A practical approach based on pinch analysis for implementation of heat recovery measures

SCCER EIP Annual Conference 2020

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Overview

- Background and Motivation
- Development of the overall workflow (iterative methodology)
- Data extraction: guided automated extraction
- Ecological considerations in the targeting stage of Pinch Analysis
- Practical experience and expected impacts of the work
- Conclusions
Motivation and Background: WP1 energy and CO₂ savings

Today, Swiss industry uses approx. 43 TWh/a, of which 24 TWhth/a is used for process heating. The estimated EE potential based on the research in WP1 relative to today’s energy consumption is:

<table>
<thead>
<tr>
<th>Research</th>
<th>Economically feasible EE potential (of 43 TWh/a)</th>
<th>Potential energy savings (GWh/a)</th>
<th>Potential CO₂ savings (MtCO₂-eq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EE Improvements (1)</td>
<td>6 – 7 %</td>
<td>2’520 – 2’915</td>
<td>0.45 – 0.52 (2)</td>
</tr>
<tr>
<td>Process integration and heat recovery (3)</td>
<td>9 %</td>
<td>3’930</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td>(16 % of thermal energy demand)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multiple Benefits (4)</td>
<td>Increases above values 10 – 20 %</td>
<td>645 – 1’370</td>
<td>0.12 – 0.25</td>
</tr>
<tr>
<td>Total</td>
<td>approx. 16.5-19 %</td>
<td>7’095 – 8’215</td>
<td>1.27 – 1.47</td>
</tr>
</tbody>
</table>

(1) Research at UNIGE estimates the total economic EE potential across all sectors at 6-7% excluding heat recovery. (a)
(2) CO₂ savings based on Swiss industrial energy consumption weighted average: 0.180 kgCO₂-eq/kWh. (b)
(3) Assuming realization of all pinch analyses in Swiss industry (3’930 GWh/a, see CER 2019). Process integration is (by far) the most effective individual measure. With the use of better methods and tools developed in WP1, process integration can also be applied in SMEs, i.e. the potential can be increased in the future.
(4) Monetized Multiple Benefits decrease payback periods markedly, increasing the number of economically feasible EEMs. A conservative estimate places this increase at approx. 10-20 %.

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(b) SCCER EIP Report in Response to Requirements No. 3 to 5 CER 2019
Motivation and Background
Pinch Analysis Principles

- **Vision of SCCER EIP**
  
  "[...] sustainable use of energy in [...] processes [...] while at the same time keeping the impacts on the economics of the corresponding processes to a minimal."\(^1\)

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\(^1\) SCCER EIP CTI Project Proposal Phase II, 2017
What are the typical challenges that industry faces in order to increase energy efficiency?

- Fast and reliable estimation of saving potential is required to keep costs low
- But the effort required for data extraction is large (60-70% of project duration)
- **Why? Because understanding the process from an energy perspective is difficult**

**Methods and tools for data extraction and energy modelling:**
- Linking process simulation and pinch analysis bi-directionally

**Problem statement** – the duration (and hence cost) of an energy optimization project is largely dependent on understanding the process energetically, correct process requirements extraction, and validating the conceptual design
Extending Pinch Analysis with Process Simulation and Ecological Impact Assessment

**Goal:** Development of a general workflow to guide the engineer in accelerating data extraction, energy modelling and design validation.
Workflow
Overview of iterative methodology

Supports the evolutionary process of conceptual design (pinch analysis) and detailed design (process simulation)
Workflow
General procedure for obtaining implementation concept

- Process requirements
- Data extraction
- Pinch analysis
- EEM concept
- Life cycle assessment
- Implementation

- Heuristics-based extraction
- Automated extraction

- Guided data extraction

- Optimization and selection of $\Delta T_{\text{min}}$

- "Extended" Pinch Analysis
  - Cost targeting
  - Eco-targeting
  - HEN design
Workflow

Data extraction: Process requirements

**Relevant process streams:**

- **Process requirements**

- **Data extraction**
  - Heuristics-based extraction
    - Engineering judgement required
    - "10 Principles of Data Extraction"
    - Grey-box modelling
  - Automated extraction
    - Automatic extraction of stream data, accounting for existing heat exchangers and well-defined unit ops
    - Black, grey, and white-box modelling

**Implementation**

**Process requirements**

(stream data)
Workflow
Data extraction: Definition of critical unit ops

- **Black-box section:** User-defined sections of the process that should remain unaltered.

- **Critical unit ops:** The composition of streams which pass through such unit operations is subject to change. The heat load of these streams may be subject to change. e.g. Reactors, mixers, etc.

- **Non-Critical unit ops:** The composition of streams which pass through such unit operations remains unchanged. The heat load of these streams may or may not be subject to change. e.g. HEXs, valves, etc.
Workflow

Data extraction: Simple example of data extraction

- Arrays of feed IDs, product IDs, Black-box section inlet and outlet IDs

- Matrices of dimension \((m,*)\) for \(m\) unit ops containing
  - Category IDs (e.g. HEX = 7)
  - Inlet IDs (1, 2, ...)
  - Outlet IDs (2, 3, ...)

- Example: The search ID (Feed ID 1) is detected as inlet to unit op 3 (Category ID = 7, HEX); detected as non-critical; Search ID is updated (2); search continues until a critical unit op with the search ID is found
Workflow
Data extraction: Mixing points

- Mixing points present a particular extraction challenge!

- Governing Rule:
  "Do not mix energy flows with different temperature levels"

- Various envisioned scenarios

- Each scenario requires different handling

Scenario:

Extracted requirement:

Heat/Cool all upstream streams to interstitial temperature $T_{\text{mix}}$

Heater/Cooler + $T_{\text{target}}$ Interstitial or black-box mixing points

Heat all upstream streams to hottest upstream temperature

Cool all upstream streams to coldest upstream temperature

Heat/Cool all upstream streams to current mixing temperature $T_{\text{mix}}$

No Heater/Cooler (neutral) or black-box mixing points
Workflow
Data extraction: ChemCAD 7.0 to PinCH 3.0 Interface

MS Excel report from CHEMCAD data, extracted with use of the CC-API and Matlab code

Process Stream Table in PinCH

Note: other software packages could be used
Workflow
Pinch analysis: Cost targeting

- **Optimizing $\Delta T_{\text{min}}$ for costs:** Annual operating costs and annualized investment costs based on economic data
- Leads to pre-design estimate of possible HEN (total HEX area and number of units)
Workflow
Pinch analysis: Eco-targeting

**Cost targeting**

- Yearly costs [CHF/year]
- Yearly environmental impact [t CO₂-eq/year]
- Total
- Operating
- Internal HEX
- Hot utility HEX
- Cold utility HEX

**Eco-targeting**

- Yearly environmental impact [t CO₂-eq/year]
- Total
- Operating
- Internal HEX
- Hot utility HEX
- Cold utility HEX

Choosing $\Delta T_{\text{min}}$: supertargeting
Workflow
Pinch analysis: Eco-targeting

“Extended” Pinch Analysis

Cost targeting Eco-targeting HEN design

Adjusting $\Delta T_{\text{min}}$ for lower environmental impact:
Annualized environmental impact (t CO$_2$-eq) based on utility systems and heat transfer area

- **Eco-targeting** brings transparency to the environmental impacts of $\Delta T_{\text{min}}$ adjustment.
Workflow
Pinch analysis: HEN design; EEM concept

- Heat Exchanger Network synthesis and initial conceptual design proposal, indicating heat exchanger specifications and necessary stream splits
- Conceptual design of other required EEMs, e.g. heat pump and thermal storage integration
- Manual implementation in simulation software for validation

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**Specification table**

<table>
<thead>
<tr>
<th>HEX ID</th>
<th>Stream Matches</th>
<th>Heat Flow (kW)</th>
<th>Hot Side Temperature</th>
<th>Cold Side Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hot Side Fluid ID</td>
<td>Cold Side Fluid ID</td>
<td>Inlet (°C)</td>
<td>Outlet (°C)</td>
</tr>
<tr>
<td>HUX</td>
<td>HU</td>
<td>C3</td>
<td>360</td>
<td>180</td>
</tr>
<tr>
<td>HEXT1</td>
<td>H1</td>
<td>C3</td>
<td>500</td>
<td>175</td>
</tr>
</tbody>
</table>
Practical experience and expected impacts
Steam reforming plant

- Simplified “Utility model” simulation created during data extraction phase:

- Such models often exist as precursors to the detailed simulation and are ideal for algorithmic extraction of requirements

- Essential aid for validation of mass and energy balances and detailed thermodynamic modelling of multi-component mixtures

- At least 25% reduction in duration of process understanding data extraction step due to utilization of workflow elements

Hydrogen production: Simplified utility model simulation
Conclusions

- Workflow forms a solid basis for optimal integration of EEMs and facilitates their implementation – directly supporting the realization of industrial savings potential.

- Process simulation aids faster process understanding and rapid requirements extraction, however the engineer remains an integral part of the procedure.

- Eco-targeting shows transparent trade-off between cost and carbon for stakeholders.

- At least 25% more pinch analyses can be expected through use of the workflow (estimated).
Thank you for your attention
Workflow
Data extraction: Conclusions

- Fully automated creation of the composite curves difficult – the correct requirements must be identified and verified.

- A coded set of extraction rules in the form of an algorithm can be utilized during extraction, accelerating the procedure, and filtering out non-critical data.

- User input is still required to set the boundary conditions, define which feeds and products are fixed requirements, provide constraint information, and review the found requirements!
Expected impact

- Difficult to quantify as there will surely be challenges as now the engineer has to know process simulation and process integration.
- However, given the learn effect of the workflow it will accelerate understanding of how to do data extraction properly and why it is not a trivial task.
- more options can be investigated from an earlier stage for plausibility (design validation).
- a PA project would be done better and with more options evaluated to greater degree in the engineering process to focus on EEMs that will work and minimize complexity and risk.
- we estimated ca. 25 % increase in the number PA being done that could translate roughly to the rate at which they can be done and hence cost which is always deciding factor. The 25 % was based on engineering judgement and simply projection modelling from Simon.
- The basis is the better and quicker process understanding that results if a model (digital twin) exists, quicker understanding how to extract the heating an cooling demands and fluid phase systems for multicomponent system (this is not possible with just PA alone and is done quickly in a Process Simulator).
Workflow
Data extraction: Splits

- Stream splits may incorrectly cause a determination of separate requirements that are, in fact, only one requirement when done manually / with current functionality in PS software.

- Heat integration solution sees the requirement as one stream (existing from stream from ID 5 to 10), rather than two separate streams, to distinguish the problem data from features of the previous solution. (In accordance with extraction rules)

- Engineers are alerted to such instances!
Workflow
Pinch analysis: Eco-targeting

- Adjusting $\Delta T_{\text{min}}$ for environmental impacts:
  Annualised environmental impact based on utility systems and heat transfer area
Workflow
Pinch analysis: Eco-targeting (for CO$_2$)

- Eco-targeting shows possibility of increased heat recovery in processes due to monetizing potential environmental impact savings

\[
\Delta C / \Delta EI \quad [\text{CHF/t CO}_2\text{-eq}]
\]

\[
\Delta (\Delta T_{\text{min,opt,C}}) \quad [\text{K}]
\]

Yearly costs
[CHF/year]

Yearly environmental impact
[t CO$_2$-eq/year]

- Total costs
- Total env. impact

\[
\Delta C = \text{additional total yearly costs}
\]

\[
\Delta EI = \text{additional total CO}_2\text{ savings}
\]