Energy Integration of Large-scale Industrial Sites
with Target-compatible Subsystem Division Strategy

Prof. François Maréchal
Nasibeh Pouransari

Industrial Process & Energy Systems Engineering
Outline:

1. Introduction
2. Methodology
   1. Concept
   2. Optimization algorithm
3. Results
4. Conclusion
Goal & Motivation:
• Energy Efficiency of large industrial sites
  • Heat recovery network synthesis for identified energy saving

Problem:
• HEN synthesis for total site integration
  • Utility/process integration
    • Marechal et al., Applied Thermal Eng., 1998
  • Heuristic methods: PDM: Manual procedure & difficult to apply, huge amount of alternatives
    • Linnhoff et al., Computers and Chemical Engineering, 1983
  • Optimization methods:
    – Simultaneous approaches: Numerical problem (non-convexity & local optimum), problem size (Combinatorial explosion)
      • Cric et al., Computers and Chemical Engineering, 1993
    – Sequential approaches: HLD + HEND: Computational problem (Combinatorial explosion)
      • Yee et al., Computers and Chemical Engineering, 1990
• The site layout: Connection between sub-systems with geographical distance, heat transfer fluid (e.g. steam)

Objective:
• Developing a Target-compatible methodology to synthesis heat recovery network for large-scale plant with minimum possible connection between process subsystems
Main steps of the algorithm

1. Compute the total site utility target
   
   => complete list of streams to be considered in the heat exchanger network synthesis

2. Define sub-systems in the total site

3. Define packed streams per sub-systems
   
   => Virtual hot and cold streams

4. Compute the heat load distribution between packed streams
   
   => non necessary connections

5. Iterative procedure
   
   5.1. Unpacking procedure by systematically unpacking sub-systems
   
   => definition of needed matches

   End when all the streams are unpacked

   => Heat load distribution results

   1. minimum number of connexion

   2. minimum number of sub-systems interconnexion

6. For each zone and each heat load distribution

   apply automatic HEND using simultaneous approach
Methodology steps

MILP: Minimum energy consumption

Definition of subsystems

Definition of virtual pair of hot and cold streams

MILP: HLD between packed subsystems

FORBIDDEN-matches $y_{ij\phi}^* = 0$

MILP: HLD between unpacked subsystem $n$ and outside streams

FORBIDDEN-matches $y_{ij\phi}^* = 0$

FORCED-matches $y_{ij\phi} = 1$

$n < n_{subsystems}$

$\text{Final solution}$

$\text{No}$

$\text{Yes}$

$n = n + 1$
First step: Minimum Cost of Energy target

- Heat transfer interfaces
  - Hot and cold streams of the process
  - Unit operation integration
    $\Rightarrow$ heating, cooling requirements
  - Sub-systems organisation

- Heat and power integration
  - Heat recovery by Heat cascade
  - Energy conversion integration
    - Combined Heat and Power
    - Combined water (solvent) and waste
  - Restricted matches constraints
    - Intermediate heat transfer fluids
    $\Rightarrow$ Mixed Integer Linear Programming

$\Rightarrow$ Energy targets
$\Rightarrow$ Complete list of streams
Minimum energy consumption: MILP optimization

Objective function

\[
\min \left( \sum_{f=1}^{nf} \left( c_f \sum_{u=1}^{nu} f_u \dot{E}_{f,u}^+ \right) + c_{el}^+ \dot{E}_{el}^+ - c_{el}^- \dot{E}_{el}^- + \sum_{u=1}^{nu} f_u c_u \right) . t \right)
\]

Heat cascade

\[
\sum_{h_k=1}^{n_{s_{h,k}}} f_u \dot{Q}_{h,k,u} - \sum_{c_k=1}^{n_{s_{c,k}}} f_u \dot{Q}_{c,k,u} + \dot{R}_{k+1} - \dot{R}_k = 0 \quad \forall k = 1, ..., nk
\]
\[
\dot{R}_1 = 0 \quad \dot{R}_{nk+1} = 0 \quad \dot{R}_k \geq 0 \quad \forall k = 2, ..., nk
\]

Electricity consumption / production

\[
\sum_{u=1}^{nu} f_u \dot{E}_{el,u}^+ + \dot{E}_{el}^+ - \sum_{u=1}^{nu} f_u \dot{E}_{el,u}^- \geq 0
\]
\[
\sum_{u=1}^{nu} f_u \dot{E}_{el,u}^+ + \dot{E}_{el}^+ - \dot{E}_{el}^- - \sum_{u=1}^{nu} f_u \dot{E}_{el,u}^- = 0
\]
\[
\dot{E}_{el}^+ \geq 0 \quad \dot{E}_{el}^- \geq 0
\]

Multiplication factors

\[
y_u f_u^{min} \leq f_u \leq y_u f_u^{max} \quad \forall u = 1, ..., nu \quad y_u \in 0, 1
\]

Mixed Integer Linear Programming (MILP) optimization

- Activation of utilities (integer variables)
- Multiplication factors (extend usage of utilities)

Papoulias et al., Computers and chemical Engineering, 1983
Marechal et al., Applied Thermal Eng., 1998

- Restricted matches constraints
Becker et al., Computers and Chemical Engineering, 2012
- Minimum cost energy balance.
Heat load distribution for each pinch zones

*Marechal et al, Computers and Chemical Eng., 1989*
Heat load distribution, MILP model

Basic MILP optimization

Objective function

\[
\min \left( \sum_{\varphi=1}^{n_{\varphi}} \sum_{j=1}^{n_{c\varphi}} \sum_{i=1}^{n_{h\varphi}} y_{ij\varphi} \right) \quad y_{ij\varphi} \in \{0, 1\}
\]

Heat balance of hot and cold streams

\[
\sum_{j=1}^{n_{s\varphi}} Q_{ijk} = Q_{ik} \quad \forall i = 1, \ldots, n_{s\varphi} \quad \forall k = 1, \ldots, n_{k\varphi} \quad \forall \varphi = 1, \ldots, n_{\varphi}
\]

Existence of the connection \((i, j)\)

\[
\sum_{i=1}^{n_{k\varphi}} \sum_{k=1}^{n_{s\varphi}} Q_{ijk} - Q_{j\varphi} \geq 0 \quad \forall j = 1, \ldots, n_{c\varphi} \quad \forall \varphi = 1, \ldots, n_{\varphi}
\]

Positive heat exchange

\[
Q_{ijk} \geq 0 \quad \forall j = 1, \ldots, n_{c\varphi} \quad \forall i = 1, \ldots, n_{s\varphi} \quad \forall k = 1, \ldots, n_{k\varphi}
\]

- More than 1 solution
- Highly combinatorial
- Difficult to define weighting factor

* Marechal et al, Computers and Chemical Eng., 1989
New heat load distribution solving method
Defining sub-systems

Heat distribution network

Energy conversion

Process 1

Process 2

Process 3
Sub-system packing: creating 2 virtual streams per sub-system

Heat distribution network

Energy conversion

Total site

Heat cascade inside each subsystem

Introduction
Methodology
Results
Conclusion

Sub-system packing: creating 2 virtual streams per sub-system

Heat distribution network

Energy conversion

Total site

Heat cascade inside each subsystem
Virtual Streams (packed streams/sub-system)

Heat distribution network

Energy conversion

Process 1

Process 2

Process 3

Definition of virtual pair of hot and cold streams

$y_{ij\varphi} \rightarrow y_{ij\varphi}^*$

New integer variable
Exchange between sub-systems
HLD between packed subsystems

Updated MILP optimization

Objective function

$$\begin{align*}
\min \left\{ \sum_{\varphi=1}^{n_\varphi} \sum_{j=1}^{n_{s_{cp}}} \sum_{i=1}^{n_{s_{hp}}} y_{ij\varphi} \right\} \\
y_{ij\varphi} \in \{0, 1\}
\end{align*}$$

Heat balance of hot and cold streams

$$\sum_{j=1}^{n_{s_{cp}}} Q_{ijk} = Q_{ik} \quad \forall i = 1, \ldots, n_{s_{cp}} \quad \forall k = 1, \ldots, n_{k\varphi} \quad \forall \varphi = 1, \ldots, n_\varphi$$

Existence of the connection \((i, j)\)

$$\sum_{j=1}^{n_{s_{cp}}} \sum_{k=1}^{n_{k\varphi}} Q_{ijk} - Q_{ij\varphi} \geq 0 \quad \forall j = 1, \ldots, n_{s_{cp}} \quad \forall \varphi = 1, \ldots, n_\varphi$$

Positive heat exchange

$$Q_{ijk} \geq 0 \quad \forall i = 1, \ldots, n_{s_{cp}} \quad \forall j = 1, \ldots, n_{s_{cp}} \quad \forall k = 1, \ldots, n_{k\varphi}$$
Results of the heat load distribution

Heat distribution network

Energy conversion

Process 1

Process 2

Process 3

MILP: HLD between packed subsystems

Non existing connexions

Forbidden-matches $y_{ij\varphi} = 0$
Unpack sub-systems

Heat distribution network

Energy conversion

Process 1

Process 2

Process 3

MILP: HLD between packed subsystems

Non existing connexions

Forbidden-matches $y_{ij\varphi} = 0$
Unpack sub-systems

MILP:
HLD between packed subsystems

Forbidden-matches
\( y^*_ij \phi = 0 \)
Methodology concept:
Methodology concept:

Forbidden-matches
\[ y_{ij\varphi} = 0 \]

MILP:
HLD between unpacked subsystems and outside streams
HLD between unpacked subsystem n and outside streams

Updated MILP optimization

Objective function

$$\min \left( \sum_{\phi=1}^{n} \sum_{j=1}^{n_{s_{cp}}} \sum_{i=1}^{n_{s_{hp}}} y_{ij\phi}^{*n} \right) \quad y_{ij\phi}^{*n} \in \{0, 1\}$$

Heat balance of hot and cold streams

$$\sum_{j=1}^{n_{s_{hp}}} Q_{ijk} - Q_{ik} \geq 0 \quad \forall j = 1, \cdots, n_{s_{cp}} \quad \forall \phi = 1, \cdots, n_{s_{cp}}$$

Existence of the connection \((i, j)\)

$$\sum_{k=1}^{n_{s_{hp}}} Q_{ijk} - y_{ij\phi}^{*n} Q_{max, ij\phi} \leq 0 \quad \forall i = 1, \cdots, n_{s_{hp}} \quad \forall j = 1, \cdots, n_{s_{cp}} \quad \forall \phi = 1, \cdots, n_{s_{cp}}$$

Positive heat exchange

$$Q_{ijk} \geq 0 \quad \forall i = 1, \cdots, n_{s_{hp}} \quad \forall j = 1, \cdots, n_{s_{cp}} \quad \forall k = 1, \cdots, n_{k_{p}}$$

HLD model with Packed & Unpacked subsystem

- \(y_{ij\phi}^{*n}\): Integer variable between original, virtual and utility streams
- Generating Forbidden-matches and Forced-matches from the result
  - \(y_{ij\phi}^{*n} = 0\)
  - \(y_{ij\phi} = 1\)
Results for step n

Forbidden-matches
\( y_{ij\varphi}^* = 0 \)

MILP:
HLD between unpacked subsystem \( n \) and outside streams

Forbidden-matches
\( y_{ij\varphi}^{*n} = 0 \)

Forced-matches
\( y_{ij\varphi} = 1 \)
goto step n+1 : Unpack the next subsystem

Forbidden-matches
\[ y_{ij \varphi}^* = 0 \]

MILP:
HLD between unpacked subsystem \( n \) and outside streams

Forbidden-matches
\[ y_{ij \varphi}^* = 0 \]
Forced-matches
\[ y_{ij \varphi} = 1 \]
Methodology steps

INTRODUCTION

Methodology

Results

Conclusion

MILP: Minimum energy consumption

Definition of subsystems

Definition of virtual pair of hot and cold streams

\[ y_{ij} \rightarrow y_{ij}^* \]

Forbidden-matches

\[ y_{ij}^* = 0 \]

Forced-matches

\[ y_{ij} = 1 \]

Forced-matches

\[ y_{ij}^* = 0 \]

\[ n < n_{subsystems} \]

Yes

No

Final solution

MILP: HLD between unpacked subsystem \( n \) and outside streams

MILP: HLD between packed subsystems

\[ n = n + 1 \]
Heat load distribution results

![Graph showing heat load distribution results with various heat loads marked at different corrected temperatures and stream numbers.](image-url)
Case study 1

23SP1 problem
(One process system)
10 cold process streams
9 hot process streams
4 utility streams

Computer: Intel(R) Xeon(R), CPU (3.1 GHz), RAM 8 GB
MILP: Ampl
Analysis: Matlab
Solver: Cplex (version 12.6.0)
Case study 1

☑ Heat recovery network synthesis procedure

☑ To unpack, start from subsystem with lowest number of streams
Case study 1

☑ Heat recovery network synthesis procedure

<table>
<thead>
<tr>
<th>Streams (i,j)</th>
<th>CA $\psi_1 \psi_2$</th>
<th>CB $\psi_1 \psi_2$</th>
<th>CC $\psi_1 \psi_2$</th>
<th>C11 $\psi_1 \psi_2$</th>
<th>C12 $\psi_1 \psi_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HA</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>HB</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>HC</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>H10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>H11</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Case study 1

Heat recovery network synthesis procedure

☑ Heat recovery network synthesis procedure

<table>
<thead>
<tr>
<th>Streams (i,j)</th>
<th>CA $\varphi_1 \varphi_2$</th>
<th>CB $\varphi_1 \varphi_2$</th>
<th>CC $\varphi_1 \varphi_2$</th>
<th>C11 $\varphi_1 \varphi_2$</th>
<th>C12 $\varphi_1 \varphi_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HA</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>HB</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>HC</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>H10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>H11</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Case study 1

☑ Heat recovery network synthesis procedure

<table>
<thead>
<tr>
<th>Streams (Lj)</th>
<th>C01</th>
<th>C06</th>
<th>C07</th>
<th>C09</th>
<th>CB</th>
<th>CC</th>
<th>C11</th>
<th>C12</th>
</tr>
</thead>
<tbody>
<tr>
<td>H01</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td>0</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>H04</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>H06</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>HB</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HC</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H10</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>H11</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
Case study 1

☑ Heat recovery network synthesis procedure

Introduction  Methodology  Results  Conclusion

<table>
<thead>
<tr>
<th>Streams</th>
<th>CO1</th>
<th>CO6</th>
<th>CO7</th>
<th>CO9</th>
<th>CB</th>
<th>CC</th>
<th>C11</th>
<th>C12</th>
</tr>
</thead>
<tbody>
<tr>
<td>H01</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>H04</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>H06</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>HB</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>HC</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>H10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>H11</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

a) MILP: minimum operating cost
b) Defining process subsystems
c) Heat cascade for subsystems to define virtual streams

d) MILP: HLD between virtual and utility streams
e) Separating subsystem A and its connection with forbidden-matches
f) Unpacking subsystem A, MILP: HLD between real and virtual streams

g) Unpacking subsystem B, MILP: HLD between real and virtual streams
h) Unpacking subsystem C, MILP: HLD between all real streams
i) Final solution, Heat recovery network

Result output

Forbidden-matches input
Forced-matches input
Case study 1

☑ Comparison with basic model result (b)

☑ Close-to-minimum number of connections network

☑ Minimum number of connections between subsystems
### Case study 1

#### Summary of MILP optimization

<table>
<thead>
<tr>
<th>MILP model</th>
<th>Restricted matches constraints</th>
<th>$y_{i,j,\varphi}$</th>
<th>Computation time [s]</th>
<th>Streams</th>
<th>Connections</th>
<th>N. Euler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum energy consumption</td>
<td>-</td>
<td>-</td>
<td>0.013</td>
<td>23</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>HLD between subsystems</td>
<td>0-3</td>
<td>26</td>
<td>0.055</td>
<td>10</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>HLD by unpacking subsystem A</td>
<td>24</td>
<td>48</td>
<td>0.069</td>
<td>15</td>
<td>15</td>
<td>16</td>
</tr>
<tr>
<td>HLD by unpacking subsystem B</td>
<td>46</td>
<td>62</td>
<td>0.016</td>
<td>18</td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td>HLD by unpacking subsystem C</td>
<td>70</td>
<td>106</td>
<td>0.162</td>
<td>23</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>HLD with subsystem approach</td>
<td>70</td>
<td>106</td>
<td>0.162</td>
<td>23</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>HLD with basic approach</td>
<td>0</td>
<td>106</td>
<td>0.339</td>
<td>23</td>
<td>21</td>
<td>22</td>
</tr>
</tbody>
</table>
Case study 1

Summary of MILP optimization

<table>
<thead>
<tr>
<th>MILP model</th>
<th>Restricted matches constraints</th>
<th>( y_{i,j} )</th>
<th>Computation time [s]</th>
<th>Streams</th>
<th>Connections</th>
<th>N. Euler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum energy consumption</td>
<td>-</td>
<td>-</td>
<td>0.013</td>
<td>23</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>HLD between subsystems</td>
<td>0-3</td>
<td>26</td>
<td>0.055</td>
<td>10</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>HLD by unpacking subsystem A</td>
<td>24</td>
<td>48</td>
<td>0.069</td>
<td>15</td>
<td>15</td>
<td>16</td>
</tr>
<tr>
<td>HLD by unpacking subsystem B</td>
<td>46</td>
<td>62</td>
<td>0.016</td>
<td>18</td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td>HLD by unpacking subsystem C</td>
<td>70</td>
<td>106</td>
<td>0.162</td>
<td>23</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>HLD with subsystem approach</td>
<td>70</td>
<td>106</td>
<td><strong>0.162</strong></td>
<td>23</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>HLD with basic approach</td>
<td>0</td>
<td>106</td>
<td><strong>0.339</strong></td>
<td>23</td>
<td>21</td>
<td>22</td>
</tr>
</tbody>
</table>
## Case study 1

### Summary of MILP optimization

<table>
<thead>
<tr>
<th>MILP model</th>
<th>Restricted matches constraints</th>
<th>$Y_{ij}$</th>
<th>Computation time [s]</th>
<th>Streams</th>
<th>Connections</th>
<th>N. Euler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum energy consumption</td>
<td>-</td>
<td>-</td>
<td>0.013</td>
<td>23</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>HLD between subsystems</td>
<td>0-3</td>
<td>26</td>
<td>0.055</td>
<td>10</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>HLD by unpacking subsystem A</td>
<td>24</td>
<td>48</td>
<td>0.069</td>
<td>15</td>
<td>15</td>
<td>16</td>
</tr>
<tr>
<td>HLD by unpacking subsystem B</td>
<td>46</td>
<td>62</td>
<td>0.016</td>
<td>18</td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td>HLD by unpacking subsystem C</td>
<td>70</td>
<td>106</td>
<td>0.162</td>
<td>23</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>HLD with subsystem approach</td>
<td>70</td>
<td>106</td>
<td>0.162</td>
<td>23</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>HLD with basic approach</td>
<td>0</td>
<td>106</td>
<td>0.339</td>
<td>23</td>
<td>21</td>
<td>22</td>
</tr>
</tbody>
</table>

### Computation time reduction

- **HLD with basic approach**: 0.339 seconds
- **HLD with subsystem approach**: 0.162 seconds

The computation time reduction is significant with the subsystem approach.
## Case study 1

### Summary of MILP optimization

<table>
<thead>
<tr>
<th>MILP model</th>
<th>Restricted matches constraints</th>
<th>$\gamma_{i,j}$</th>
<th>Computation time [s]</th>
<th>Streams</th>
<th>Connections</th>
<th>N. Euler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum energy consumption</td>
<td>-</td>
<td>-</td>
<td>0.013</td>
<td>23</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>HLD between subsystems</td>
<td>0-3</td>
<td>26</td>
<td>0.055</td>
<td>10</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>HLD by unpacking subsystem A</td>
<td>24</td>
<td>48</td>
<td>0.069</td>
<td>15</td>
<td>15</td>
<td>16</td>
</tr>
<tr>
<td>HLD by unpacking subsystem B</td>
<td>46</td>
<td>62</td>
<td>0.016</td>
<td>18</td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td>HLD by unpacking subsystem C</td>
<td>70</td>
<td>106</td>
<td>0.162</td>
<td>23</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>HLD with subsystem approach</td>
<td>70</td>
<td>106</td>
<td>0.162</td>
<td>23</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>HLD with basic approach</td>
<td>0</td>
<td>106</td>
<td>0.339</td>
<td>23</td>
<td>21</td>
<td>22</td>
</tr>
</tbody>
</table>

The table shows the comparison of computation time and system characteristics for different MILP models, with the minimum energy consumption approach achieving the lowest computation time. The table highlights the reduction in computation time with the subsystem approach compared to the basic approach.
Case study 1

**23SP1 problem** (One process system)

10 cold process streams

9 hot process streams

4 utility streams

Connection s: 22 / 21

Computation time: 0.169 [s] / 0.339 [s]

$y_{ij}\varphi$: 36 / 106

---

**Computer:** Intel(R) Xeon(R), CPU (3.1 GHz), RAM 8 GB

**MILP:** Ampl

**Analysis:** Matlab

**Solver:** Cplex (version 12.6.0)

---

Anantharaman Ret al., The sequential framework for heat exchanger network synthesis the minimum number of units sub-problem. Computers and Chemical Engineering 2010
Case study 1

23SP1 problem
(One process system)
10 cold process streams
9 hot process streams
4 utility streams
Connection s: 22 /21
Computation time: 0.169 [s] / 0.339 [s]

\[ y_{i,j} \phi \] : 36 /106

Case study 2

22SP1 problem
(Literature)†
11 cold process streams
11 hot process streams
2 utility streams
Connection s: 29/29
Computation time: 0.27 [s]/No convergence after 12 h

\[ y_{i,j} \phi \] : 34 /125

Case study 3

Anantharaman Ret al, The sequential framework for heat exchanger network synthesis the minimum number of units sub-problem. Computers and Chemical Engineering 2010

Computer: Intel(R) Xeon(R), CPU (3.1 GHz), RAM 8 GB
Analysis: Matlab
MILP: Ampl
Solver: Cplex (version 12.6.0)
**Case study 1**

**23SP1 problem**
(One process system)
10 cold process streams
9 hot process streams
4 utility streams
Connection s: 22 /21
Computation time: 0.169 [s] / 0.339 [s]

\[ y_{i,j} = 36 / 106 \]

**Case study 2**

**22SP1 problem**
(Literature)†
11 cold process streams
11 hot process streams
2 utility streams
Connection s: 29/29
Computation time: 0.27 [s] / No convergence after 12 h

\[ y_{i,j} = 34 / 125 \]

**Case study 3**

**52SP1 problem**
(Large-scale site)
23 cold process streams
25 hot process streams
4 utility streams
Connection s: 61/59
Computation time: 0.34 [s] / No convergence after 24 h

\[ y_{i,j} = 63 / 325 \]

---

**Computer:** Intel(R) Xeon(R), CPU (3.1 GHz), RAM 8 GB  
**MILP:** Ampl  
**Analysis:** Matlab  
**Solver:** Cplex (version 12.6.0)

† Anantharaman Ret al, The sequential framework for heat exchanger network synthesis the minimum number of units sub-problem. Computers and Chemical Engineering 2010
• A sequential methodology to design heat exchanger network of large-scale industrial plants
  • Application of geographical separated subsystems
  • Compatible with the minimum cost of energy requirement target

• Minimization of number of connections between process subsystems
  • Overcome the computational complexity of models with numerous streams
  • Satisfy the interest of Total Site Integration between industrial clusters

• Generating optimum or close-to-optimum network
• Generating feasible network for large size models
• Extreme computation time reduction
• Applicable for both grassroots and retrofit design
• Compatible with restricted matches and indirect exchange
• Perspectives
  • Integer cuts to systematically generate heat load distributions
  • Integrate heuristic rules to favour integer sets
  • Improved solving algorithm but introducing connections priorities
  • Integrate with HEN design MINLP algorithms
Thank you for your attention!

Questions

Acknowledgment : Solvay (Rhodia) for the financial support
Case study 2

☑ Heat recovery network synthesis procedure
Case study 2

☑ Heat Load Distribution

result
Case study 3

☑ Heat Load Distribution result
Case study 3

☑ Heat Load Distribution

result
Case study 3

☑ Heat Load Distribution result