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. By applying pinch analysis methods, the first step is to calculate the maximum heat recovery between hot and cold streams. The second step consists in designing the corresponding heat recovery exchanger network, based on a fixed list of streams.
For the heat cascade, it is assumed that any heat exchange between hot and cold streams is possible, but due to industrial constraints, in many cases, this assumption cannot be accepted in practice and it is necessary to impose restricted matches. This may introduce energy penalties, which could be reduced by using intermediate heat transfer systems. Dealing with restricted matches, this paper introduces a targeting method that ensures feasible solutions for the heat exchanger network. Intermediate heat transfer systems are integrated so that restricted heat exchanges become possible and heat recovery penalties, created by those constraints, can be reduced.
The problem is formulated as a MILP (mixed integer linear programming) problem, which considers not only restricted matches but also the optimal integration of the energy conversion system, like heat pumping and combined heat and power production. Moreover a new mathematical formulation is presented to show the envelope composite curves for heat transfer system units. For solutions avoiding the energy penalty, the composite curves of optimal heat transfer units have to be embedded between the envelope hot and cold composite curves. Therefore optimal technology to transfer heat can be chosen easily for a given process.
The application of the method is illustrated by an industrial example from the pulp and paper industry.

Keywords: Pinch integration, Utility integration, Restricted matches, Process sub-system, Envelope composite curves, Heat load distribution

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Nomenclature

Latin letters

$\dot{M}$	Mass flow [kg/s]
$\dot{m}$	Nominal mass flow [kg/s]
$\dot{E}_{el,u}$	Consumed ($^+$) / produced ($^-$) electricity by unit u [kW]
$\dot{E}_{el}$	Total electricity demand ($^+$) or excess ($^-$) [kW]
$\dot{E}_{f,u}$	Consumed ($^+$) fuel by unit u [kW]
c_{el}	Electricity price buying price ($^+$) selling price ($^-$) [Euro/kWh$_{el}$]
c_f	Fuel price [Euro/kWh]
f_u	Multiplication factor of unit u [-]
h	Specific enthalpy [J/kg]
nk	Number of temperature intervals [-]
ns	Number of streams [-]
$nsub$	Number of sub systems [-]
nu	Number of units [-]
q	Specific heat load [kJ/kg]
T	Temperature [K]
y_{ij}	Integer variable representing connection between hot stream i and cold stream j [-]
y_u	Integer variable representing the existence (1) or not (0) of unit u [-]

Subscripts

c	Cold streams
h	Hot streams
hts	Index for heat transfer system
k	Temperature interval
s	Index for subsystem

Superscripts

$+$	Entering the system
$-$	Leaving the system
max	Maximum value
min	Minimum value

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 heating and cooling requirement, a heat exchanger network has to be designed, considering process and utility streams. 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.
The total site approach, presented by Dhole et al. [1] and later by Klemes et al. [2], implicitly accounts for restricted matches. 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; the heat recovery is calculated, but there is no systematic approach to define the members of sub-systems that allows to generate the self sufficient pockets. Moreover the integration of the energy conversion units is not considered. Especially, the self-sufficient pockets are suppressed, which penalizes the combined heat and power integration. Bagajewicz et al. [3] propose a single heat belt, which exchanges heat between process

plants by an intermediate fluid. Only for special cases (3 process plants) this problem is solved by using a MILP formulation. Forbidden matches between certain pairs of process streams are considered by Papoulias et al.[4]. 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 et al. [5] 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. Maréchal et al. [6] propose a MILP strategy, which integrates forbidden heat exchange connections as constraints in the targeting phase, and allows the integration of heat transfer fluids. Heat load distribution constraints are introduced in the heat cascade formulation and the penalty in terms of utility and operating costs can be considered.
For solving a site scale process integration problem, this paper presents an extension of this MILP strategy and introduces the approach of process integration by sub-systems, which makes the practical implementation easier and considers restricted matches between sub-systems. In addition, the envelope composite curves are introduced, in order to chose optimal heat transfer units.
With this approach self sufficient pockets are not neglected and can be exploited to improve the global energy efficiency of the system. Combined heat and power production is optimized by integrating utilities and intermediate heat transfer units.

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 (Figure 1).

[Figure 1 about here.]

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 transfered between two sub-systems (e.g. intermediate water loop). CUs (e.g. steam boiler or cooling water) can be

defined as heat transfer system when they can exchange without restrictions with all sub-systems. If not it is also possible to define them in a sub-system, but 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 mass flows rates of the heat transfer fluids are optimized in order to minimize the cost of 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 envelope composite curves for indirect heat exchange. The problem is solved in several steps which are summarized in Table 1.

[Table 1 about here.]

In the first step, a MILP problem without restricted matches is solved, to define 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 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. For large scale problems, it is possible to perform an optional multi-objective optimization in order to choose among different HTUs (Section 3.4). 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 can be resolved. Their flow rates are calculated by solving again the MILP problem of Section 3.2. As a last step, the heat load distribution problem (HLD), proposed by Maréchal and Kalitventzeff [7], 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.

- Contrary to the total site integration methodology, 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 easily
- The combinatorial nature of the HEN design is reduced.

3. Heat cascade formulations

3.1. General MILP formulation without restricted matches

First the general MILP formulation proposed in [8] is described. The objective is to minimize the operating costs (equation (1)).

$$F_{obj} = min(c_f^+ \sum_{u=1}^{nu} f_u \dot{E}_{f,u}^+ + c_{el}^+ \sum_{u=1}^{nu} f_u \dot{E}_{el,u}^+ - c_{el}^- \sum_{u=1}^{nu} f_u \dot{E}_{el,u}^-) \tag{1}$$

$\dot{E}_{f,u}^+$ is the energy delivered to unit u by the fuel (e.g. natural gas) and $\dot{E}_{el,u}$ is the electricity demand$^{(+)}$ or excess$^{(-)}$ of unit u. For the electricity cost, c_{el}^+ is the purchase cost and c_{el}^- is the selling price. c_f is the fuel price. The decision variables are $\dot{R}_k$ and f_u (multiplication factor of unit u). Without considering restricted matches, the general heat cascade for each temperature interval k is given by equation (2), where $\dot{M}$ is the mass flow rate [kg/s] and q is the specific heat load [MJ/kg] of hot (h) and cold (c) streams. The subscript k refers to the temperature interval k of the heat cascade. R_k is the cascaded heat from the temperature interval k to the lower temperature intervals.

$$\sum_{h_k=1}^{ns_{h,k}} \dot{M}_h q_{h,k} - \sum_{c_k=1}^{ns_{c,k}} \dot{M}_c q_{c,k} + \dot{R}_{k+1} - \dot{R}_k = 0 \quad \forall k = 1..., nk \tag{2}$$

$$\dot{R}_1 = 0 \quad \dot{R}_{nk+1} = 0 \qquad \dot{R}_k^- \geq 0 \quad \forall k = 2..., nk \tag{3}$$

The electricity consumption and exportation are given by equations (4) and (5) respectively.

$$\sum_{u=1}^{nu} f_u \dot{E}^{+}_{el,u} + \dot{E}^{+}_{el} - \sum_{u=1}^{nu} f_u \dot{E}^{-}_{el,u} \geq 0 \tag{4}$$

$$\sum_{u=1}^{nu} f_u \dot{E}^{+}_{el,u} + \dot{E}^{+}_{el} - \dot{E}^{-}_{el} - \sum_{u=1}^{nu} f_u \dot{E}^{-}_{el,u} = 0 \tag{5}$$

To calculate the flow rates of the cold stream c or the hot stream h, the nominal flow of this cold or hot stream $\dot{m}_c$ or $\dot{m}_h$ is multiplied by the multiplication factor of the unit of the corresponding stream (equations (6) and (7)).

$$\dot{M}_h = f_u * \dot{m}_h \tag{6}$$

$$\dot{M}_c = f_u * \dot{m}_c \tag{7}$$

Hot and cold streams can be process streams or utility streams. The difference is that the mass flow rate is fixed for process streams, and variable for utility streams in order to optimize the appropriate flow rates.
The multiplication factor is limited by a minimum and a maximum value. The associated entire variable y_u defines if the utility unit uw is added to process ($y_u = 1$) or not ($y_u = 0$).

$$y_u * f_u^{min} \leq f_u \leq y_u * f_u^{max} \tag{8}$$

The utilities are dimensioned that the process demand is satisfied. The corresponding thermodynamical feasibility is guarantied by Eqs. (9) and (3).

$$\dot{E}^{+}_{el} \geq 0 \qquad \dot{E}^{-}_{el} \geq 0 \tag{9}$$

3.2. MILP formulation with restricted matches of sub-systems

Like for the normal heat cascade the objective is to minimize the operating costs (equation (10)).

$$F_{obj} = min(c_f^{+} \sum_{u=1}^{nu} f_u \dot{E}^{+}_{f,u} + c_{el}^{+} \sum_{u=1}^{nu} f_u \dot{E}^{+}_{el,u} - c_{el}^{-} \sum_{u=1}^{nu} f_u \dot{E}^{-}_{el,u}) \tag{10}$$

When the industrial plant is divided into sub-systems, the normal heat cascade (equations (2) and (3)) is replaced by following equations (11) - (17) in order to take account of heat exchange restrictions.

For each sub-system (s) the heat cascade is given by equations (11) to (12). 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 ($\dot{Q}^-_{hts,s,k}$) or respectively removed by the heat transfer system ($\dot{Q}^+_{hts,s,k}$). $\dot{R}_{s,k}$ is the cascaded heat the to lower temperature interval k in sub-system s. The new decision variables are $\dot{R}_{s,k}$, $\dot{R}_{hts,k}$, $\dot{R}_k$, f_u and $\dot{Q}_{hts,s,k}$.

$$\begin{aligned} \sum_{h_{s,k}=1}^{ns_{h,s,k}} \dot{M}_h q_{h,s,k} - \sum_{c_{s,k}=1}^{ns_{c,s,k}} \dot{M}_c q_{c,s,k} + \dot{Q}^-_{hts,s,k} - \dot{Q}^+_{hts,s,k} + \dot{R}_{s,k+1} - \dot{R}_{s,k} \\ = 0 \quad \forall k = 1..., nk \quad \forall s = 1..., nsub \end{aligned} \tag{11}$$

$$\dot{R}_{s,1} = 0 \quad \dot{R}_{s,nk+1} = 0 \qquad \dot{R}_{s,k} \geq 0 \qquad \forall k = 2..., nk \quad \forall s = 1..., nsub \tag{12}$$

$$\dot{Q}^+_{hts,s,k} \geq 0 \quad \dot{Q}^-_{hts,s,k} \geq 0 \qquad \forall k = 1..., nk \quad \forall s = 1..., nsub \tag{13}$$

The heat cascade for the heat transfer system ($_{hts}$) is given by equations (14) to (15).

$$\begin{aligned} \sum_{h_{hts,k}=1}^{ns_{h,hts,k}} \dot{M}_h q_{h,hts,k} - \sum_{c_{hts,k}=1}^{ns_{c,hts,k}} \dot{M}_c q_{c,hts,k} - \sum_{s=1}^{nsub_k} \dot{Q}^-_{hts,s,k} + \sum_{s=1}^{nsub_k} \dot{Q}^+_{hts,s,k} \\ + \dot{R}_{hts,k+1} - \dot{R}_{hts,k} = 0 \quad \forall k = 1..., nk \end{aligned} \tag{14}$$

$$\dot{R}_{hts,1} = 0 \quad \dot{R}_{hts,nk+1} = 0 \qquad \dot{R}_{hts,k} \geq 0 \qquad \forall k = 2, ..., nk \tag{15}$$

To ensure that heat is cascaded correctly, a second set of equations is necessary. Equation (16) express the heat balance of the hot streams and equation (17) express the heat balance of the cold streams in the heat transfer system. The flow rates of the heat transfer fluids have to be optimized in order to satisfy the remaining heat demand of all sub-systems.

$$\sum_{h_{hts,k}=1}^{ns_{h,hts,k}} \dot{M}_h q_{h,hts,k} + \dot{R}_{hts,k+1} - \dot{R}_{hts,k} - \sum_{s=1}^{nsub_k} \dot{Q}^-_{hts,s,k} \geq 0 \qquad \forall k = 1..., nk \tag{16}$$

$$-\sum_{c_{hts,k}=1}^{ns_{c,hts,k}} \dot{M}_{c,} q_{c,hts,k} + \dot{R}_{hts,k+1} - \dot{R}_{hts,k} + \sum_{s=1}^{nsub_k} \dot{Q}^+_{hts,s,k} \leq 0 \qquad \forall k = 1..., n_k \tag{17}$$

The total cascaded heat from an upper interval k is expressed by equation (18).

$$\dot{R}_k = \dot{R}_{hts,k} + \sum_{s=1}^{nsub_k} \dot{R}_{s,k} \qquad \forall k = 1..., nk + 1 \tag{18}$$

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 general 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 fixed list of units defined with the temperature levels and its technologies. Their mass-flow rates are optimized. However this formulation does not provide informations 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 designs 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 design the envelope composite curves, which embed intermediate heat transfer units to avoid energy penalties due to restricted matches.

For each temperature interval in the heat transfer heat cascade, one fictive hot stream $\dot{Q}_{h,env,k}$ and one fictive cold stream $\dot{Q}_{c,env,k}$ are added to the heat cascade formulation. Equations (13) - (15) are replaced by equations (19) - (21).

$$\begin{aligned} &\sum_{h_{hts,k}=1}^{ns_{h,hts,k}} \dot{M}_h q_{h,hts,k} - \sum_{c_{hts,k}=1}^{ns_{c,hts,k}} \dot{M}_c q_{c,hts,k} + \dot{Q}_{h,env,k} - \dot{Q}_{c,env,k} \\ &- \sum_{s=1}^{nsub_k} \dot{Q}^-_{hts,s,k} + \sum_{s=1}^{nsub_k} \dot{Q}^+_{hts,s,k} + \dot{R}_{hts,k+1} - \dot{R}_{hts,k} = 0 \qquad \forall k = 1, ..., n_k \end{aligned} \tag{19}$$

$$\dot{R}_{hts,1} = 0, \dot{R}_{hts,nk+1} = 0 \qquad \dot{R}_{hts,k} \geq 0 \qquad \forall k = 2, ..., nk \tag{20}$$

$$\begin{aligned} \dot{Q}^+_{hts,s,k} \geq 0 \quad \dot{Q}^-_{hts,s,k} \geq 0 \quad \dot{Q}^+_{h,env,k} \geq 0 \quad \dot{Q}^-_{c,env,k} \geq 0 \\ \forall k = 1..., nk \quad \forall s = 1..., nsub \end{aligned} \tag{21}$$

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. A supplementary constraint (equation (22)) is necessary, to ensure that the heat absorbed by the cold streams is equal to the heat delivered to the hot streams. It is assumed that there are no heat losses in the intermediate heat transfer networks.

$$\sum_{k=1}^{nk} \dot{Q}_{h,env,k} = \sum_{k=1}^{nk} \dot{Q}_{c,env,k} \tag{22}$$

In order to ensure that the cold composite curve of the fictive cold streams is hotter than the hot composite curve, equation (23) is added to the formulation.

$$\dot{Q}_{h,env,k} - \dot{Q}_{c,env,k} \leq 0 \qquad \forall k = 1, ..., nk \tag{23}$$

Auxiliary constraints have to be added, to avoid energy penalty, and to ensure that the resources correspond to the case with no restricted matches. For this it is either possible to fix multiplication factors of utilities (e.g. steam boiler and refrigeration cycles). But at least one utility has to be kept free in order to be able to optimize the yearly operating costs. It could also be possible to fix the yearly operating costs. The results of both approaches are similar for tested case studies.

Also the original objective function has to be modified like it is shown in equation (24).

$$\begin{aligned} F_{obj} = min(\kappa \cdot (c_f^+ \sum_{u=1}^{nu} f_u \dot{E}_{f,u}^+ + c_{el}^+ \sum_{u=1}^{nu} f_u \dot{E}_{el,u}^+ - c_{el}^- \sum_{u=1}^{nu} f_u \dot{E}_{el,u}^-) \\ + \sum_{k=1}^{nk} \dot{Q}_{h,env,k} + \sum_{k=1}^{nk} \dot{R}_k) \end{aligned} \tag{24}$$

$$\kappa = 1e^{-6} \tag{25}$$

The new objective function is composed of the operating costs and the penalty for the heat transfer networks:

- minimizing the operating costs
- minimizing the heat load transfered by the intermediate heat network

- minimizing the heat cascaded to the next interval $\dot{R}_k$; This makes the fictive cold streams as hot as possible and fictive hot streams as cold as possible. Therefore the resulted envelope curve of fictive hot and cold streams embed all possible temperature levels for heat transfer units to provide indirect heat exchange between sub-systems.

The graphs 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 Figure 5. 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 exchange restrictions. Each section (between two pinch points) of the the envelope curves can therefore be analyzed separately. And consequently, the heat transfer fluids have to be defined in a way to maintain the independence of of these sections. Once optimal temperature levels are known, appropriate indirect heat transfer unit can be chosen and integrated with the MILP formulation presented in section 3.2. In the next step the heat load distribution can be computed to give information about connections between hot and cold streams.

3.4. Multi objective optimization - choice of intermediate heat transfer networks

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 for the choice among several networks. This can be done by a multi-objective optimization approach, based on an evolutionary algorithm [9]. The chosen strategy is based on the decomposition of the optimization problem in master and slave sub-problems [10]. Figure 2 shows the optimization problem.

[Figure 2 about here.]

The decisions variables are the temperature conditions of the heat transfer units (e.g. networks). In our example four networks can be integrated, however the approach is generic and can be extended to a higher number of networks. The objectives are minimizing the operating cost (evaluated by the cost for the natural gas, electricity or cooling water) and the investment cost (evaluated by equation (27)). The pumping costs of the heat networks is included in the operating costs, in order to ensure that the size of the networks is optimal and to distinguish between different networks options. It is considered that the pumping cost is proportional to the flow rate. The operating costs (OpC) corresponds to the minimum objective function from the energy integration shown in equation (26).

$$OpC = F_{obj} = min(c_f^+ \sum_{u=1}^{nu} f_u \dot{E}_{f,u}^+ + c_{el}^+ \sum_{u=1}^{nu} f_u \dot{E}_{el,u}^+ - c_{el}^- \sum_{u=1}^{nu} f_u \dot{E}_{el,u}^-) \quad (26)$$

The investment costs (InvC) are estimated according to available correlations. As a function of the total heat exchange area ($Area$) and the minimum number of heat exchange connections (N_{min}) the mean area ($Area_{mean}$) is computed. From this, the investment costs are estimated with equation (27), which consists of the investment cost for heat exchangers. For the example, following values have been considered: $c_{ref} = 8.8kEuro$ is the reference cost for the reference area $Area_{ref} = 1m^2$ and $\gamma = 0.65$.

$$InvC = N_{min} * c_{ref} * (Area_{mean}/Area_{ref})^{\gamma} \quad (27)$$

As a result the pareto front shows optimal solution 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 is very time consuming.

3.5. Heat load distribution

The heat load distribution is the first step to design the heat exchanger network. It is calculated by following equations as presented in Maréchal and Kalitventzeff [7]. The objective function is minimizing the number of connections (equation (28)).

$$F_{obj_{hld}} = min(\sum_{j=1}^{ns_c} \sum_{i=1}^{ns_h} y_{ij}) \quad (28)$$

Equations (29) and (30) describes the heat balances of the hot and cold streams. Equation (31) shows the existence of a connection between hot stream i and cold stream j. Each heat load must be positive (equation (32)).

$$\sum_{j=1}^{ns_c} Q_{ijk} = Q_{ik} \qquad \forall i = 1, ..., ns_h, \forall k = 1..., nk \tag{29}$$

$$\sum_{i=1}^{ns_h} \sum_{k=1}^{nk} Q_{ijk} - Q_j \geq 0 \qquad \forall j = 1, ..., ns_c, \tag{30}$$

$$\sum_{k=1}^{nk} Q_{ijk} - y_{ij} Qmax_{ij} \leq= 0 \qquad \forall j = 1, ..., ns_c, \forall j = 1, ..., ns_h \tag{31}$$

$$Q_{ijk} \leq 0 \qquad \forall j = 1, ..., ns_c, \forall j = 1, ..., ns_h, \forall k = 1, ..., nk \tag{32}$$

To consider restricted matches a constraint on the integer variable $y_{ij} \in [0, 1]$ has to be added (equation (33)). The integer variable for stream i from a sub-system and stream j from another sub-system is set to 0. Considering all process and calculated utility streams with their corresponding multiplication factors, at least one solution exists to this problem.

$$y_{ij} = 0 \tag{33}$$

4. Numerical example - drying process in paper industry

[Figure 3 about here.]

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

The humid pulp is first preheated and enters the dryer unit. Currently steam, produced by a boiler that is burning natural gas, is used as a hot utility. It is used for drying by heating paper mill rolls and for producing hot air, which introduces heat to the dryer but its main function is to evacuate the evaporated water from the pulp. Possible heat recuperation is modeled by a humid air stream which has to be cooled down to the final temperature of 30°C. The list of involved process streams is given in Table 2.

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

[Table 2 about here.]

This means, for example when no indirect heat transfer units are available, that the heat demand of sub-system 1 has to be satisfied by a hot utility even if the excess heat of sub-system 2 is sufficient to satisfy the demand (Figure 3).

4.1. Step 1: Minimum utility cost without restricted matches

The minimum operating costs (utility costs) are 2.4 MEuro. It corresponds to a natural gas utilization of 6073 kW and a cooling water consumption of 1668 kW. The flow rates of the boiler and cooling water are defined.

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 boiler and the cooling water are defined as common units (CU) in the heat transfer system. They allow to exchange heat wit the process units (sub-system 1 & 2). The penalty, which consumes by the same amount 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 (Figure 4). The results are compared in Table 7.

[Figure 4 about here.]

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

In the example it is 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.
In the example, the pulping and drying sub-system cannot exchange heat directly. The flue gases of the boiler are also defined as a subsystem which cannot exchange heat directly with the process. 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 (figure 5).

[Figure 5 about here.]

According to the pinch point location, 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-system 1 and 2 to make heat recovery possible below the pinch point.

4.4. Step 3b: 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. The pareto front presented on Figure 6 has been obtained after 3000 iterations and an initial population of 1000 points. 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).

[Figure 6 about here.]

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 higher difference between lower and smaller temperature, the pumping cost become smaller. But on the other side the investment costs become higher because the necessary heat exchanger area increases. Table 6 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.

[Table 3 about here.]

The multi-objective optimization can add interesting informations, 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 informations.
In the next step, the intermediate heat recovery network is integrated for the last solution.

4.5. 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 composite envelope (Figure 5) 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 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). 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, a 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 Figure 7.

[Figure 7 about here.]

With the new heat transfer units the targeting MILP problem (formulation from section 3.2) is solved. The multiplication factors 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 figure 8. The global system is optimized and the energy penalty due to heat exchange restrictions is minimized.

[Figure 8 about here.]

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. A part of the heat load distribution is shown in Figure 9.

[Figure 9 about here.]

3 different zones (between utility pinch point at 9 °C, process pinch at at 105 °C, utility pinch point at 119 °C and the utility pinch point at 1002 °C) can be distinguished. The heat load distributions for these 3 zones are presented in Tables 4 to 6. They show the exchanged heat amount between a hot and a cold stream. The results can be later used to design the heat exchanger network.

[Table 4 about here.]

[Table 5 about here.]

[Table 6 about here.]

4.5.2. Summary of results

The summary of all results are given in table 7. For better comparison the heat delivered by the boiler is reported. The natural gas flow will also include the efficiency of the boiler, but it is not included in this table. 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 about here.]

5. Conclusion

A method for targeting the optimal integration of energy conversion systems and maximizing heat recovery in an industrial process by considering heat exchange constraints is proposed. The method considers total site integration and defines sub-systems. Between them heat exchange can not be realized, without using heat transfer units. A new MILP formulation to design the envelopes composite curves is presented and helps to chose optimal heat transfer units. The targeting problem defines the complete list of streams to be considered. Including the constraints due to restricted matches the heat load distribution problem is reduced considerably.

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 constraints). The sub-system concept is also considered 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 method allows to solve total site integration problems and maximizes the heat recovery in the system and the combined heat and power production. The method can also be used to solve batch problems (non simultaneously operations in one period) considering that during one operation step the streams cannot exchange directly with another operation step. In this case, the heat exchange between two batch operations requires the use of a heat transfer system that will be optimized by the proposed method. The batch operations can exchange heat by storing temporarily this heat in vessels.

6. Acknowledgements

The authors wish to thank ECLEER for supporting this research and collaborating in its realization.

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List of Figures

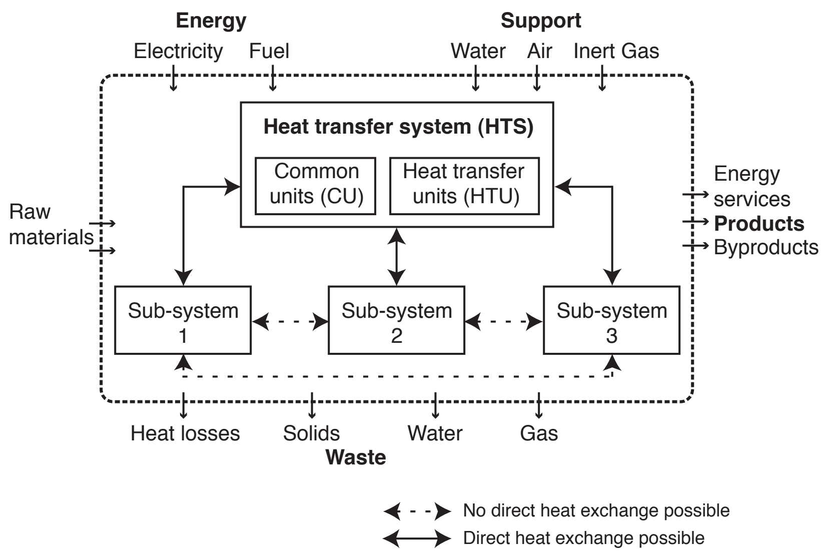

Figure 1: Definition of subsystems

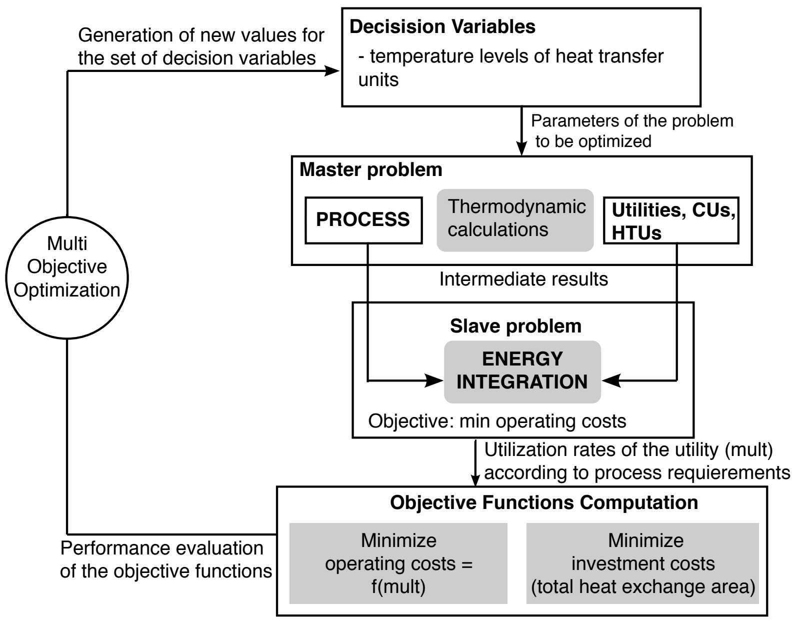

Figure 2: Multi-objective optimization problem

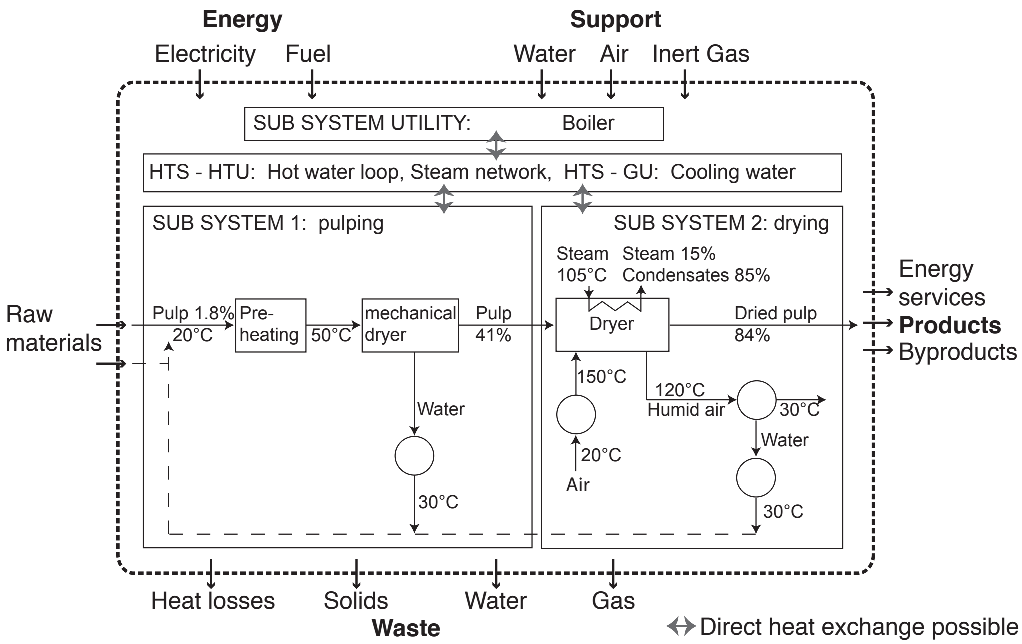

Figure 3: Representation of the process

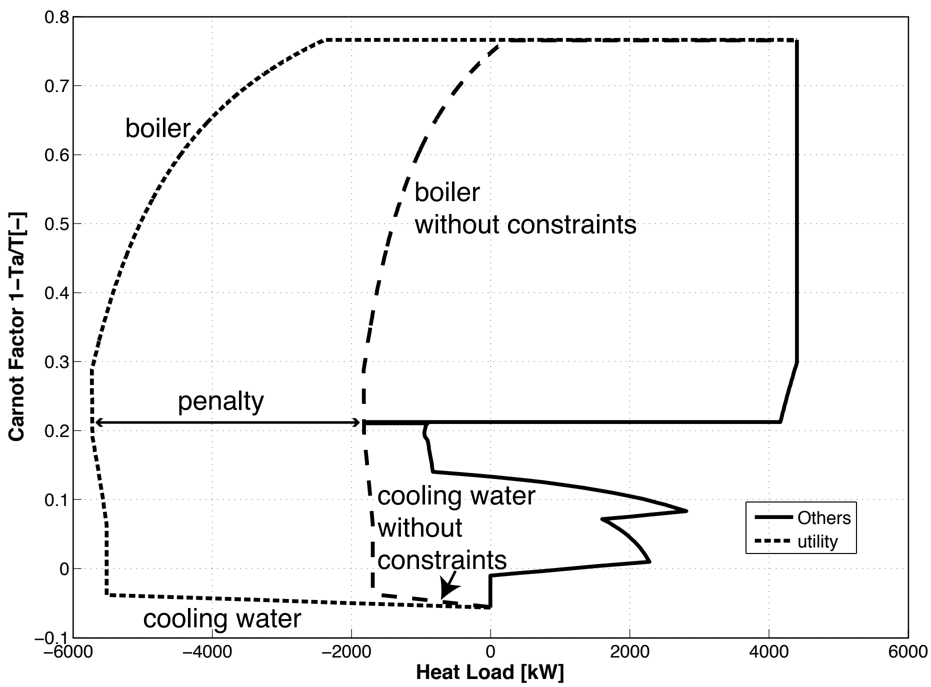

Figure 4: Penalty of the system

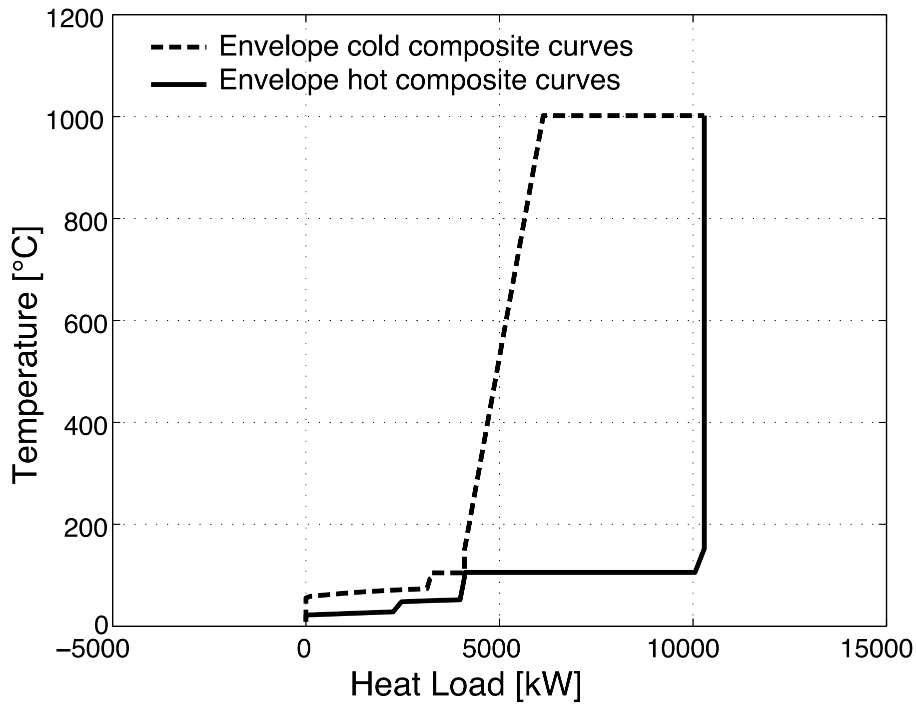

Figure 5: Envelope composite curves for intermediate heat transfer units

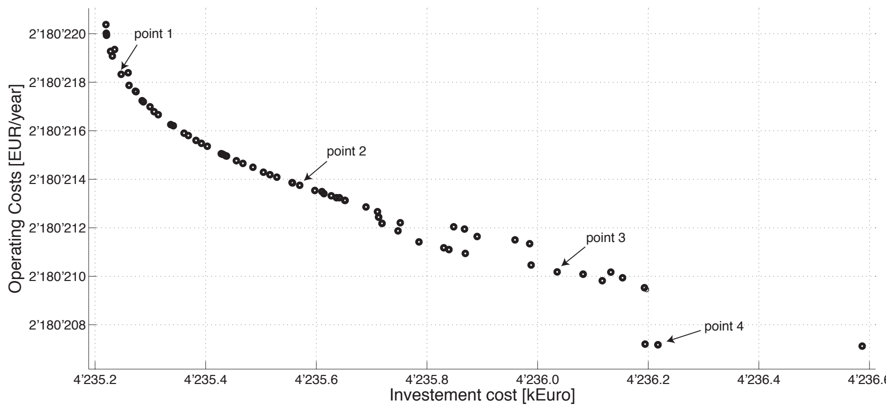

Figure 6: Pareto front to select intermediate heat transfer networks

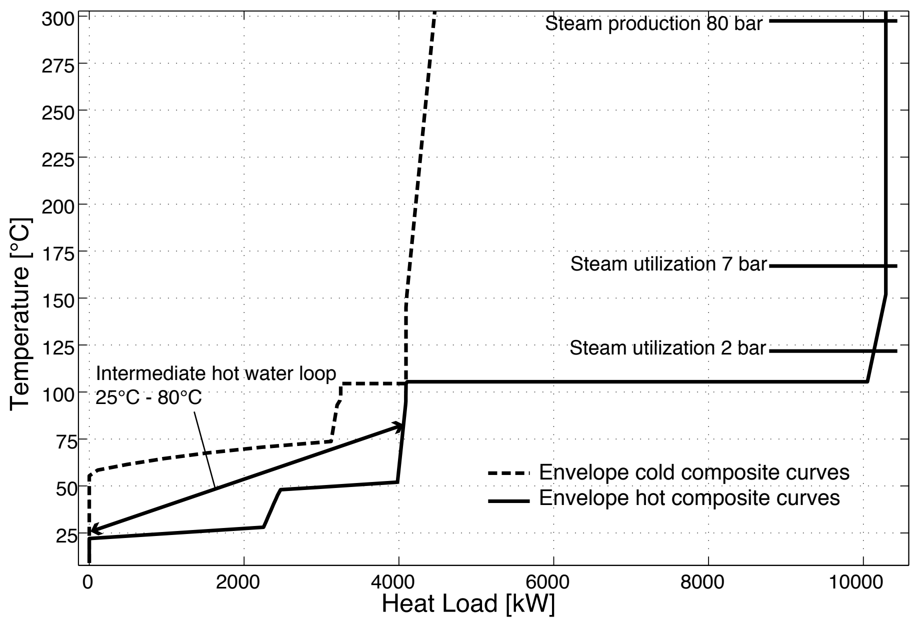

Figure 7: Choice of temperature levels of intermediate heat transfer units

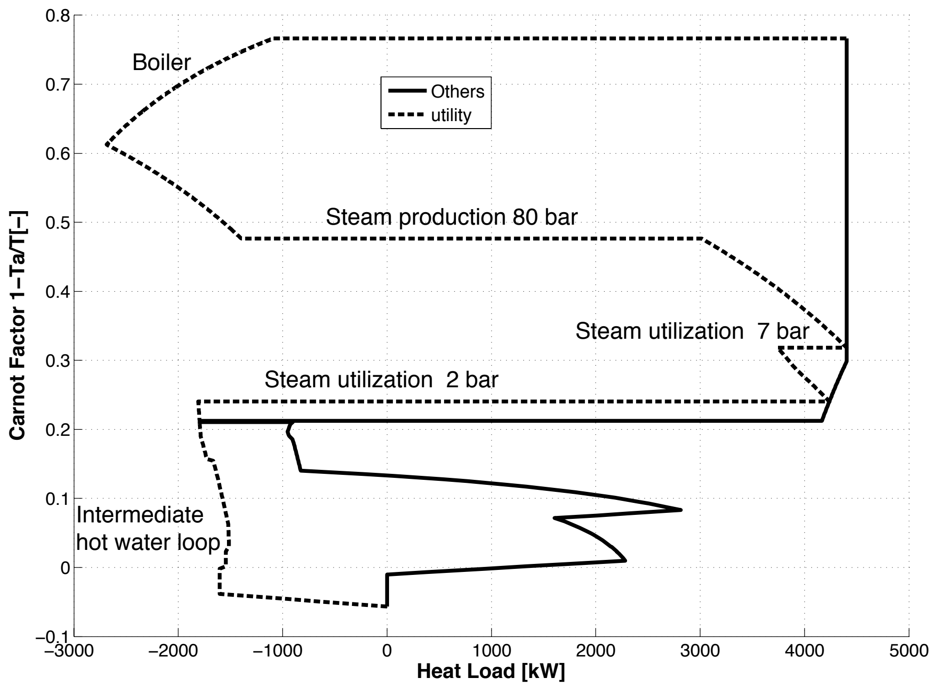

Figure 8: Integrated utility composite curves

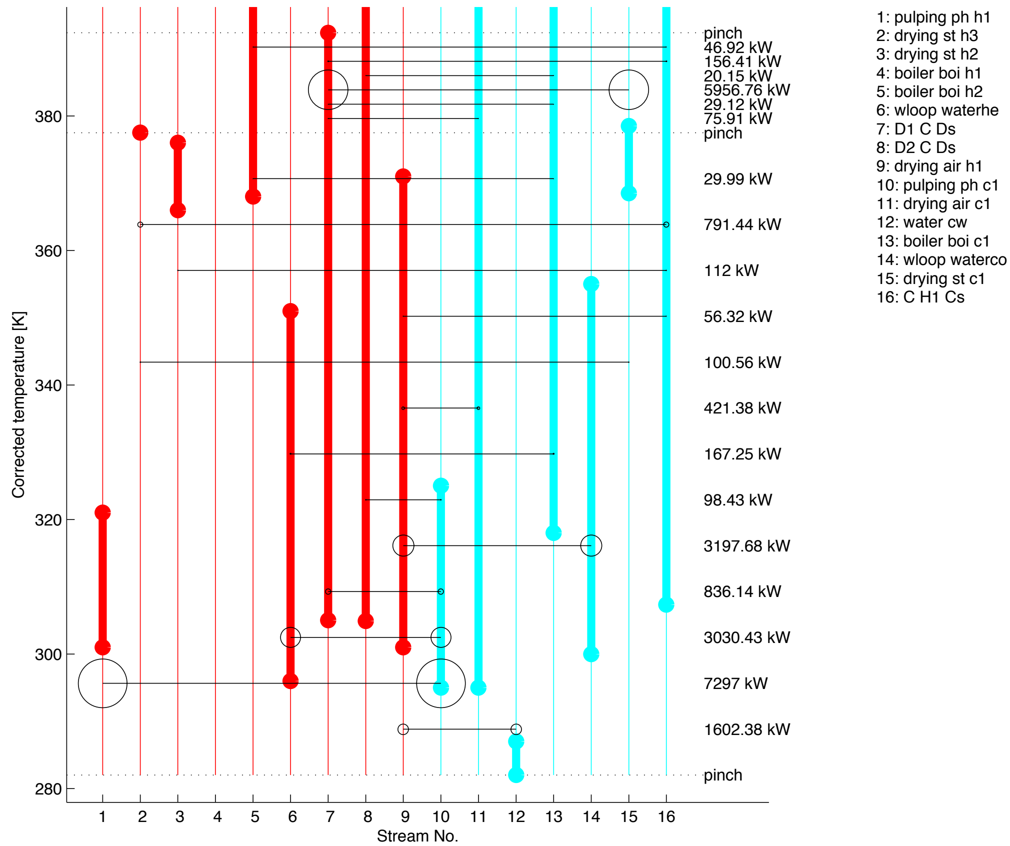

Figure 9: Heat load distribution

List of Tables

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
3a	Envelope	Visualize envelope composite curves for defining optimal HTUs (input: multiplication factors or operating costs from step 1)	Section 3.3
3b	Optimization	Multi objective optimization for choosing among several possibilities	Section 3.4
4	Integrated HTUs	With help of the previous step HTUs are chosen and integrated	Section 3.2
5	Heat load distribution	Compute heat load distribution of final solution	Section 3.5

Table 2: Process streams

Unit	Name	Tin [°C]	Tout [°C]	Heat load [kWh/tprod]	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

Table 3: Results of multi-objective optimization

Point	OpC [Euro]	InvC [kEuro]	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

Hot stream	Cold stream	Heat load [kW]
pulping_ph_h1	pulping_ph_c1	7297.0
wloop_eauhe	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

Table 5: Heat load distribution for zone 2

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

Table 6: Heat load distribution for zone 3

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

Table 7: Results

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