Utility systems
How to satisfy the energy requirements of a process

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Grand composite curves

Linear programming formulation

\[
\min_{R_r} R_{n_r+1}
\]

subject to heat balance of the temperature intervals

\[
\sum_{i=1}^{n} Q_{i,r} + R_{r+1} - R_r = 0 \quad \forall r = 1, \ldots, n_r
\]  

\[R_r \geq 0 \quad \forall r = 1, \ldots, n_r + 1\]

with \(n\) the number of specified process streams; \(n_r\) the number of temperature intervals; \(R_r\) the energy cascaded from the temperature interval \(r\) to the lower temperature intervals in the time period \(p\); \(Q_{i,r}\) the heat load of the reference level of process stream \(i\) in the temperature interval \(r\); \(Q_{i,r} > 0\) for hot streams and \(\leq 0\) for cold streams;
Utility definition

Type of utility (e.g.: Hot stream)

Outlet conditions (T,P) (environment, operation)

inlet conditions (T, P) (fuel type, combustion, operation)

3 characteristics:
- H-T diagram (from GCC analysis)
- Cost as a function of flowrate
- Flowrate: to be determined to satisfy the

Utility integration

GCC = cold stream
GCC = hot stream
Heat sink
Heat source
Self sufficient zones
Exchange process -> process

Counter current analogy
Hot utility - cold process

Counter current analogy
Hot process - cold utility

Ambient T
Multiple utilities

Identify the temperature levels

Hot Utility : combustion
Fuel : $C_xH_yO_zS_sN_n$

$$xC + xO_2 + = xCO_2$$

$$yH + \frac{y}{4}O_2 = \frac{y}{2}H_2O$$

$$nN + nO_2 = nNO_2$$

$$sS + sO_2 = sSO_2$$

$$\left(\frac{x + \frac{y}{4} + n + s - \frac{z}{2}}{0.21} \right) \cdot (1 + \lambda_a) \cdot (0.21O_2 + 0.79N_2)$$

Flue gases

Heat
Combustion

Adiabatic temperature of combustion

Useful heating value

Stack temperature $T_c$

$T_0=25\, ^\circ C$

$Q_{\text{fuel}} = LHV + \int_{25}^{t_f} \dot{m}_{\text{fuel}} c_p(t_f - 25) dt$

$Q_{\text{pertes}} = \dot{m}_{\text{fumées}} c_p(t_c - 25)$

Environnement

Eléments spéciaux

Conversion du soufre : contrôle cinétique

$0.95 \times s_S + 0.95 \times s_{O_2} = 0.95 \times s_{SO_2}$

$0.05 \times s_S + 0.05 \times \left( \frac{3}{2} \right) s_{O_2} = 0.05 \times s \times SO_3$

$0.05 \times s \times SO_3 + 0.05 \times s \times H_2O = 0.05 \times s \times H_2SO_4$

Affinités avec l’eau $\Rightarrow$ temperature de condensation + élevée (+70°C)

Problèmes de corrosion

$NO_x = NO, N_2O, NO_2$ différentes formes contrôlées par la cinétique (vitesse) donc par $T$ et conditions de mélange

Imbrûlés = combustible non brûlés $\Rightarrow$ cendres et poussières, perte de pouvoir calorifique.
**Fuels containing S**

\[
\text{SO}_3 \text{ (ppm)} = -27,712 + 4,331 \text{ S(\%)} + 29.863 \text{ O}_2 \text{ (\%)} - 3,707 \text{ S(\%) O}_2 \text{ (\%)} + 54,396 \log(\text{O}_2 \text{ (\%)})
\]

avec \(\text{SO}_3\text{ (ppm)}\) la teneur en ppm de \(\text{SO}_3\) dans les fumées;

\(\text{S(\%)}\) le pourcentage massique de soufre dans le combustible;

\(\text{O}_2\text{ (\%)}\) le pourcentage molaire de \(\text{O}_2\) dans les fumées;

limite de validité: \(0.5 < \text{S(\%)} < 5\)

1 \(< \text{O}_2\text{ (\%)} < 4\)

\[
T_{ra} = T_{ch2o} + \Delta T_c
\]

\[
= 273.15 + 100 \sqrt[4]{\frac{[\text{H}_2\text{O}]/P}{[\text{SO}_3\text{ (ppm)}]}} + 49,7041 (\frac{\text{SO}_3\text{ (ppm)}}{\text{H}_2\text{O}\text{ (\%)}})^0.1173
\]

avec \([\text{H}_2\text{O}]\) la fraction molaire de \(\text{H}_2\text{O}\) dans les fumées;

\(T_{ch2o}\) le point de rosée de la vapeur d'eau dans les fumées;

\(\Delta T_c\) l'avance à la condensation;

\(T_{ra}\) la température de rosée acide des fumées (\(^\circ\text{K}\));

\(P\) la pression dans la cheminée (bar).

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**Fuels example**

<table>
<thead>
<tr>
<th>LHV (kJ/kg)</th>
<th>(T_{ad}) (°K)</th>
<th>(T_{stack}) (°K)</th>
<th>Air (kg/(\text{kJ}_{LHV}))</th>
<th>Cost ($/GJ)</th>
<th>(CO_2) (kg/(\text{kJ}_{LHV}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{CH}_4)</td>
<td>50000</td>
<td>2646.5</td>
<td>374</td>
<td>17.1</td>
<td>-</td>
</tr>
<tr>
<td>Natural gas</td>
<td>39680</td>
<td>2270</td>
<td>374</td>
<td>13.9</td>
<td>7.67</td>
</tr>
<tr>
<td>Light fuel oil</td>
<td>45316</td>
<td>2425</td>
<td>440</td>
<td>14.4</td>
<td>6.9</td>
</tr>
<tr>
<td>Heavy fuel oil</td>
<td>44500</td>
<td>2423</td>
<td>441</td>
<td>14.3</td>
<td>4.67</td>
</tr>
<tr>
<td>Coal (lignite)</td>
<td>25450</td>
<td>2111</td>
<td>438</td>
<td>7.29</td>
<td>2.53</td>
</tr>
<tr>
<td>Wood</td>
<td>18900</td>
<td>2185.43</td>
<td>374</td>
<td>7.9</td>
<td>5</td>
</tr>
<tr>
<td>Biogas</td>
<td>13358</td>
<td>2077</td>
<td>374</td>
<td>4.63</td>
<td>-</td>
</tr>
</tbody>
</table>

Natural gas composition: 87% Methane, 13% \(\text{N}_2\)

Light fuel oil: C-86.2\% mass, H-12.4\% mass, S-1.4\% mass

Heavy fuel oil: C-86.1\% mass, H-11.8\% mass, S-2.1\% mass

Lignite: C-56.52\%, H-5.72\%, O-31.89\%, N-0.81\%, S-0.81\%, Ash-4.25\%

Wood (wt) composition: C-49.5\%, H-6\% , O-44.6\% \(\rightarrow C_1H_{1.4}O_{0.7}\), \(CO_2\) neutral

50%\(CO_2\) and 50% \(\text{CH}_4\), \(CO_2\) neutral

Cost 2004, European market
### Values for different fuels

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>LHV (kJ/kg)</th>
<th>O2(s) (kg/kg)</th>
<th>T(ad) (K)</th>
<th>Tch (K)</th>
<th>LHV(\text{u}) (kJ/kg)</th>
<th>(\Delta\text{LHV})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaz naturel</td>
<td>39680</td>
<td>13,879</td>
<td>2270</td>
<td>374</td>
<td>38163</td>
<td>-3.82%</td>
</tr>
<tr>
<td>Gaz de cokerie</td>
<td>2780</td>
<td>0.696</td>
<td>1688</td>
<td>346</td>
<td>2685</td>
<td>-3.43%</td>
</tr>
<tr>
<td>Distrigaz</td>
<td>44945</td>
<td>15,693</td>
<td>2290</td>
<td>374</td>
<td>43225</td>
<td>-3.83%</td>
</tr>
<tr>
<td>Mer du Nord</td>
<td>47900</td>
<td>16,735</td>
<td>2292</td>
<td>374</td>
<td>46047</td>
<td>-3.87%</td>
</tr>
<tr>
<td>Gaz de charbon</td>
<td>27270</td>
<td>8.557</td>
<td>2373</td>
<td>376</td>
<td>26246</td>
<td>-3.75%</td>
</tr>
<tr>
<td>Essence</td>
<td>47798</td>
<td>15,003</td>
<td>2431</td>
<td>438</td>
<td>44665</td>
<td>-6.55%</td>
</tr>
<tr>
<td>Vaporizing oil</td>
<td>46105</td>
<td>15</td>
<td>2389</td>
<td>438</td>
<td>43023</td>
<td>-6.69%</td>
</tr>
<tr>
<td>Diesel</td>
<td>45867</td>
<td>14,583</td>
<td>2426</td>
<td>439</td>
<td>42838</td>
<td>-6.60%</td>
</tr>
<tr>
<td>Kérozéne</td>
<td>46924</td>
<td>14,826</td>
<td>2429</td>
<td>438</td>
<td>43850</td>
<td>-6.55%</td>
</tr>
<tr>
<td>Fuel léger</td>
<td>45316</td>
<td>14,454</td>
<td>2425</td>
<td>440</td>
<td>42303</td>
<td>-6.65%</td>
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<tr>
<td>Fuel lourd</td>
<td>44500</td>
<td>14,264</td>
<td>2423</td>
<td>441</td>
<td>41507</td>
<td>-6.73%</td>
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<tr>
<td>Essence</td>
<td>33220</td>
<td>11,53</td>
<td>1819</td>
<td>434</td>
<td>30256</td>
<td>-8.92%</td>
</tr>
<tr>
<td>Bitume</td>
<td>31520</td>
<td>10,21</td>
<td>1954</td>
<td>435</td>
<td>28929</td>
<td>-8.22%</td>
</tr>
<tr>
<td>Lignite</td>
<td>25450</td>
<td>7.23</td>
<td>2111</td>
<td>438</td>
<td>23488</td>
<td>-7.71%</td>
</tr>
<tr>
<td>Anthracite</td>
<td>33220</td>
<td>11,53</td>
<td>1819</td>
<td>434</td>
<td>30256</td>
<td>-8.92%</td>
</tr>
<tr>
<td>Bitume</td>
<td>31520</td>
<td>10,21</td>
<td>1954</td>
<td>435</td>
<td>28929</td>
<td>-8.22%</td>
</tr>
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<td>Lignite</td>
<td>25450</td>
<td>7.23</td>
<td>2111</td>
<td>438</td>
<td>23488</td>
<td>-7.71%</td>
</tr>
</tbody>
</table>

### CO2 Impact

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>DPCU</th>
<th>CO2 (LHV)</th>
<th>CO2 (LHV(u))</th>
<th>DCO2</th>
<th>(\Delta\text{CO2}) (LHV)</th>
<th>(\Delta\text{CO2}) (LHV(u))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaz naturel</td>
<td>-3.82%</td>
<td>55</td>
<td>57</td>
<td>3.97%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Gaz de cokerie</td>
<td>-3.43%</td>
<td>186</td>
<td>193</td>
<td>3.56%</td>
<td>239%</td>
<td>238%</td>
</tr>
<tr>
<td>Distrigaz</td>
<td>-3.83%</td>
<td>57</td>
<td>59</td>
<td>3.98%</td>
<td>3.54%</td>
<td>3.55%</td>
</tr>
<tr>
<td>Mer du Nord</td>
<td>-3.87%</td>
<td>55</td>
<td>58</td>
<td>4.03%</td>
<td>1.26%</td>
<td>1.31%</td>
</tr>
<tr>
<td>Gaz de charbon</td>
<td>-3.75%</td>
<td>58</td>
<td>60</td>
<td>3.90%</td>
<td>5.19%</td>
<td>5.11%</td>
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<tr>
<td>Essence</td>
<td>-6.55%</td>
<td>65</td>
<td>70</td>
<td>7.01%</td>
<td>19.53%</td>
<td>23.02%</td>
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<tr>
<td>Vaporizing oil</td>
<td>-6.69%</td>
<td>69</td>
<td>74</td>
<td>7.16%</td>
<td>25.77%</td>
<td>29.63%</td>
</tr>
<tr>
<td>Diesel</td>
<td>-6.60%</td>
<td>69</td>
<td>74</td>
<td>7.07%</td>
<td>25.71%</td>
<td>29.45%</td>
</tr>
<tr>
<td>Kérozéne</td>
<td>-6.55%</td>
<td>67</td>
<td>72</td>
<td>7.01%</td>
<td>22.88%</td>
<td>26.47%</td>
</tr>
<tr>
<td>Fuel léger</td>
<td>-6.65%</td>
<td>70</td>
<td>75</td>
<td>7.12%</td>
<td>27.08%</td>
<td>30.92%</td>
</tr>
<tr>
<td>Fuel lourd</td>
<td>-6.73%</td>
<td>71</td>
<td>76</td>
<td>7.21%</td>
<td>29.29%</td>
<td>33.31%</td>
</tr>
<tr>
<td>Anthracite</td>
<td>-8.92%</td>
<td>100</td>
<td>109</td>
<td>9.80%</td>
<td>81.53%</td>
<td>91.69%</td>
</tr>
<tr>
<td>Bitume</td>
<td>-8.22%</td>
<td>86</td>
<td>94</td>
<td>8.96%</td>
<td>56.84%</td>
<td>64.35%</td>
</tr>
<tr>
<td>Lignite</td>
<td>-7.71%</td>
<td>81</td>
<td>88</td>
<td>8.35%</td>
<td>48.39%</td>
<td>54.64%</td>
</tr>
</tbody>
</table>
Utilities definitions

Utility cost: \( C(\text{CHF/s}) = \text{cost(\text{CHF/kg})} \times \text{flow(\text{kg/s})} \)

\[ T(K) \quad Q(kW) \]

Increasing flow

Tad

Tstack

Infeasible

Corrected temperature domain

Useful heating value of a fuel

\[ LHV_u = c_{pf} \left[ T_{ad}^0 - T_{stack} \right] : \text{Useful heating value} \]

\[ c_{pf} \approx \frac{LHV}{(T_{ad}^0 - T_0)} \quad \text{in kW/(kg fuel°C)}, \quad T_0 = 25°C \]

\[ c_{pf} \approx c_{pgc} \times \frac{m_{gc}}{m_{fuel}} \]

Intrinsic Losses = 1 - \( \frac{LHV_u}{LHV} \)

Real losses = \( m_{\text{fuel}} \times LHV_u - \dot{Q}_{\text{mer}} \)
Utilities definitions

For the same MER !!!

Utility 1: \( C_1 = \text{cost 1} \times \text{flow 1} \)

Utility 2: \( C_2 = \text{cost 2} \times \text{flow 2} \)

Different utility heat loads

Energy available or excess

Intégration de la combustion

Effet de la préchauffe
Pour un même débit de combustible:
plus d’énergie au-dessus du pincement

Excès d’air: moins d’énergie disponible
Cogeneration: gas turbines

\[ m_{\text{fuel}} = \max_k \left[ \frac{\dot{Q}_{\text{mer}}}{(\eta_{\text{GT}} - \eta_{\text{stack}})} \right] \]

\[ \dot{E} = \eta_{\text{GT}} \cdot \dot{m}_{\text{fuel}} \cdot LHV_{\text{fuel}} \]

Energy available or excess

\[ \eta_{\text{GT}_e} = 30 - 38\% \quad s \]
\[ \eta_{\text{GT}_{\text{gc}}} = 55 - 47\% \]
\[ \eta_{\text{GT}} = 85\% \]

Inv = 1000 - 2500 CHF/kWe
Size = 50000 - 1000 kW\text{e}

Gas Turbine: fixed size

\[ Q_{\text{GT}} = \dot{m}_{\text{fuel}_{\text{GT}}} \cdot LHV_{\text{fuel}} \cdot \eta_{\text{GT}_0} \]

\[ \dot{E} = \eta_{\text{GT}_e} \cdot \dot{m}_{\text{fuel}_{\text{GT}}} \cdot LHV_{\text{fuel}} \]

Energy available or excess

\[ \eta_{\text{GT}_e} = 30 - 38\% \quad s \]
\[ \eta_{\text{GT}_{\text{gc}}} = 55 - 47\% \]
\[ \eta_{\text{GT}} = 85\% \]
Systèmes de cogénération

Marginal efficiency : Electricity/(additional fuel)

\[ \eta_{el}^\text{marg} = \frac{\dot{E}}{\dot{m}_{fuel} - \dot{m}_{fuel,\text{eqiv}}} = \frac{\eta_{el} \times (1 - \eta_{th}^* \times \eta_{th})}{\eta_{th}^* - \eta_{th}} \]

Energy savings : equivalent energy consumption

\[ \frac{\eta_{th}^* \times \eta_{th} + \eta_{el} \times \eta_{el} - 1}{\eta_{th}^* \times \eta_{th} + \eta_{el} \times \eta_{el}} \]
Systèmes de cogénération

Energy savings

Fuel | Natural gas | Light Fuel Oil | Heavy Fuel Oil | Coal (anthracite) | Coal (Lignite)
---|-------------|----------------|----------------|-------------------|-------------------
LHV (GJ/kg) | 47900 | 45316 | 44500 | 33220 | 25450
CO2 (kg/GJ LHV) | 55.00 | 70.00 | 71.00 | 100.00 | 81.00
[nulth] | 95% | 92% | 91% | 89% | 90%
[nuel equiv] | 55% | 42% | 42% | 40% | 40%

Using the CO\textsubscript{2} production factor of each fuel, the CO\textsubscript{2} production without cogeneration would have been:

\[
\dot{m}_{\text{CO}_2}^* = F_{\text{fuel} \text{th}}^* \cdot \chi_{\text{CO}_2}^* + F_{\text{fuel} \text{el}}^* \cdot \chi_{\text{CO}_2}^* = m_{\text{fuel} \text{th}}^* \cdot LHV_{\text{fuel}}^* \cdot \left( \eta_{\text{th}}^\text{el} \cdot \chi_{\text{CO}_2}^\text{el} + \eta_{\text{el}}^\text{th} \cdot \chi_{\text{CO}_2}^\text{th} \right)
\]

where \( \chi_{\text{CO}_2}^* \) is the CO\textsubscript{2} production factor in kg CO\textsubscript{2} kJ LHV for the fuel substituted in the boiler,

\( \chi_{\text{CO}_2}^\text{el} \) is the CO\textsubscript{2} production factor in kg CO\textsubscript{2} kJ LHV for the fuel substituted in the electricity production.

The relative CO\textsubscript{2} reduction is therefore:

\[
\frac{\dot{m}_{\text{CO}_2} - \dot{m}_{\text{CO}_2}^*}{\dot{m}_{\text{CO}_2}} = 1 - \frac{\eta_{\text{th}}^\text{el} \cdot \chi_{\text{CO}_2}^\text{el} + \eta_{\text{el}}^\text{th} \cdot \chi_{\text{CO}_2}^\text{th}}{\eta_{\text{th}} \cdot \eta_{\text{el}} \cdot \chi_{\text{CO}_2}^\text{th} + \eta_{\text{th}} \cdot \eta_{\text{el}} \cdot \chi_{\text{CO}_2}^\text{el}}
\]

where \( \chi_{\text{CO}_2} \) is the CO\textsubscript{2} production factor in kg CO\textsubscript{2} kJ LHV for the fuel used in the cogeneration system.
Economie de CO₂

\[ CO₂^{el} = \frac{\dot{E}_{\text{fuel}} \chi_{\text{CO₂}} - \dot{E}_{\text{fuel}} \chi_{\text{CO₂}^{th}}}{\dot{E}} = \left( \frac{\chi_{\text{CO₂}} - \eta_{\text{th}} \chi_{\text{CO₂}^{th}}}{\eta_c} \right) \frac{\eta_{\text{th}} \chi_{\text{CO₂}^{th}} - \eta_{\text{th}} \chi_{\text{CO₂}}}{\eta_{\text{th}} \eta_c} = \left( \frac{\chi_{\text{CO₂}}}{GJ_{el}} \right) \]·

- Fuel el\fuel th Natural gas
  - Natural gas: 13.99% 24.70% 25.69% 39.68% 31.25%
  - Light Fuel Oil: 36.98% 42.93% 43.50% 51.97% 46.77%
  - Heavy Fuel Oil: 37.58% 43.42% 43.98% 52.32% 47.20%
  - Coal (anthracite): 52.77% 56.19% 56.53% 61.72% 58.49%
  - Coal (Lignite): 44.90% 49.50% 49.95% 56.71% 52.54%

System cost

- Fuel cost
- Electricity
  - selling
  - or bill reduction
- Maintenance
- Operating time
- Annualized investment

\[ \text{cost} = (\dot{M}_{\text{fuel}} e_{\text{fuel}} - \dot{E}^- c_{\text{grid}} + \dot{E}^+ c_{\text{grid}} - \dot{Q}_{c_q}) \cdot \text{time} + C_{\text{maint}} + \frac{1}{\tau} I \]
## Cost estimation

### Aeroderivative gas turbines - \( W \), electrical power in [kW]

<table>
<thead>
<tr>
<th>( \eta_{\text{generator}} )</th>
<th>( \eta_{\text{elec}} )</th>
<th>( \eta_{\text{heat}} )</th>
<th>( \eta_{\text{fuel}} )</th>
<th>( \eta_{\text{thirld}} )</th>
<th>( \eta_{\text{ref}} )</th>
<th>( \eta_{\text{exchp}} )</th>
<th>( \eta_{\text{g}} )</th>
<th>( \eta_{\text{trd}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>([-] )</td>
<td>(-[]</td>
<td>(-[]</td>
<td>(-[]</td>
<td>(-[]</td>
<td>(-[]</td>
<td>(-[]</td>
<td>(-[]</td>
<td>(-[]</td>
</tr>
</tbody>
</table>
| \( \eta_{\text{gen}} = 0.016 \cdot \ln(W_e) + 0.8687, W_e \leq 845 \) [kW] \| \( \eta_{\text{gen}} = 0.0013 \cdot \ln(W_e) + 0.9611, W_e > 845 \) [kW] \| \( \eta_{\text{elec}} = 0.0439 \cdot \ln(W_e) - 0.684 \)

### Heavy duty gas turbines - \( W \), electrical power in [kW]

<table>
<thead>
<tr>
<th>( \eta_{\text{generator}} )</th>
<th>( \eta_{\text{elec}} )</th>
<th>( \eta_{\text{fuel}} )</th>
<th>( \eta_{\text{heat}} )</th>
<th>( \eta_{\text{thirld}} )</th>
<th>( \eta_{\text{ref}} )</th>
<th>( \eta_{\text{g}} )</th>
<th>( \eta_{\text{trd}} )</th>
</tr>
</thead>
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<tr>
<td>([-] )</td>
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</tbody>
</table>
| \( \eta_{\text{gen}} = 0.016 \cdot \ln(W_e) + 0.8687, W_e \leq 845 \) [kW] \| \( \eta_{\text{gen}} = 0.0013 \cdot \ln(W_e) + 0.9611, W_e > 845 \) [kW] \| \( \eta_{\text{elec}} = 0.0187 \cdot \ln(W_e) + 0.1317 \)

### Turbine lifetime \([\text{hours}]\)

- \( \text{Turbine} \quad 48000 \)
- \( \text{Turbine} \quad 50000 \)

### Reference cost \([\text{€}]\)

- \( \text{Fuel} \quad C_{\text{fuel}} = 0.035 \cdot \eta_{\text{fuel}} \cdot \eta_{\text{ENG}} \cdot \eta_{\text{LHV}} \cdot \text{LHV}_{\text{fuel}} \)
- \( \text{Fuel} \quad E = \eta_{\text{ENG}} \cdot m_{\text{fuel}} \cdot \eta_{\text{LHV}} \cdot \text{LHV}_{\text{fuel}} \)

### Cogeneration engines

- \( \text{Inv} = 800 - 4000 \text{ CHF/kWe} \)
- \( \text{Size} = 10000 - 100 \text{ kWe} \)

\( Q_e = \eta_{\text{ENG}} \cdot m_{\text{fuel}} \cdot \eta_{\text{LHV}} \cdot \text{LHV}_{\text{fuel}} \)

\( T_e = 500^\circ\text{C} \)

\( \eta_{\text{ENG}} = 0.30 \%
\)

\( \eta_{\text{ENG}} = 0.30 \%
\)

\( \eta_{\text{ENG}} = 0.25 \%
\)

\( \eta_{\text{ENG}} = 0.85 - 0.90 \%
\)
Combined heat and power

Example: Rankine cycle

Carnot: \[ \dot{E} = \dot{Q} \left( 1 - \frac{T_{vap}}{T_{cond}} \right) \]

Steam network and restricted matches
\[ \dot{Q}_1 + \dot{W} + \dot{Q}_2 = \dot{Q}_{MER}^{Hotu} + \dot{W} \]

\[ \dot{Q}_3 - \dot{W} + \dot{Q}_4 = \dot{Q}_{MER}^{Coldu} - \dot{W} \]
How to integrate mechanical power production?

Above the pinch point:
1 thermal kW = 1 mechanical kW

Below the pinch point:
1 cold utility kW = 1 mechanical kW

Across the pinch point:
Energy penalty

The constraint limits the flowrate

Choose the appropriate pressure levels

- Exploit the self-sufficient zones to maximise the mechanical power production: insert rectangles

\[ P = \left( \frac{T - 273}{100} \right)^4 \]

\[ \dot{E}_{\text{Carnot}} = \dot{Q}^* \left(1 - \frac{T_v}{T_c}\right) \]
Estimate the mechanical power production

• Above the pinch point: A is the area of the integrated rectangles = $\Delta Q \times \Delta T$

$$\hat{E} = \dot{q}_c \left( \frac{T_v - T_c}{\eta_c} \right) = \frac{A}{\eta_c \left( T_v - (T_v - T_c) \right)}$$

• Below the pinch point: A is the area of the integrated rectangles = $\Delta Q \times \Delta T$

$$\hat{E} = \dot{q}_c \eta_c \left( \frac{T_v - T_c}{T_v} \right) = \eta_c \frac{A}{T_v}$$

Heat pump and refrigeration

![Diagram of heat pump and refrigeration process](image)
The integrated composite curve of the heat pump system (figure 17) is a useful tool to verify the appropriate integration of the system.

\[
\dot{Q}_{MER}^{Hotu} - (\dot{Q} + \dot{W})
\]

\[
\dot{Q}_{MER}^{Coldu} + \dot{W}
\]

Above pinch point

Below pinch point
**Définition des niveaux de recompression**

La figure ci-dessus montre les niveaux de recompression avec des courbes de température et de puissance. Les différents niveaux sont indiqués par des lignes horizontales et verticales.

**Integrating MVR**

Au-dessus du point de vente, \( W_{mec} = \text{utilité chaude} \)

Au-dessous du point de vente, \( W_{mec} = \text{utilité chaude} !!! \)

À travers le point de vente, \( W_{mec} \Rightarrow \text{savings d'énergie}: W+Q \)
Refrigeration cycle integration

Single stage cooling

Three stages cooling + condensation

Two stages cooling
**Combined heat and power: important rules**

**Producing mechanical power**

**Appropriate placement: Never across the pinch**

- Above: 1 thermal kW for 1 mechanical kW
- Below: 1 kW cold utility becomes 1 mechanical kW
- Use self-sufficient zones

**Using mechanical power**

**Take heat below the pinch and send it back above**

Use if:
- Hot utility at low temperature
- Cold utility at high temperature
- Small temperature difference

**Utilities**

- Gas turbine?
- Fuels?
- Gas engines?
- Enriched air?
- Preheating?
- Steam?
- Heat pumps?
- Organic Rankine cycles?
- Water?
- Air?
- Liquid Fuel?
- Natural gas?
- PSA?
- VSA?
- Membrane?
- Cryogenic?
- Temperature?
- Pressure?
- Turbine?
- Compressor?
- Absorption?
- Refrigerant?
- Pressure?
- Compressor?
Energy balance of a temperature interval

- Integrating heat producers and consumers
- Sharing energy by counter current heat exchange
- Excess of energy from the upper intervals

\[ R_{i+1} \]

\[ \tau_{i+1} \]

Energy for the hot streams in interval \( i \)

\( f_j q_{ji} \)

Energy for the cold streams in interval \( i \)

\( f_j q_{ji} \)

Energy to the lower intervals

\( R_i \)

\( \tau_i \)

- For each utility stream
  - Unknown flowrate -> \( f_j \) : Continuous variable
  - Use YES/NO ? -> \( y_j \) : Integer variable 1/0

Optimalisation

- Minimum cost of energy requirement (MCER)
- Mixed Integer Linear Programming (MILP)

\[
\begin{align*}
\min_{R_i, f_j, y_j} \quad & R_u \sum_{j=1}^{n_u} C_1 j y_j + C_2 f_j \\
\text{Submit to :} \quad & \text{Hot stream } j \text{ in interval } i \\
\text{Heat balance} \quad & R_{i+1} + \sum_{j=1}^{n_f} f_j q_{ji} - \sum_{j=1}^{n_f} q_f f_j q_{ji} - R_i = 0 \\
\text{Utility} \quad & f_{\min} y_j \leq f_j \leq f_{\max} y_j \\
2\text{nd principle} \quad & R_{i+1} = 0; R_1 = 0; R_{i+1} = 0 \\
\text{ideal HEN model} \quad & y_j \in \{0, 1\} 
\end{align*}
\]
Combined mechanical power production

- Linear constraints

Mechanical power consumption
\[ \sum_{w=1}^{\nu} w_w f_w \eta_w + \text{Wel} - W_p \geq 0 \]  (3.1)

- Export of electricity
\[ \sum_{w=1}^{\nu} w_w f_w \eta_w + \text{Wel} - \text{Welv} - W_p = 0 \]  (3.2)

- Operating cost
\[ \text{Cost} = \sum_{w=1}^{\nu} (C_1 w_w + C_2 w f_w) + \text{Cel Wel} - \text{Celv Welv} \]  (1)

Use of integer variables

- 1 integer variable for each flowrate

\[ y_j = 0 \] : the utility j is not used

\[ y_j = 1 \] : the utility j is used

Linear constraint
\[ f_{\min j} y_j \leq f_j \leq f_{\max j} y_j \]

if \( y_j = 0 \Rightarrow f_{\min j} \leq f_j \leq f_{\max j} = 0 \)

if \( y_j = 1 \Rightarrow f_{\min j} \leq f_j \leq f_{\max j} \)

Linear cost:
\[ \text{Cost}_j = C_1 j + C_2 j f_j \]

if \( y_j = 0 \Rightarrow \text{Cost}_j = C_1 j + C_2 j = 0 \)

if \( y_j = 1 \Rightarrow \text{Cost}_j = C_1 j + C_2 j f_j \)
**MILP formulation**

\[
\begin{align*}
\text{minimize} & \quad \sum_{i=1}^{n_f} C_i f_i + C_e W_{el} - C_{el} W_{el} \\
\text{subject to} & \quad \sum_{i=1}^{n_f} C_i f_i + C_e W_{el} - C_{el} W_{el} \\
& \quad \sum_{i=1}^{n_f} I_i f_i + C_{IF} W_{el} + C_{IP} f_i \\
& \quad \sum_{i=1}^{n_f} (I_i f_i) + C_{IF} W_{el} + C_{IP} f_i \leq f_{top} \\
& \quad \sum_{i=1}^{n_f} I_i f_i + C_{IF} W_{el} + C_{IP} f_i \geq f_{bottom} \\
& \quad f_i \geq f_{min} \\
& \quad f_i \leq f_{max} \\
& \quad \forall i \in [1, n_f] \\
& \quad \forall r \in [1, n_r] \\
& \quad \forall w \in [1, n_w] \\
& \quad \forall r \in [1, n_r] \\
& \quad \forall w \in [1, n_w] \\
\end{align*}
\]

**Feasibility**

\[
\begin{align*}
W_{el} & \geq 0, W_{el} \geq 0 \\
R_0 & = 0, R_{n-1} = 0, R_r \geq 0 \\
\forall r & \in [1, n_r + 1] \\
\end{align*}
\]

---

**Targeting the optimal integration: model**

- **MILP formulation**

Gas turbine \( g \): hot stream from \( \text{T}_{0T} \) to \( \text{T}_{stack} \)

\[
Q_{\text{tg}} = f_g \cdot m_g \cdot \text{cp}_{fg} \cdot (\text{T}_{\text{OTg}} - \text{T}_{\text{stackg}})
\]

unknown

**Fuel**

\[
\sum_{i=1}^{n_c} f_c \cdot \text{LHV}_c - \sum_{q=1}^{n_q} y_q \cdot \text{FCI}_q + f_g \cdot \text{FCP}_g = 0
\]

**Electricity**

\[
W_{gt} = \sum_{g=1}^{n_g} y_g \cdot W_{Ig} + f_g \cdot W_{P_g} = 0
\]

**Part load efficiency**

**Operating cost**

\[
\sum_{g=1}^{n_g} (y_g \cdot \text{OCI}_g + f_g \cdot \text{OCP}_g) - \text{OC}_{gt} = 0
\]

**Investments**

\[
\sum_{g=1}^{n_g} y_g \cdot \text{ICL}_g - \text{IC}_{gt} = 0
\]
**Linear cost function: MILP formulation**

\[ C_1 = \text{Cost}(f_{\text{min}}) - C_2 f_{\text{min}} \]

\[ C_2 = \frac{\text{Cost}(f_{\text{max}}) - \text{Cost}(f_{\text{min}})}{f_{\text{max}} - f_{\text{min}}} \]

\[ C_1 y \]

**Combustion model**

**Post combustion**

\[ Q_{pc} = f_{pc}^* m_g^* c_p f_g^* (\text{Trad} - T_{OT_g}) \]

\[ f_g^* \leq f_g \]

- **O2 balance**
  \[ \sum_{q=1}^{n_q} f_{pc}^* m_g^* x_{O2}^g + f_{air}^* x_{air}^O2 \quad + \sum_{a=1}^{n_a} f_a^* m_a^* x_{O2}^a - \sum_{c=1}^{n_c} f_c^* x_{C2}^c \geq 0 \]

- **Heat above Trad**
  \[ \sum_{c=1}^{n_c} (f_c^* (LHV_c + c_{\text{air}}^* x_{O2}^a + (\text{Trad} - T_0))) - f_{air}^* c_{\text{air}}^* (\text{Trad} - T_b) \]
  \[ - \sum_{a=1}^{n_a} f_a^* m_a^* c_{\text{air}}^* (\text{Trad} - T_O) + Q_{\text{preheating}} - Q_{\text{rad}} = 0 \]

- **Heat from Trad to stack**
  \[ f_{air}^* c_{\text{air}}^* (\text{Trad} - T_{stack}) + \sum_{c=1}^{n_c} (f_c^* (m_c^* c_{\text{air}}^* - c_{\text{air}}^* x_{O2}^a) + (\text{Trad} - T_{stack})) \]
  \[ + \sum_{a=1}^{n_a} f_a^* m_a^* c_{\text{air}}^* (\text{Trad} - T_{stack}) - Q_{\text{conv}} = 0 \]
Outlet temperature calculation

Stream from $T_i^{air}$ to $T_{i+1}^{air} = T_i^{air} + \Delta T$

Add linear constraints

\[ f_{air} \geq f_{a_i} \quad \forall i = 1, \ldots, n_i \quad (19a) \]
\[ Q_{preh} = \sum_{i=1}^{n_i} f_{a_i} c_{p_{air,i}} (T_{i+1} - T_i) \quad (19b) \]

- $f_{a_i}$: the flowrate of air preheated from $T_i$ to $T_{i+1}$.
- $c_{p_{air,i}}$: the specific heat capacity of the air flowrate between $T_i$ to $T_{i+1}$.

Compute the temperature a posteriori

(1) solve the model and compute the optimal flowrates in each interval ($f_{a_i}$);
(2) compute the resulting temperature $T_{o_{i+1}}$ by solving from $i = 1$ to $n_i$,

\[ T_{o_{i+1}} = \frac{(f_{a_i-1} - f_{a_i}) T_{i-1} + f_{a_i} T_{i+1}}{f_{a_i-1}} \quad \text{with} \quad T_{0} = T_{a_{in}} \quad \text{the inlet temperature of the stream} \ a. \]
Non linear cost function

- piecewise linearisation

\[ C = \sum_{i=1}^{n_{\text{segments}}} \left( \left( C(S_{i-1}^{\text{max}}) - \frac{C(S_{i-1}^{\text{max}}) - C(S_{i}^{\text{max}})}{S_{i-1}^{\text{max}} - S_{i}^{\text{max}}} \right) \cdot S_{i-1}^{\text{max}} \right) + \sum_{i=1}^{n_{\text{segments}}} y_i \cdot \left( \frac{C(S_{i-1}^{\text{max}}) - C(S_{i}^{\text{max}})}{S_{i-1}^{\text{max}} - S_{i}^{\text{max}}} \right) \cdot S_{i}^{\text{max}} \cdot S_p \]

\[ S = \sum_{i=1}^{n_{\text{segments}}} S_{p_i} \]

\[ y_i \cdot S_{i-1}^{\text{max}} \leq S_{p_i} \leq y_i \cdot S_{i}^{\text{max}} \quad \forall i = 1, \ldots, n_{\text{segments}} \]

\[ y_i \in \{0, 1\} \]

- \( C(S) \) the installed cost of the equipment of size \( S \)
- \( S_{i}^{\text{max}} \) The maximum size in segment \( i \)
- \( S_{p_i} \) the size of the equipment in segment \( i \)
- \( y_i \) the integer variable used to select the segment \( i \)

Results: balanced hot and cold composite curves

Multiple pinch points

Optimal use of the cheapest utility

Combustion

Exothermic reactor

Steam production

Steam consumption

Water cooling

Air cooling
Evaluate: the Integrated Composite Curves

Sub-set A

\[ R_{Ak} = \sum_{r=1}^{n_A} \left( \sum_{w=1}^{n_{Aw}} f_w q_{wr} + \sum_{i=1}^{n_A} Q_{ir} \right) + R_{nk+1} \]

Sub-set B: complement

\[ RB_k = R_{ref} + \sum_{r=1}^{n_B} \left( \sum_{w=1}^{n_{Bw}} f_w q_{wr} + \sum_{i=1}^{n_B} Q_{ir} \right) \]

Hot and cold streams

\[ RB_{kp} = 0 \Rightarrow R_{ref} = - \sum_{r=1}^{n_B} \left( \sum_{w=1}^{n_{Bw}} f_w q_{wr} + \sum_{i=1}^{n_B} Q_{ir} \right) \]

Understand the results?
ICC for utility system integration

- Process
- Utility system

ICC for the integration of the fumes

- Other systems
- Furnace

Excess of heat in the fumes
ICC for refrigeration cycle integration

![Graph showing T(K) vs Q(kW) with process and cooling water refrigeration highlighted.]

ICC of the steam network

![Graph showing T(K) vs Q(kW) with steam network, energy supplement, steam production, and steam consumption highlighted.]

Other systems Steam network
Energy supplement Steam production Steam cons.
Mechanical production
Heat exchanger placement audit

Systematic drawing of the ICC of the existing heat exchangers

Heat exchange through the pinch point

Penalty
MER
Existing Heat Exchanger
Rest of the process
of remaining problem

Heat exchanger below the pinch point

Penalty of heat exchanger
MER
Heat exchanger
Overall process
Remaining
Integration of refrigeration cycles

A tool for optimal synthesis of industrial refrigeration systems: Application to an olefins plant

Content

• Problem statement: goals and strategy
• Modelling the refrigeration cycle integration
• Application to the olefins plant refrigeration cycle
  – Targeting the minimum energy requirement of the plant
• Reducing the refrigeration requirements
  – Options for improving the energy efficiency of the refrigeration system
• Conclusions
A tool for optimal synthesis of industrial refrigeration systems:
Application to an olefins plant

Laboratory of Industrial Energy Systems - LENI - Swiss Federal Institute of Technology (Lausanne-CH)

R&D context and goals

- In the frame of a European R&D project
- Goal of the R&D project
  - Develop methodology and tools to optimise the integration of energy technologies in industrial processes
  - Refrigeration systems is one of the energy technologies considered
- Methodology
  - Method development for energy technologies integration
    - targeting method for preliminary design in grassroots and process retrofit cases
  - Validation with real cases studies
- Real case study: olefin plant
  - Results of a data reconciliation and on-line optimisation software
    - Prof Pierucci, Politecnico di Milano
  - Interface with energy integration software
    - LASSC, University of Liege
  - Evaluation of feasibility
    - LASSC & Politecnico

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Problem statement: the context

- The olefin plant

A tool for optimal synthesis of industrial refrigeration systems:
Application to an olefins plant

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A tool for optimal synthesis of industrial refrigeration systems:
Application to an olefins plant

The energy requirement
• Compute the composite curves

<table>
<thead>
<tr>
<th>Heat Requirement</th>
<th>120 hot and cold streams</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q(kW)</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
</tr>
<tr>
<td>100000</td>
<td></td>
</tr>
<tr>
<td>120000</td>
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</tr>
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<td>140000</td>
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</tr>
<tr>
<td>T(K)</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
</tr>
<tr>
<td>200</td>
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<td>400</td>
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<td>600</td>
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<tr>
<td>1200</td>
<td></td>
</tr>
<tr>
<td>1400</td>
<td></td>
</tr>
</tbody>
</table>

1. Cooling
2. Ambient temperature
3. Cracking section
4. Quench
5. Compression
6. C3-C4 and C5-C6 separation
7. Cold box

The refrigeration system
• Multi components
• Multi pressure levels
• Methane: 1 level
• Ethylene: 3 levels
• Propylene: 4 levels

<table>
<thead>
<tr>
<th>Cycle</th>
<th>T evaporator (K)</th>
</tr>
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<tbody>
<tr>
<td>METH1</td>
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<tr>
<td>ETH1</td>
<td>171,6</td>
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<tr>
<td>ETH2</td>
<td>199,25</td>
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<tr>
<td>ETH3</td>
<td>212,51</td>
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<tr>
<td>PROP1</td>
<td>233</td>
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<tr>
<td>PROP2</td>
<td>248</td>
</tr>
<tr>
<td>PROP3</td>
<td>277</td>
</tr>
<tr>
<td>PROP4</td>
<td>291</td>
</tr>
</tbody>
</table>

Complex systems

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A tool for optimal synthesis of industrial refrigeration systems: Application to an olefins plant

Integrated process and refrigeration system

Goal and strategy

• Goal: develop a preliminary retrofit step model to target:
  – Optimal integration of process and refrigeration system
  – Optimal flow-rates in the refrigeration system
  – Interactions between refrigeration cycles
  – The minimum mechanical power consumption
  – And to identify the major energy penalty and improvement routes
    • Process and Heat exchanger network modification
  – Quick evaluation of process changes impact (support to the engineer creativity)

• Method proposed: EMO: Effect Modelling and Optimisation
  – Based on process data and thermodynamic based models
  – Heat exchanger network modelling using the heat cascade constraints
    • HEN modifications allowed
  – Combined heat (fridge) and power
A tool for optimal synthesis of industrial refrigeration systems:
Application to an olefins plant

**EMO for one refrigeration effect:** reference flow = flow in the condenser

**Condenser:** hot stream \( q_{\text{cond}}^r = (h_{\text{out\_comp}}^r - h_{\text{out\_cond}}^r) \)

**Compression:** mechanical power
\[
w^{c,f} = \sum_{i=1}^{n_c} P_i \left( h_{\text{out\_comp}}^{c,f}(P_i) - h_{\text{in\_cond}}^{c,f}(P_i) \right)
\]

**Evaporation:** cold stream
\[
a^{c,f} = (h_{\text{out\_cond}}^r - h_{\text{in\_evap}}^c(P_{n_c}^r)) = \prod_{i=1}^{n_c} \left( 1 - \alpha^{c,f}(P_i) \right) \left( h_{\text{in\_cond}}^{c,f}(P_i) - h_{\text{in\_sat\_liq}}^{c,f}(P_i) \right)
\]

**Heat load in the condenser**
\[
Q_{\text{cond}}^r = \sum_{c=1}^{n_c} f_{c,f}^r \cdot q_{\text{cond}}^r
\]

**Mechanical power**
\[
W^r = \sum_{c=1}^{n_c} f_{c,f}^r \cdot W_{c,f}^r
\]
Optimisation model

Goal: to compute the optimal flow-rate in each effect

Minimise $\sum_{k} \left( Q_{k} c_{1} + f_{k} c_{2} a_{k} \right) + C_{el} * E_{L} - C_{el} * E_{L}$

subject to:

- heat balance of the temperature interval $k$
  $$\sum_{i} f_{i} q_{i} + \sum_{i} f_{i} q_{c} c_{i} \leq \sum_{i} f_{i} q_{c} c_{i} + \sum_{i} Q_{i} + R_{i+1} - R_{i} = 0$$
  $$W_{c} - \sum_{i} f_{i} c_{i} w_{i} = 0$$
  $$f_{\min} \leq f_{i} \leq f_{\max}, \quad y \approx [0,1]$$

- Electricity production:
  $$\sum_{i} f_{i} w_{i} - \sum_{i} W_{c} + E_{L} - E_{L} = 0$$

- Flow-rate modifications:
  $$f_{\min} \leq f_{i} \leq f_{\max}, \quad y \approx [0,1]$$
  $$R_{i} \geq 0 \quad \forall k = 1, \ldots, n_{i} + 1$$
  $$R_{i} = 0, \quad R_{i+1} = 0$$
A tool for optimal synthesis of industrial refrigeration systems: Application to an olefins plant

The first results

<table>
<thead>
<tr>
<th></th>
<th>Actual Wmec</th>
<th>Optimized Wmec</th>
<th>Simulation Wmec</th>
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<tr>
<td>Total propylene</td>
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<td>-</td>
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<tr>
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</tr>
</tbody>
</table>

25% 8%

Sensitivity to refrigeration requirements saving

Reducing the refrigeration requirement of 1 unit reduces the mechanical requirement of:

<table>
<thead>
<tr>
<th>Cycles</th>
<th>135 K</th>
<th>170 K</th>
<th>197 K</th>
<th>210 K</th>
<th>231 K</th>
<th>246 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meth</td>
<td>0.833</td>
<td>0.070</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Eth1</td>
<td>0.483</td>
<td>0.621</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Eth2</td>
<td>0.056</td>
<td>0.005</td>
<td>0.525</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Eth3</td>
<td>0.014</td>
<td>0.001</td>
<td>0.484</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Prop1</td>
<td>0.830</td>
<td>0.906</td>
<td>0.835</td>
<td>0.810</td>
<td>0.750</td>
<td>0.526</td>
</tr>
<tr>
<td>Prop2</td>
<td>0.064</td>
<td>0.064</td>
<td>0.059</td>
<td>0.057</td>
<td>0</td>
<td>0.199</td>
</tr>
<tr>
<td>Total</td>
<td>2.281</td>
<td>1.667</td>
<td>1.419</td>
<td>1.351</td>
<td>0.750</td>
<td>0.725</td>
</tr>
</tbody>
</table>

Laboratory of Industrial Energy Systems - LENI - Swiss Federal Institute of Technology (Lausanne-CH)
A tool for optimal synthesis of industrial refrigeration systems:
Application to an olefins plant

**Ethane valorisation**

- \( T = 270 \text{ K} \)
- \( P = 20 \text{ bar} \)

- \( T = 205 \text{ K} \)
- \( P = 3 \text{ bar} \)

+ 860 kW

- 860 kW (FRG) => 1500 kW (MEC)

- Total saving

**Methane valorisation**

- \( T = 298 \text{ K} \)
- \( P = 3 \text{ bar} \)

- Total saving

+ 633 kW mec produced by the turbine
+ 1414 kW mec saved in the refrigeration system
+ 2047 kW mec

Laboratory of Industrial Energy Systems - LENI - Swiss Federal Institute of Technology (Lausanne-CH)
A tool for optimal synthesis of industrial refrigeration systems: Application to an olefins plant

Hydrogen valorisation

Other usage?
if not re-expand

Total saving
+ 320 kW mec produced by the turbine
+ 764 kW mec saved in the refrigeration system
+ 1084 kW mec

After process modifications

<table>
<thead>
<tr>
<th></th>
<th>Actual Wmec</th>
<th>Optimized Wmec</th>
<th>Simulation Wmec</th>
<th>Off streams Wmec</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kW</td>
<td>kW</td>
<td>kW</td>
<td>kW</td>
</tr>
<tr>
<td>PROP1</td>
<td>17297</td>
<td>12685</td>
<td>-</td>
<td>10524</td>
</tr>
<tr>
<td>PROP2</td>
<td>5314</td>
<td>4281</td>
<td>-</td>
<td>4114</td>
</tr>
<tr>
<td>PROP3</td>
<td>6598</td>
<td>4759</td>
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<td>4569</td>
</tr>
<tr>
<td>PROP4</td>
<td>1489</td>
<td>377</td>
<td>-</td>
<td>367</td>
</tr>
<tr>
<td>PROP1_1</td>
<td>1520</td>
<td>2029</td>
<td>-</td>
<td>2061</td>
</tr>
<tr>
<td>PROP2_1</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Total propylene</td>
<td>32218</td>
<td>24131</td>
<td>26284</td>
<td>22045</td>
</tr>
<tr>
<td>ETH1</td>
<td>919</td>
<td>706</td>
<td>-</td>
<td>281</td>
</tr>
<tr>
<td>ETH2</td>
<td>312</td>
<td>463</td>
<td>-</td>
<td>248</td>
</tr>
<tr>
<td>ETH3</td>
<td>1378</td>
<td>655</td>
<td>-</td>
<td>343</td>
</tr>
<tr>
<td>Total ethylene</td>
<td>2609</td>
<td>1823</td>
<td>2001</td>
<td>872</td>
</tr>
<tr>
<td>METH1</td>
<td>746</td>
<td>655</td>
<td>655</td>
<td>0</td>
</tr>
<tr>
<td>Off streams contribution</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>-827</td>
</tr>
<tr>
<td>TOTAL</td>
<td>35573</td>
<td>26609</td>
<td>28940</td>
<td>22090</td>
</tr>
</tbody>
</table>

Laboratory of Industrial Energy Systems - LENI - Swiss Federal Institute of Technology (Lausanne-CH)
Interest of the proposed targeting method

- Suitable for retrofit and grassroots problems
- Based on the existing process performances
  - Offers an overall view of the energy integration including the utility system
- Identify and quantify energy savings potentials (heat and power)
  - Optimal flow-rates in the cycle
  - Incentive for cycles improvements in terms of costs of energy (and investment)
  - Graphical representation => better knowledge of the system interactions
  - Quick evaluation of the process modifications with an overall system view
- Study the valorisation of “off-streams”
  - Quick evaluation (no heat exchanger network model needed)
  - Sensitivity analysis
- First step of process improvement: Target optimal flowrates
  - Use heat load distribution to identify heat exchanger network modifications
  - Estimate the investment and the profitability of solutions
  - More precise simulation needed

Outcome for the olefin plant test case

- The refrigeration system integration has been included in an overall approach
  - Hot and cold utilities
    - gas turbine, partial oxidation gas turbine,…
  - Steam network integration also important
- Targeted energy savings for the refrigeration system
  - Up to 25 % of refrigeration power consumption
  - New flow-rates targeted
  - Heat exchanger network modifications
    - After heat load distribution and heat exchanger network modelling
- Valorise “off-streams”
  - Exergy valorisation
  - Expansions + refrigeration effects
  - 12 % of additional energy savings
- HEN evaluation: preliminary step
  - Structure modifications
  - Requires further optimization to estimate the investment
Integration of Organic Rankine Cycles

Why integrating ORC systems?

Transform low grade energy into mechanical power

- Geothermal
  - hot source up to 150°C, size: 300 kW to 2.5 MW
- Renewables
  - Biogas, Biomass burning, solar energy (hybrid systems)
  - Up to 300°C efficiency up to 20%
  - Sizes from 5kW (scroll) to 1MW (turbo-expander)
- Use in industrial processes
  - Valorise low quality process / utilities waste heat
  - Typical pinch point location = 100°C to 150°C
What are the questions?

- Should I integrate an ORC to my process?
- If yes
  - What is(are) the fluid(s)?
  - What are the best operating conditions?
    - Evaporation pressure
    - Condensing pressure
    - Superheating temperature
  - What are the technologies?
  - Which process/cycle configuration?
    - Multiple cycles?
    - Process/cycle integration?
  - What are the competing technologies?
    - Heat pumps?
    - Steam Rankine cycle?
    - District heating?

---

**Process requirement**

* Composite curves

<table>
<thead>
<tr>
<th>Tin (K)</th>
<th>Tout (K)</th>
<th>Heat load (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>773.00</td>
<td>393.00</td>
<td>100.00</td>
</tr>
<tr>
<td>373.00</td>
<td>373.00</td>
<td>120.00</td>
</tr>
<tr>
<td>523.00</td>
<td>523.00</td>
<td>100.00</td>
</tr>
<tr>
<td>493.00</td>
<td>493.00</td>
<td>100.00</td>
</tr>
</tbody>
</table>

---

2nd International Symposium on process integration, Halifax (CA) 2001
**STEP1 : Identify the temperature levels**

Minimum heat transfer exergy losses

Utilities = $q_k$ at $T_k$ cst

Limit the number of levels $q_k \geq 0$

![Equation](image)

**STEP1 : Results of the levels identification**

- **Difficulties**
  - Integer variables
  - Combinatorial
  - Use of bounds
  - Distinction between close levels
  - High precision not required
  - $DT_{min}$ assumption
  - “Intelligent” results evaluation algorithm

![Graph](image)
STEP 2 : selection

- For each couple : \((T_{vap}, Q_{vap}), (T_{cond}, Q_{cond})\)
  - ORC requirement between 357.77 (K) and 298.15 (K)
- For each fluid in the list
  - Compute \(P_{vap} \& P_{cond}\)
  - Compute \(w_{mec}, q_{vap}, q_{liq} => flow\)
  - \(\text{intersection with requirement}\)
- Compute \(T_{superheatingR}\)
  - Vapour fraction > 0.85
  - \(w_{mec} \times \text{flow increases}\)
- Select the n bests

STEP 2 : Results

- List of possible fluids
  - Heat transfer coefficient \(\rightarrow D\)
  - Vaporisation temperature
  - Compute the pressure
  - Superheating temperature
  - Condensation temperature
  - Flowrate reference
  - Efficiency
**STEP 3 : Cycles calculation**

- For each cycle and its reference flowrate

**Grand composite curve of an ORC**

FROM the hot source : $Q_h$

- The composite has to "fit" the process
- $Q_h$ "Free" waste energy

$$\eta = \frac{W}{Q_h} = 17.2 \%$$
$$= 23.72 / 137.7$$

Heat load saving
- Greater production
  - $\Rightarrow + 9 \%$

Integration of an ORC

FROM the hot source : $Q_h$

- The composite has to "fit" the process
- $Q_h$ "Free" waste energy

$$\eta = \frac{W}{Q_h} = 17.2 \%$$
$$= 23.72 / 137.7$$

Heat load saving
- Greater production
  - $\Rightarrow + 9 \%$
STEP 3: MILP superstructure model for selection

Minimise $\sum_{k,t} \left( y_{i,k} C_{i,k} + f_i C_{i,k} \right) + C_{el}^t E_{i,t} - C_{el}^t E_{i,t}$ (P2)

Objective function = total cost of technologies

Including competing technologies

subject to:

Heat balance of the temperature interval k

$$\sum_{k,t} f_{i,k,t} + \sum_{k,t} (w_{i,k,t} - q_{h_{i,k,t}}) * f_i + \sum_{k,t} Q_{i,k,t} * R_{i,k,t} = 0$$

$\forall k = L, \ldots, n_k$

Heat cascade constraint

$Q_{h_{i,k,t}} - \sum_{k,t} (q_{h_{i,k,t}}) * f_i = 0$

$\forall r = L, \ldots, n_r$

ORC sizing

$Q_{h_{i,k,t}} - \sum_{k,t} (q_{h_{i,k,t}}) * f_i = 0$

$\forall r = L, \ldots, n_r$

ORC selection

Electricity production:

$$W_{e} = \sum_{k,t} \left( \eta_{i,k,t} C_{i,k} E_{i,k,t} + \frac{P_{e,i}}{E_{i,k,t} - \eta_{i,k,t}} \right) * f_i = 0$$

$\forall r = L, \ldots, n_r$

Electricity balances

Electricity consumption:

$$f_{min} \leq f_i \leq f_{max}, \quad y_{i,j,k} \in \{0,1\}$$

$$R_{i,k,t} = 0 \quad \forall k = L, \ldots, n_k$$

Other technologies selection

2nd International Symposium on process integration, Halifax (CA) 2001
**STEP 3 : Difficulties/Limitations**

- **Solving integer programming**
  - Consistent bounds set !
- **Linear model**
  - Linearised cost
  - Estimated $A$
- **Multiple alternatives**
  - Multi criteria selection
- **Heat Exchanger Network**
  - Structure unknown
  - Cost not considered

  - **Flowrate estimation**
    - Reference
  - + DTmin assumption
  - **Integer cuts**
    - Multiple solutions
    - Multi objective (linear)
    - Break even
  - **List of streams complete**
    - Automated or Pinch design method
    - Complete system !
Result of selection: report & evaluation

- Solution evaluation

**MER**: Hot = 36.8 kW, Tpinch = 255°C
Cold = 256.8 kW
Fuel: 41.76 kW (-> 88%)
Air preheating: 0.39 kW (-> 51°C)
Cooling water: 213.13 kW

---

**Heat (kW)**

<table>
<thead>
<tr>
<th>ORC 1 C6H6</th>
<th>ORC 2 R134a</th>
</tr>
</thead>
<tbody>
<tr>
<td>157.6</td>
<td>237.0</td>
</tr>
</tbody>
</table>

**Wmec (kW)**

<table>
<thead>
<tr>
<th>ORC 1 C6H6</th>
<th>ORC 2 R134a</th>
</tr>
</thead>
<tbody>
<tr>
<td>21.6</td>
<td>22.4</td>
</tr>
</tbody>
</table>

**Total**: 44.0 (17%)

---

C6H6
R134a

Conclusion

- **ORC allow to valorise industrial process waste heat**
  - Efficiency of 7 to 17% can be reached (according to process)
  - At the price of the system investment

- **3 steps method for ORC integration into industrial processes**
  - Minimum exergy losses for temperature levels
  - Thermodynamic based algorithm for fluid and T
  - MILP for ORC integration with a holistic approach
    - Represent the competition with other technologies
    - Multi-criteria evaluation - Multi-solution generation

- **Preliminary step before**
  (super-)structures thermo-economic optimisation
  - Time varying demand
  - Non-linear optimisation required
Integration of steam network

Site scale integration

Energy saving through process/process integration
**Role of the steam network**

**site scale integration**

- **Process 1**
- **Process 2**

- **Fuel**
- **Cooling system**
- **Flue gases**

- **ignoring pockets**
- **with pockets**
Steam network model

Constant T
Preheating? Superheating?

What about using a gas turbine?
What about CHP?

Steam network

Process 1

Cooling system

Process 2

Fuel
Integrated Combined Heat and Power

Choose the pressure levels from \( T_v \) and \( T_c \)

Estimate the CHP potential using Carnot cycle approximation

\[
W = \text{Area} \times \frac{1}{T_v} \left( \frac{T_v}{T_c} - 1 \right)
\]

HT diagram of steam production?

HT diagram of condensation?

From the list of steam levels

Generate a steam network superstructure with fixed steam qualities

Effects:
- Hot streams
- Cold streams
- Mechanical power

Modelling:
Heat and mass balance

Optimisation:
Minimum Cost Target

P_i, T_i \Rightarrow h_i
Effects in the steam network

Mechanical power
\[ w_{ij} = \min\{h_i - h_j, \sum_{k=i}^{j} w_{k(k+1)}\} \]

Where:
\[ k_{ij} = h_i - w_{ij} - h_k \]
\[ r_{j-1} = (1 + h_{j-1} - h_k) \]
\[ h_k = h_{(k-1)} - w_{(k-1)j} \]

\[ P_i, T_i \Rightarrow h_i \]

Cold stream

Superheating

Vaporising

Preheating

The steam network model

Steam header model

\[ n_v \sum_{i=1}^{n_v} \sum_{k=1}^{n_{co}} D_{ij} + \sum_{j=1}^{n_v} A_j + \sum_{k=1}^{n_{co}} k_j \cdot DT_j = 0 \]

Where:
\[ k_{ij} = h_i - w_{ij} - h_k \]
\[ r_{j-1} = (1 + h_{j-1} - h_k) \]

Condensate header model

\[ n_v \sum_{i=1}^{n_v} \sum_{k=1}^{n_{co}} D_{kj} + \sum_{j=1}^{n_v} k_j \cdot A_k + \sum_{i=1}^{n_v} D_{ij} - \sum_{j=1}^{n_v} (h_j - h_k) \cdot S_i = 0 \]
Targeting the optimal integration

Minimise \( \sum_{w=1}^{n_w} (C_{1w} y_{w} + C_{2w} f_{w}) + C_{\text{in}} \text{ Wel}_{\text{in}} - C_{\text{ex}} \text{ Wel}_{\text{ex}} + \sum_{i=1}^{n_{\text{CO+HV}}} (C_{1i} y_{ai} + C_{2i} A_{i}) + \sum_{i=1}^{n_{\text{CO+HV}}} (C_{1i} y_{si} - C_{2i} S_{i}) \)

Subject to

\( \sum_{w=1}^{n_w} q_{w} + \sum_{i=1}^{n_{\text{CO}}} \sum_{j=1}^{n_{\text{HV}}} D_{cij} q_{cij} + \sum_{i=1}^{n_{\text{CO}}} \sum_{j=1}^{n_{\text{HV}}} D_{fij} q_{fij} + \sum_{i=1}^{n_{\text{CO}}} Q_{ai} + R_{k-1} - R_{k} = 0 \quad \forall k=1,...,n_{k} \)

\( f_{\text{in}} \leq f_{w} \leq f_{\text{max}}, \quad f_{\text{in}} \leq D_{cij} \leq f_{\text{max}}, \quad f_{\text{in}} \leq D_{fij} \leq f_{\text{max}}, \quad y_{w} \in \{0,1\} \)

\( R_{k} \geq 0 \quad \forall k=1,...,n_{k} \)

Import

\( \sum_{j=i+1}^{n_{\text{HV}}} \sum_{i=1}^{n_{\text{CO}}} \sum_{j=1}^{n_{\text{HV}}} \sum_{i=1}^{n_{\text{CO}}} D_{\text{Tij}} w_{ij} - \sum_{k=1}^{n_{\text{CO}}} \sum_{i=1}^{n_{\text{CO}}} \sum_{k=1}^{n_{\text{CO}}} \sum_{i=1}^{n_{\text{CO}}} D_{\text{fki}} \cdot \text{wpki} + \sum_{w=1}^{n_{w}} f_{w} w_{w} + \text{ Wel}_{\text{in}} - \text{ Wel}_{\text{ex}} = 0 \)

Export

\( \sum_{i=1}^{n_{\text{CO}}} \sum_{j=1+1}^{n_{\text{HV}}} \sum_{i=1}^{n_{\text{CO}}} \sum_{k=1}^{n_{\text{CO}}} \sum_{i=1}^{n_{\text{CO}}} D_{\text{Tij}} w_{ij} - \sum_{k=1}^{n_{\text{CO}}} \sum_{i=1}^{n_{\text{CO}}} \sum_{k=1}^{n_{\text{CO}}} \sum_{i=1}^{n_{\text{CO}}} D_{\text{fki}} \cdot \text{wpki} + \sum_{w=1}^{n_{w}} f_{w} w_{w} + \text{ Wel}_{\text{in}} = 0 \)

+ Model of steam network

Steam network integration

Integrated composite curves of the steam network

\( + 127 \text{ kW} \)

\( 436 \text{ kW} \)
Restricted matches : our goals

• **Targeting the Minimum Cost Energy Requirement**
  taking into account the restricted matches
  – Energy penalty of the constraints ?
  – Cost of the energy penalty ?
  – Solve site scale problems
  – Find technological solutions to minimise the cost
    penalty of the restricted matches
  • **choice of the heat transfer fluids**

• **Before the HEN synthesis task**
  – Start HEN synthesis with the complete list of streams

The heat cascade a LP formulation

\[ \min \sum_{k=1}^{n} R_{nk+1} \]
\[ R_k \]

Heat balance of a temperature interval
\[ R_k + \sum_{i=1}^{n_h} f_i q_{ik} - \sum_{j=1}^{n_c} f_j q_{jk} = 0 \quad \forall k=1,\ldots,n_k \]
\[ R_k \geq 0 \quad \forall k=1,\ldots,n_k+1 \]

\[ (R^*_k,T_k) \quad \text{the MER heat cascade} \]
\[ (G\ r\ and\ composite\ curve) \]
The constraints

Heat balance of a temperature interval
\[ R_{k+1} + \sum_{i=1}^{n_h} f_i q_{ik} - R_k - \sum_{j=1}^{n_c} f_j q_{jk} = 0 \quad \forall k=1,...,n_k \] (1)

Heat balance of a hot stream \( i \) in a restricted match
\[ \sum_{j=1}^{n_c} Q_{ijk} + R_{ik} - f_i q_{ik} - R_{ik+1} = 0 \quad \forall k=1,...,k_i, \forall i=1,...,n_h \] (R1)

Heat cascade of the cold stream \( j \)
\[ \sum_{i=1}^{n_h} Q_{ijk} = f_j q_{jk} \quad \forall k=1,...,n_k, \forall j=1,...,n_c \] (R2)

Overall heat cascade
\[ \sum_{i=1}^{n_h} R_{ik} = R_k \quad \forall k=1,...,n_k \] (R3)

Accepted Matches

New variables

Compute the energy penalty

- **Target the Minimum Cost Energy Requirement without constraints**
  - Optimal heat cascade : \( R^*_k \)
  - Fix the flowrates
  - Add the restricted matches constraints
  - Solve the problem (P1)

\[ \text{minimise} \quad R_{n_k+1} \]
\[ R_{ik}, Q_{ijk}, R_k \]

\( R_{n_k+1} - R^*_{n_k+1} \) is the energy penalty

- if penalty is acceptable goto HEN Synthesis
- if not choose the heat transfer fluid
Choose the heat transfer fluid

Choose the heat transfer fluid

Heat source

Heat sink

Process pinch point

Grand composite curve

Restricted matches cascade

Energy penalty 6810 kJ

MER 4807 kJ

\[ \sum_{i=1}^{n_h} R_{ik} \]

\[ \sum_{i=1}^{n_h} \]

\[ R_{ok} = R_k \]

for all \( k = 1, \ldots, n \)

Restricted matches cascade

Conditions to be satisfied by the heat transfer fluid

1) All the \( R_k \) must be positive (definition of the MER);
2) \( R_{nk+1} = R^*_{nk+1} \) (no energy penalty is due to the use of the intermediate stream);
3) \( R_{ok} = R_k \) for all \( k = 1, \ldots, n \) (the intermediate fluids solve the restricted matches constraints).

Heat transfer fluid characteristics

Process : Hot streams

Process : Cold streams

Heat transfer fluid hot stream

Heat transfer fluid cold stream
Choose the heat transfer fluid

Above the pinch point

Choose the heat transfer fluid

Place the heat transfer fluid between Red and Blue lines

Energy penalty if 1.5 b steam is used
Steam network and restricted matches

Target the minimum cost of energy requirement

- Add the heat transfer fluids
  - Hot and cold streams
  - Unknown flowrate
- Use the MILP model
  - Heat cascade
  - Mechanical power balance
  - EMO models
    - Energy technologies
    - Heat transfer fluids or steam network
  - Restricted matches constraints
- Objective function: Minimum Cost of Energy
  Fuels - Electricity - CHP - Investments
Targeting the Minimum Cost Energy Requirement

Minimise \( \sum_{w=1}^{n_w} (C_{1w} y_w + C_{2w} f_w) + C_{el_in} W_{el_in} - C_{el_ex} W_{el_ex} \)

subject to

\( \sum_{w=1}^{n_w} f_w q_{wk} + \sum_{i=1}^{n} Q_{ik} + R_{k+1} - R_k = 0 \) \( \forall k = 1, \ldots, n_k \)

\( f_{min_w} y_w \leq f_w \leq f_{max_w} y_w \) \( \forall w = 1, \ldots, n_w \)

\( y_w \in \{0, 1\} \)

\( R_k \geq 0 \) \( \forall k = 1, \ldots, n_k+1 \)

\( R_1 = 0, R_{n_k+1} = 0 \)

\( \text{Import} \sum_{w=1}^{n_w} f_w w_w + W_{el_in} = 0 \)

\( \text{Export} \sum_{w=1}^{n_w} f_w w_w + W_{el_in} \geq 0 \)

Evaluate the results

Energy supplement

Integrated composite curves

Others

Steam network

Heat transfer

Penalty

Mechanical power
Example

- **System with constraints**
  - MER : 4143,0 kW
  - With steam network: 4560,0 kW
  - CHP: 417,0 kWe ($\eta = 100 \%$)

- **System with constraints**
  - MER : 10017,0 kW
  - Energy penalty : 5874,0 kW ($142 \%$ MER)

- **System with constraints and steam network**
  - Steam network without modif. 6557,0 kW
    - CHP: 755,0 kWe ($\eta = 31 \%$)
    - Energy penalty : 1659,0 kW (40 % MER)
  - Adapted steam network 4658,0 kW
    - CHP: 418,0 kWe ($\eta = 81 \%$)
    - Energy penalty 97,0 kW (2.3 % MER)