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

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LENI Systems

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Outline

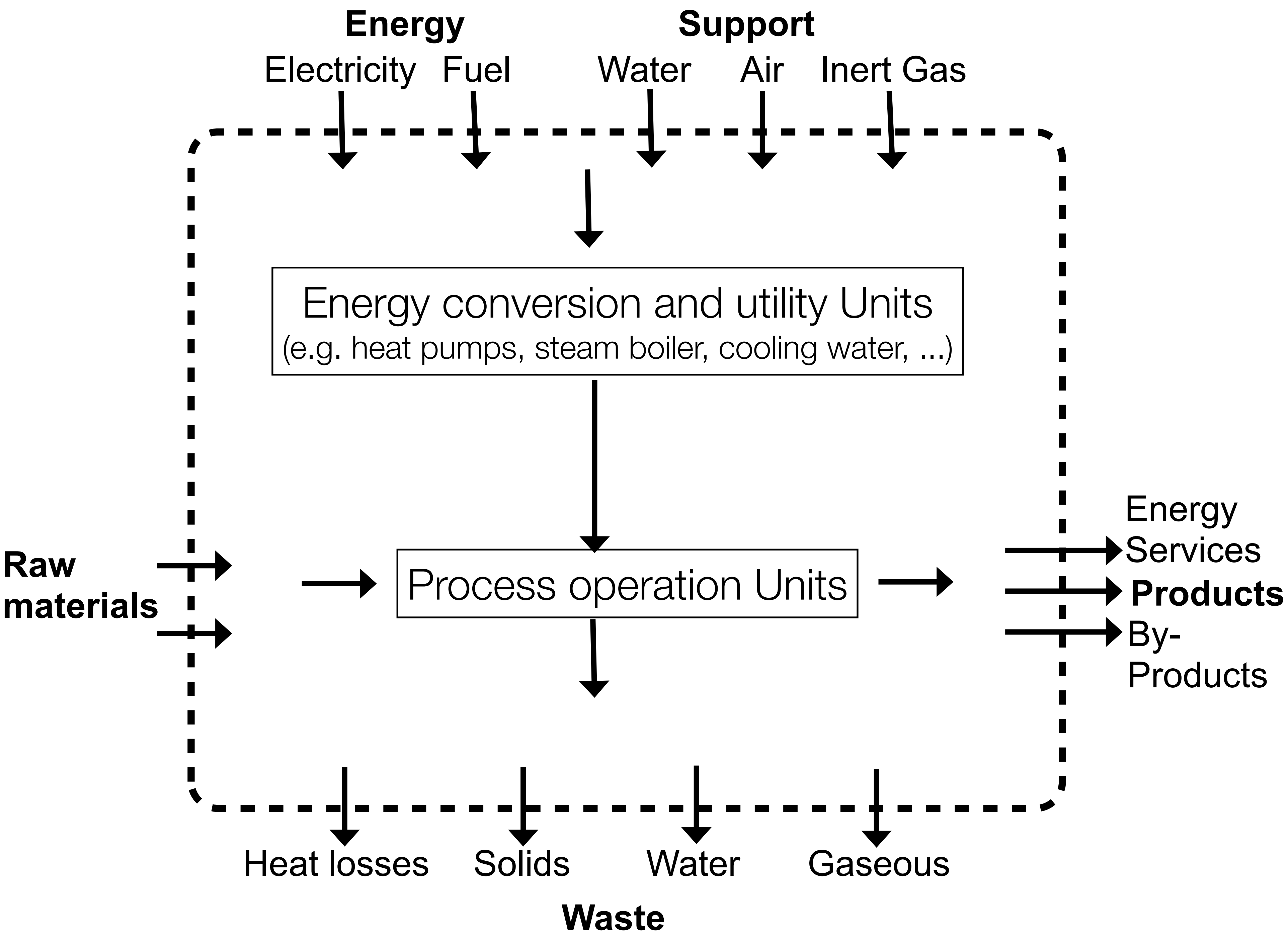
- Introduction
  - Process integration / Case study
  - Challenges
- Methodology
  - Multi - objective optimization
  - Heat pump data base
- Optimization Algorithm
- Results
- Conclusion

Process integration: Optimize the energy efficiency

Representation of industrial processes

Reducing energy consumption and operating costs

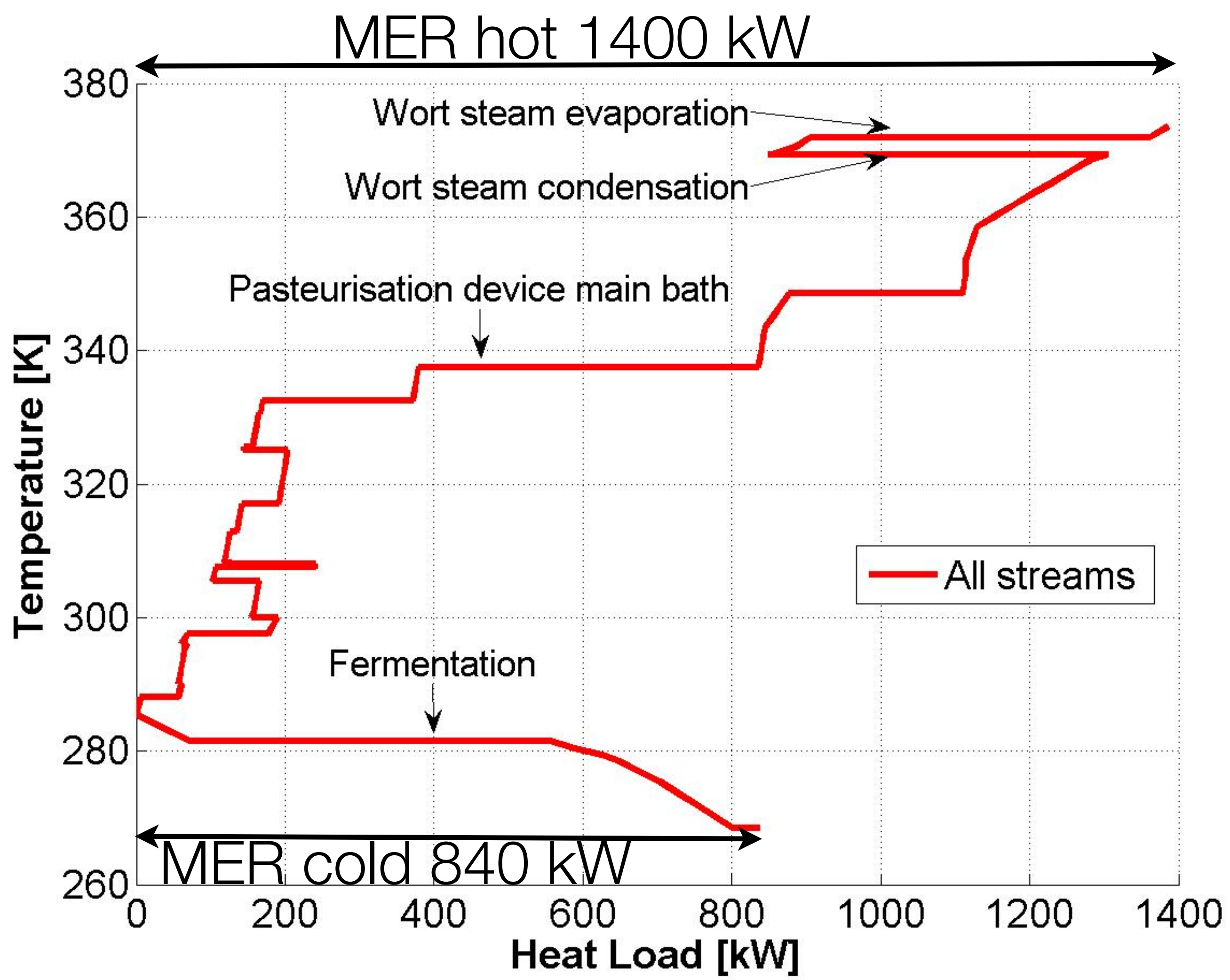
Heat pump integration ?!



Case study : Brewery process

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

Grand composite curve



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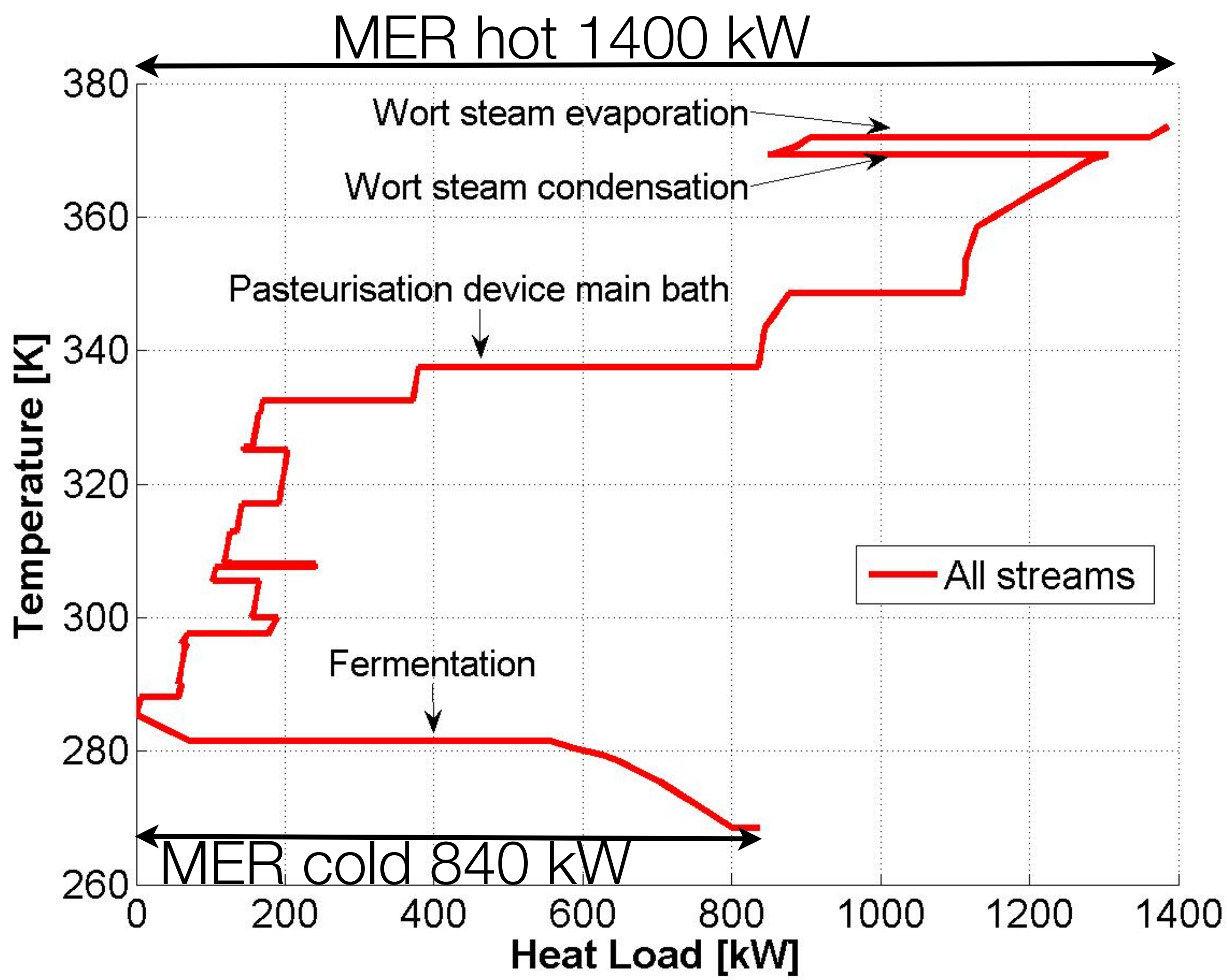

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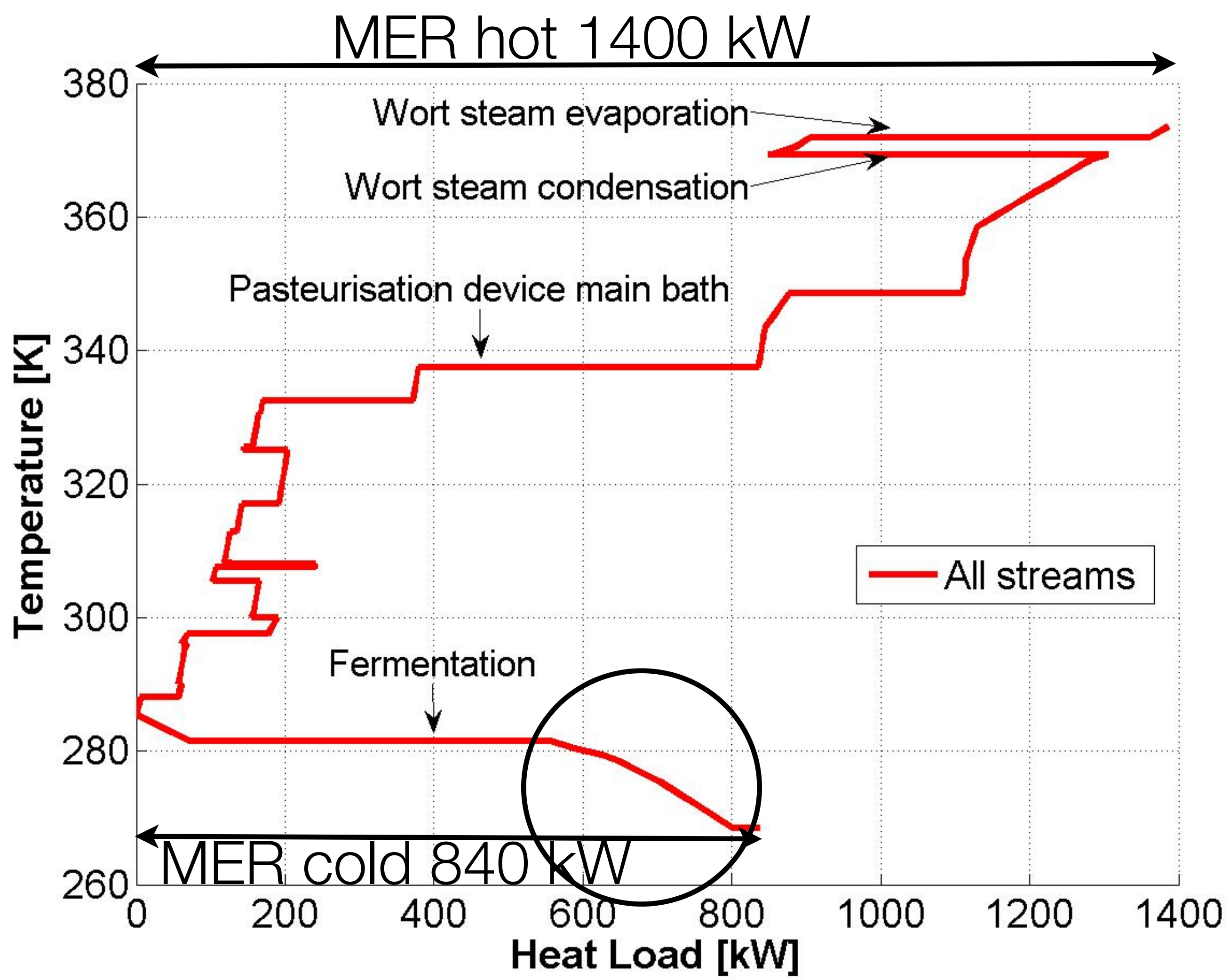

Temperature levels of refrigeration ? Different evaporation levels ?

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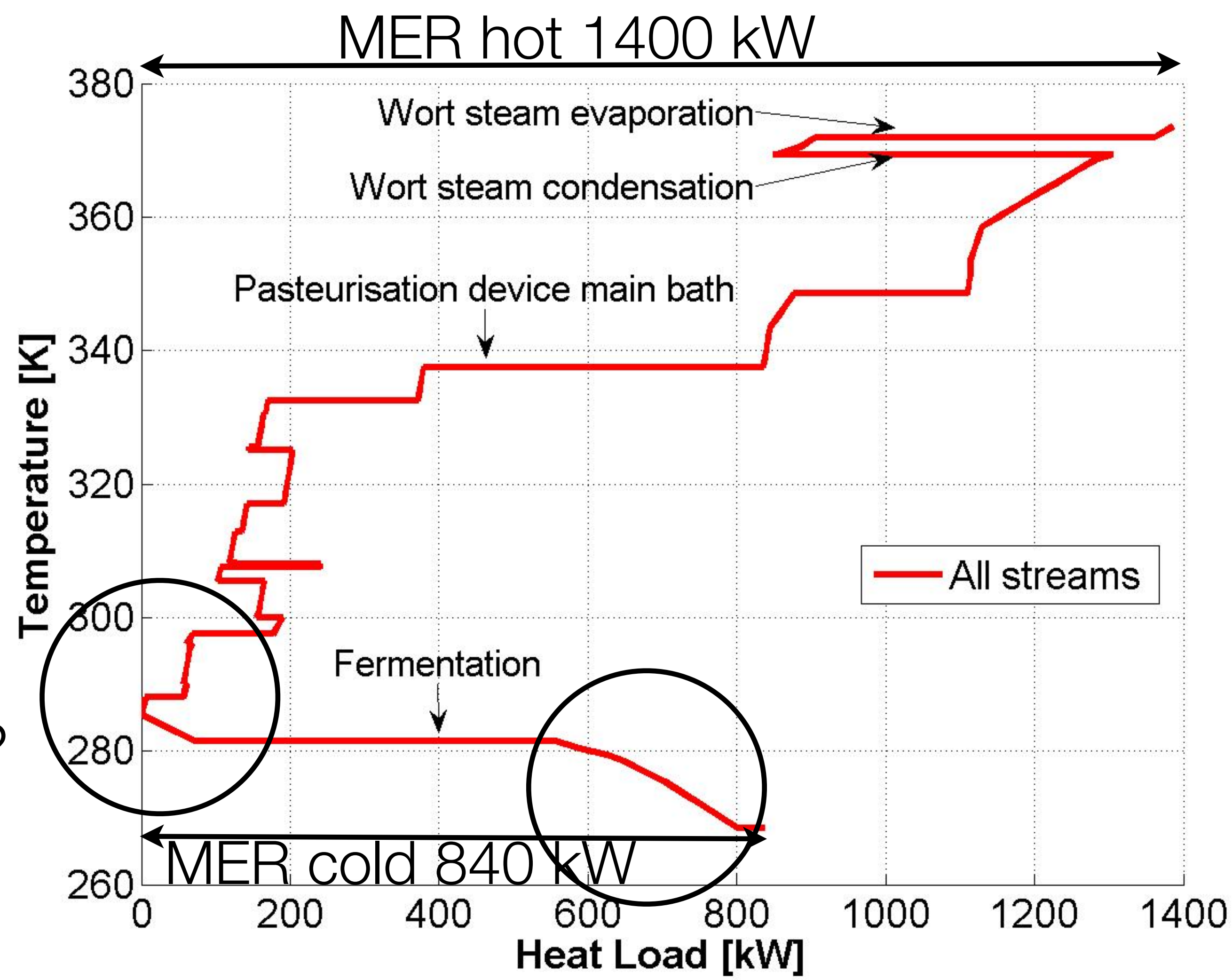

Heat pump integration with refrigeration cycles ?

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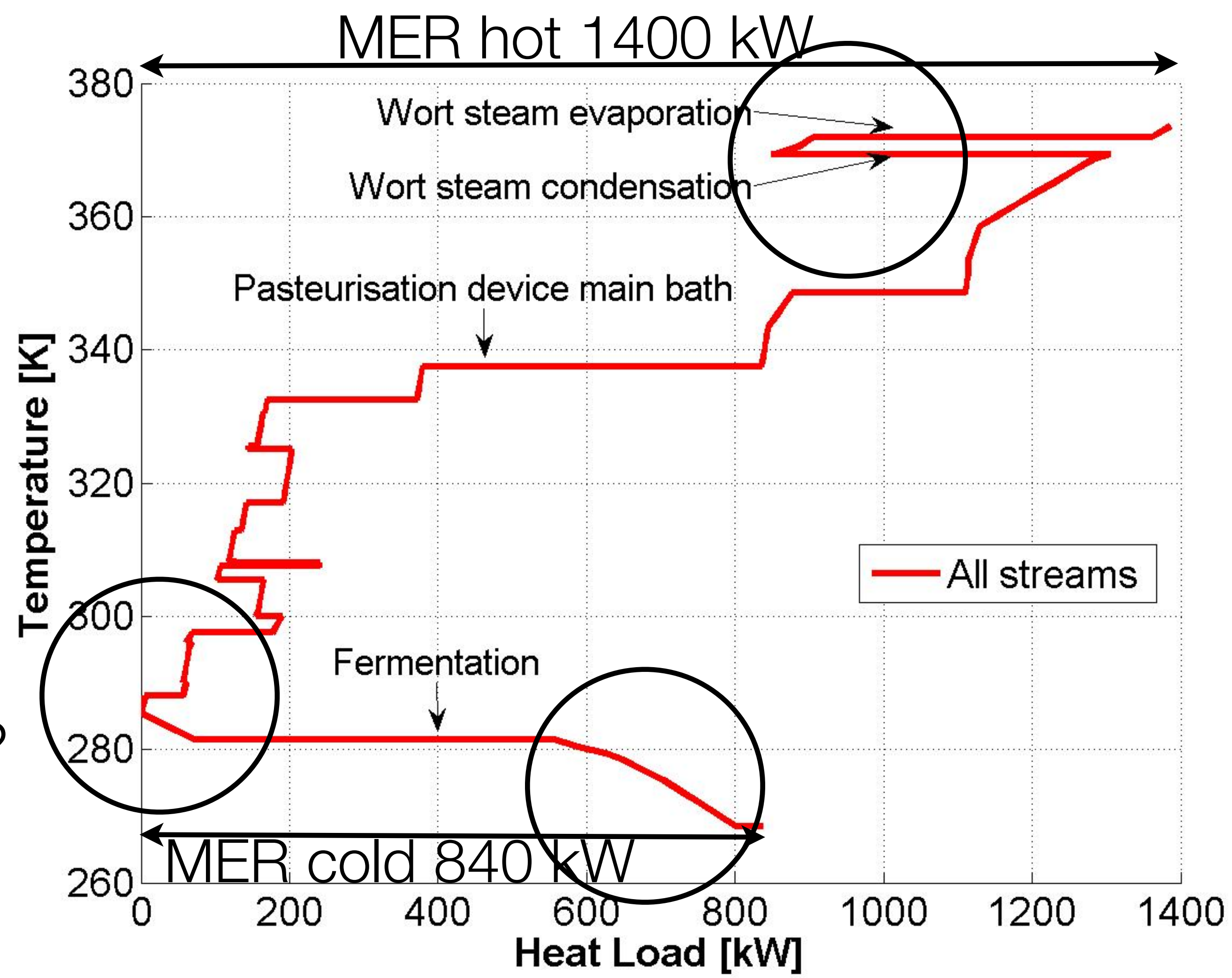

Heat pump potential ? e.g. Mechanical vapour compression ?

Heat pump integration with refrigeration cycles ?

Temperature levels of refrigeration ? Different evaporation levels ?

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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

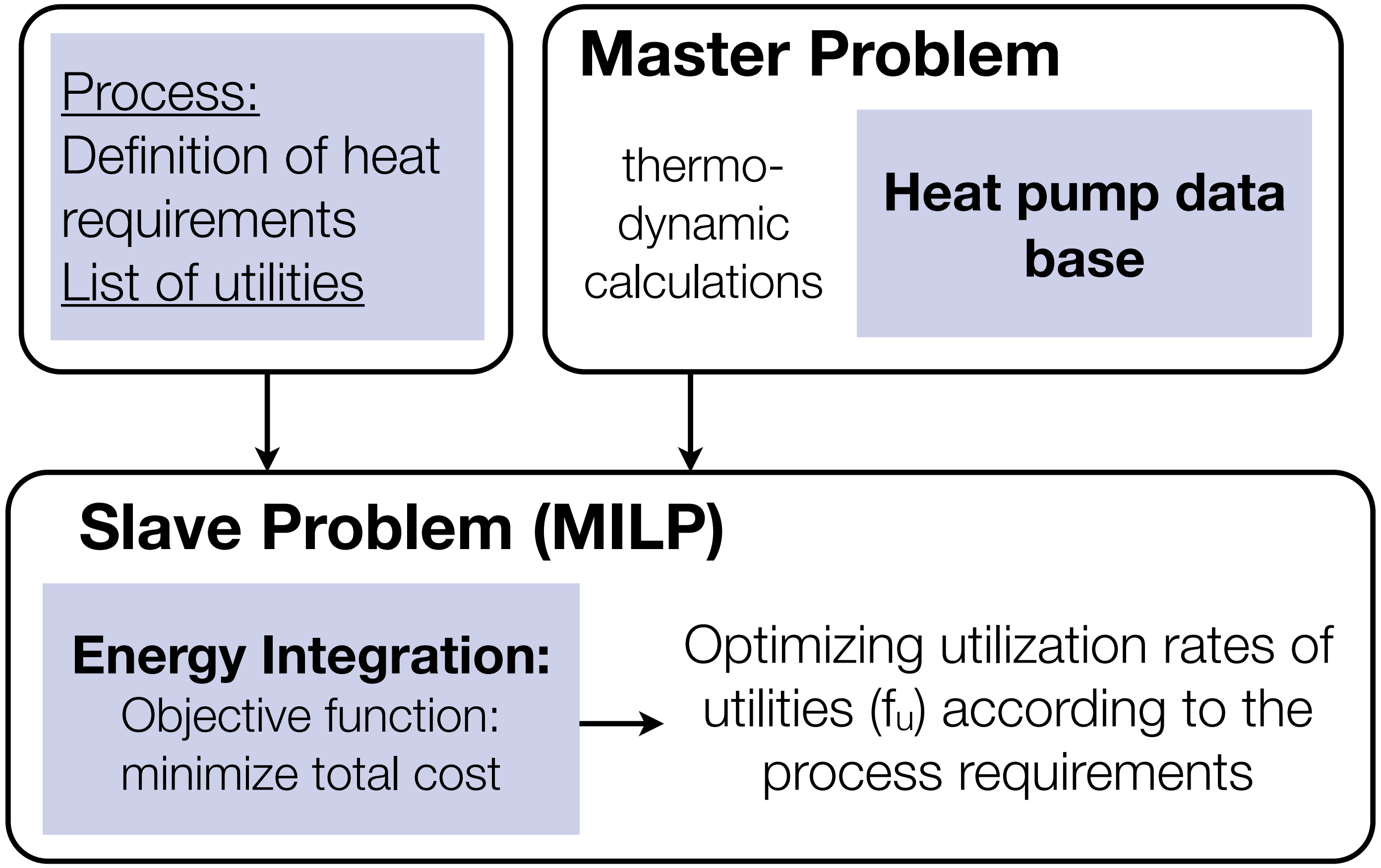
Process:
Definition of heat requirements
List of utilities

Master Problem

thermo-dynamic calculations

Heat pump data base

Method- Master & Slave Problem



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

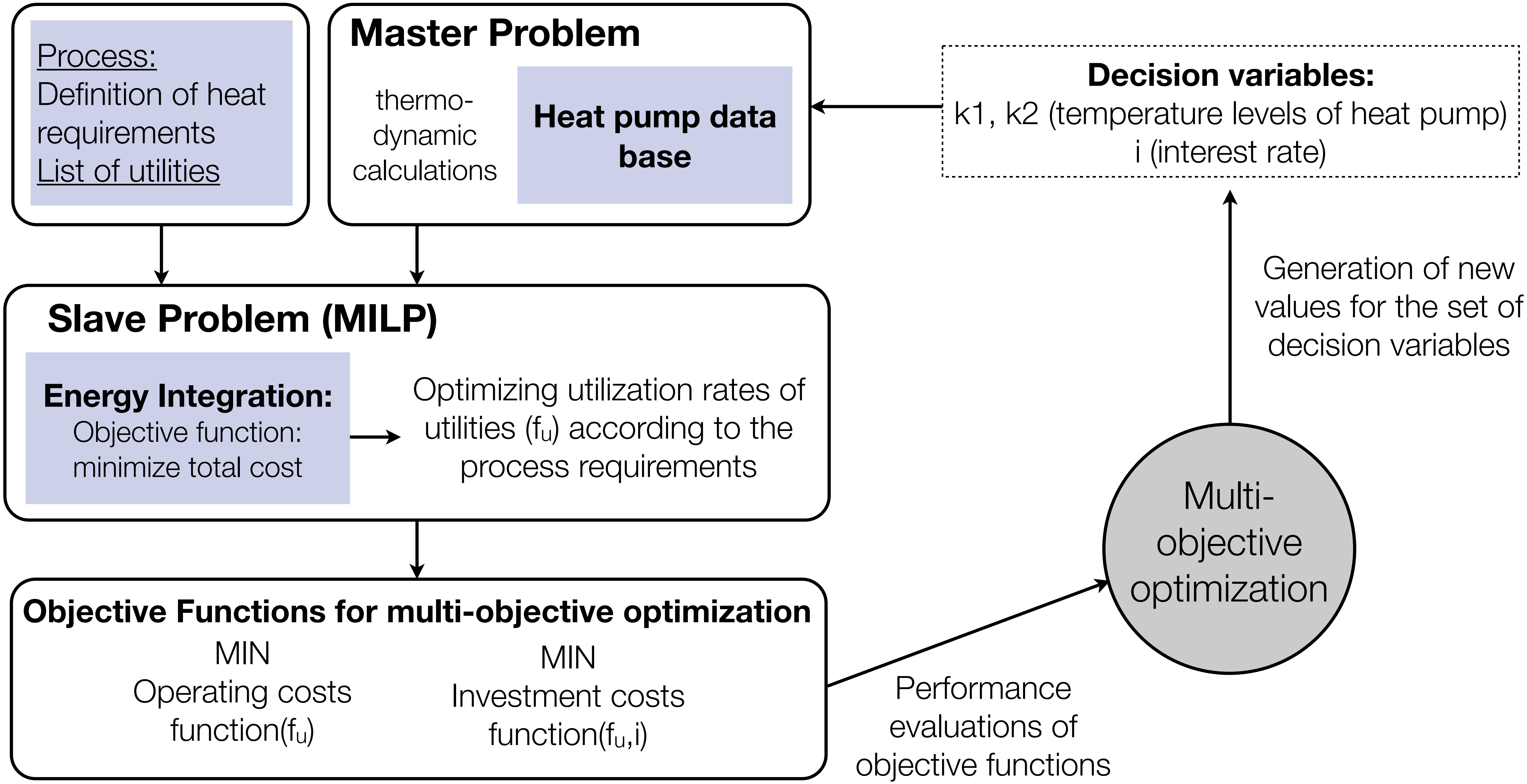
Optimizing utilization rates of utilities (f_u) according to the process requirements

Objective Functions for multi-objective optimization

MIN
Operating costs
function(f_u)

MIN
Investment costs
function(f_u,i)

Method- Master & Slave Problem



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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

$$\forall c = 1 : n_c \qquad \forall f = 1 : n_f$$

1. Definition of decision variables

2. Master problem

3. Slave problem

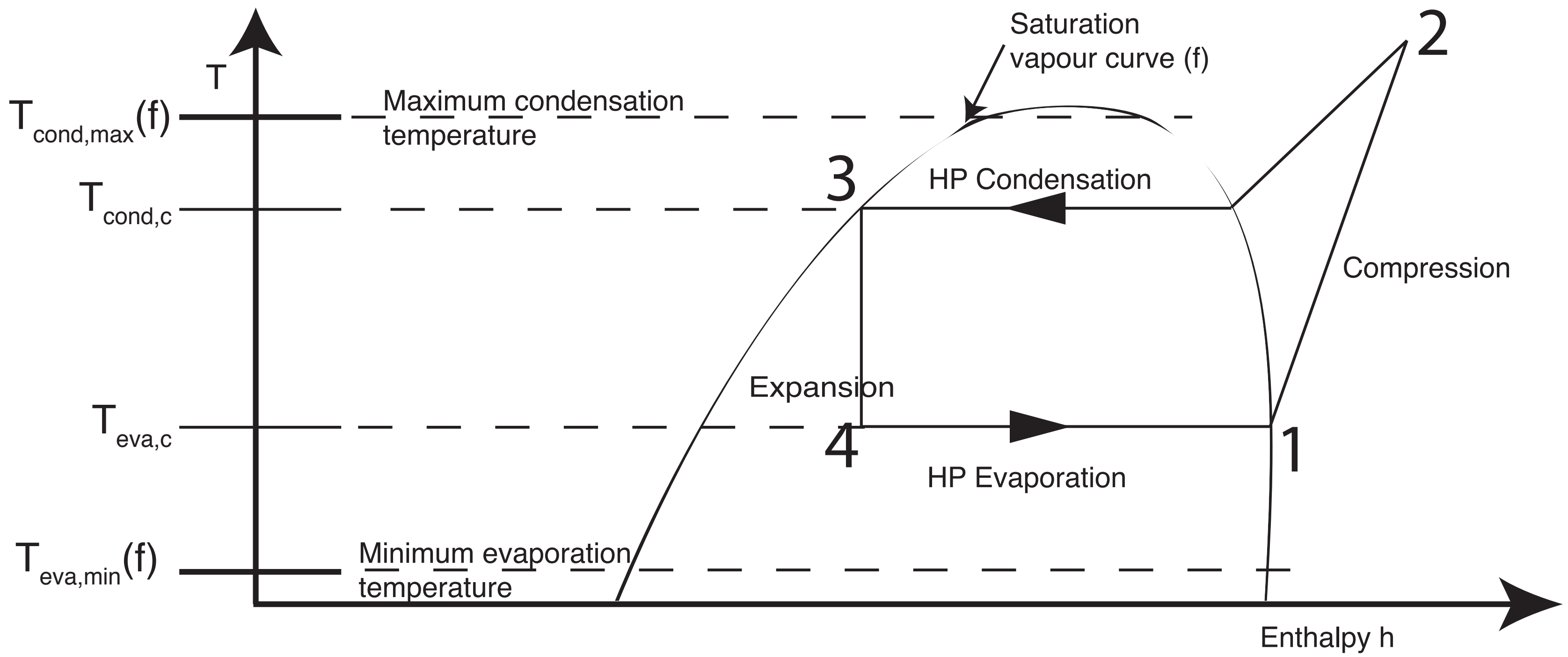
4. Evaluation objective functions

i : investment rate [0%,20%]

$k_{1,c}$ & $k_{2,c}$: temperature levels [0,0.99]

$\forall c = 1 : n_c \qquad \forall f = 1 : n_f$

Example for one refrigerant



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

$$T_{eva,c} = T_{eva,min}(f) + k_{2,c} \cdot (T_{cond,c} - T_{eva,min}(f))$$

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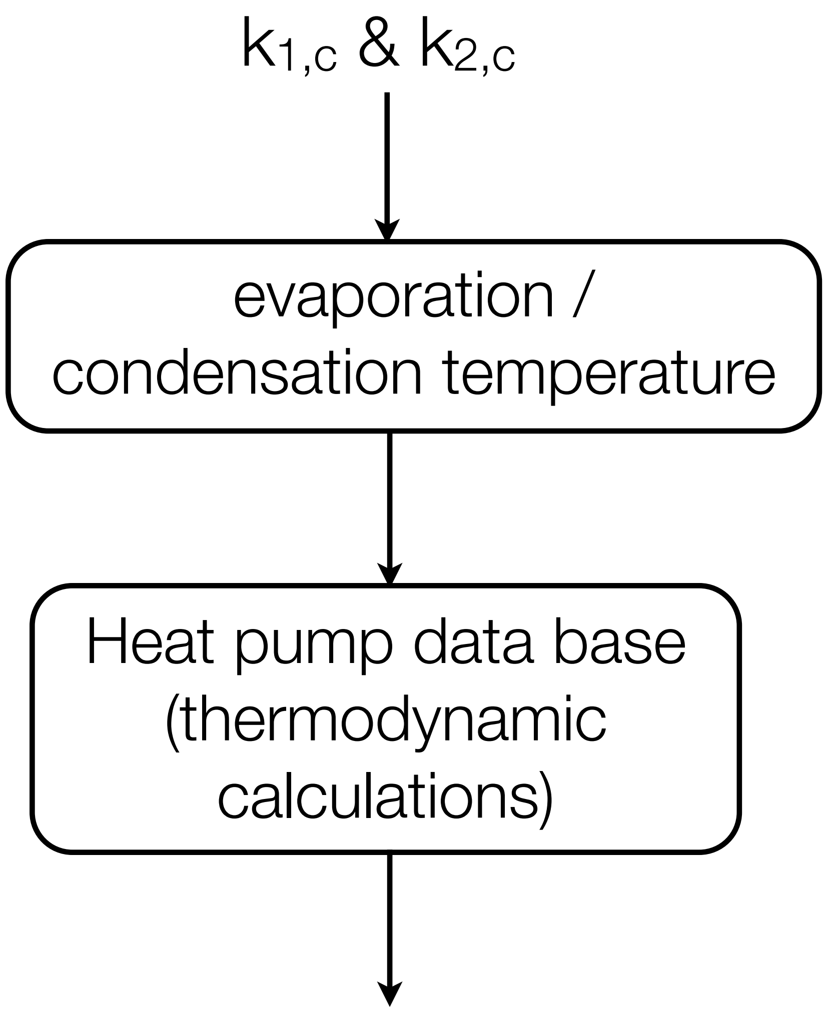

Calculation of thermodynamical heat pump cycle for a nominal flow rate
Definition of thermal streams of heat pumps for heat integration

Optimization Algorithm

$$\forall c = 1 : n_c \qquad \forall f = 1 : n_f$$

1. Definition of decision variables
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Heat cascade for Energy integration

$$\sum_{h_k=1}^{ns_{h,k}} \dot{M}_h q_{h,k} - \sum_{c_k=1}^{ns_{c,k}} \dot{M}_c q_{c,k} + \dot{R}_{k+1} - \dot{R}_k = 0 \quad \forall k = 1..., nk$$

$$\dot{R}_1 = 0 \quad \dot{R}_{nk+1} = 0 \qquad \dot{R}_k^- \geq 0 \quad \forall k = 2..., nk$$

$$\dot{M}_h = f_u * \dot{m}_h \qquad \dot{M}_c = f_u * \dot{m}_c$$

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)

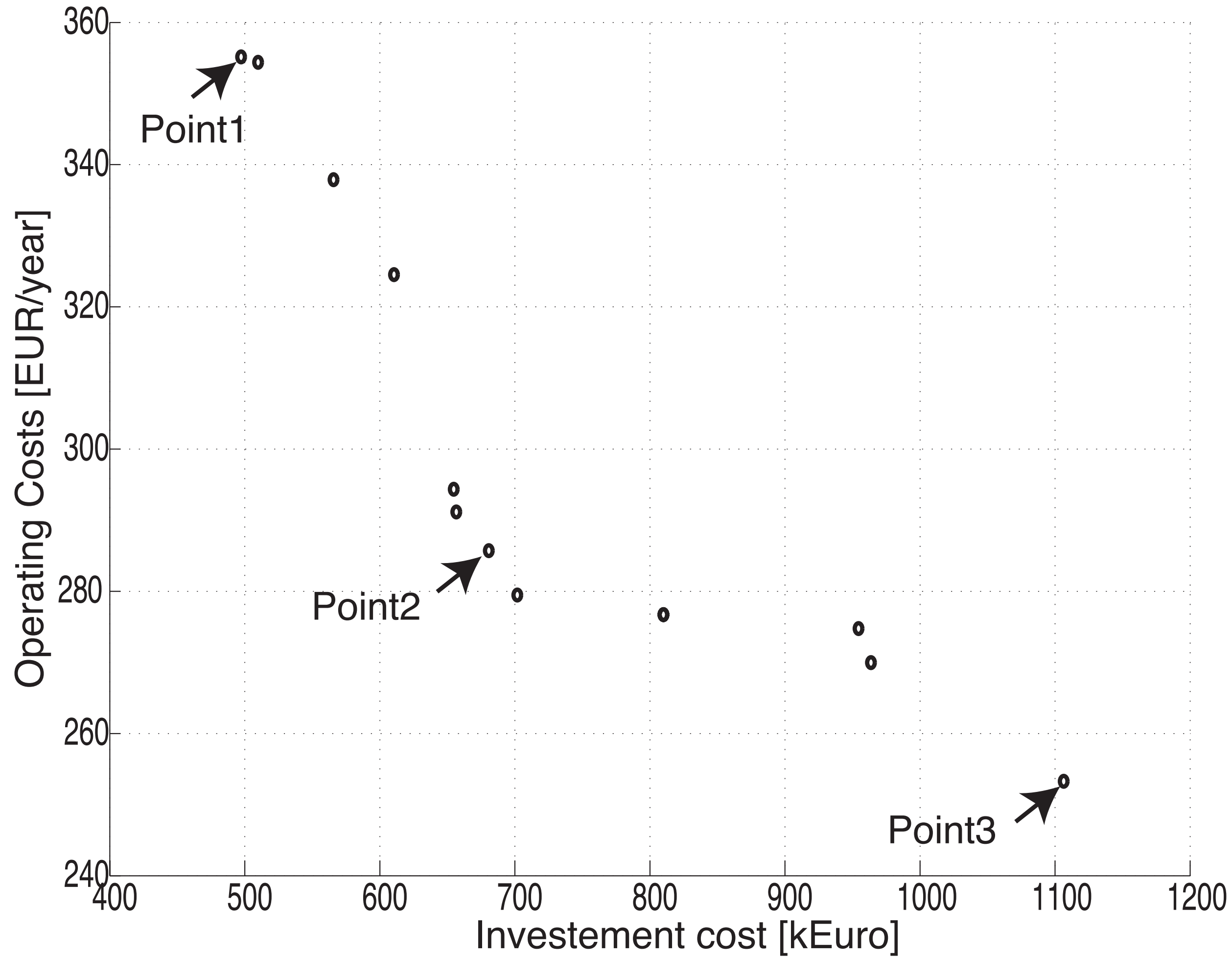
$$OpC = c_f^+ \sum_{u=1}^{nu} f_u \dot{E}_{f,u}^+ + c_{el}^+ \sum_{u=1}^{nu} f_u \dot{E}_{el,u}^+ - c_{el}^- \sum_{u=1}^{nu} f_u \dot{E}_{el,u}^-$$

Minimize investment costs (f_{HPc})

$$InvC = \sum a \cdot (f_{HP_c} \dot{E}_{el_{HP_c}}^+)^b$$

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)

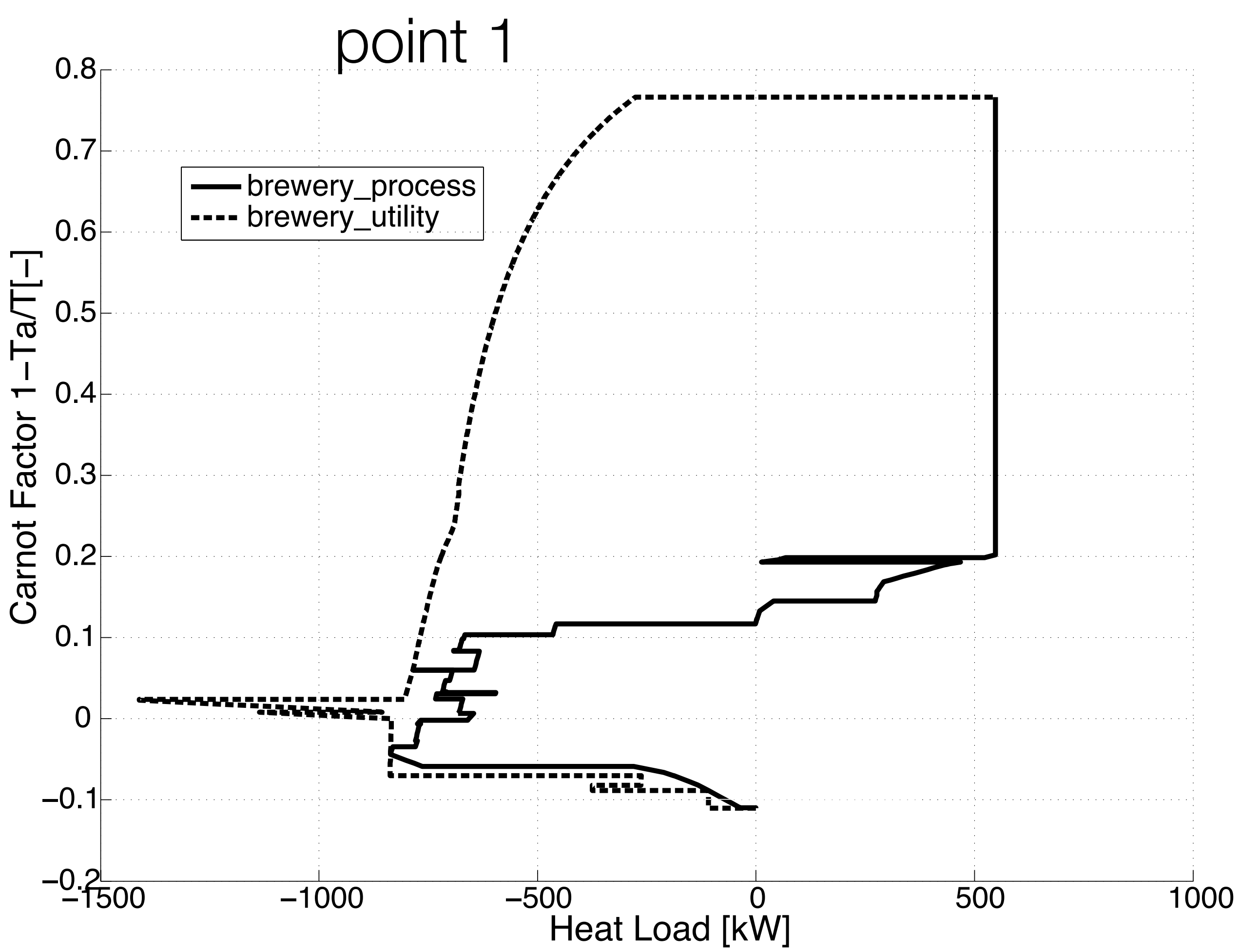


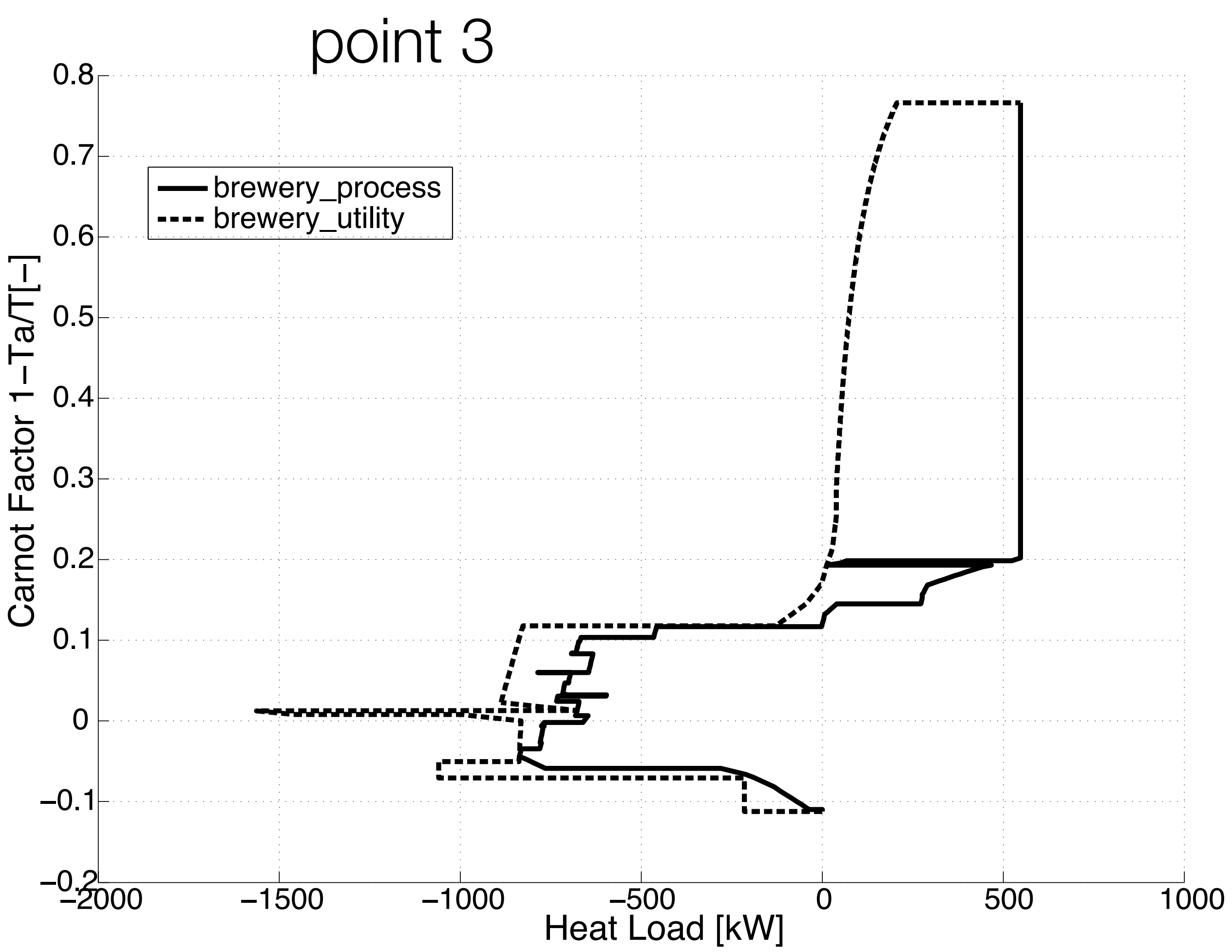
Pareto front: optimal solutions in terms of operating and investment costs

after 1000 iterations
refrigerants: R717 / R134a HPs

	InvC [kEuro]	OpC [kEuro/year]	Fuel [kW]	Cooling water [kW]	Electricity [kW]	HP units [-]
point1	497.3	355.2	1485	860	206	3
point2	680.8	285.7	615.3	482.4	532.3	5
point3	1106.0	253.3	562.3	368.2	461.3	5

Example of Integrated composite curves





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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 !