Systemic usage of water in industrial processes

PART

I

HEAT-INTEGRATED WATER ALLOCATION NETWORK

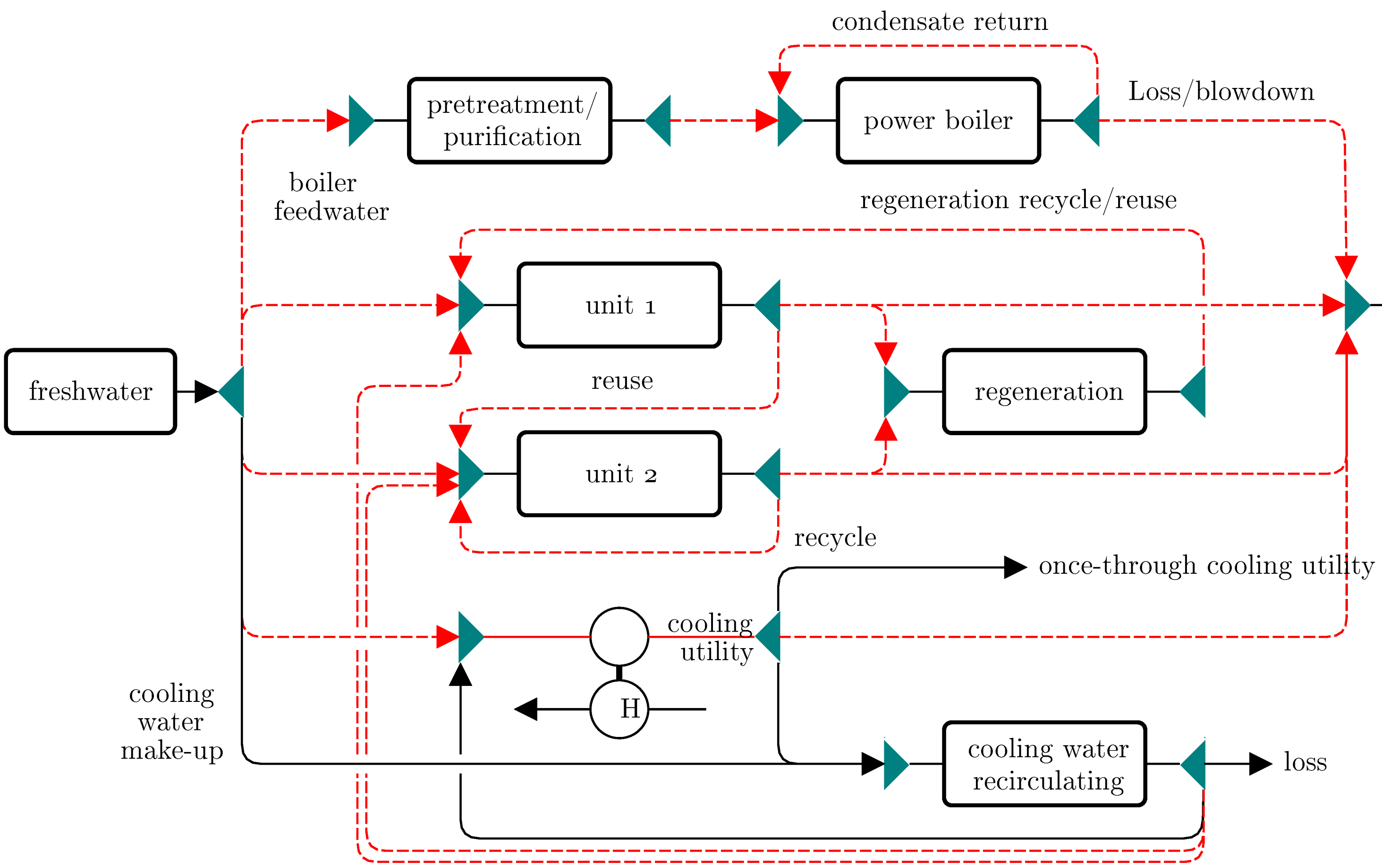
How can heat and water exchanges be systematically managed within industrial processes? How can industrial specificities be addressed in the solution strategy? What are the main criteria in optimizing such systems? What approach can be used to generate a set of energy and water saving opportunities?

- background and context
- a comprehensive literature survey:
- an iterative sequential solution strategy
- generating a set of promising solutions → integer-cut constraint (ICC)

Kermani, M., Kantor, I.D., Maréchal, F., 2018. Synthesis of heat-integrated eater allocation networks: a meta-analysis of solution strategies and network features. Energies, 11, 1158

Kermani, M., Périn-Levasseur, Z., Benali, M., Savulescu, L., Maréchal, F., 2017. A novel MILP approach for simultaneous optimization of water and energy: application to a Canadian softwood kraft pulping mill. Computers & Chemical Engineering. Sustainability & Energy Systems 102, 238–257.

Water flows in an industrial process



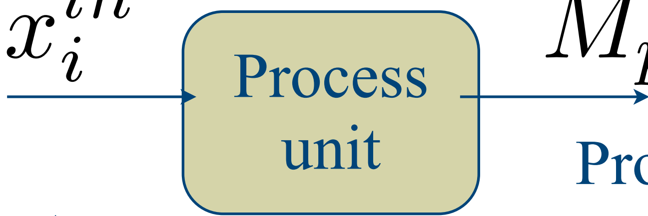
water flows subject to thermal duties

Process integration techniques for rational use of water

- Analogy
  - Temperature = concentration
  - Heat flow = flowrate
  - Hot stream : producers
  - Cold streams : consumers

Source and demands

$$\dot{M}_{process} x_i^{in} \qquad \dot{M}_{process} x_i^{out}$$



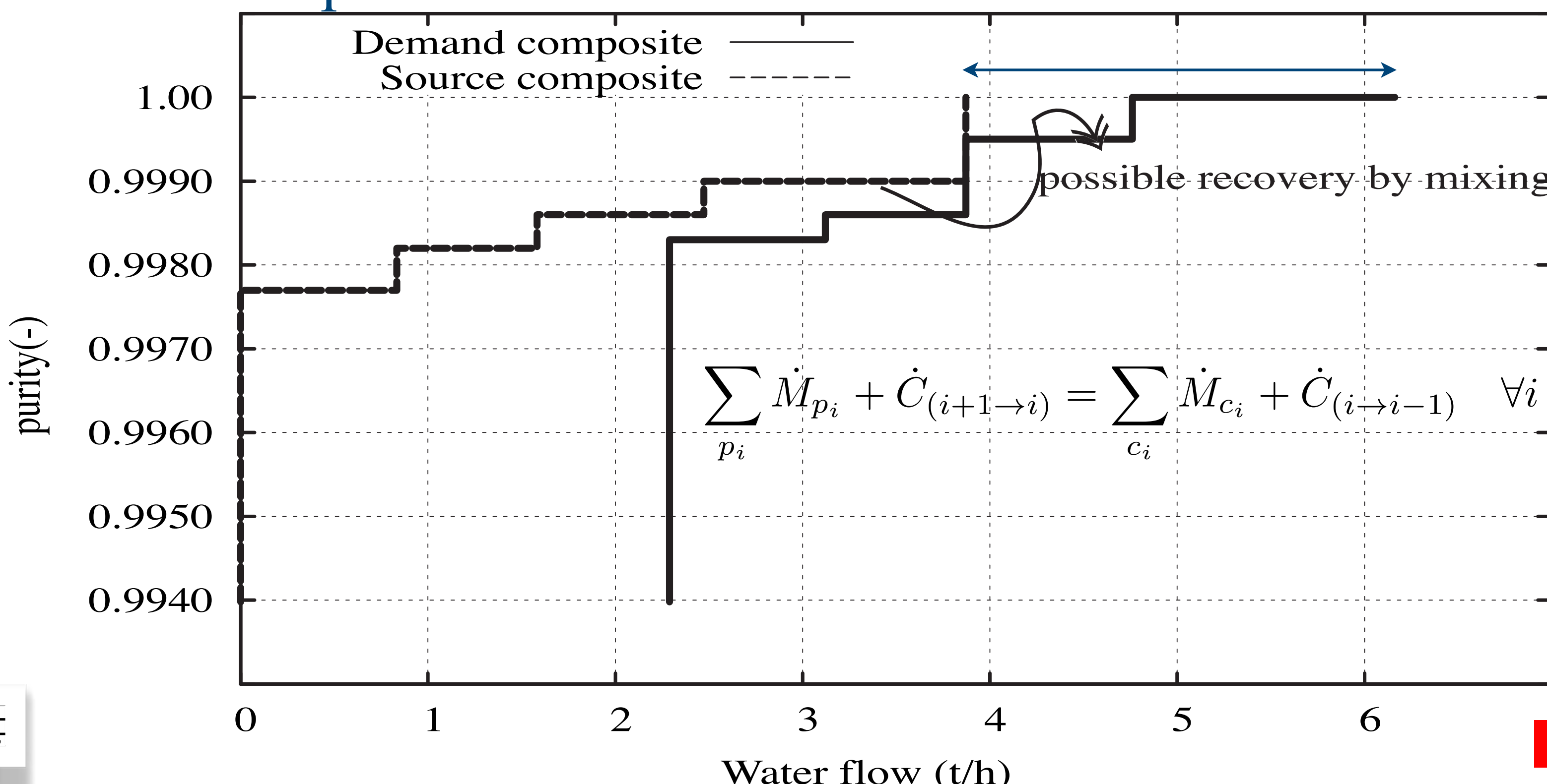
Consumer

i : contaminant

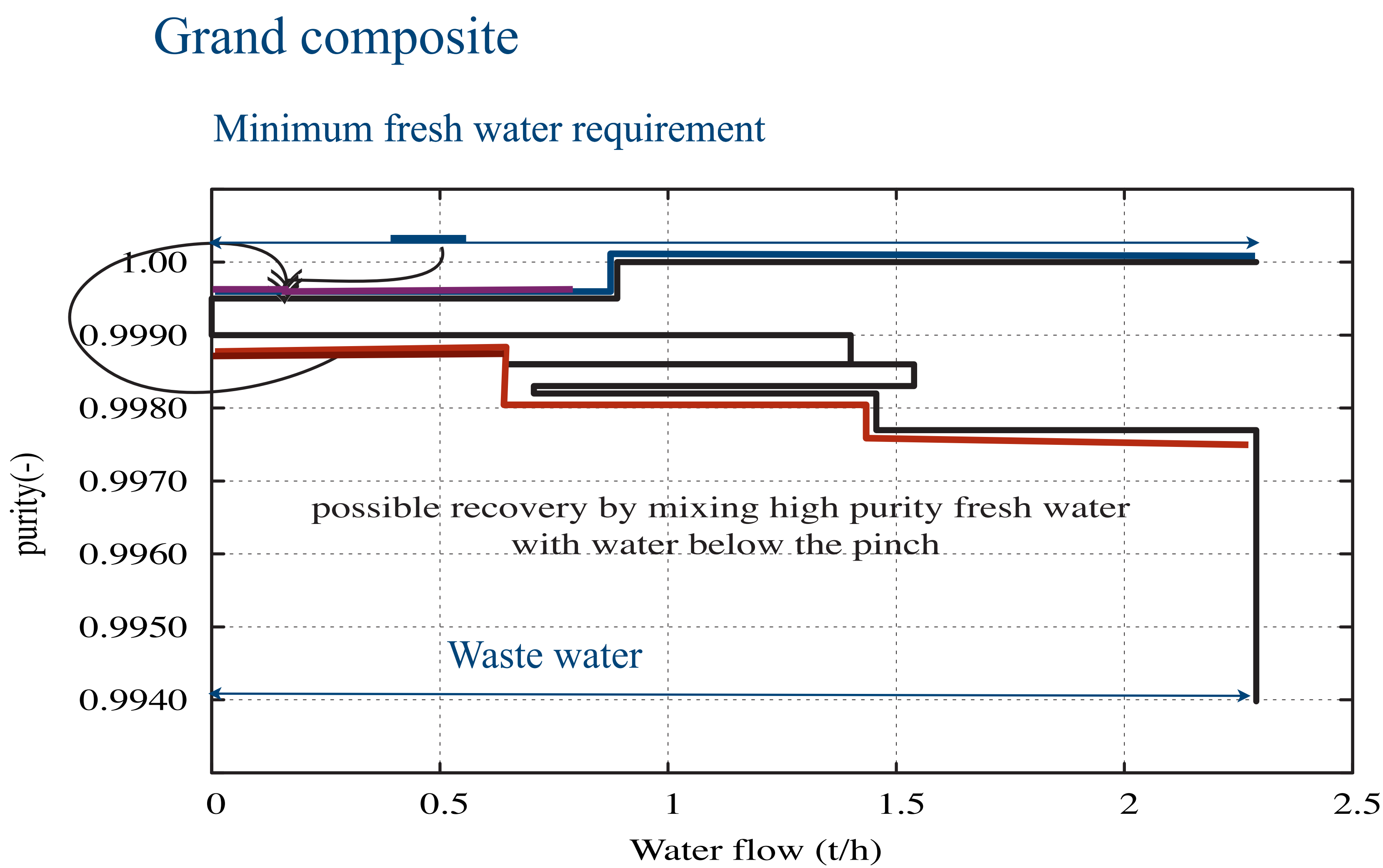
Producer

Composite curve

Minimum fresh water requirement



Water surplus composite



Integrated water management

- Waste water streams from the process
  - i contaminants : x_i
  - Water flow

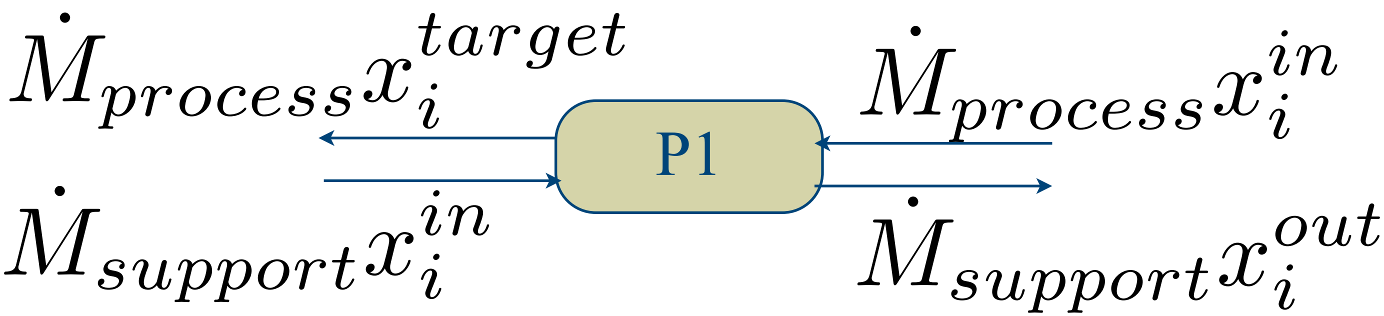
$$\dot{M}_{support} \qquad x_i^{in} \rightarrow x_i^{target} \Rightarrow \dot{M}_i = \dot{M}_{support}(x_i^{in} - x_i^{target})$$

  - Hot stream

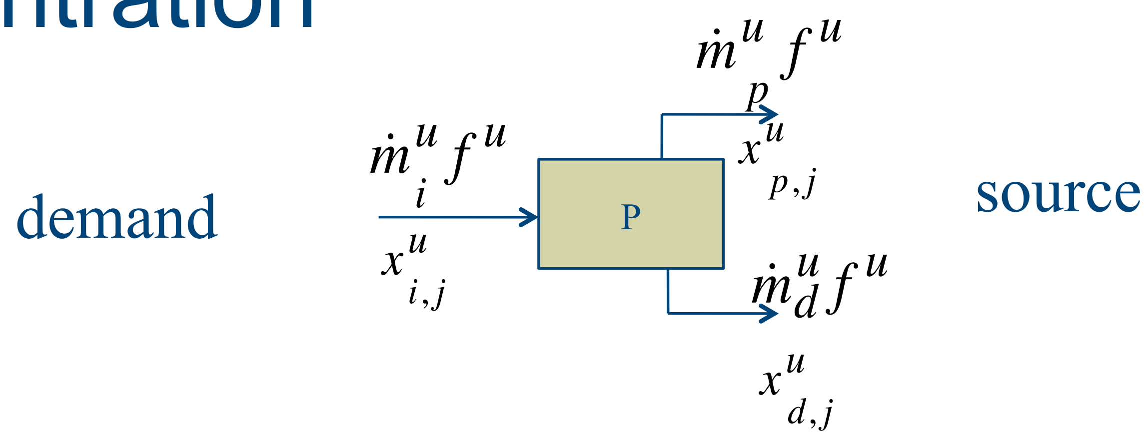
Water treatment units

- Destruction of pollutant

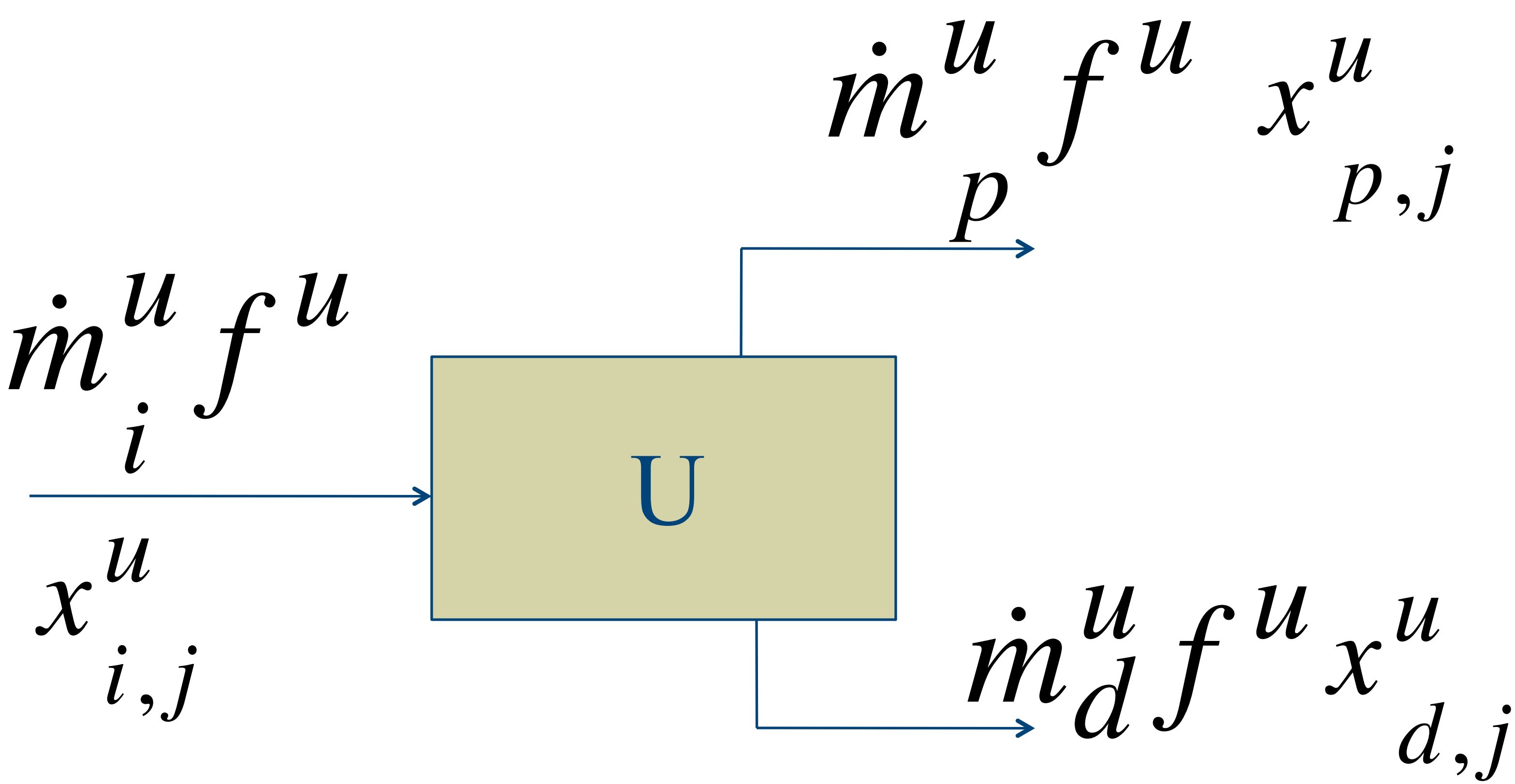
- Extraction



- Concentration



Generic formulation

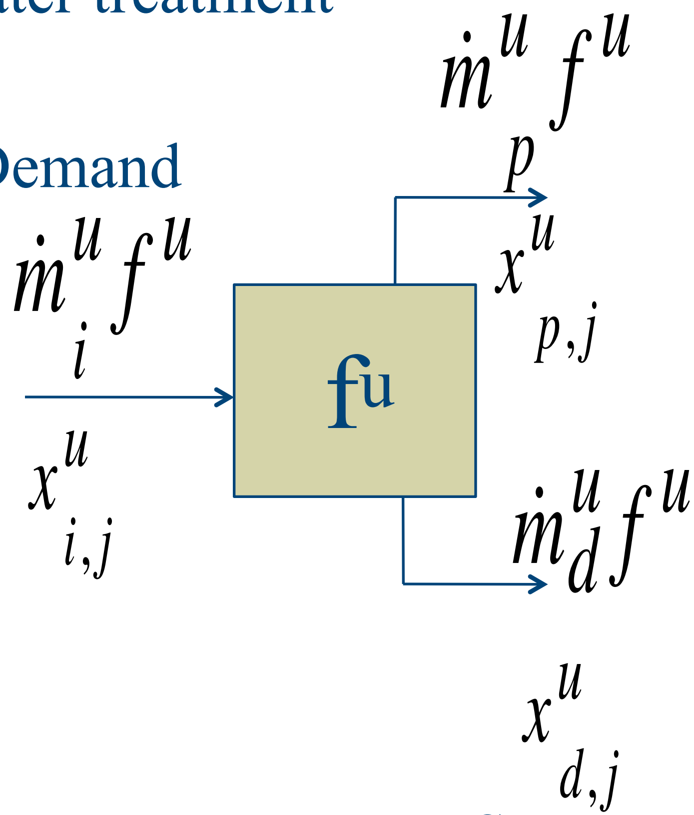


Unit U : operation model : out = f(in)

consumers/producers

Water treatment

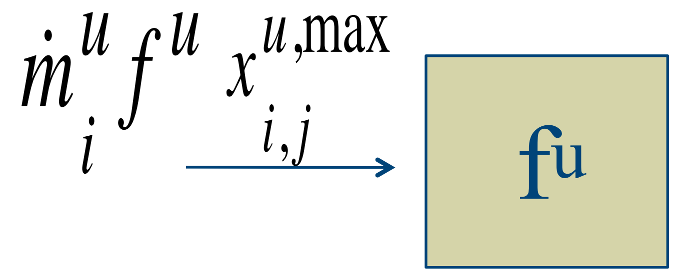
Demand



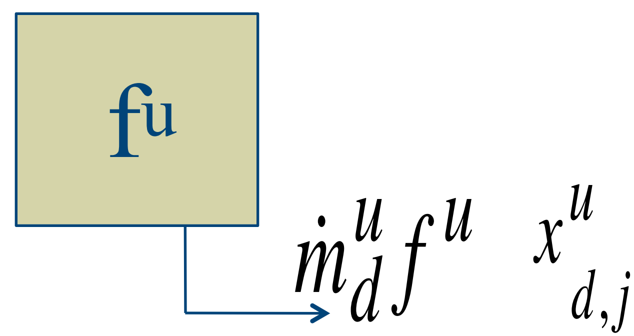
Sources
for process units

$f^u = const$

Demand



*Waste water with unknown flow but cost



Sources

*Fresh water source with unknown flow but cost

Problem formulation

s : supplier
d : demand

$$\min_{c_{s,d}, y_u} \sum_{u=1}^{n_u} (C_u^2 * f_u + C_u^1 * y_u)$$

Cost => use of the units
Inc. fresh water

$$\sum_{s=1}^{n_s} c_{s,d} - \dot{m}_d * f_u(d) = 0 \quad \forall d = 1,\ldots,n_{demande}$$

$$\dot{m}_s * f_u(s) - \sum_{d=1}^{n_d} c_{s,d} \geq 0 \quad \forall s = 1,\ldots,n_{sources}$$

Mixer

$$\sum_{s=1}^{n_s} \frac{c_{s,d}}{X_s} * x_{s,j} \leq \frac{\dot{m}_d}{X_d} * f_u(d) * x_{d,j}^{\max} \quad \forall j = 1, n_{impureté} \quad \forall d = 1, n_d$$

$$\sum_{s=1}^{n_s} \frac{c_{s,d}}{X_s} * (1 - X_s) \leq \frac{\dot{m}_d}{X_d} * f_u(d) * (1 - X_d^{\max}) \quad \forall d = 1, n_d$$

$$f_u = 1 \quad \forall u = 1,\ldots,n_{u,procédé}$$

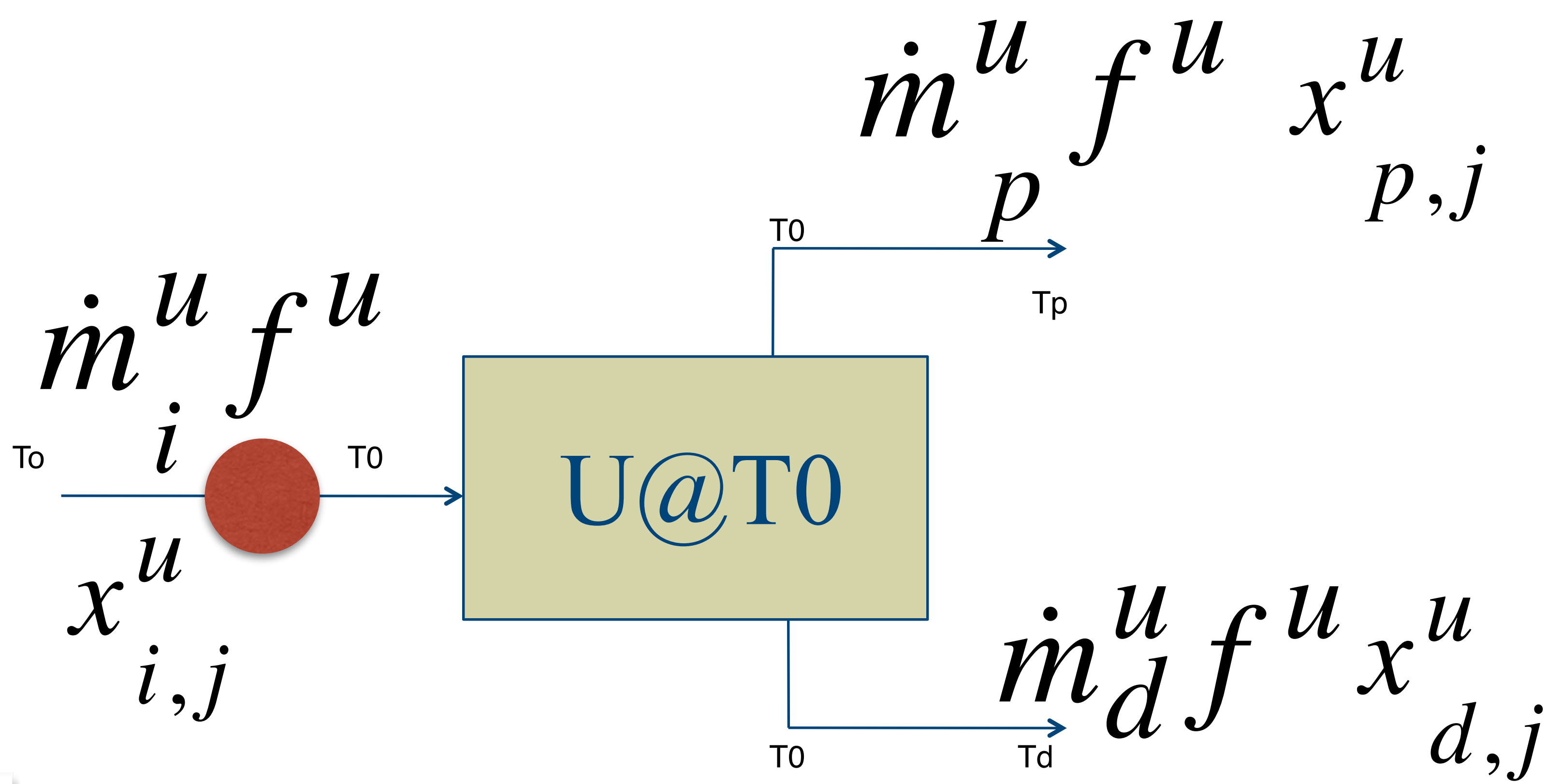
$$X_i = 1 - \sum_{j=1}^{n_{impureté}} x_{i,j}$$

$$f_u^{\min} * y_u \leq f_u \leq f_u^{\max} * y_u \quad \forall u = 1,\ldots,n_{util}$$

$$y_u \in \{0,1\}$$

Combined heat and mass integration

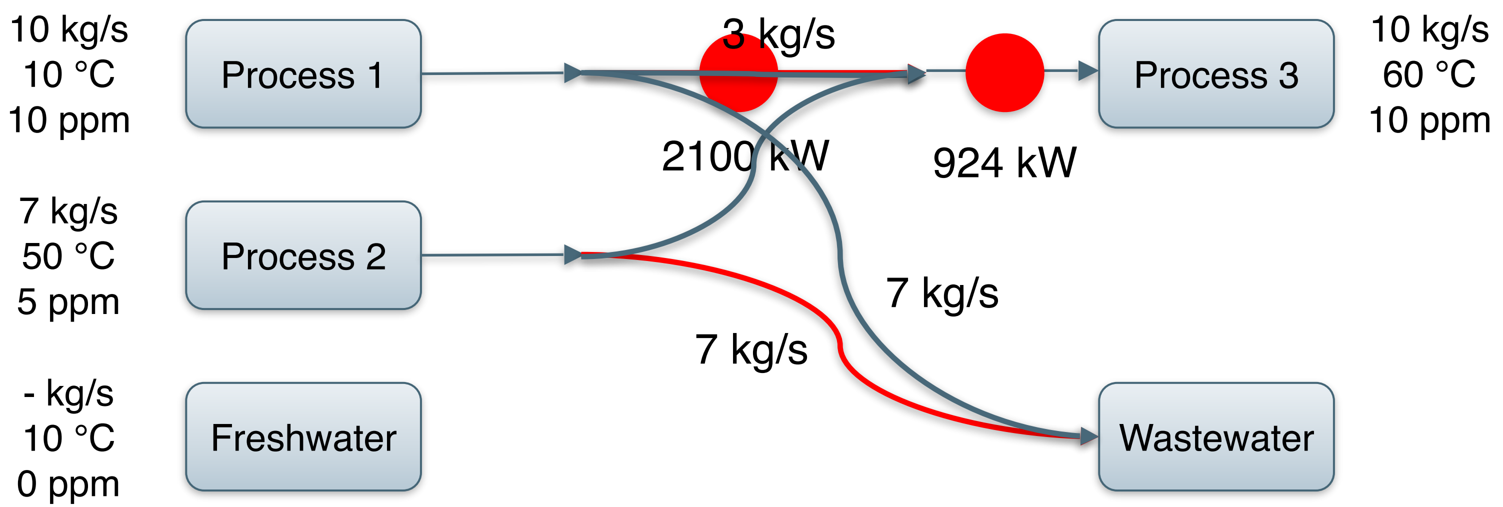
- 1rst approach
  - realise the mass integration at ambient temperature



Why combined mass and energy integration?

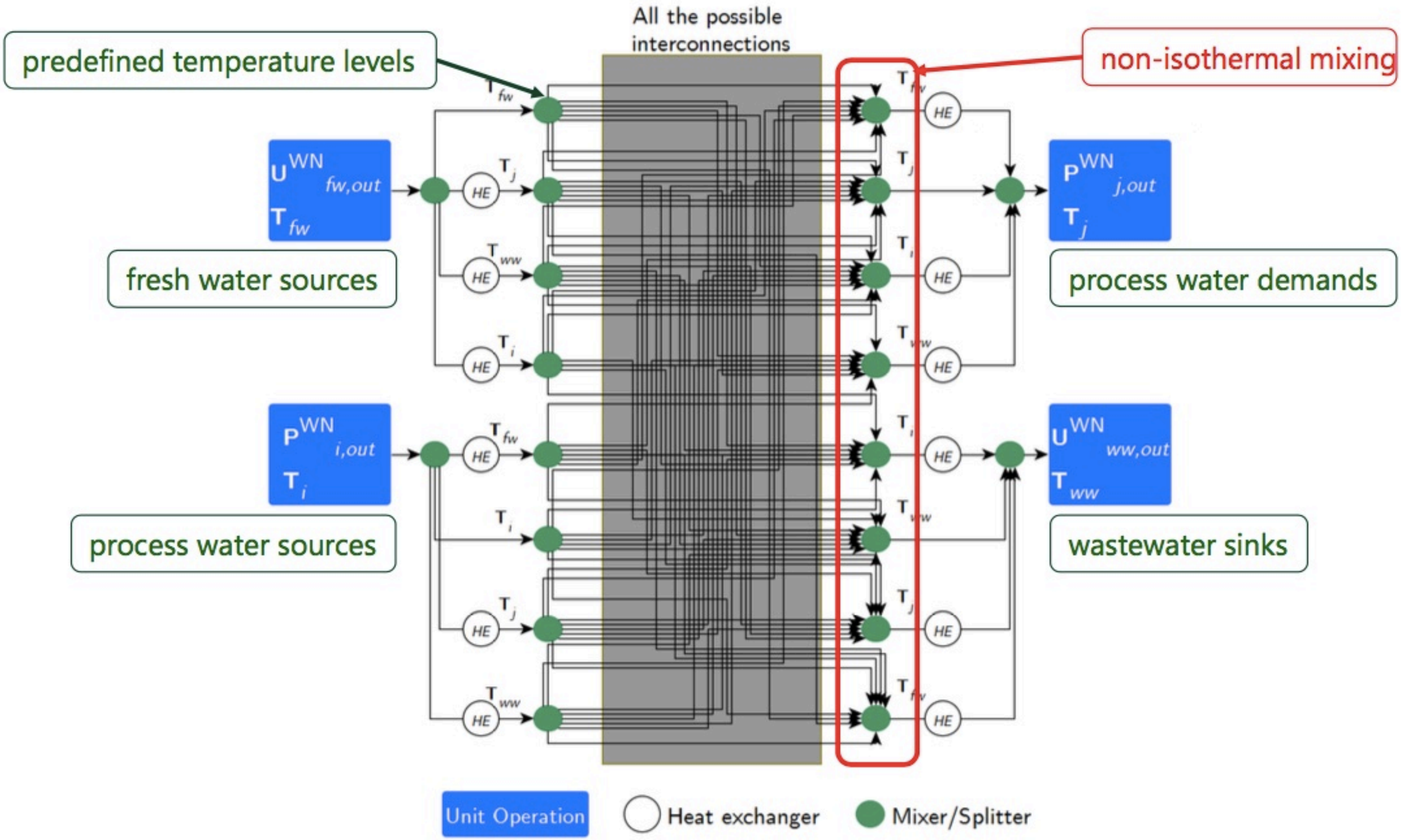
Sequential approach: 1 - Design of water network
2 - Design of heat exchange network

Drawback: Not considering energy implication and heat integration aspects in water network design.



	Sequential	Simultaneous
Fresh water consumption (kg/s)	0	0
Wastewater production (kg/s)	7	7
Hot utility (kW)	2100	924

Detailed super-structure



Objective function: minimize the total cost of the network

$$
\min \left\{
\begin{array}{c}
\left(\sum_{fw \in U^{WN}_{out}} m_{fw}.C_{fw} + \sum_{ww \in U^{WN}_{in}} m_{ww}.C_{ww}\right).t_{operating} \\
+ \\
\left(\sum_{u \in U^{H}} f^{H}_{u}.q^{H}_{u} + \sum_{u \in U^{C}} f^{C}_{u}.q^{C}_{u}\right).t_{operating} \\
+ \\
\frac{i.(1+i)^{n_{year}}}{(1+i)^{n_{year}}-1}.\left(
\begin{array}{c}
\sum_{u \in U^{H}} \left(y^{H}_{u}.I^{H}_{f,u} + f^{H}_{u}.I^{H}_{p,u}\right) \\
+ \\
\sum_{u \in U^{C}} \left(y^{C}_{u}.I^{C}_{f,u} + f^{C}_{u}.I^{C}_{p,u}\right)
\end{array}
\right) \\
+ \\
\frac{i.(1+i)^{n_{year}}}{(1+i)^{n_{year}}-1}.\left(\sum_{i \in P^{WN} \cup U^{WN}} \left(\sum_{t \in T, t \neq i} m_{i,t}.I^{WN}_{p,i,t}\right)\right)
\end{array}
\right\}
$$

cost of fresh water and wastewater

cost of hot and cold utilities

investment cost of thermal utilities

Subjected to:

- Existence of a system (e.g. utility of fresh water, sub-units, hot utility);
- Heat cascade model (Maréchal and Kalitventzeff, 1996);
- Mass balance;
- Temperature and contamination constraints;

Problem P1- targeting

mathematical formulation and superstructure generation

$\mathbf{P1}: \min C^{\text{tac}} = C^{\text{op}} + C^{\text{inv}}$

$$= \Big[\sum_{fw \in \mathbf{U}_{out}^{WAN}} \dot{m}_{fw} C_{fw} + \sum_{ww \in \mathbf{U}_{in}^{WAN}} \dot{m}_{ww} C_{ww} + \sum_{u \in \mathbf{U}^H} \dot{f}_u^H q_u^H C_u^H + \sum_{u \in \mathbf{U}^C} \dot{f}_u^C q_u^C C_u^C \Big] \cdot t^{op}$$

resource consumption

$$+ \frac{irr(1+irr)^{n_{year}}}{(1+irr)^{n_{year}}} \Big[\sum_{u \in \mathbf{U}^H} (y_u^H I_{f,u}^H + \dot{f}_u^H I_{p,u}^H) + \sum_{u \in \mathbf{U}^C} (y_u^C I_{f,u}^C + \dot{f}_u^C I_{p,u}^C) \Big]$$

investment cost

$$+ \frac{irr(1+irr)^{n_{year}}}{(1+irr)^{n_{year}}} \Big[\sum_{i \in \mathbf{WAN}} \Big(\sum_{T \in \mathbf{T}_i^{WAN}} (y_{i,T} \cdot I_{f,i,T}^{WAN} + \dot{m}_{i,T} \cdot I_{p,i,T}^{WAN}) \Big) \Big]$$

penalty cost

subject to:

- mass balance
- contamination constraint [75]

$$\sum_{i \in \mathbf{WAN}_{out}} \sum_{T' \in \mathbf{T}_i^{WAN}} \sum_{T \in \mathbf{T}_j^{WAN}} \dot{m}_{i,j,T',T} \cdot c_{i,T}^{k} = \dot{m}_j \cdot c_j^{k} \quad \forall j \in \mathbf{WAN}_{in}$$

nonlinear equality

$$\sum_{i \in \mathbf{WAN}_{out}} \sum_{T' \in \mathbf{T}_i^{WAN}} \sum_{T \in \mathbf{T}_j^{WAN}} \dot{m}_{i,j,T',T} \cdot c_i^{k,max} \leq \dot{m}_j \cdot c_j^{k,max} \quad \forall j \in \mathbf{WAN}_{in}$$

linear inequality

- energy balance (heat cascade model) [84]
- fixed-load vs fixed-flow formulations

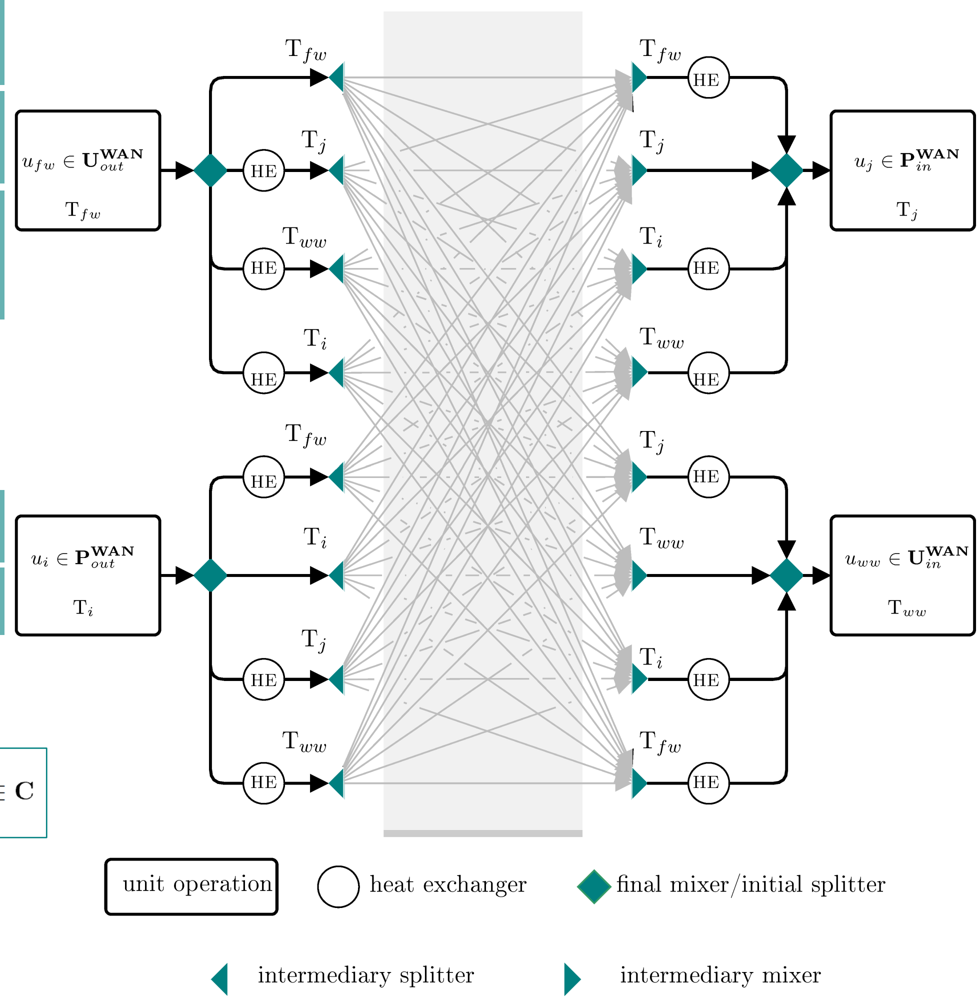
$$\dot{m}_u = \frac{L_u^k}{(c_u^{k,out} - c_u^{k,in})} \quad \leftrightarrow \quad \dot{m}_u \cdot c_u^{k,in} + L_u^k = \dot{m}_u \cdot c_u^{k,out} \quad \forall k \in \mathbf{C}$$

$$m_u^{min} = \frac{L_u^k}{c_u^{k,out,max}}$$

$$m_u^{max} = \frac{L_u^k}{(c_u^{k,out,max} - c_u^{k,in,max})}$$

$$\sum_{i \in \mathbf{WAN}_{out}} \sum_{T' \in \mathbf{T}_i^{WAN}} \dot{m}_{i,j,T',T} \cdot T' = \dot{m}_{j,T} \cdot T \qquad \forall j \in \mathbf{WAN}_{in}, \quad \forall T \in \mathbf{T}_j^{WAN}$$

all possible interconnections



WAN water allocation network, irr interest rate

Simultaneous optimisation of water and energy

Embedded concepts in SOWE

Restricted matches

- Addressing contamination constraints (lack of data)
- Addressing heat and mass exchange restriction

Water tanks

- Influence of tank temperature on water network design
- Seasonal variations in the temperature of water

Process-specific constraints

- Uncertainties (or unavailability) of measurements
  - Heat exchangers replaced by water-using units
- Economic, topological and any practical constraint in the mill:
  - Geographical allocation of process operations
  - Cost of piping

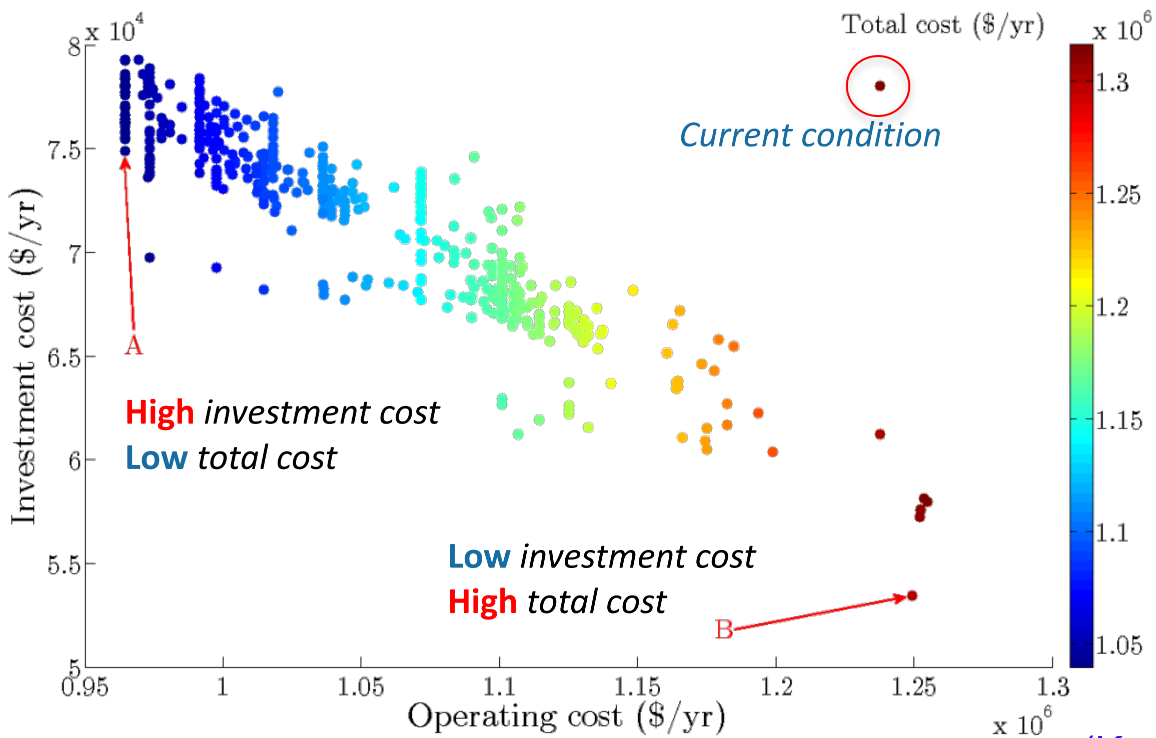
(Kermani et al. 2014)

Simultaneous optimisation of water and energy

Mathematical techniques: Integer-Cut Constraint (ICC)

- Finding ordered set of solutions for the same problem.
- Finding the most attractive solution considering other criteria.

$$\min_{R_r, y_w, x_w} \left(\sum_{w=1}^{N_w} (C_{FW} f_{FW} + C_{HU} f_{HU} + C_{CU} f_{CU}) \right) * t + \sum_{w=1}^{n_w} (ICF_w * y_w + ICP_w * x_w)$$



(Kermani et al. 2014)

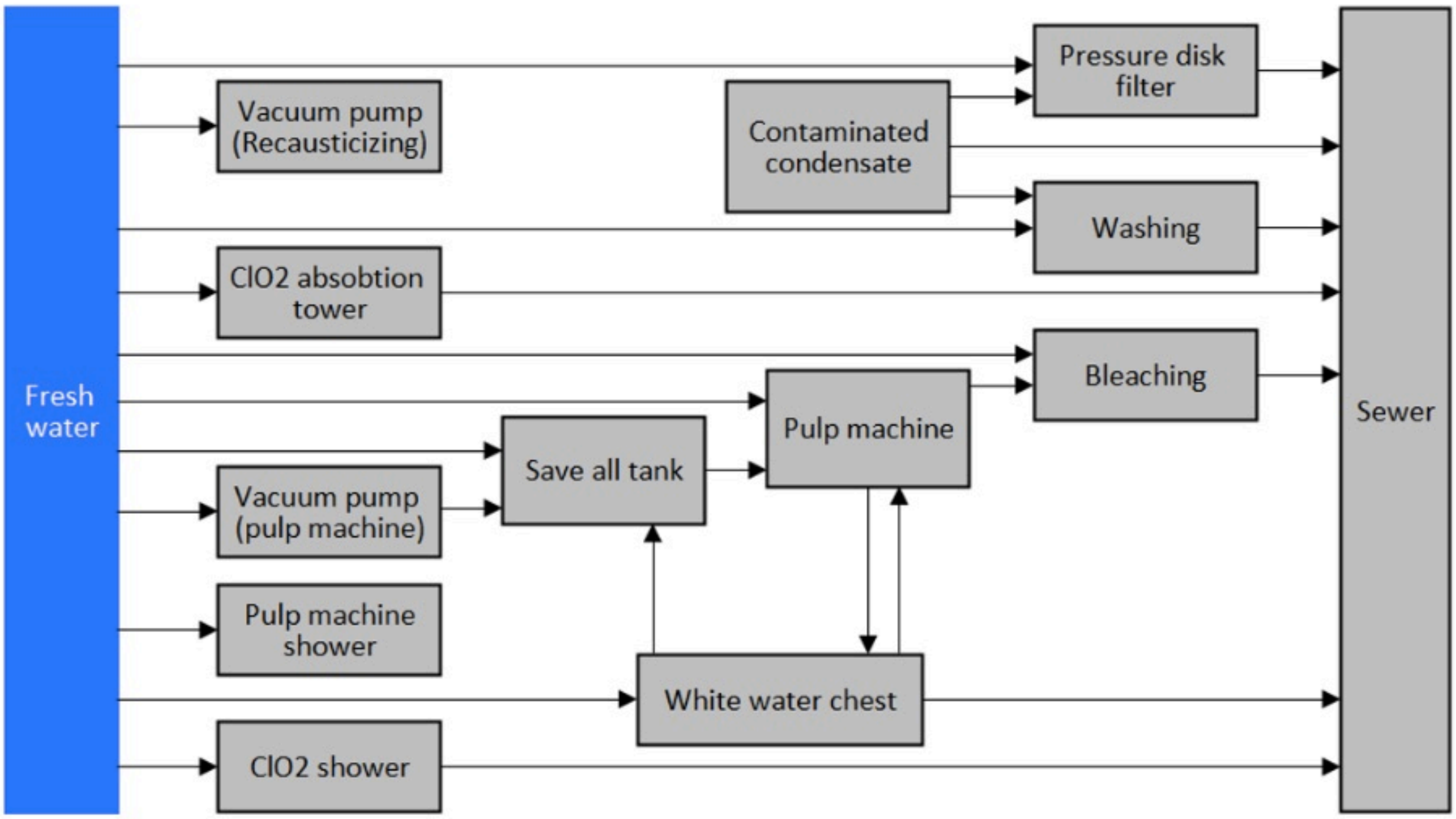
Industrial application

Pulp and paper process

- **1,000 adt pulp /d**

			Current condition of the mill
Steam Consumption	# 60 [1]	MW	136
	# 160 [2]	MW	41
Total hot utility		MW	177
Water consumption		kg/s	592

[1] 413 kPa (g)
[2] 1100 kPa (g)

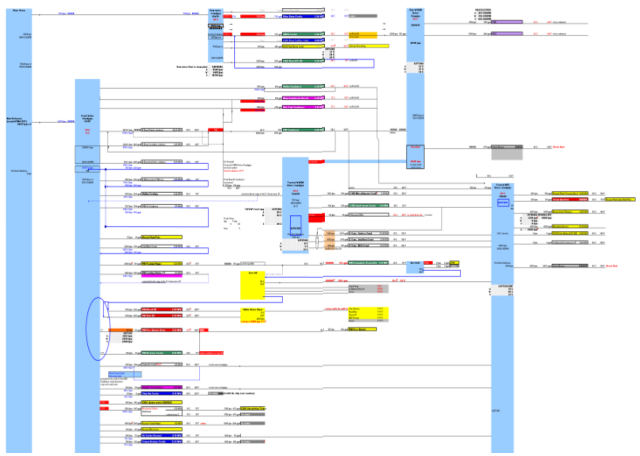


Simultaneous optimisation of water and energy

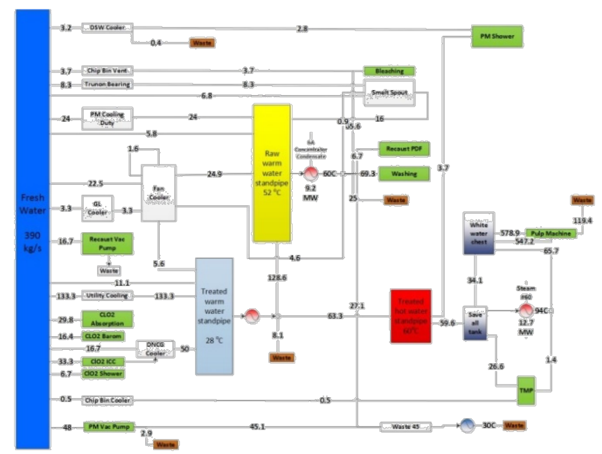
Industrial case study - results

- **Pulp and paper industry producing 1,000 adt/d of pulp:**
  - Number of thermal streams: **37**
  - Number of tanks: **3**
  - Number of water-using operations: **12**

From current water network



To optimized water network



			Current condition of the mill	SOWE
Steam Consumption	# 60 [(1)]	MW	136	131 (-3.6 %)
	# 160 [(2)]	MW	41	8.7
Total hot utility		MW	177	139.7 (-21%)
Water consumption		kg/s	592	390 (-34%)

[(1)] 413 kPa (g)
[(2)] 1100 kPa (g)

(Kermani et al. 2014)