A Multi-Objective Optimization Method to integrate Heat Pumps in Industrial Processes

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Outline

- Introduction
  - Process integration / Case study
  - Challenges
- Methodology
  - Multi-objective optimization
  - Heat pump data base
- Optimization Algorithm
- Results
- Conclusion
Process integration: Optimize the energy efficiency

Representation of industrial processes

Reducing energy consumption and operating costs

Heat pump integration ?!

Energy conversion and utility Units (e.g. heat pumps, steam boiler, cooling water, ...)

Energy conversion and utility Units

Raw materials

Process operation Units

Waste

Energy Services

Products

By-Products

Heat losses

Solids

Water

Gaseous
In the following examples we are discussing the integration of a trigeneration energy conversion system in a brewing process. 

The first step of the methodology is the definition of the energy requirement. In an industrial process, the energy requirement is defined by the set of streams to be heated up and cooled down. The definition of the requirement is obtained from a process model in which the process units are calculated in order to define the hot and cold streams enthalpy-temperature profiles. The details of the analysis are presented in [vx]s the focus being here to comment on the integration of the trigeneration system. This analysis results in the definition of the hot and cold composite curve of the process [Figure v. that allows one to calculate the possible heat recovery by heat exchange between process streams. Resulting from the heat balance of the process requirements, the hot and cold composite define also the heating and cooling requirement of the process. The calculation of the grand composite curve [Figure w. defines the enthalpy-temperature profile of the heating, cooling, and refrigeration requirement. Resulting from the pinch analysis, the heat recovery potential corresponds to 1400 kW in hot and 840 kW in cold, which is more or less doubling the present heat exchange recovery.

Definition of process requirements → Process integration → Definition of minimum energy requirements (hot/cold utility)

Case study: Brewery process

Definition of process requirements

Process integration

Grand composite curve

Definition of minimum energy requirements (hot/cold utility)

Heat pump integration:

- MER hot 1400 kW
- MER cold 840 kW

Case study: Brewery process

Definition of process requirements

PROCESS INTEGRATION

Grand composite curve

Heat pump integration:

Definition of minimum energy requirements (hot/cold utility)

Temperature levels of refrigeration? Different evaporation levels?

Case study: Brewery process

Definition of process requirements

Heat pump integration:

Process integration

Grand composite curve

Definition of minimum energy requirements (hot/cold utility)

Temperature levels of refrigeration? Different evaporation levels?

Heat pump integration with refrigeration cycles?

MER hot 1400 kW

MER cold 840 kW

Case study: Brewery process

Definition of process requirements

Heat pump integration:

Process integration

Grand composite curve

Definition of minimum energy requirements (hot/cold utility)

Heat pump potential? e.g. Mechanical vapour compression?

Temperature levels of refrigeration? Different evaporation levels?

Heat pump integration with refrigeration cycles?


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Challenges for heat pump integration

• Simultaneously integration with other utilities (e.g. cooling water, steam boiler, cogeneration units, ...)

• Find optimal integrated heat pump(s) system for a given process
  • Select appropriate fluids
  • Cycle configuration and operating conditions
  • Temperature / pressure levels (discontinuous optimization problem)
  • Size of installations and economic evaluation

• Realistic solutions: Heat pump data base (collection of realistic heat pumps to be integrated)

• Systematic methodology: Easy to add new heat pumps
Method- Master & Slave Problem

**Process:**
- Definition of heat requirements
- List of utilities

**Master Problem**
- thermo-dynamic calculations
- Heat pump database
Method- Master & Slave Problem

**Process:**
- Definition of heat requirements
- List of utilities

**Master Problem**
- thermo-dynamic calculations
- Heat pump data base

**Slave Problem (MILP)**
- Energy Integration:
  - Objective function: minimize total cost
  - Optimizing utilization rates of utilities ($f_u$) according to the process requirements
Method- Master & Slave Problem

Process:
- Definition of heat requirements
- List of utilities

Master Problem
- Definition of heat requirements
- List of utilities
- Heat pump data base
- thermo-dynamic calculations

Slave Problem (MILP)

Energy Integration:
- Objective function: minimize total cost

Optimizing utilization rates of utilities ($f_u$) according to the process requirements

Objective Functions for multi-objective optimization

MIN
- Operating costs function($f_u$)

MIN
- Investment costs function($f_u,i$)
Method - Master & Slave Problem

**Process:**
Definition of heat requirements
List of utilities

**Master Problem**
- thermo-dynamic calculations
- Heat pump data base

**Decision variables:**
- $k_1$, $k_2$ (temperature levels of heat pump)
- $i$ (interest rate)

**Energy Integration:**
Objective function: minimize total cost

**Slave Problem (MILP)**
Optimizing utilization rates of utilities ($f_u$) according to the process requirements

**Objective Functions for multi-objective optimization**
- $\text{MIN} \quad \text{Operating costs function}(f_u)$
- $\text{MIN} \quad \text{Investment costs function}(f_u, i)$

**Multi-objective optimization**
Performance evaluations of objective functions

Generation of new values for the set of decision variables
Heat pump data base

• Definition of heat pump technologies
  • Compressor types (8) --> Operating condition ranges (volumetric flow rate, pressure ratio)
  • Refrigerants (2) --> Operating condition ranges (temperature levels)

• Each technology is implemented n times --> possibility of multi-stage heat pumps and several times the same type of heat pump

• Heat pump data base is developed in a way that new heat pump models can be added easily

• User can define the list of available heat pumps & change the limits of operating conditions
Optimization Algorithm

\[ \forall c = 1 : n_c \quad \forall f = 1 : n_f \]

1. Definition of decision variables
   - i : investment rate [0\%, 20\%]
   - \( k_{1,c} \) & \( k_{2,c} \) : temperature levels [0, 0.99]

2. Master problem

3. Slave problem

4. Evaluation objective functions

\[
T_{\text{cond},c} = T_{\text{cond},\text{max}}(f) - k_{1,c} \cdot (T_{\text{cond},\text{max}}(f) - T_{\text{eva},\text{min}}(f))
\]

\[
T_{\text{eva},c} = T_{\text{eva},\text{min}}(f) + k_{2,c} \cdot (T_{\text{cond},c} - T_{\text{eva},\text{min}}(f))
\]
Optimization Algorithm

1. Definition of decision variables

2. Master problem

3. Slave problem

4. Evaluation objective functions

\[ \forall c = 1 : n_c \quad \forall f = 1 : n_f \]

- Heat pump data base (thermodynamic calculations)
- Calculation of thermodynamical heat pump cycle for a nominal flow rate
- Definition of thermal streams of heat pumps for heat integration
Optimization Algorithm

\[ \forall c = 1 : n_c \quad \forall f = 1 : n_f \]

1. Definition of decision variables
2. Master problem

3. Slave problem

4. Evaluation objective functions

Heat cascade for Energy integration

\[ \sum_{h,k=1}^{n_{sh,k}} \dot{M}_h q_{h,k} - \sum_{c,k=1}^{n_{sc,k}} \dot{M}_c q_{c,k} + \dot{R}_{k+1} - \dot{R}_k = 0 \quad \forall k = 1, ..., nk \]
\[ \dot{R}_1 = 0 \quad \dot{R}_{nk+1} = 0 \quad \dot{R}_k^- \geq 0 \quad \forall k = 2, ..., nk \]
\[ \dot{M}_h = f_u * \dot{m}_h \quad \dot{M}_c = f_u * \dot{m}_c \]

Operating costs

\[ OpC = c_f^+ \sum_{u=1}^{nu} f_u \dot{E}_{f,u}^+ + c_{el}^+ \sum_{u=1}^{nu} f_u \dot{E}_{el,u}^+ - c_{el}^- \sum_{u=1}^{nu} f_u \dot{E}_{el,u}^- \]

Minimize objective function (MILP - problem)

\[ F_{obj, slave} = TC = OpC + InvC \left( \frac{i(i+1)^n}{(i+1)^n - 1} \right) \]

Optimizing flow rates and utilization factors (f_u) of utilities
Optimization Algorithm

1. Definition of decision variables

2. Master problem

3. Slave problem

4. **Evaluation objective functions**

**Minimize operating costs (f_u)**

\[ OpC = c_f^+ \sum_{u=1}^{nu} f_u \dot{E}_{f,u}^+ + c_{el}^+ \sum_{u=1}^{nu} f_u \dot{E}_{el,u}^+ - c_{el}^- \sum_{u=1}^{nu} f_u \dot{E}_{el,u}^- \]

**Minimize investment costs (f_{HPc})**

\[ InvC = \sum a \cdot (f_{HPc} \dot{E}_{el,HPc}^+)^b \]

Performances to multi-objective optimization using evolutionary algorithm
(Generating new values for the set of decision variables for the next iteration step)
Results for the case study (brewery process)

Pareto front: optimal solutions in terms of operating and investment costs after 1000 iterations: refrigerants: R717 / R134a HPs

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<td>562.3</td>
<td>368.2</td>
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Example of Integrated composite curves

<table>
<thead>
<tr>
<th></th>
<th>InvC</th>
<th>OpC</th>
<th>Fuel</th>
<th>Cooling water</th>
<th>Electricity</th>
<th>HP units</th>
</tr>
</thead>
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Heat pump integration

- **Advantages**
  - Systematic and flexible integration of heat pumps (technologies, fluids, multi-stage)
  - Optimal solutions which can be analyzed in a second step for approbation

- **Drawbacks**
  - Time - consuming
  - Experts can find easily good results by analyzing grand composite curves
    - Initialization procedure?
Conclusion

- Optimal heat pump integration (single & multi stage)

- Systematic heat pump data base approach
  - Easy to add new heat pump model (fluids, mixtures, ...)

- All points on the pareto front represent optimal feasible solutions

- Final solution can be chosen by applying economical analysis
Thank you for your attention!