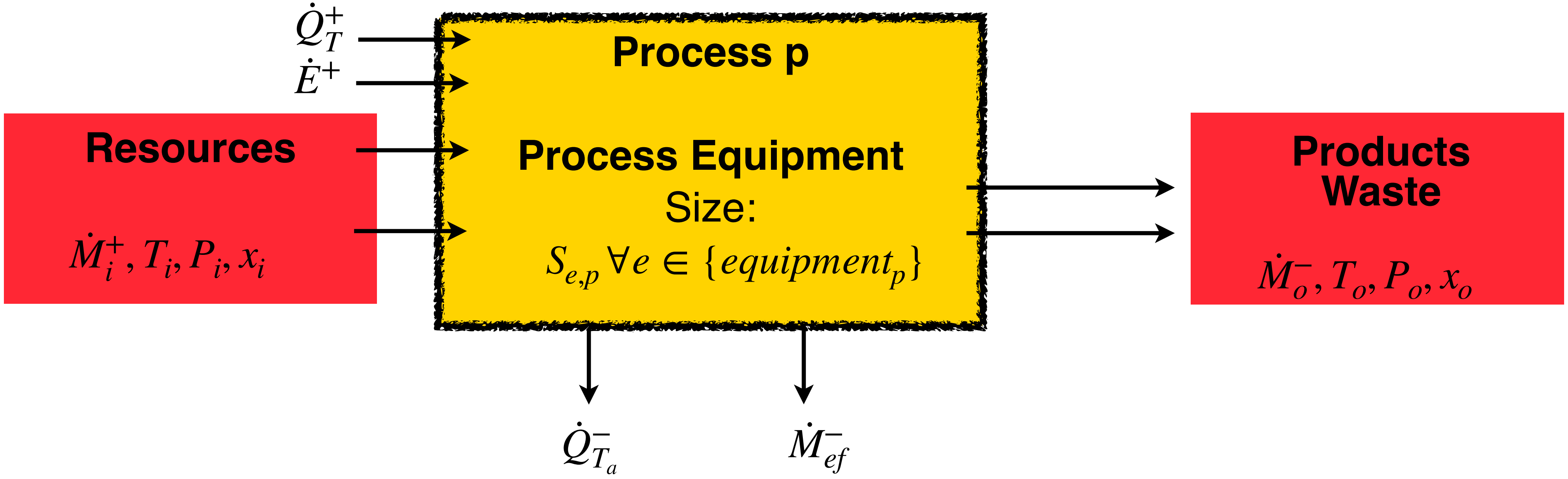
$$\dot{Q}^{-}_{T_a,products} = \sum_{p}^{products} \dot{M}_p \,.\, (h(T_p, P_p, x_p) - h(T_a, P_a, x_p))$$

  - p : conditions at exhaust of the plant to the supply chain
  - a: ambient conditions/supply chain
- Note that there is also an energy loss in the pressure

- Exergy destruction

$$\dot{L}_r = \dot{M}_p \,.\, (h(T_p, P_p, x_p) - T_a \,.\, s(T_p, P_p, x_p) - (h(T_a, P_a, x_p) - T_a \,.\, s(T_a, P_a, x_p)))$$

Conclusions



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Products
Waste

$\dot{M}_o^-, T_o, P_o, x_o$

$\dot{Q}_{T_a}^-$

$\dot{M}_{ef}^-$

- Energy Audits aims at identifying the process system flows
  - Input & output ⇒defines the bill
  - Looses & emissions ⇒ sources inefficiencies
    - $\dot{Q}_{T_a}^-$: energy inefficiency realised as heat to the environment
    - $\dot{M}_{ef}^-$: materials inefficiency as emissions to the environment
  - Level of understanding of the process energetics ($\dot{E}_{unexplained}^-$)

Mass Balance and Energy Balance : Conclusions

- **Mass balance**
  - No mass losses
  - Chemical reactions
- **Energy Balance**
  - Energy is conserved but inefficiency is lost in the environment
  - Enthalpy includes energy of formation (chemical reactions)
  - Lower Heating Value is the energy of formation of a fuel for a given reference
  - Losses ≠ Ignorance (i.e. not the error of the energy balance)
    - Losses corresponds always to a loss mechanism (mass/heat transfer)
  - Energy flows to the environment needs to be characterized

- Mass flows : $$\sum_{o=output \notin products} \dot{M}_o^- \cdot h_o$$
- Heat $$\sum_{l=losses} \dot{Q}_l^-$$