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Energy integration of industrial sites with heat exchange restrictions

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ABSTRACT

Process integration methods aim at identifying options for heat recovery and optimal energy conversion in industrial processes. This paper introduces a targeting method, which includes heat exchange restrictions between process sub-systems. The problem is formulated as a MILP (mixed integer linear programming) problem, which considers not only restricted matches but also the optimal integration of intermediate heat transfer units and the energy conversion system, like heat pumping and combined heat and power production. Moreover a new mathematical formulation is presented to chose optimal heat transfer technologies. For solutions avoiding the energy penalty, the composite curves of optimal heat transfer units have to be embedded between the new generated hot and cold envelope composite curves. The application of the method is illustrated through an industrial example from the pulp and paper industry.

1. Introduction

Pinch analysis is a promising tool to optimize the energy efficiency of industrial processes. To realize the maximum heat recovery and the optimal integration of utilities to supply process heating and cooling requirements, first the heat load distribution based on process and optimal utility streams has to be calculated. One major difficulty is the assumption that any hot stream can exchange heat with any cold stream. In reality, heat exchanges become difficult or even impossible, due to constraints such as the distance between streams or product quality and/or safety reasons, or due to system dynamics such as non-simultaneous operations.

Forbidden matches between certain pairs of process streams are considered by Papoulias and Grossmann (1983). They propose a mathematical formulation to identify the heat load distribution that minimizes the energy penalty of restricted matches without proposing any solutions for adding heat transfer fluids or integrating utility systems. Also Cerda and Westerberg (1983) studied heat exchanger networks with restricted matches and propose an algorithm which imposes constraints disallowing in part or in total the matching of stream pairs.

The total site approach, presented by Dhole and Linnhoff (1992) and later by Klemeš, Dhole, Raissi, Perry, and Puigjaner (1997), implicitly accounts for restricted matches before designing the heat exchanger network. The hot and cold streams, resulting from sub-systems without considering self-sufficient pockets, are separated graphically. The sub-systems can only exchange heat via the steam system. Also Hui and Ahmad (1994) studied total site integration with indirect heat transfer between process plants through steam utilization from the steam network. In this work exergy analysis is used and the self-sufficient zones were not always suppressed. More directly, Rodera and Bagajewicz (1999) pointed out that skipping the self sufficient pocket can reduce significantly the opportunities for heat recovery and they present a transship model which calculates the heat to be transferred between two process plants. An extension to several plants is proposed later by the same authors (Bagajewicz & Rodera, 2000, 2002). Bagajewicz and Rodera (2001) propose a single heat belt, which exchanges heat between process plants by an intermediate fluid. Only for special cases (3 process plants) this problem can be solved with a MILP formulation. Combining the total site proposed by Dhole and Linnhoff (1992) and the approach of Bagajewicz and Rodera (2000), Bandyopadhyay, Varghese, and Bansal (2010) introduces site level grand composite curves for indirect heat transfer. Indirect heat transfer between plants and an extension to industrial zones containing several process plants is presented by Stijepovic and Linke (2011). Mainly the utility system is optimized and only waste heat can be transferred between process plants.

Maréchal and Kalitventzeff (1999) propose a MILP strategy, which integrates forbidden heat exchange connections as constraints in the targeting phase, and allows the integration of heat transfer fluids. The penalty in terms of utility and operating costs can be considered.

This paper proposes an extension of the MILP strategy and, depending on a given process or system, a systematic approach to define the members of sub-systems. Heat exchange between

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Nomenclature

Latin letters

$\dot{\boldsymbol{E}}_{\boldsymbol{el}}$	total electricity demand (+) or excess (−) [kW]
$\dot{\boldsymbol{Q}}_{\boldsymbol{c,env,k}}$	heat load of fictive cold envelope stream in interval k [kW]
$\dot{\boldsymbol{Q}}_{\boldsymbol{h,env,k}}$	heat load of fictive hot envelope stream in interval k [kW]
$\dot{\boldsymbol{Q}}_{\boldsymbol{hts(s),s,k}}$	heat provided by the heat transfer system (−) to sub-system s or heat removed by the heat transfer system (+) from sub-system s in interval k [kW]
$\dot{\boldsymbol{Q}}_{\boldsymbol{hts+1,k}}$	heat provided by the higher heat transfer system (−) or heat removed by the higher heat transfer system (+)
$\dot{\boldsymbol{R}}_{\boldsymbol{k}}$	cascaded heat to lower interval k [kW]
$\boldsymbol{f_u}$	multiplication factor of unit u
$\mathbf{y_{ij}}$	integer variable representing connection between hot stream i and cold stream j
$\mathbf{y_u}$	integer variable representing the existence (1) or not (0) of unit u
$\dot{E}_{el,u}$	consumed (+)/produced (−) nominal electricity by unit u [kW]
$\dot{E}_{f,u}$	consumed (+) nominal fuel by unit u [kW]
$\dot{Q}$	heat load [kW]
A	heat exchanger area [m^2]
c_{el}	electricity price for import (+) or export (−) [€/kWh$_{el}$]
c_f	fuel price [€/kWh]
c_u	nominal utility operating cost (excluding fuel and electricity costs) [€/h]
d	yearly operating hours [h/year]
$InvC$	investment costs [€]
N_{min}	minimum number of heat exchanger connections
nf	number of different fuels
nk	number of temperature intervals
nps	number of parent sub-systems
ns	number of streams
$nsub$	number of sub-systems
nu	number of units
OpC	operating costs [€/year]
T	temperature [K]

Greek letters

δ	numerical precision parameter for optimization
γ	exponent for investment cost estimation
κ	weighting factor

Subscripts

c	cold streams
env	index for envelope composite curves
h	hot streams
hts	index for heat transfer system
k	temperature interval
$mean$	mean value
o	optimal value
ref	reference value
s	index for sub-system
u	index for unit

Superscripts

+	entering the system
−	leaving the system
max	maximum value
min	minimum value

Conventions

bold italic characters optimization variables

sub-systems is not allowed, but heat can be transferred indirectly through the heat transfer system. The main contributions are summarized in the following. First, it is important to emphasize that the heat exchange restrictions are considered in the targeting stage, contrary to the approaches presented by Papoulias and Grossmann (1983) and Cerda and Westerberg (1983). Compared to conventional pinch analysis based on graphical methods, which assumes that any heat exchange connection is feasible, the problem is formulated as a MILP problem with heat exchange restrictions. Heat transfer units (e.g. steam network but also heat transfer technologies such as heat recovery loops) can be considered and are integrated simultaneously with the energy conversion system (utility units) and the process units. Another advantage of the proposed targeting method is that the self-sufficient pockets are not suppressed and therefore the combined heat and power production is not penalized. The proposed method can be used for plant wide integration (or total site integration) where each plant is defined as a sub-system, but it can also be used inside a plant (e.g. heat exchange restrictions between process operation units because of safety reasons or non simultaneous process operations). An extension of multi level sub-systems definition (e.g. heat exchange restrictions between several plants combined with heat exchange restrictions inside a process plant) easily becomes possible and the corresponding equations are presented. In addition, the envelope composite curves are introduced, in order to choose optimal heat transfer units. Based on the sub-system definition, a new MILP formulation is proposed to calculate the fictive hot and cold streams, which embed optimal heat transfer technology.

2. Method

The new methodology, proposed here, takes into account heat exchange restrictions at the targeting stage by dividing industrial plants into sub-systems. By definition, heat recovery and heat exchanges between hot and cold streams inside a sub-system are possible but no direct heat exchange with other sub-systems is allowed (Fig. 1).

The only way to satisfy heat demands of sub-systems is to exchange heat with units belonging to the heat transfer system. Two types of units can be distinguished: heat transfer units (HTU) and common utilities (CU). HTUs are defined when heat has to be transferred between two sub-systems (e.g. hot water heat recovery loop). CUs (e.g. steam boiler or cooling water) can be defined as heat transfer system when they can exchange heat without restrictions with all sub-systems. If not, it is also possible to define them in a related sub-system. In this case, suitable HTUs (e.g. a steam network for transferring heat from a boiler to the process) have to be defined to ensure the indirect heat transfer.

The flows rates of the heat transfer fluids are optimized in order to minimize the energy penalty of restricted matches between sub-systems.

Particular attention is given to the choice of optimal heat transfer technology by using a new mathematical formulation to draw the envelope composite curves for indirect heat exchange. The problem is solved in several steps which are summarized in Table 1.

In the first step, a MILP problem without restricted matches is solved. This defines the optimal flow rates in the energy conversion systems (utility system) and the minimum operating costs (Section 3.1). The energy penalty is then calculated by solving a MILP problem including restricted matches between sub-systems but with

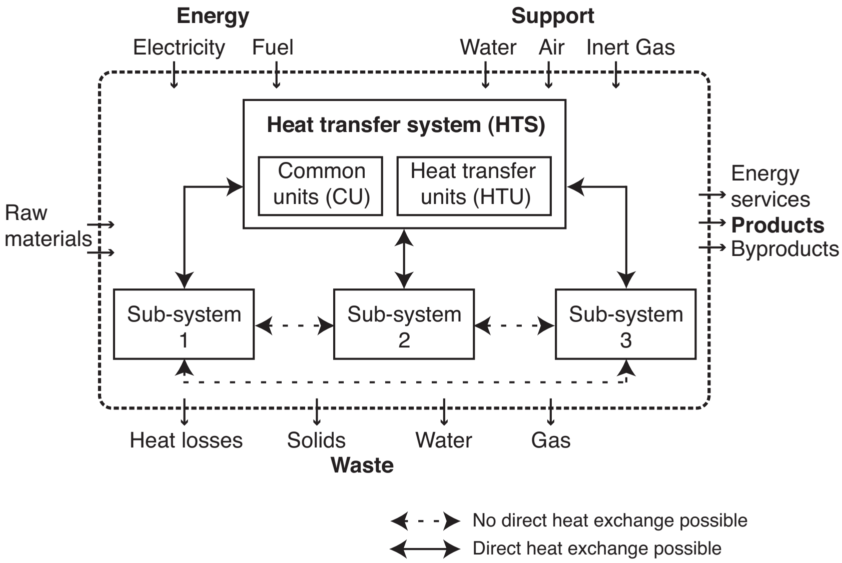

Fig. 1. Definition of subsystems.

no possibility to integrate heat transfer technologies (Section 3.2). In the next step the envelope composite curves are computed by using a MILP problem including industrial constraints and fictive hot and cold streams for the heat transfer system (Section 3.3). It represents the necessary enthalpy temperature profiles for optimal heat transfer systems to avoid the energy penalty. The identified HTUs are then added in the list of hot and cold streams and a final MILP problem including restricted matches and chosen optimal heat transfer units can be resolved. Their flow rates are calculated by solving again the MILP problem of Section 3.2. For large scale problems, it is possible to perform an optional multi-objective optimization in order to choose between different HTUs (Section 3.4). As a last step, the heat load distribution problem (HLD), proposed by Maréchal and Kalitventzeff (1989), is then adapted to incorporate the definition of sub-systems and restricted matches (Section 3.5). The resolution of the HLD problem becomes much easier and is the basis for the heat exchanger network design. The major advantages of the presented method are:

- The process is divided into sub-systems (more realist than just heat restriction constraints between two streams); heat exchange inside sub-systems is favored.
- On the contrary to the total site approach, self-sufficient pockets are not suppressed. This allows the maximization of the combined heat and power production.
- The design of the heat exchanger network becomes easier and more flexible and implicitly includes topological constraints.
- Simultaneous optimization of the utility integration and the heat transfer system defines the complete list of streams including utility streams for the heat load distribution.
- Optimal heat transfer technologies can be identified and optimized.
- The combinatorial nature of the HEN design is reduced.

3. Heat cascade formulations

3.1. General MILP formulation without restricted matches

This MILP formulation proposed by Maréchal and Kalitventzeff (1998) solves the heat cascade and calculates the maximum heat recovery. Energy conversion units are integrated and combined heat and power production is maximized. The objective is to minimize the operating costs (Eq. (1)).

$$F_{obj} = min \left(d \cdot \left(\sum_{f=1}^{nf} \left(c_f^+ \sum_{u=1}^{nu} \boldsymbol{f_u} \dot{E}_{f,u}^+ \right) + c_{el}^+ \dot{\boldsymbol{E}}_{\boldsymbol{el}}^+ - c_{el}^- \dot{\boldsymbol{E}}_{\boldsymbol{el}}^- + \sum_{u=1}^{nu} \boldsymbol{f_u} c_u \right) \right) \quad (1)$$

Table 1
Problem algorithm.

Step	Name	Goal	MILP problem
1	No restrictions	Find best case and corresponding multiplication factors and operating costs	Section 3.1
2	Restrictions	Visualize energy penalty including heat exchange restrictions	Section 3.2
3	Envelope	Visualize envelope composite curves for defining optimal HTUs (input: multiplication factors or operating costs from step 1)	Section 3.3
4	Integrated HTUs	Choose and integrate HTUs with the help of the previous step	Section 3.2
4a	Optimization (optional)	Multi objective optimization for choosing among several possibilities	Section 3.4
5	Heat load distribution	Compute heat load distribution of final solution	Section 3.5

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The electricity import and export are given by Eqs. (2) and (3) respectively. Both equations are necessary to distinguish the price for electricity import and export.

$$\sum_{u=1}^{nu} \boldsymbol{f_u} \dot{\boldsymbol{E}}^{+}_{\boldsymbol{el,u}} + \dot{\boldsymbol{E}}^{+}_{\boldsymbol{el}} - \sum_{u=1}^{nu} \boldsymbol{f_u} \dot{\boldsymbol{E}}^{-}_{\boldsymbol{el,u}} \geq 0 \tag{2}$$

$$\sum_{u=1}^{nu} \boldsymbol{f_u} \dot{\boldsymbol{E}}^{+}_{\boldsymbol{el,u}} + \dot{\boldsymbol{E}}^{+}_{\boldsymbol{el}} - \dot{\boldsymbol{E}}^{-}_{\boldsymbol{el}} - \sum_{u=1}^{nu} \boldsymbol{f_u} \dot{\boldsymbol{E}}^{-}_{\boldsymbol{el,u}} = 0 \tag{3}$$

The corresponding thermodynamical feasibility is guarantied by Eq. (4).

$$\dot{\boldsymbol{E}}^{+}_{\boldsymbol{el}} \geq 0 \qquad \dot{\boldsymbol{E}}^{-}_{\boldsymbol{el}} \geq 0 \tag{4}$$

For the electricity cost, c^{+}_{el} is the purchase cost and c^{-}_{el} is the selling price. c^{+}_{f} is the fuel price. $\dot{E}^{+}_{f,u}$ is the nominal energy delivered to unit u by the fuel (e.g. natural gas) and $\dot{E}_{el,u}$ is the nominal electricity demand$^{(+)}$ or excess$^{(-)}$ of unit u. c_u is the nominal operating cost per hour of unit u (excluding the fuel and electricity costs of unit u).

A unit can be a process ($\boldsymbol{f_u} = 1$) or a utility ($\boldsymbol{f_u}$ variable) unit. The flow rates of streams belonging to utility units are proportional to the multiplication factor, which is limited by a minimum and a maximum value. The associated integer variable $\boldsymbol{y_u}$ defines if the utility unit u is added to process ($\boldsymbol{y_u} = 1$) or not ($\boldsymbol{y_u} = 0$).

$$\boldsymbol{y_u} \cdot \boldsymbol{f^{min}_u} \leq \boldsymbol{f}_u \leq \boldsymbol{y_u} \cdot \boldsymbol{f^{max}_u} \tag{5}$$

Streams of utility units are defined with nominal heat loads. If necessary nominal fuel, electricity consumption or electricity surplus (e.g. for heat pumps or steam network) and additional nominal operating costs (e.g. for cooling water) of the corresponding nominal thermal streams can be defined. In the process integration step, the multiplication factors are optimized and the necessary flow rates, fuel and electricity consumption and additional operating costs for the utility units are calculated.

The objective function includes the fuel and electricity costs, but it can also include the possibility of selling heat surpluses, by defining a utility unit with a nominal operating cost (selling price) for a nominal heat demand at a given temperature.

Without considering restricted matches, the general heat cascade for each temperature interval k is given by Eq. (6), where $\dot{Q}_{h/c,k,u}$ is the nominal heat load of hot or cold stream h/c in interval k and belonging to unit u. $\dot{\boldsymbol{R}}_{\boldsymbol{k}}$ is the cascaded heat from the temperature interval k to the lower temperature intervals.

$$\sum_{h_k=1}^{ns_{h,k}} \boldsymbol{f_u} \dot{Q}_{h,k,u} - \sum_{c_k=1}^{ns_{c,k}} \boldsymbol{f_u} \dot{Q}_{c,k,u} + \dot{\boldsymbol{R}}_{\boldsymbol{k+1}} - \dot{\boldsymbol{R}}_{\boldsymbol{k}} = 0 \quad \forall k = 1, \ldots, nk \tag{6}$$

$$\dot{\boldsymbol{R}}_{\boldsymbol{1}} = 0 \quad \dot{\boldsymbol{R}}_{\boldsymbol{nk+1}} = 0 \quad \dot{\boldsymbol{R}}_{\boldsymbol{k}} \geq 0 \quad \forall k = 2, \ldots, nk \tag{7}$$

Eqs. (1)–(7) form the set of equations for the MILP formulation (Maréchal & Kalitventzeff, 1998) without restricted matches. In the next sections this formulation will be adapted to include restricted matches and to introduce the envelope composite curves.

3.2. MILP formulation with restricted matches of sub-systems

Like for the conventional heat cascade the objective is to minimize the operating costs (Eq. (1)). When the industrial plant is divided into sub-systems, the normal heat cascade (Eqs. (6) and (7)) is replaced by Eqs. (8)–(14) in order to take into account heat exchange restrictions. It is important to remark that units and their streams can either be part of a sub-system or they belong to the heat transfer system (common units or heat transfer units).

For each sub-system s the heat cascade is given by Eqs. (8) and (10). When a sub-system has a deficit or a surplus of heat in the temperature interval k, the heat is supplied from the heat transfer system ($\dot{\boldsymbol{Q}}^{-}_{\boldsymbol{hts,s,k}}$) or respectively removed by the heat transfer system ($\dot{\boldsymbol{Q}}^{+}_{\boldsymbol{hts,s,k}}$). $\dot{\boldsymbol{R}}_{\boldsymbol{s,k}}$ is the cascaded heat to the lower temperature interval k in sub-system s.

$$\sum_{h_{s,k}=1}^{ns_{h,s,k}} \boldsymbol{f_u} \dot{Q}_{h,s,k,u} - \sum_{c_{s,k}=1}^{ns_{c,s,k}} \boldsymbol{f_u} \dot{Q}_{c,s,k,u} + \dot{\boldsymbol{Q}}^{-}_{\boldsymbol{hts,s,k}} - \dot{\boldsymbol{Q}}^{+}_{\boldsymbol{hts,s,k}} + \dot{\boldsymbol{R}}_{\boldsymbol{s,k+1}} - \dot{\boldsymbol{R}}_{\boldsymbol{s,k}} = 0 \quad \forall k = 1, \ldots, nk \;\; \forall s = 1, \ldots, nsub \tag{8}$$

$$\dot{\boldsymbol{R}}_{\boldsymbol{s,1}} = 0 \quad \dot{\boldsymbol{R}}_{\boldsymbol{s,nk+1}} = 0 \quad \dot{\boldsymbol{R}}_{\boldsymbol{s,k}} \geq 0 \quad \forall k = 2, \ldots, nk \;\; \forall s = 1, \ldots, nsub \tag{9}$$

$$\dot{\boldsymbol{Q}}^{+}_{\boldsymbol{hts,s,k}} \geq 0 \quad \dot{\boldsymbol{Q}}^{-}_{\boldsymbol{hts,s,k}} \geq 0 \quad \forall k = 1, \ldots, nk \;\; \forall s = 1, \ldots, nsub \tag{10}$$

The heat cascade for the heat transfer system ($_{hts}$), which contains all process or utility units not belonging to a sub-system, is given by Eqs. (11) and (12).

$$\sum_{h_{hts,k}=1}^{ns_{h,hts,k}} \boldsymbol{f_u} \dot{Q}_{h,hts,k,u} - \sum_{c_{hts,k}=1}^{ns_{c,hts,k}} \boldsymbol{f_u} \dot{Q}_{h,hts,k,u} - \sum_{s=1}^{nsub_k} \dot{\boldsymbol{Q}}^{-}_{\boldsymbol{hts,s,k}} + \sum_{s=1}^{nsub_k} \dot{\boldsymbol{Q}}^{+}_{\boldsymbol{hts,s,k}} + \dot{\boldsymbol{R}}_{\boldsymbol{hts,k+1}} - \dot{\boldsymbol{R}}_{\boldsymbol{hts,k}} = 0 \quad \forall k = 1, \ldots, nk \tag{11}$$

$$\dot{\boldsymbol{R}}_{\boldsymbol{hts,1}} = 0 \quad \dot{\boldsymbol{R}}_{\boldsymbol{hts,nk+1}} = 0 \quad \dot{\boldsymbol{R}}_{\boldsymbol{hts,k}} \geq 0 \quad \forall k = 2, \ldots, nk \tag{12}$$

A graphical representation of the heat cascade for sub-systems and the heat transfer system is given in Fig. 2.

To ensure that heat is cascaded correctly, a second set of equations is necessary. Eq. (13) expresses the heat balance of the hot streams and Eq. (14) expresses the heat balance of the cold streams in the heat transfer system. The flow rates of the heat transfer units have to be optimized in order to satisfy the remaining heat demand of all sub-systems.

$$\sum_{h_{hts,k}=1}^{ns_{h,hts,k}} \boldsymbol{f_u} \dot{Q}_{h,hts,k,u} + \dot{\boldsymbol{R}}_{\boldsymbol{hts,k+1}} - \dot{\boldsymbol{R}}_{\boldsymbol{hts,k}} - \sum_{s=1}^{nsub_k} \dot{\boldsymbol{Q}}^{-}_{\boldsymbol{hts,s,k}} \geq 0 \quad \forall k = 1, \ldots, nk \tag{13}$$

$$-\sum_{c_{hts,k}=1}^{ns_{c,hts,k}} \boldsymbol{f_u} \dot{Q}_{c,hts,k,u} + \dot{\boldsymbol{R}}_{\boldsymbol{hts,k+1}} - \dot{\boldsymbol{R}}_{\boldsymbol{hts,k}} + \sum_{s=1}^{nsub_k} \dot{\boldsymbol{Q}}^{+}_{\boldsymbol{hts,s,k}} \leq 0 \quad \forall k = 1, \ldots, nk \tag{14}$$

The total cascaded heat from an upper interval k is expressed by Eq. (15).

$$\dot{\boldsymbol{R}}_{\boldsymbol{k}} = \dot{\boldsymbol{R}}_{\boldsymbol{hts,k}} + \sum_{s=1}^{nsub_k} \dot{\boldsymbol{R}}_{\boldsymbol{s,k}} \quad \forall k = 1, \ldots, nk + 1 \tag{15}$$

The complete mathematical formulation consists in Eqs. (1)–(5) and the modified heat cascade Eqs. (8)–(15).

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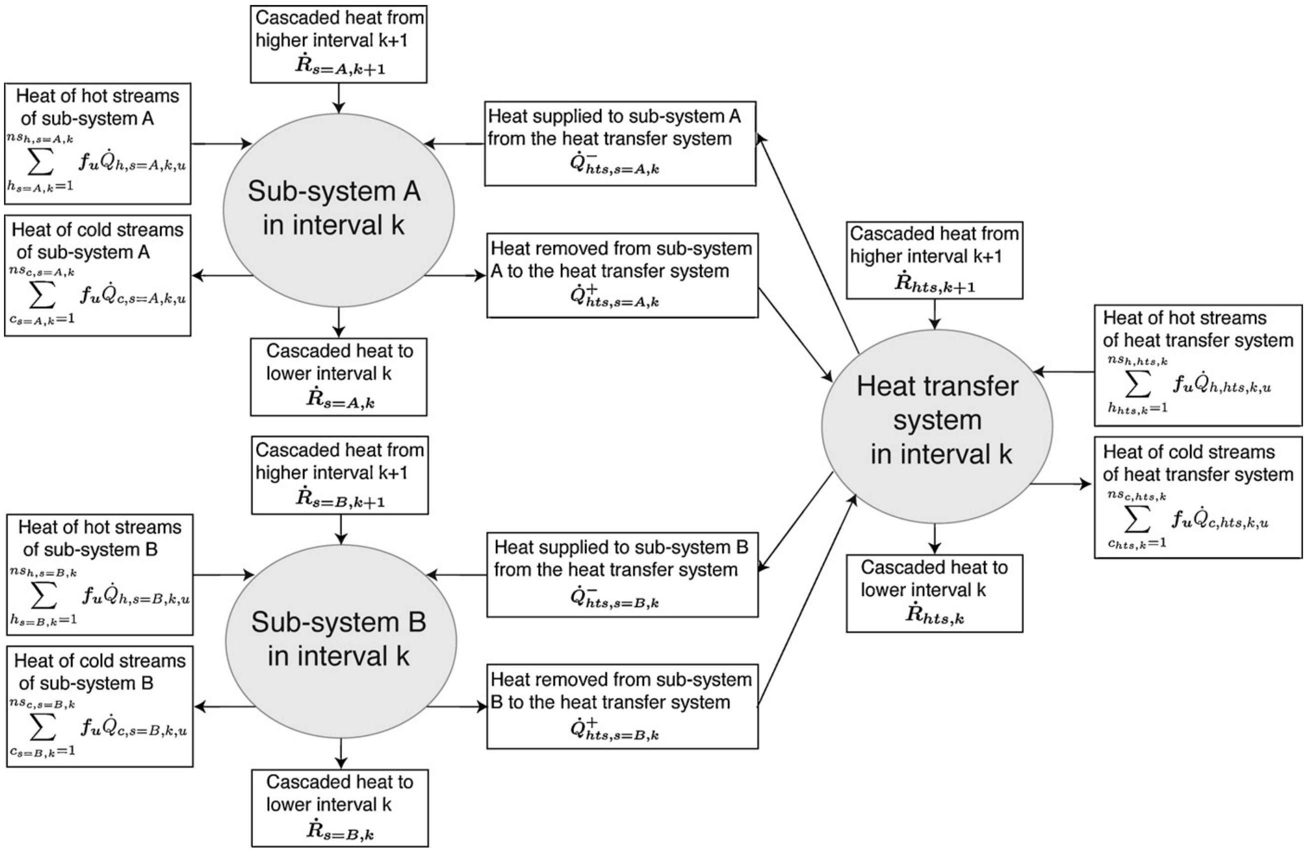

Fig. 2. Graphical heat cascade representation for MILP formulation with restricted matches of sub-systems.

When no heat transfer unit is considered, the MILP problem presented here allows to calculate the cost of the energy penalty. For this at least one common hot and cold utility have to be defined in the heat transfer system in order to satisfy the heat cascade equations. It is also possible to integrate indirect heat transfer units, based on a list of units defined with their enthalpy temperature profiles and the corresponding technologies. Pumping costs, proportional to their optimized flow rates have to be included, in order to size them correctly when solving the MILP formulation presented in this section.

However this formulation does not provide information on optimal temperature levels of heat transfer units. For example when several sub-systems are defined for a given process it is difficult to define necessary temperature levels for hot water loops. In the next section a MILP formulation is presented, which draws the envelope composite curves. It helps to choose the optimal intermediate heat transfer units.

3.3. Envelope composite curves – choice of intermediate heat transfer networks

The goal of this formulation is to calculate the envelope composite curves, which will embed the intermediate heat transfer units avoiding energy penalties due to restricted matches. For each temperature interval k in the heat transfer heat cascade, one fictive hot stream $\dot{\boldsymbol{Q}}_{\boldsymbol{h,env,k}}$ and one fictive cold stream $\dot{\boldsymbol{Q}}_{\boldsymbol{c,env,k}}$ are added to the heat cascade formulation and Eqs. (10)–(12) are replaced by Eqs. (16)–(18).

$$\sum_{h_{hts,k}=1}^{ns_{h,hts,k}} \boldsymbol{f_u} \dot{Q}_{h,hts,k,u} - \sum_{c_{hts,k}=1}^{ns_{c,hts,k}} \boldsymbol{f_u} \dot{Q}_{c,hts,k,u} + \dot{\boldsymbol{Q}}_{\boldsymbol{h,env,k}} - \dot{\boldsymbol{Q}}_{\boldsymbol{c,env,k}} - \sum_{s=1}^{nsub_k} \dot{\boldsymbol{Q}}^{-}_{\boldsymbol{hts,s,k}} + \sum_{s=1}^{nsub_k} \dot{\boldsymbol{Q}}^{+}_{\boldsymbol{hts,s,k}} + \dot{\boldsymbol{R}}_{\boldsymbol{hts,k+1}} - \dot{\boldsymbol{R}}_{\boldsymbol{hts,k}} = 0 \quad \forall k = 1, \ldots, nk \tag{16}$$

A graphical representation is given in Fig. 3. The fictive hot and cold streams form the envelope composite curves.

To cascade heat correctly following constraints have to be added to the mathematical formulation.

$$\dot{\boldsymbol{R}}_{\boldsymbol{hts,1}} = 0, \quad \dot{\boldsymbol{R}}_{\boldsymbol{hts,nk+1}} = 0 \quad \dot{\boldsymbol{R}}_{\boldsymbol{hts,k}} \geq 0 \quad \forall k = 2, \ldots, nk \tag{17}$$

$$\dot{\boldsymbol{Q}}^{+}_{\boldsymbol{hts,s,k}} \geq 0 \quad \dot{\boldsymbol{Q}}^{-}_{\boldsymbol{hts,s,k}} \geq 0 \quad \dot{\boldsymbol{Q}}_{\boldsymbol{h,env,k}} \geq 0 \quad \dot{\boldsymbol{Q}}_{\boldsymbol{c,env,k}} \geq 0 \quad \forall k = 1, \ldots, nk \ \forall s = 1, \ldots, nsub \tag{18}$$

The cold envelope composite curve takes the excess heat from the sub-systems, whereas the hot envelope composite curves give back the same amount of heat to the sub-systems requiring heat. The cold envelope curve is therefore a set of cold streams and can be interpreted as the maximum enthalpy temperature profile for the cold streams of the heat transfer units. In the same way, the hot envelope curve defines the minimum enthalpy temperature profile for the hot streams of the heat transfer units. A supplementary

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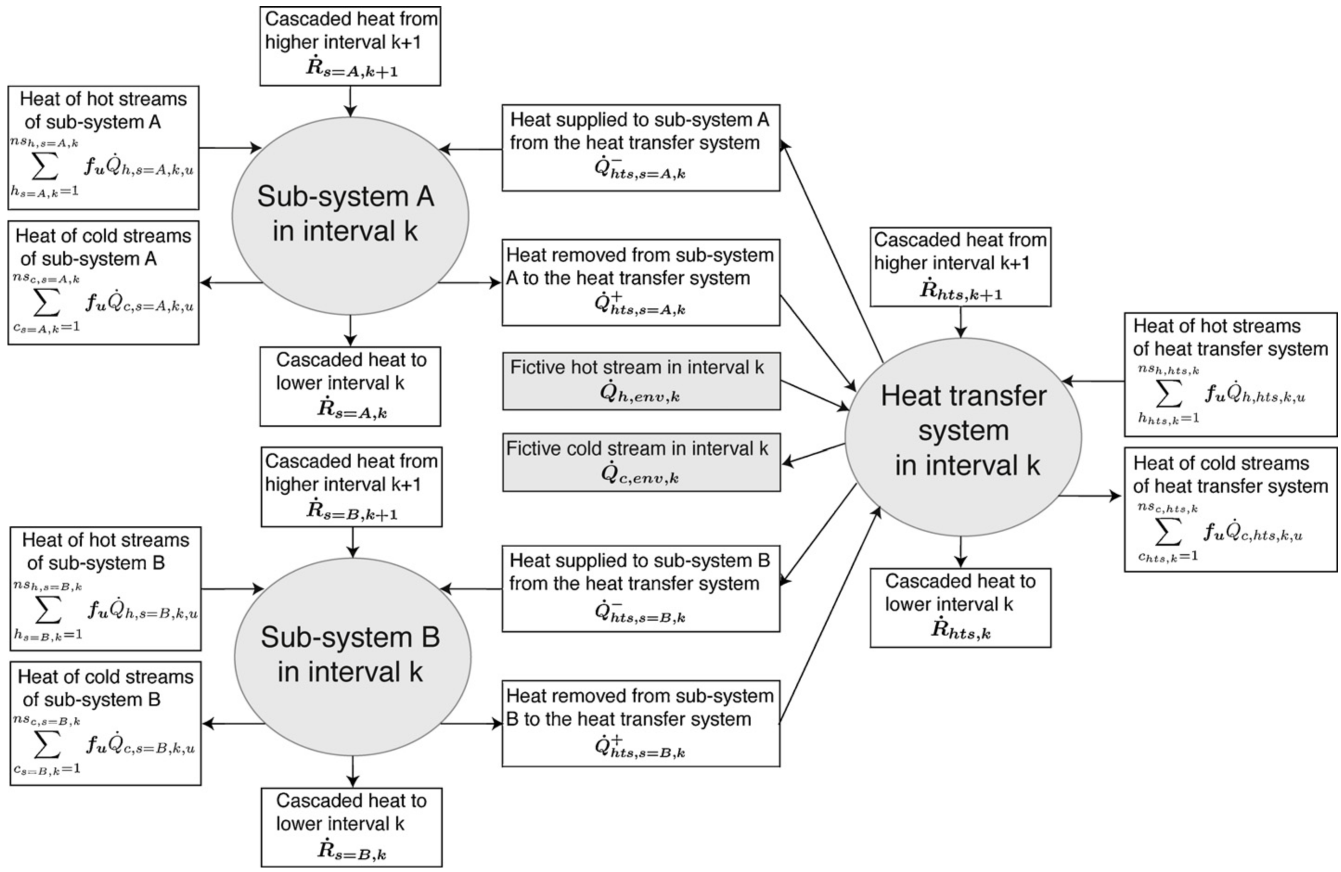

Fig. 3. Graphical heat cascade representation for MILP formulation for envelope composite curves.

constraint (Eq. (19)) is necessary, to ensure that the heat absorbed by the cold streams is equal to the heat delivered by the hot streams. When calculating the envelope, it is assumed that there are no heat losses in the intermediate heat transfer networks.

$$\sum_{k=1}^{nk}\dot{\boldsymbol{Q}}_{\boldsymbol{h,env,k}}=\sum_{k=1}^{nk}\dot{\boldsymbol{Q}}_{\boldsymbol{c,env,k}} \tag{19}$$

In order to ensure that the cold composite curve of the fictive cold streams is hotter than the hot composite curve, Eq. (20) is added to the formulation.

$$\sum_{r=k}^{nk}\dot{\boldsymbol{Q}}_{\boldsymbol{h,env,k}}-\sum_{r=k}^{nk}\dot{\boldsymbol{Q}}_{\boldsymbol{c,env,k}}\le 0 \quad \forall k=2,\ldots,nk \tag{20}$$

The fictive hot and cold heat loads ($\dot{\boldsymbol{Q}}_{\boldsymbol{h,env,k}}$, $\dot{\boldsymbol{Q}}_{\boldsymbol{c,env,k}}$) are added as decision variables in the MILP formulation to calculate the envelope composite curves. The problem is resolved considering all process and utility streams including the fictive hot and cold streams for the envelope composite curves. Therefore, auxiliary constraints have to be added, to avoid the energy penalty of restricted matches. For this, the MILP problem without constraints (Section 3.1) is first solved in order to obtain the utility flow rates that minimize the yearly operating costs. Then two options are possible: The first alternative is to fix the flow rates of utility streams, which correspond to the case without constraints (Eq. (21)).

$$f_{u_o}-\delta\le\boldsymbol{f_u}\le f_{u_o}+\delta \tag{21}$$

The degree of freedom analysis however shows that at least one utility flow rate cannot be fixed since it will be calculated to choose the system balance. The second alternative is to fix the optimized value for the yearly operating costs. This value can then be used as a maximum bound constraint of the envelope problem formulation (Eq. (22)).

$$d\cdot\left(\sum_{f=1}^{nf}\left(c_f^+\sum_{u=1}^{nu}\boldsymbol{f_u}\dot{E}^+_{f,u}\right)+c^+_{el}\dot{\boldsymbol{E}}^{\boldsymbol{+}}_{\boldsymbol{el}}-c^-_{el}\dot{\boldsymbol{E}}^{\boldsymbol{-}}_{\boldsymbol{el}}+\sum_{u=1}^{nu}\boldsymbol{f_u}c_u\right)\le OpC_o+\delta \tag{22}$$

The results of both approaches are similar for tested case studies. In this paper the first option has been chosen to solve the problem.

Furthermore the original objective function has to be modified like it is shown in Eq. (23).

$$F_{obj}=min\left(\kappa\cdot d\cdot\left(\sum_{f=1}^{nf}\left(c_f^+\sum_{u=1}^{nu}\boldsymbol{f_u}\dot{E}^+_{f,u}\right)+c^+_{el}\dot{\boldsymbol{E}}^{\boldsymbol{+}}_{\boldsymbol{el}}-c^-_{el}\dot{\boldsymbol{E}}^{\boldsymbol{-}}_{\boldsymbol{el}}+\sum_{u=1}^{nu}\boldsymbol{f_u}c_u\right)+\sum_{k=1}^{nk}\dot{\boldsymbol{Q}}_{\boldsymbol{h,env,k}}+\sum_{k=1}^{nk}\dot{\boldsymbol{R}}_{\boldsymbol{k}}\right) \tag{23}$$

The new objective function is composed of three terms that aim at

- minimizing the yearly operating costs of the energy conversion system and therefore maximizing the heat recovery (κ is a weighting factor)
- minimizing the heat load transferred by the fictive hot and cold streams, representing the heat transfer envelope
- minimizing the cascaded heat; this makes the fictive cold streams as hot as possible and the fictive hot streams as cold as possible.

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The last two terms are important to be able to draw the envelope composite curves, however the operating costs must also be included in the objective function, in order to calculate the heat cascade. Since either some of the multiplication factors or the operating costs are fixed, the first term becomes less important and therefore the weighting factor κ has to be chosen rather small but significantly higher than 0 (e.g. in our case $10e^{-7}$).

The graph of hot and cold envelope composite curves allows to define the temperature enthalpy profiles in the corrected temperature domain. An example of envelope composite curves is given in Fig. 8. In order to minimize the energy penalty due to restricted matches, the hot and cold composite curves of the heat transfer system have to be embedded between the hot and cold envelope composite curves. The envelope composite curves will feature as many pinch points as the process without heat exchange restrictions including the one generated by the utility streams. Each section (between two pinch points) of the envelope curves can therefore be analyzed separately. Consequently, the heat transfer fluids have to be defined in a way to maintain the independence of these sections. Once the optimal temperature profiles are known, appropriate indirect heat transfer units can be chosen and integrated with the MILP formulation presented in Section 3.2. The complete mathematical formulation for the envelope composite curves consists in the new objective function (Eq. (23)), Eqs. (2)–(5), the heat cascade equations of sub-systems (Eqs. (8) and (9)) and the new heat cascade for the heat transfer system (Eqs. (16)–(20)). Additional equations are necessary. For the first alternative (fixing the flow rates of utilities) Eq. (21) is added while for the second alternative (fixing the operating costs) Eq. (22) has to be added.

3.4. Optimizing the heat transfer units using multi objective optimization

When several heat transfer units are possible, or when the temperature levels of the heat transfer units are not precisely identified, a non linear programming approach can be interesting to choose between heat transfer units. This can be done by a multi objective optimization approach, based on an evolutionary algorithm (Molyneaux, Leyland, & Favrat, 2010). The chosen strategy is adapted from the decomposition of the optimization problem in master and slave sub-problems as presented by Gassner and Maréchal (2009). Fig. 4 shows the optimization algorithm.

The decisions variables of the master problem are the temperature conditions of the heat transfer units (e.g. networks). Their ranges can be deduced from the analysis of the envelope composite curves. In our example four networks can be integrated, however the approach is generic and can be extended to a higher number of networks. The two objectives are minimizing the operating cost (evaluated by the cost for the natural gas, electricity or cooling water) and minimizing the investment cost (evaluated by Eq. (25)). The pumping costs of the heat transfer units are included in the operating costs, in order to ensure that the flow rates and operating temperatures of heat transfer units are optimal and to distinguish between different networks options. The operating costs (OpC) corresponds to the minimum objective function from the energy integration shown in Eq. (24) and is calculated by solving the MILP problem presented in Section 3.2 as the slave problem.

$$OpC = F_{obj} = \min\left(d\cdot\left(\sum_{f=1}^{nf}\left(c_f^+\sum_{u=1}^{nu}\boldsymbol{f_u}\dot{E}_{f,u}^+\right)\right.\right.$$
$$\left.\left.+c_{el}^+\dot{\boldsymbol{E}}_{\boldsymbol{el}}^+ - c_{el}^-\dot{\boldsymbol{E}}_{\boldsymbol{el}}^- + \sum_{u=1}^{nu}\boldsymbol{f_u}c_u\right)\right) \quad (24)$$

The investment costs ($InvC$) are estimated according to available correlations. Once the flow rates are defined in the slave problem, the vertical heat exchange area (A) and the minimum number of heat exchange connections (N_{min}) are calculated. Then, the mean area (A_{mean}) is computed and the investment costs of the heat exchangers are estimated with Eq. (25). In this paper, following values have been considered: $InvC_{ref}$ = 8.8 k€ is the reference cost for the reference area A_{ref} = 1 m^2 and γ = 0.65.

$$InvC = N_{min}\cdot InvC_{ref}\cdot\left(\frac{A_{mean}}{A_{ref}}\right)^{\gamma} \quad (25)$$

As a result after a given number iterations, the Pareto front shows optimal solutions in terms of operating and investment costs. The final solution can be chosen among optimal solutions. One major disadvantage is that the multi-objective optimization can be time consuming.

Instead of using a multi-objective optimization approach, the problem could also be solved by a single objective function based on the net present value. But by varying operating conditions of heat transfer units, different pinch points can be activated and the problem becomes non-linear and non-discontinuous. Hence, the problem will be more difficult to solve using mathematical programming methods. An alternative is the chosen approach using an evolutionary algorithm. It can be quite inefficient for solving a single objective function, but it is interesting for multi-objective problems. Moreover it allows generating a set of solutions instead of one single solution. A better and in most case more realistic final solution can be selected from the Pareto front by applying other criteria (e.g. financial, environmental).

3.5. Heat load distribution

At the end of the targeting procedure, the list of hot and colds streams of system is known. The heat load distribution is then the first step to design the heat exchanger network. It is calculated by the formulation presented by Maréchal and Kalitventzeff (1989). The objective function is minimizing the number of connections (Eq. (26)).

$$F_{obj_{hld}} = \min\left(\sum_{j=1}^{ns_c}\sum_{i=1}^{ns_h}\boldsymbol{y_{ij}}\right) \quad (26)$$

Eqs. (27) and (28) describes the heat balances of the hot and cold streams. Eq. (29) shows the existence of a connection between hot stream i and cold stream j. Each heat load must be positive (Eq. (30)).

$$\sum_{j=1}^{ns_c}\boldsymbol{Q_{ijk}} = Q_{ik} \quad \forall i = 1,\ldots,ns_h, \forall k = 1,\ldots,nk \quad (27)$$

$$\sum_{i=1}^{ns_h}\sum_{k=1}^{nk}\boldsymbol{Q_{ijk}} - Q_j \geq 0 \quad \forall j = 1,\ldots,ns_c, \quad (28)$$

$$\sum_{k=1}^{nk}\boldsymbol{Q_{ijk}} - \boldsymbol{y_{ij}}Q_{max\,ij} <= 0 \quad \forall j = 1,\ldots,ns_c, \forall j = 1,\ldots,ns_h \quad (29)$$

$$\boldsymbol{Q_{ijk}} \geq 0 \quad \forall j = 1,\ldots,ns_c, \forall j = 1,\ldots,ns_h, \forall k = 1,\ldots,nk \quad (30)$$

To consider restricted matches, a constraint on the integer variable $\mathbf{y_{ij}} \in [0, 1]$ has to be added (Eq. (31)). Considering the results of the targeting phase, it is known that at least one solution of the heat

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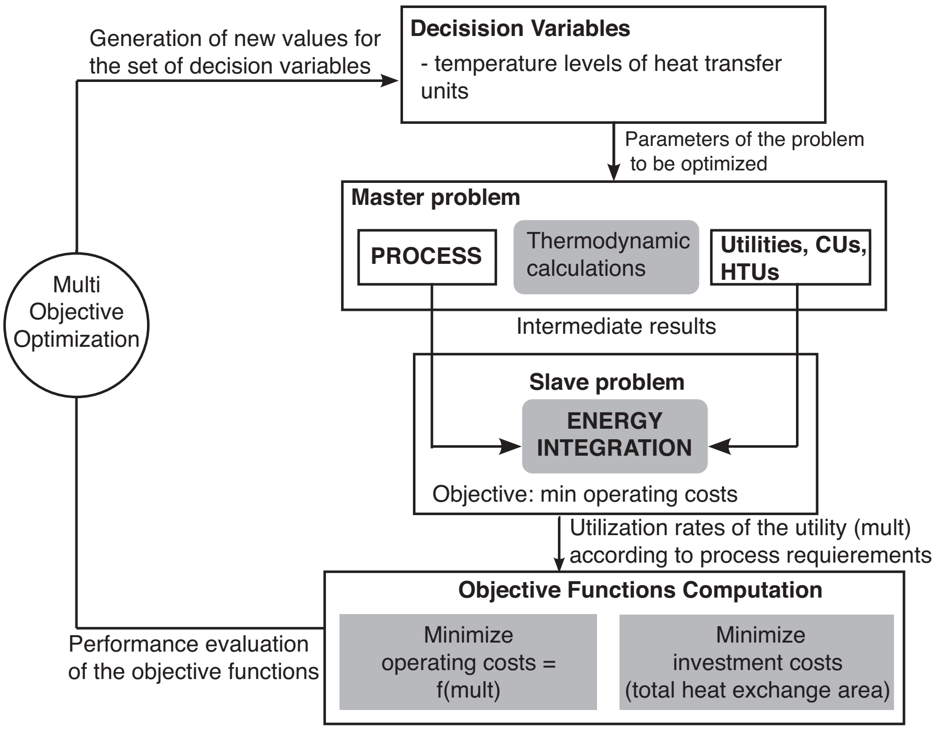

Fig. 4. Multi-objective optimization algorithm.

load distribution problem exits. Thus, the restricted matches can be introduced as constraints to the heat load distribution problem.

$$\boldsymbol{y_{ij}} = 0 \tag{31}$$

3.6. Extension to multi level sub-systems

The previous introduced concept of restricted matches between sub-systems can be extended to multi-level sub-systems (Fig. 5). The definition of sub-systems inside sub-systems becomes possible. For each level a heat transfer system is necessary. It consists in units which can exchange heat with all sub-systems of the corresponding level. The global problem is represented by the last sub-system which contains all sub-systems and the global heat transfer system with no heat exchange restrictions.

For each sub-system s the heat cascade is given by Eqs. (32)–(34).

$$\sum_{h_{s,k}=1}^{ns_{h,s,k}} \boldsymbol{f_u} \cdot \dot{Q}_{h,s,k,u} - \sum_{c_{s,k}=1}^{ns_{c,s,k}} \boldsymbol{f_u} \cdot \dot{Q}_{c,s,k,u} + \dot{\boldsymbol{Q}}^{-}_{\boldsymbol{hts(s),s,k}} - \dot{\boldsymbol{Q}}^{+}_{\boldsymbol{hts(s),s,k}} + \dot{\boldsymbol{R}}_{\boldsymbol{s,k+1}} - \dot{\boldsymbol{R}}_{\boldsymbol{s,k}} = 0 \quad \forall k = 1, \ldots, nk \quad \forall s = 1, \ldots, nsub \tag{32}$$

$$\dot{\boldsymbol{R}}_{\boldsymbol{s,1}} = 0 \quad \dot{\boldsymbol{R}}_{\boldsymbol{s,nk+1}} = 0 \quad \dot{\boldsymbol{R}}_{\boldsymbol{s,k}} \geq 0 \quad \forall k = 2, \ldots, nk \quad \forall s = 1, \ldots, nsub \tag{33}$$

$$\dot{\boldsymbol{Q}}^{+}_{\boldsymbol{hts(s),s,k}} \geq 0 \quad \dot{\boldsymbol{Q}}^{-}_{\boldsymbol{hts(s),s,k}} \geq 0 \quad \forall k = 1, \ldots, nk \quad \forall s = 1, \ldots, nsub \tag{34}$$

$\dot{Q}_{h,s,k,u}$ is the nominal heat load of hot stream h in sub-system s and interval k and belonging to unit u. The real heat load is calculated with the multiplication factor $\boldsymbol{f_u}$. When a sub-system has a deficit or a surplus of heat in the temperature interval k, the heat is supplied from the heat transfer system of its sub-system ($\dot{\boldsymbol{Q}}^{-}_{\boldsymbol{hts(s),s,k}}$) or respectively removed by the same heat transfer system ($\dot{\boldsymbol{Q}}^{+}_{\boldsymbol{hts(s),s,k}}$). $\dot{\boldsymbol{R}}_{\boldsymbol{s,k}}$ is the cascaded heat to the lower temperature interval k in sub-system s.

The heat cascade for the heat transfer system ($_{hts}$) for each parent sub-system is given by Eqs. (35)–(36). $\dot{\boldsymbol{Q}}^{+}_{\boldsymbol{hts+1,k}}$ is the heat supplied from the heat transfer system a level above and $\dot{\boldsymbol{Q}}^{-}_{\boldsymbol{hts+1,k}}$ is the heat transferred to the heat transfer system of the higher level.

$$\sum_{h_{hts,k}=1}^{ns_{h,hts,k}} \boldsymbol{f_u} \cdot \dot{Q}_{h,hts,k,u} - \sum_{c_{hts,k}=1}^{ns_{c,hts,k}} \boldsymbol{f_u} \cdot \dot{Q}_{c,hts,k,u} + \dot{\boldsymbol{Q}}^{-}_{\boldsymbol{hts+1,k}} - \dot{\boldsymbol{Q}}^{+}_{\boldsymbol{hts+1,k}} - \sum_{s=1}^{nsub(hts)_k} \dot{\boldsymbol{Q}}^{-}_{\boldsymbol{hts(s),s,k}} + \sum_{s=1}^{nsub(hts)_k} \dot{\boldsymbol{Q}}^{+}_{\boldsymbol{hts(s),s,k}} + \dot{\boldsymbol{R}}_{\boldsymbol{hts,k+1}} - \dot{\boldsymbol{R}}_{\boldsymbol{hts,k}} = 0 \quad \forall k = 1, \ldots, nk \ \forall hts = 1, \ldots, nps \tag{35}$$

$$\dot{\boldsymbol{R}}_{\boldsymbol{hts,1}} = 0 \quad \dot{\boldsymbol{R}}_{\boldsymbol{hts,nk+1}} = 0 \quad \dot{\boldsymbol{R}}_{\boldsymbol{hts,k}} \geq 0 \quad \forall k = 2, \ldots, nk \quad \forall hts = 1, \ldots, nps \tag{36}$$

Like before, to ensure that heat is cascaded correctly, a second set of equations for the global heat transfer system is necessary. Eq. (37) expresses the heat balance of the hot streams and Eq. (38) expresses the heat balance of the cold streams in the heat transfer system. The flow rates of the heat transfer units have to be optimized in order to satisfy the remaining heat demand of all sub-systems.

$$\sum_{h_{hts,k}=1}^{ns_{h,hts,k}} \boldsymbol{f_u} \cdot \dot{Q}_{h,hts,k,u} + \dot{\boldsymbol{Q}}^{-}_{\boldsymbol{hts+1,k}} + \dot{\boldsymbol{R}}_{\boldsymbol{hts,k+1}} - \dot{\boldsymbol{R}}_{\boldsymbol{hts,k}} - \sum_{s=1}^{nsub(hts)_k} \dot{\boldsymbol{Q}}^{-}_{\boldsymbol{hts(s),s,k}} \geq 0 \quad \forall k = 1, \ldots, nk \ \forall hts = 1, \ldots, nps \tag{37}$$

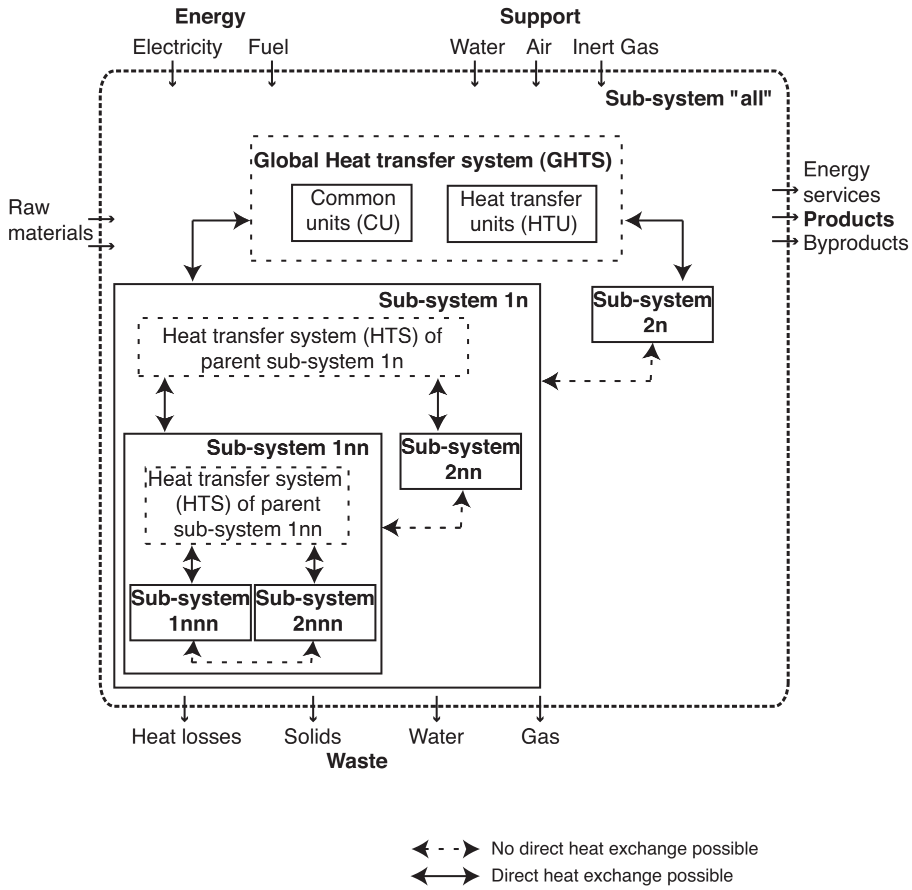

Fig. 5. Definition of sub-systems with several levels.

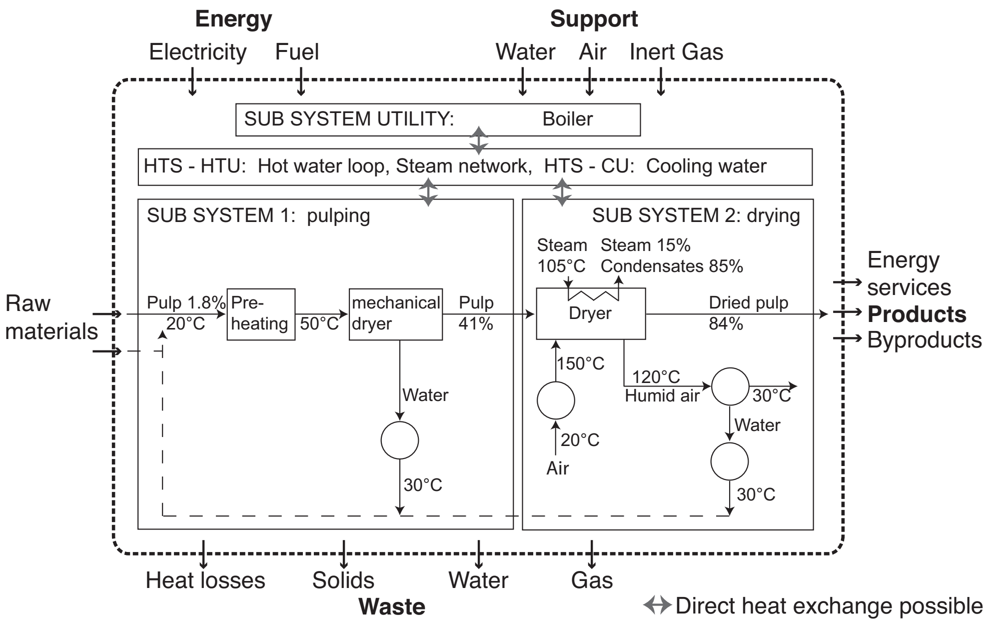

Fig. 6. Representation of the process.

Table 2
Process streams with $\Delta T_{min/2}$ values: 2 °C (liquids) and 0.5 °C (gases).

Unit	Name	Tin [°C]	Tout [°C]	Heat load [kW]	Remarks
Pulping	ph_c1	20	50	11262	Preheating
	ph_h1	50	30	7297	Water cooling
Drying	st_c1	95	105	6057	Steam demand
	st_h3	105	105	892	Condensation of 15% steam
	st_h2	105	95	112	Cooling of condensates
	air_c1	20	150	664	Air heating
	air_h1	100	30	5278	Humid air cooling

$$- \sum_{c_{hts,k}=1}^{ns_{c,hts,k}} \boldsymbol{f_u} \cdot \dot{Q}_{c,hts,k,u} - \dot{\mathbf{Q}}^{+}_{\mathbf{hts+1,k}} + \dot{\boldsymbol{R}}_{\mathbf{hts,k+1}} - \dot{\boldsymbol{R}}_{\mathbf{hts,k}}$$
$$+ \sum_{s=1}^{nsub(hts)_k} \dot{\mathbf{Q}}^{+}_{\boldsymbol{hts(s),s,k}} \leq 0 \quad \forall k = 1, \ldots, nk \;\; \forall hts = 1, \ldots, nps \qquad (38)$$

4. Numerical example – drying process in the paper industry

In order to illustrate the application of the method, a dryer process of a paper production plant will be studied (Fig. 6).

The humid pulp is first preheated in the pulping unit before entering the dryer unit. Currently steam, produced by a natural gas fired boiler, is defined as a hot utility. It is used for drying by heating paper mill rolls and for producing hot air, which is mainly used to evacuate the evaporated water from the pulp. Possible heat recovery is introduced by a humid air stream (hot stream which has to be cooled down to the final temperature of 30 °C). The list of process streams is given in Table 2.

The pulping unit (sub-system 1), drying unit (sub-system 2) and later the boiler (sub-system utility) are considered as different sub-systems. Heat cannot be exchanged directly between these sub-systems.

This means in the case with no defined heat transfer units, that the heat demand of sub-system 1 can only be satisfied by an external hot utility even if the excess heat of sub-system 2 is sufficient to satisfy the demand (Fig. 6).

In the following, each step for the case study is presented. Except the multi-objective optimization, all problems are MILP problems which are solved with ampl and cplex. The problem size is reported in the summary of results (Table 8).

Being in the French context, the fuel price (natural gas) and the electricity price (purchase price) are considered to be 0.0392 €/kWh and 0.0620 €/kWh respectively. The exported electricity can be sold for 0.0496 €/kWh. The cost of cooling water is small, since a near located river can be used as a cold source.

4.1. Step 1: minimum utility cost without restricted matches

The MILP formulation presented in Section 3.1 is used to integrate the process and utility units. With the steam boiler and cooling water two utility units are proposed to the process. This corresponds to two integer variables in the MILP problem. The characteristics of the steam boiler and cooling water are briefly described below. The boiler produces steam by taking heat from the flue gases at a temperature higher than 1000 °C and cooled down to the stack temperature (120 °C). Also air preheating from the ambient (20 °C) to the stack temperature is included. In order to better show the exergy losses, the boiler has been modeled with the fumes. On the other hand, the cooling water enters the system at 7 °C. Considering a given ΔT_{min} value, the maximum heat recovery leads to a natural gas consumption of 6073 kW and a cooling water consumption of 1668 kW. It corresponds without restricted matches to the minimum operating costs (utility costs) of 2.4 M€/year.

4.2. Step 2: calculation and visualization of the energy penalty due to restricted matches

The energy penalty due to restricted matches can be evaluated using the MILP formulation presented in Section 3.2. For this calculation, the two utility units (steam boiler and cooling water) are defined as common units (CUs) in the heat transfer system. They are allowed to exchange heat with the process units (sub-systems 1 and 2). The penalty, which consumes by the same amount (about 3850 kW) more of the hot and the cold utility, can also be visualized when comparing the integrated composite curve of the utility system in both configurations (Fig. 7). The results are compared in Table 7.

4.3. Step 3a: hot and cold envelope composite curves and choice of intermediate heat transfer units

In the example, the pulping and drying sub-systems cannot exchange heat directly. The flue gases of the boiler are also defined as a sub-system which cannot exchange heat directly with the process.

It can be possible to find optimal heat transfer units by analyzing the required temperature levels of the process demand. However this is not evident when more sub-systems are defined. The envelope composite curves helps to identify intermediate heat transfer units.

Including the multiplication factor of the boiler (calculated in step 1) and the heat exchange constraints between sub-systems a second problem can be solved, using the MILP formulation presented in Section 3.3. With this, the envelope composite curves can be visualized (Fig. 8).

According to the pinch point locations, two separate heat transfer units are necessary: one to transfer the heat from the boiler to the process demand above the pinch point (105 °C) and another one to transfer heat between sub-systems 1 and 2 to make heat recovery possible below the pinch point.

4.4. Step 4: restricted matches and integration of intermediate heat transfer units

The definition of the heat transfer system is based on the temperature levels of the envelope composite curves (Fig. 8) but also technological aspects have to be considered. To transfer heat from the boiler to the process, a simple steam network could transfer heat by producing steam in the boiler and returning condensates after heat exchange with the process. It is also possible to consider combined heat and power integration in the steam network by using high pressure steam from the boiler in steam turbines to produce lower pressure steam delivering heat to the process at lower temperatures. Because of a better exergy efficiency the

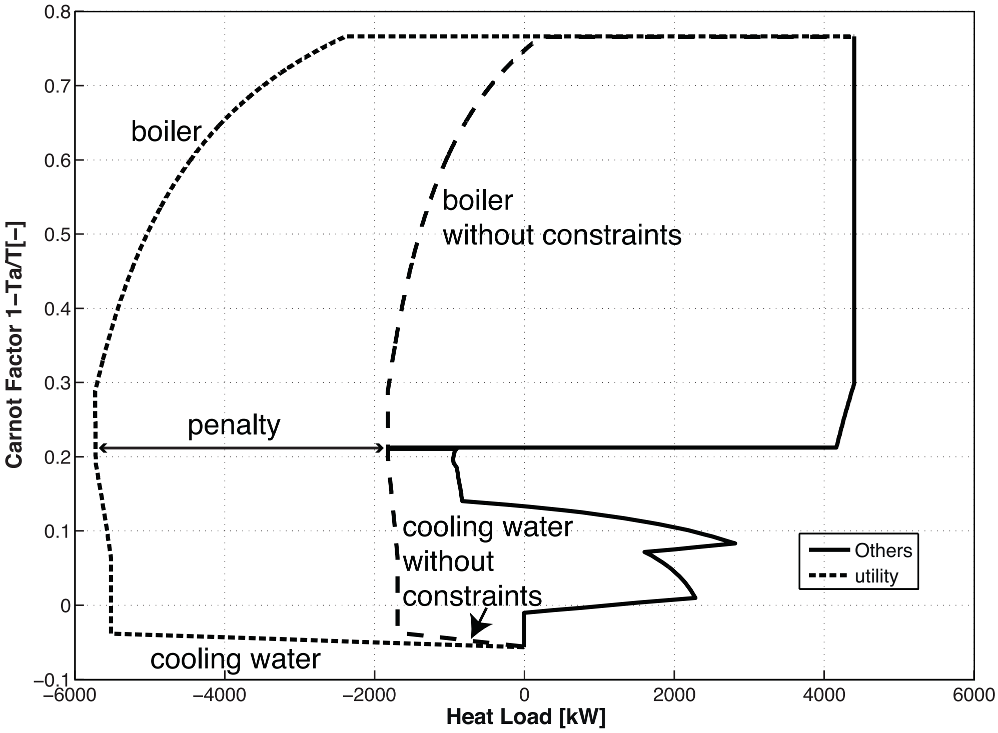

Fig. 7. Penalty of the system.

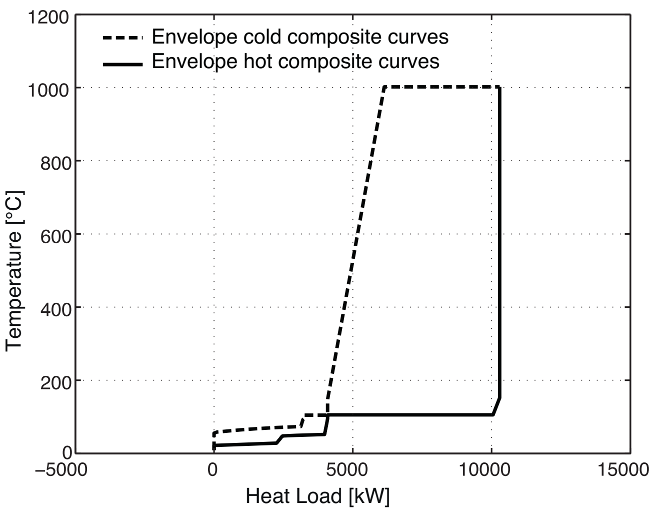

Fig. 8. Envelope composite curves for intermediate heat transfer units.

second option is preferred and integrated in the following. The steam network acts as heat transfer unit between the boiler (steam production at 80 bar, 295 °C) and the process demand (steam utilization at 7 bar, 165 °C and 2 bar, 120 °C). On the envelope composite curves it can be seen that two steam extractions pressures are needed (Fig. 9).

It is important to remark that even without constraints, the energy integration will choose the steam network when it is useful to use this electricity in the process or when the selling price is attractive.

For the second network, an intermediate hot water loop can be integrated. In this case, water is heated up from 25 °C to 80 °C with streams from the drying unit and heat is given back to the pulping unit by cooling down the water from 80 °C to 25 °C. The pumping costs are included, in order to size correctly the recovery loop.

The summary of selected temperature levels for the heat transfer units is given in Fig. 9.

With the new utility units for indirect heat transfer, the targeting problem (MILP formulation from Section 3.2) is solved. The multiplication factors of the utility units (steam boiler, cooling water, steam network and intermediate heat recovery loop) are calculated to minimize the cost of the energy conversion system, while satisfying the restricted matches constraints. As the utility streams depend on the combined heat and power production, the multiplication factor may differ from the one calculated without constraints. For example, the utilization rate of the boiler will be higher when a steam network, producing electricity, is integrated. The integrated utility composite curves, including a steam network at higher temperature and an intermediate hot water loop below the pinch point, are shown in Fig. 10. The overall system is optimized and the energy penalty due to heat exchange restrictions is minimized.

4.5. Step 4b (optional): multi-objective optimization and choice of intermediate heat transfer units

Applying the method presented in Section 3.4, the Pareto front for the presented example is resulting (Fig. 11). Approximative solutions are obtained after 3000 iterations. Considering the results of the envelope composite curves the decision variables have been chosen in order to accept the minimal and maximal temperature level of the intermediate heat recovery loop (25 °C and 100 °C respectively).

The variation in the operating cost is small, because the only difference come from the pumping cost which is proportional to the mass flow rate. For a higher temperature difference, the

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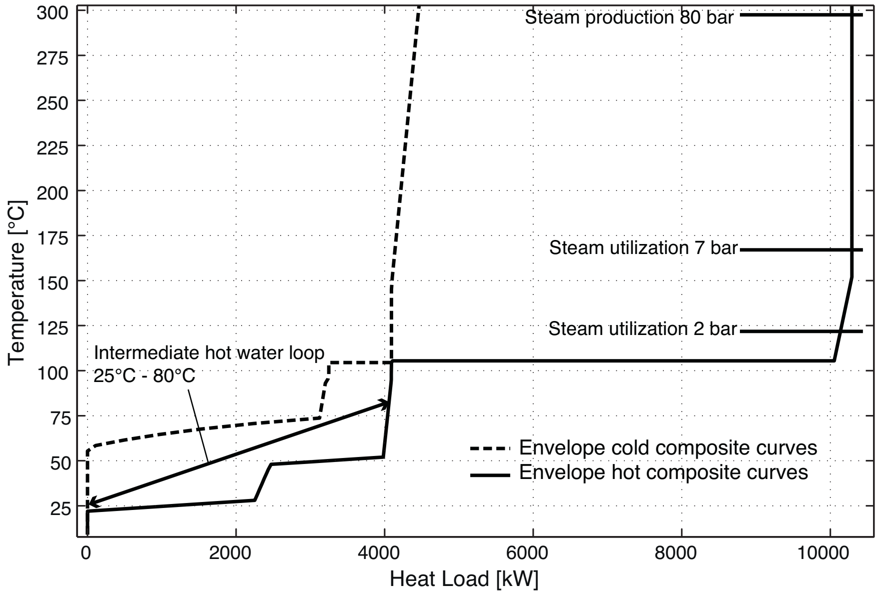

Fig. 9. Choice of temperature levels of intermediate heat transfer units.

Table 3
Results of multi-objective optimization.

Point	*OpC* [€/year]	*InvC* [k€]	T_{low} [°C]	T_{up} [°C]
1	2,180,218	4.2353	49.3	69.5
2	2,180,214	4.2356	46.3	73.4
3	2,180,210	4.2361	40.0	78.0
4	2,180,207	4.2362	25.4	81.6
Man	2,180,207	4.2363	25.0	80.0

Table 4
Heat load distribution for zone 1 (119–1000 °C).

Hot stream	Cold stream	Heat load [kW]
D2_C_Ds	drying_air_c1	166.7
boiler_boi_h1	boiler_boi_c1	85.0
boiler_boi_h1	C_H1_Cs	5409.3
boiler_boi_h2	C_H1_Cs	2786.4
D2_C_Ds	C_H1_Cs	555.9

pumping cost become smaller. But on the other side the investment costs become higher because the necessary heat exchanger area increases. Table 3 shows the results of 4 points on the pareto curve and compares it with the manual (man) chosen intermediate loop (T_{low} = 25 °C, T_{up} = 80 °C), by studying the envelope composite curves.

The multi-objective optimization can add interesting information, especially it can be a help when several possible networks are regarded. On the other side it is quite time consuming for the small additional information.

In the next step, the intermediate heat recovery network is integrated for the last solution.

4.5.1. Step 5: heat load distribution

Finally, the heat load distribution is computed for the case with integrated steam network and a hot water loop from 25 °C to 80 °C. The complete heat load distribution for this example is shown in Fig. 12.

Three different zones (between utility pinch point at 9 °C, process pinch at 105 °C, utility pinch point at 119 °C and the utility pinch point at 1002 °C) can be distinguished. The heat load distribution for these 3 zones is also given in Tables 4–6. They show

Table 5
Heat load distribution for zone 2 (105–119 °C).

Hot stream	Cold stream	Heat load [kW]
D1_C_Ds	drying_air_c1	75.9
D1_C_Ds	boiler_boi_c1	29.1
D2_C_Ds	boiler_boi_c1	20.1
D1_C_Ds	drying_st_c1	5956.8
boiler_boi_h2	C_H1_Cs	46.9
D1_C_Ds	C_H1_Cs	156.4

Table 6
Heat load distribution for zone 3 (9–105 °C).

Hot stream	Cold stream	Heat load [kW]
pulping_ph_h1	pulping_ph_c1	7297.0
wloop_waterhe	pulping_ph_c1	3030.4
D1_C_Ds	pulping_ph_c1	836.1
D2_C_Ds	pulping_ph_c1	98.4
drying_air_h1	drying_air_c1	421.4
drying_air_h1	water_cw	1602.4
boiler_boi_h2	boiler_boi_c1	30.0
wloop_waterhe	boiler_boi_c1	167.3
drying_air_h1	wloop_waterco	3197.7
drying_st_h3	drying_st_c1	100.6
drying_st_h3	C_H1_Cs	791.4
drying_st_h2	C_H1_Cs	112.0
drying_air_h1	C_H1_Cs	56.3

the exchanged heat amount between a hot and a cold stream. The results can be later used to design the heat exchanger network.

4.5.2. Summary of results and discussion

The summary of all results is given in Table 7. For better comparison the net heat delivered to the process by the boiler is reported. The corresponding natural gas consumption, which takes into account the boiler efficiency is calculated, but not included in Table 7. Compared to the case with no constraints, the same amount of energy has to be added to the boiler and the cooling water when constraints are integrated. In the case of integrating intermediate heat transfer units (hot water loop and steam network), the boiler consumption increases but at the same time electricity is produced.

Table 7
Results.

	Unit	No constraints	With constraints	Constraints and heat transfer system
Operating costs	[k€/year]	2353.6	3844.8	2180.2
Fuel consumption	[kW]	6073	9920	8026
Cooling water	[kW]	1668	5516	1602
Electricity	[kW]			2019

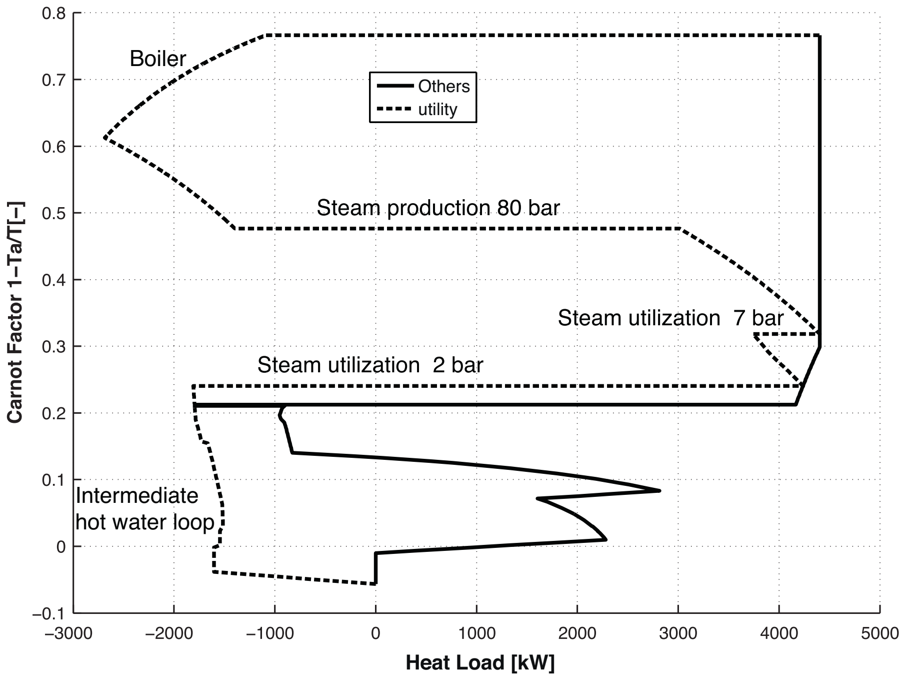

Fig. 10. Integrated utility composite curves.

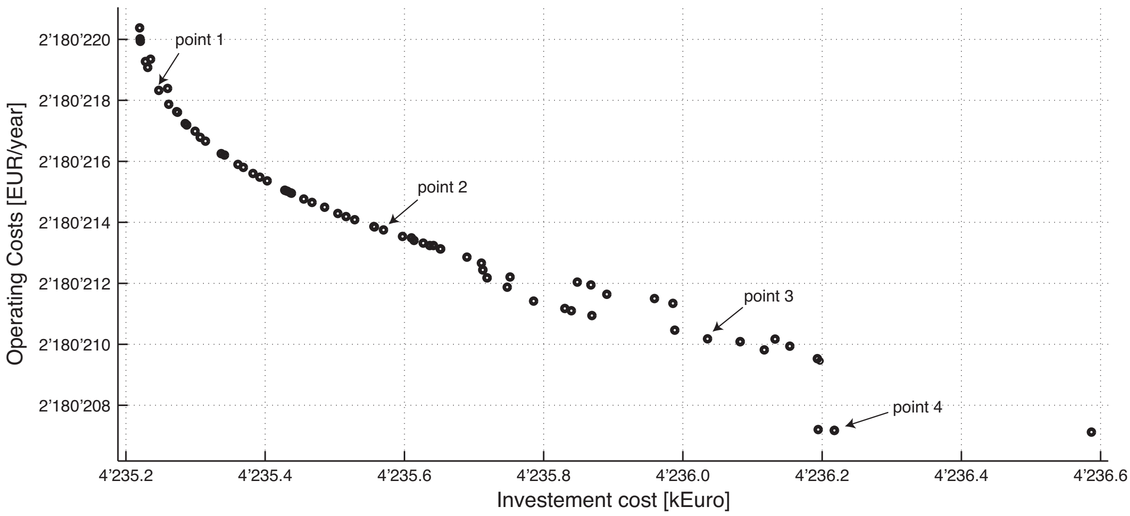

Fig. 11. Pareto front to select intermediate heat transfer networks.

Table 8 compares the number of constraints and variables and the computation time for the MILP problems. Introducing restricted matches increases the number of constraints and variables and also the computation time.

For this example the complete piping cost and investment costs have not been included. Pumping costs proportional to flow rates are included in the electricity consumption of intermediate heat transfer networks (here recovery loop and steam network). However the complete piping costs cannot easily be integrated in the proposed targeting method, as they depend not only on the flow rate but also on the distance between interconnected units. Estimating the cost would require the calculation of the heat load

Table 8
Problem size.

MILP problem	Constraints	Variables	Computation time
No constraints	133	125	0.016 s
With constraints	499	385	0.031 s
Envelope composite curves	834	676	0.047 s
Constraints and heat transfer system	764	674	0.047 s
Heat load distribution	1679	1399	0.203 s

distribution in order to be able to consider the interconnections as cost. For this, Weber, Heckl, Friedler, Maréchal, and Favrat (2006) have developed a method for the system design, which will be the next step of the presented approach. Taking the presented example, neglecting the investment costs of CHP unit gives good solutions in a first step, since the boiler and process units have been defined in sub-systems, so that intermediate heat transfer units are necessary. The presented method is optimizing the operating costs, but the annualized investment of the CHP and other utility units could easily be added to the formulation by defining fixed and proportional costs, as demonstrated in Maréchal and Kalitventzeff (2003). A second possibility is to perform a multi-objective optimization like it is presented in Sections 3.4 and 4.5 to include the investment costs for new utility units. Optimal solutions representing the trade-off between operating and investment costs are located on a resulting Pareto curve.

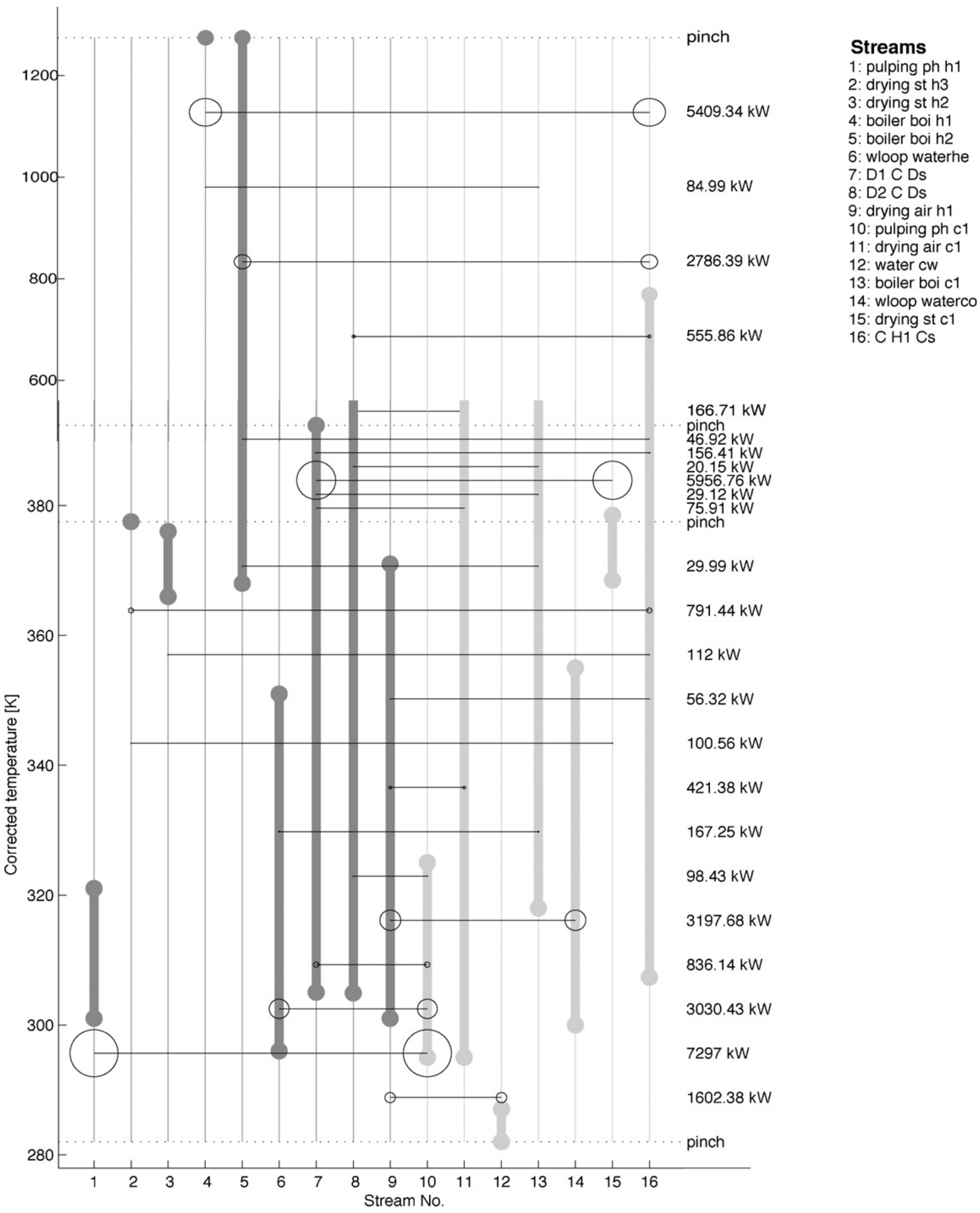

Fig. 12. Heat load distribution.

5. Conclusion

A method for targeting the optimal integration of energy conversion systems is proposed. Including heat exchange restrictions, the heat recovery and the combined heat and power production are maximized for an industrial process. The method considers total site integration and defines sub-systems. Between them heat exchange cannot be realized, without using heat transfer units. The problem is formulated as a MILP problem that calculates simultaneously the flow rates of the utility system and the heat transfer units by minimizing the operating costs of the energy conversion system.

Furthermore a new MILP formulation is proposed to draw the envelope composite curves. It helps to characterize the heat transfer units, which will minimize the energy penalty due to restricted matches.

The targeting problem, including optimal heat transfer units, defines the complete list of streams to be considered in the heat load distribution problem. The heat exchange constraints can be included and therefore the number of integer variable is considerably reduced.

Although, the method presented in this paper is illustrated by a simple example with three sub-systems, the method aims at solving complex examples with multiple sub-systems (e.g. process units with different locations or other industrial site problems). The method has been applied successfully to two more complex examples from the industry [Brewery process (Dumbliauskaite, Becker, & Maréchal, 2010) with 4 process sub-systems and 55 streams and a cheese factory (Becker, Vuillermoz, & Maréchal, 2011) with 7 process sub-systems and 60 streams].

The sub-system concept is also possible for calculating the integration of utility systems, for example the produced heat in a boiler cannot exchange directly with process streams, but a steam network makes the heat exchange possible.

The use of restricted matches reveals to be a great importance in process integration as demonstrated by Pouransari, Mercier, Salgueiro, and Maréchal (2011). By understanding restricted matches and the required heat transfer units, the proposed tool allows to generate process integration solutions.

Also for large scale integration of energy systems like cities, restricted matches become important. For example each district or location can be considered as a separate sub-system and to connect them, district heating/cooling systems can be defined as heat transfer units.

The method can also be used to identify the required heat transfer units when solving batch process integration. Applying the time average method, the non simultaneous operations can be considered in different sub-systems for which the direct heat exchange is not possible. This would be the first step before realizing the detailed integration as presented by Krummenacher, Favrat, and Renaud (2010).

The proposed formulation is based on the decomposition of the problem into sub-systems. The extension for defining sub-systems inside sub-systems has also been shown. In the case, where only one specific heat exchange is forbidden, the involved hot and cold streams could be defined in two separate sub-systems. But if the decomposition into sub-systems is not possible, the proposed formulation is not applicable anymore and other methods like the one presented by Maréchal and Kalitventzeff (1999) have to be used.

Finally, the method is presented for one single period, but it can easily be extended to solve a multi-period problems as presented in Maréchal and Kalitventzeff (2003).

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