Process integration techniques for rational use of water

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

$M_{process} x_i^{in}$

Process unit

$M_{process} x_i^{out}$

Consumer

i : contaminant

Producer

Minimum fresh water requirement

Composite curve

$\sum_{p_i} M_{p_i} + \dot{C}_{(i+1 \rightarrow i)} = \sum_{c_i} M_{c_i} + \dot{C}_{(i \rightarrow i-1)} \quad \forall i$

Water flow (t/h)

purity(\(\cdot\))

Water flow (t/h)
Possible recovery by mixing high purity fresh water with water below the pinch.
Integrated water management

- Waste water streams from the process
  - \( i \) contaminants: \( x_i \)
  - Water flow
    \[
    \dot{M}_{\text{support}} \quad x_i^{\text{in}} \rightarrow x_i^{\text{target}} \Rightarrow \dot{M}_i = \dot{M}_{\text{support}}(x_i^{\text{in}} - x_i^{\text{target}})
    \]
  - Hot stream
Water treatment units

- **Destruction of pollutant**
  \[ \dot{M}x_i^{in} \rightarrow \text{P1} \rightarrow \dot{M}x_i^{out} \]

- **Extraction**
  \[ \dot{M}_{\text{process}}x_i^{\text{target}} \rightarrow \text{P1} \rightarrow \dot{M}_{\text{process}}x_i^{in} \]

- **Concentration**
  \[ \dot{M}_{\text{support}}x_i^{in} \rightarrow \dot{M}_{\text{support}}x_i^{out} \]

\[ \begin{align*}
\dot{m}_i^{u} & \rightarrow \dot{m}_i^{u} \\
\dot{x}_i^{u} & \rightarrow \dot{x}_i^{u} \\
\dot{m}_d^{u} & \rightarrow \dot{m}_d^{u} \\
\dot{x}_d^{u} & \rightarrow \dot{x}_d^{u} \\
\end{align*} \]
Generic formulation

Unit U: operation model: out = f(in)
consumers/producers

Water treatment

Demand

\[ \dot{m}_u f_u x^u_{i,j} \]

\[ \dot{m}_d f_u x^u_{d,j} \]

\[ f^u = \text{const} \] for process units

Sources

Demand

\[ \dot{m}_i f_u x^u_{i,j} \]

\[ \dot{m}_d f_u x^u_{d,j} \]

\[ \dot{m}_m f_u x^u_{m,\max} \]

\[ j_u = \text{cost} \] for process units

Sources

\* Waste water with unknown flow but cost

\* Fresh water source with unknown flow but cost
Problem formulation

\[ \min \sum_{u=1}^{n_u} (C_u^2 \cdot f_u + C_u^1 \cdot y_u) \quad \text{Cost} \rightarrow \text{use of the units} \]

\[ \sum_{s=1}^{n_s} c_{s,d} \cdot y_u = 1 \quad \forall u = 1, \ldots, n_u \text{demande} \]

\[ \sum_{d=1}^{n_d} c_{s,d} \geq 0 \quad \forall s = 1, \ldots, n_{sources} \]

\[ \sum_{s=1}^{n_s} \frac{c_{s,d}}{X_s} \cdot x_{s,j} \leq \frac{\dot{m}_d}{X_d} \cdot f_u(d) \cdot x_{\max_{d,j}} \quad \forall j = 1, n_{\text{impureté}} \quad \forall d = 1, n_d \]

\[ \sum_{s=1}^{n_s} \frac{c_{s,d}}{X_s} \cdot (1 - X_s) \leq \frac{\dot{m}_d}{X_d} \cdot f_u(d) \cdot (1 - X_{\max_d}) \quad \forall d = 1, n_d \]

\[ f_u = 1 \quad \forall u = 1, \ldots, n_{\text{util procédé}} \]

\[ f_{u_{\min}} \cdot y_u \leq f_u \leq f_{u_{\max}} \cdot y_u \quad \forall u = 1, \ldots, n_{\text{util}} \]

\[ y_u \in \{0, 1\} \]
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.

<table>
<thead>
<tr>
<th>Process</th>
<th>Mass Flow Rate (kg/s)</th>
<th>Temperature (°C)</th>
<th>Concentration (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process 1</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Process 2</td>
<td>7</td>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td>Freshwater</td>
<td>-</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Process 3</td>
<td>10</td>
<td>60</td>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Process</th>
<th>Heat Flow Rate (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process 1</td>
<td>2100</td>
</tr>
<tr>
<td>Process 2</td>
<td>7</td>
</tr>
<tr>
<td>Freshwater</td>
<td>-</td>
</tr>
<tr>
<td>Process 3</td>
<td>924</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Sequential</th>
<th>Simultaneous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh water consumption (kg/s)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Wastewater production (kg/s)</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Hot utility (kW)</td>
<td>2100</td>
<td>924</td>
</tr>
</tbody>
</table>
Detailed super-structure
**Objective function**: minimize the total cost of the network

\[
\begin{align*}
\min \left\{ & \left( \sum_{f \in \text{in}, w \in \text{out}} m_{fw} \cdot c_{fw} + \sum_{w \in \text{in}, w' \in \text{in}} m_{ww'} \cdot c_{ww'} \right) \cdot t_{\text{operating}} \\
& \quad + \left( \sum_{u \in \mathcal{U}_H} f_u^H \cdot q_u^H + \sum_{u \in \mathcal{U}_C} f_u^C \cdot q_u^C \right) \cdot t_{\text{operating}} \\
& \quad + \frac{i \cdot (1+i)^n_{\text{year}}}{(1+i)^n_{\text{year}} - 1} \left( \sum_{u \in \mathcal{U}_H} \left( y_{u,1}^H \cdot I_{f,u}^H + f_{u,1}^H \cdot I_{p,u}^H \right) + \sum_{u \in \mathcal{U}_C} \left( y_{u,1}^C \cdot I_{f,u}^C + f_{u,1}^C \cdot I_{p,u}^C \right) \right) + \frac{i \cdot (1+i)^n_{\text{year}}}{(1+i)^n_{\text{year}} - 1} \left( \sum_{t \in \text{in}, w \in \text{in}} \left( m_{i,t} \cdot I_{p,t}^W \right) \right) \right\}
\end{align*}
\]

- 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;
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.

\[
\min_{R_t, y_w, x_w} \left( \sum_{w=1}^{N_w} (C_{FWfFW} + C_{HUfHU} + C_{CUfCU}) \right) * t + \sum_{w=1}^{n_w} (ICF_w * y_w + ICP_w * x_w)
\]

(Kermani et al. 2014)
Simultaneous optimisation of water and energy

Mathematical techniques: Heat Load Distribution (HLD)

Objective:
Preliminary heat exchange network design before going into detail design

Approach:
- MILP formulation
- Min number of matches

Outcome:
- What the matches?
- What is the related heat load?

(Kermani et al. 2014)
Simultaneous optimisation of water and energy

Benchmarking

- Dong et al. 2008: MINLP formulation (Simultaneous approach)
- Bagajewicz et al. 2002: MILP formulation (Sequential approach)
- Manan et al. 2009: Insight-based method

Results

- Minimum water and energy targets are achieved
- Lower number of water thermal streams
- Lower achievable total cost

Main issue of the available case studies: Addressing only the optimization problems with few constraints and low number of process streams

- Industrial processes are highly constrained and complex in terms of operational structure:
  - High number of process streams
  - Process topology constraints
  - Thermodynamic and/or practical constraints
  - Lack of available and reliable data
Simultaneous optimisation of water and energy

Methodology algorithm in industrial applications

- **Global analysis** of the existing water-energy network
- Systematic **data extraction**
- Application of **restricted matches** and qualitative contamination constraints
- **Preliminary targeting** for different sub-systems
- Implementation of model constraints
- Heat load distribution (**HLD**) combined with **ICC** method
- Energy and water reduction **projects**
- **Economic evaluation**
- **Recommendations**

(Kermani et al. 2014)
Industrial application

Pulp and paper process

- 1,000 adt pulp /d

<table>
<thead>
<tr>
<th>Current condition of the mill</th>
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<tbody>
<tr>
<td>Steam Consumption # 60 (1)</td>
</tr>
<tr>
<td>Steam Consumption # 160 (2)</td>
</tr>
<tr>
<td>Total hot utility</td>
</tr>
<tr>
<td>Water consumption</td>
</tr>
</tbody>
</table>

(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

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<th>Steam Consumption</th>
<th>Current condition of the mill</th>
<th>SOWE</th>
</tr>
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<tbody>
<tr>
<td>60 (1) MW</td>
<td>136</td>
<td>131 (-3.6 %)</td>
</tr>
<tr>
<td>160 (2) MW</td>
<td>41</td>
<td>8.7</td>
</tr>
<tr>
<td><strong>Total hot utility</strong></td>
<td><strong>177</strong> MW</td>
<td><strong>139.7 (-21%)</strong></td>
</tr>
<tr>
<td><strong>Water consumption</strong></td>
<td><strong>592 kg/s</strong></td>
<td><strong>390 (-34%)</strong></td>
</tr>
</tbody>
</table>

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

(Kermani et al. 2014)
IPESE
Industrial Process and Energy Systems Engineering