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TARGETING PROCEDURES FOR ENERGY SAVINGS IN THE TOTAL SITE

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Abstract

Heat integration across plants can be accomplished either directly using process streams or indirectly using intermediate fluids. In this paper, an extension of previous work performed for a system of two plants is presented. It is first shown that for a set of more than two plants, the heat transfer leading effectively to energy savings occurs at temperature levels between the pinch points of supplying and receiving plants. In some cases, however, additional heat transfer in other regions is required so that heat transfer leading to savings can be realized. A systematic procedure, based on an extension of an LP model developed for a two-plant system, which identifies energy-saving targets, is discussed. This procedure determines amounts of heat to be transferred within the established temperature intervals. Alternative solutions exist, which allow flexibility for the subsequent design of the multipurpose heat exchanger network.

1. Introduction

Since the onset of heat integration as a tool for process synthesis, energy saving methods have been developed for the design of energy efficient individual plants. Heat integration across plants (i.e., involving streams from different plants in a complex) has been always considered impractical for various reasons. Among the arguments used is the fact that plants are physically apart from each other and, because of this separation, pumping and piping costs are high. However, an even more powerful argument against integration was the fact that different plants have different startup and shutdown schedules. Therefore, if integration is done between two plants and one of the plants is put out of service, the other plant may have to resort to an alternative heat exchanger network to reach its target temperatures. Plants may also operate at different production rates departing from design conditions and needing additional exchangers to reach desired operating temperatures. All these discouraging aspects of the problem led practitioners and researchers to leave opportunities for heat integration between plants unexplored.

Integration across plants can be accomplished either directly using process streams or indirectly using intermediate fluids, like steam or dowtherms. Total site integration is the name coined referring to this complex problem. Early studies by Dhole and Linnhoff (1992) and Hui and Ahmad (1994) on total site heat integration helped to determine levels of generation of steam to indirectly integrate different processes. Since the generation and use of steam has to be performed at a fixed temperature level, opportunities for integration are lost. This was shown by Rodera and Bagajewicz (1999a) who developed targeting procedures for direct and indirect integration applied to the special case of two plants. Application of pinch analysis showed that the heat transfer that effectively leads to savings occurs at temperature levels between the pinch points of both plants. In some other cases, however, heat transfer in the external regions is also required to attain maximum savings (assisted heat integration).

The use of cascade diagrams for each plant makes possible the detection of unassisted or assisted cases, identification that was overlooked by procedures that make use of combined grand composite curves (Dhole and Linnhoff, 1992; Hui and Ahmad, 1994). Rodera and Bagajewicz (1999b,c) presented a methodology to design multipurpose heat exchanger networks that can realize these savings and function in the two modes, integrated and not integrated.

In this paper, generalized mathematical models are presented that extend the results first developed for two plants (Rodera and Bagajewicz, 1999a) to the case of multiple plants. First, an LP that considers all possible heat transfer among plants leading to savings is presented. An example that shows the importance of detecting assisted cases is solved and compared with the grand composite curve technique.

2. Maximum Transferable Heat

Background material for the case of two plants was presented by Rodera and Bagajewicz (1999a).

2.1 *Heat Transfer Region Leading to Savings*

Consider a set of n plants on which minimum utility targets are obtained independently. Moreover, assume that the resulting pinch points are located at different temperatures. In order to apply the targeting procedures, the plants are sorted from left to right in order of increasing pinch temperatures. Figure 1, taken from Rodera and Bagajewicz (1999a), shows this for the case of three plants.

When any two plants of the set of n plants is considered, the region between pinches is the region where effective transfer leading to utility savings takes place. Indeed, these regions are the only ones where the plant with the higher pinch is a net heat source and the plant with the lower pinch is a net heat sink.

However, sometimes transfer outside the region between pinches is required to allow maximum savings within this region. Therefore, the following definitions are included.

Supplier Plant. Plant that releases heat to the plant in which savings are attained due to this transfer.

Receiver Plant. Plant that receives heat from the plant in which savings are attained due to this transfer.

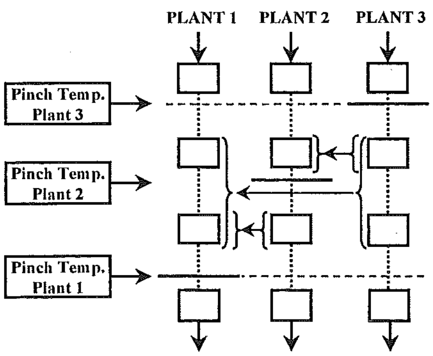

Figure 1. Heat transfer leading to savings

2.2 *Unassisted and Assisted Heat Transfer*

Let us analyze first the case in which only heat transfer in the respective regions between the pinch of each plant and the pinch of their suppliers or receivers is needed to achieve maximum savings. In this case, no transfer limitations to attain maximum savings are imposed to the heat that the plant under consideration can give or receive in these regions. Therefore, the concept of unassisted heat transfer introduced by Rodera and Bagajewicz (1999a) for the case of two plants can be extended to this set of n plants. Figure 2 shows an instance of unassisted heat transfer among a set of three plants.

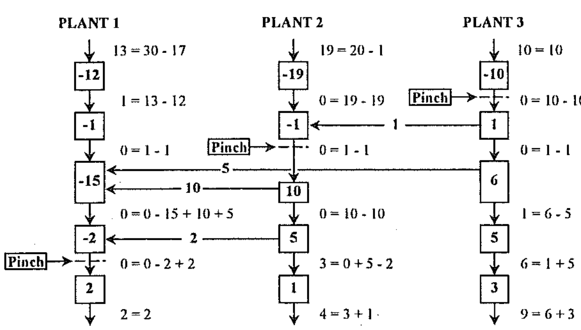

Figure 2. Unassisted heat transfer

Assume now that certain limitations are imposed in the amount that a single plant can give or receive between its pinch and the pinch of their suppliers or receivers. Moreover, assume that these limitations prevent the whole system of n plants from achieving maximum energy savings. The referred limitations occurred whenever a surplus/demand of heat, outside the region between the pinches under consideration, has to be used/fulfilled by this region (Rodera and Bagajewicz, 1999a). If this surplus/demand is transferred in the region in which occurs (outside the region between pinches) and in the direction opposite to the one that leads to effective savings, the limitation is reduced and can eventually be removed.

The concept of assisted heat transfer introduced by Rodera and Bagajewicz (1999a) is therefore applicable to this set of n plants when at least one transfer outside the respective regions between pinches is required to achieve maximum savings. Figure 3 shows an instance of assisted heat transfer among a set of three plants. In this figure, plant 1 transfers heat to plant 2 above the pinch of plant 2. If this heat is not transferred, then the maximum heat supplied by the other plants to plant 1 is reduced to 13 units.

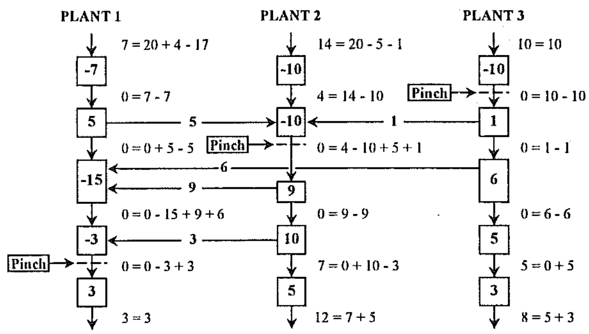

Figure 3. Assisted heat transfer

3. Targeting Model for Heat Integration

3.1 *Maximum Energy Savings Model for the Two-Plant Case*

For this particular case, the following transshipment model was introduced by Rodera and Bagajewicz (1999a) to establish the maximum heat that can be transferred within each interval.

$$Min(\delta_0^I + \delta_m^{II})$$

$$s.t$$

$$\delta_0^I = \hat{\delta}_0^I + Q_A - Q_E$$

$$\delta_0^{II} = \hat{\delta}_0^{II} - Q_A$$

$$\left.\begin{array}{l} \delta_i^I = \delta_{i-1}^I + q_i^I - q_i^A \\ \delta_i^{II} = \delta_{i-1}^{II} + q_i^{II} + q_i^A \end{array}\right\} \quad \forall i = 1,\dots,p^{II}$$

$$\left.\begin{array}{l} \delta_i^I = \delta_{i-1}^I + q_i^I + q_i^E \\ \delta_i^{II} = \delta_{i-1}^{II} + q_i^{II} - q_i^E \end{array}\right\} \quad \forall i = (p^{II}+1),\dots,p^I \qquad (1)$$

$$\left.\begin{array}{l} \delta_i^I = \delta_{i-1}^I + q_i^I - q_i^B \\ \delta_i^{II} = \delta_{i-1}^{II} + q_i^{II} + q_i^B \end{array}\right\} \quad \forall i = (p^I+1),\dots,m$$

$$\delta_m^I = \hat{\delta}_m^I - Q_B$$

$$\delta_m^{II} = \hat{\delta}_m^{II} + Q_B - Q_E$$

$$\delta_{p^I}^I = 0, \ \delta_{p^{II}}^{II} = 0$$

$$\delta_i^I, \delta_i^{II}, q_i^A, q_i^E, q_i^B \geq 0$$

Note that a single direction of heat transfer in each region is allowed based on the analysis of the directions that effectively lead to savings. Heat flows only from plant 2 to plant 1 between pinches and only from plant 1 to plant 2 outside this region. Figure 4 illustrates the notation for total heat amounts transferred in each region.

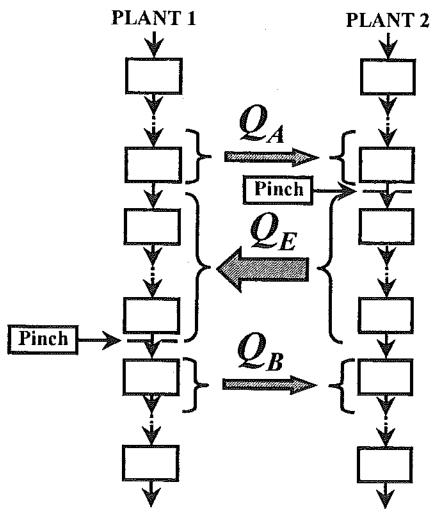

Figure 4. Heat transfer among intervals

The objective function used in problem 1 minimizes the heating utility of plant 1 and the cooling utility of plant 2. These utilities are therefore, reduced in the amount transferred between pinches from plant 2 to plant 1. Moreover, the minimization assures that the heat transferred from plant 1 to plant 2 is strictly the amount required in the assisted cases.

A simple balance around plant 1 or plant 2 proves that the summation of the solutions (heat transferred amounts q_i^E, q_i^A, and q_i^B) represents the total possible amounts of heat Q_E, Q_A, and Q_B to be transferred in their respective regions. Therefore, an equivalent objective function for this problem is.

$$Max\,\{Q_E-(Q_A+Q_B)\}$$

Maximization of the heat that effectively leads to savings and minimization of the assisted amounts is clearly achieved.

3.2 *Maximum Energy Savings Model for the Total-Site*

Let us introduce first the following sets of plants.

P : set of n plants considered for direct or indirect integration.

R_{ij}^F : set of receiver plants k of plant j in interval i present in region F.

S_{ij}^F : set of supplier plants k of plant j in interval i present in region F.

The transfer regions F are the following.

A: region above both the pinch of plant j and the pinch of receiver plant k.

F: region between the pinch of plant j and the pinch of receiver plant k.

B: region below both the pinch of plant j and the pinch of receiver plant k.

Based on these sets, the model that considers independent transfer of heat within each interval is.

$$Max\,\{Q_E-(Q_A+Q_B)\}$$

$$s.t.$$

$$\left.\begin{array}{l}
\delta_o^j=\hat{\delta}_o^j-\sum\limits_{\forall k\in S_j^E}Q_{kj}^E+\sum\limits_{\forall k\in R_j^A}Q_{jk}^A-\sum\limits_{\forall k\in S_j^A}Q_{kj}^A\\
\delta_i^j=\delta_{i-1}^j+q_i^j-\sum\limits_{\forall k\in R_{ij}^A}q_{ijk}^A+\sum\limits_{\forall k\in S_{ij}^A}q_{ikj}^A\\
\qquad\qquad\forall i=1,\ldots,p^n\\
\delta_i^j=\delta_{i-1}^j+q_i^j+\sum\limits_{\forall k\in S_{ij}^E}q_{ikj}^E-\sum\limits_{\forall k\in R_{ij}^A}q_{ijk}^A+\sum\limits_{\forall k\in S_{ij}^A}q_{ikj}^A\\
\qquad\qquad\forall i=p^n+1,\ldots,p^j;\,j\neq n\\
\delta_i^j=\delta_{i-1}^j+q_i^j-\sum\limits_{\forall k\in R_{ij}^E}q_{ijk}^E+\sum\limits_{\forall k\in S_{ij}^B}q_{ikj}^B-\sum\limits_{\forall k\in R_{ij}^B}q_{ijk}^B\\
\qquad\qquad\forall i=p^j+1,\ldots,p^1;\,j\neq 1\\
\delta_i^j=\delta_{i-1}^j+q_i^j+\sum\limits_{\forall k\in S_{ij}^B}q_{ikj}^B-\sum\limits_{\forall k\in R_{ij}^B}q_{ijk}^B\\
\qquad\qquad\forall i=p^1+1,\ldots,m\\
\delta_o^j=\hat{\delta}_o^j-\sum\limits_{\forall k\in R_j^E}Q_{jk}^E+\sum\limits_{\forall k\in S_j^B}Q_{kj}^B-\sum\limits_{\forall k\in R_j^B}Q_{jk}^B
\end{array}\right\}\forall j\in P \tag{2}$$

$$\delta_i^j,\,q_{ijk}^A,\,q_{ikj}^E,\,q_{ijk}^B\geq 0$$

The following balances around each pair of plants relate the heat transferred amounts in each interval q_{ijk}^E, q_{ijk}^A, and q_{ijk}^B with the overall heat amounts Q_{jk}^E, Q_{jk}^A, and Q_{jk}^B, respectively.

$$\left.\begin{array}{l}
Q_{jk}^E=\sum\limits_{i=p^j+1,\ldots,p^k;\,j\neq 1}q_{ijk}^E=\sum\limits_{i=p^k+1,\ldots,p^j;\,j\neq n}q_{ikj}^E\\
Q_{jk}^A=\sum\limits_{i=1,\ldots,p^k;\,j\neq n}q_{ijk}^A+\sum\limits_{i=1,\ldots,p^j;\,j\neq 1}q_{ikj}^A\\
Q_{jk}^B=\sum\limits_{i=p^{j+1},\ldots,m;\,j\neq n}q_{ijk}^B+\sum\limits_{i=p^k+1,\ldots,m;\,j\neq 1}q_{ikj}^B
\end{array}\right\}k\neq j \tag{3}$$

Finally, the overall effective heat transfer amount Q_E and the eventual assisted heat amounts Q_A and Q_B are the summation of the corresponding heat amounts transferred between all the pair combinations.

The following balances define these overall heat amounts by guaranteeing that the heat transfer to the receivers is equal to the heat given by the suppliers.

$$
\begin{aligned}
Q_E &= \sum_{j\in P}\ \sum_{\forall k\in R_j^E;k\neq j} Q_{jk}^E = \sum_{j\in P}\ \sum_{\forall k\in S_j^E;k\neq j} Q_{kj}^E \\
Q_A &= \sum_{j\in P}\ \sum_{\forall k\in R_j^A;k\neq j} Q_{jk}^A = \sum_{j\in P}\ \sum_{\forall k\in S_j^A;k\neq j} Q_{kj}^A \\
Q_B &= \sum_{j\in P}\ \sum_{\forall k\in S_j^B;k\neq j} Q_{kj}^B - \sum_{j\in P}\ \sum_{\forall k\in R_j^B;k\neq j} Q_{jk}^B
\end{aligned}
\tag{4}
$$

4. Results and Discussion

A combination of examples 4 and 5 from Rodera and Bagajewicz (1999a) is presented to show the integration among four plants. The results of applying individual pinch analysis to each of the plants are shown in Table 1.

Table 1. Individual plant pinch analysis

Problem	Pinch Temp. (°C)	Minimum Heating Utility (kW)	Minimum Cooling Utility (kW)
Test Case #2	90	107.5	40.0
Trivedi	160	404.8	688.6
Ciric & Floudas	200	600.0	2100.0
4sp1	249	128.0	250.0

4.1 *Direct Integration*

Figure 5 shows the result of the direct heat integration for the proposed example. This is an instance of an assisted heat integration case because heat is sent from plant 2 to plant 3.

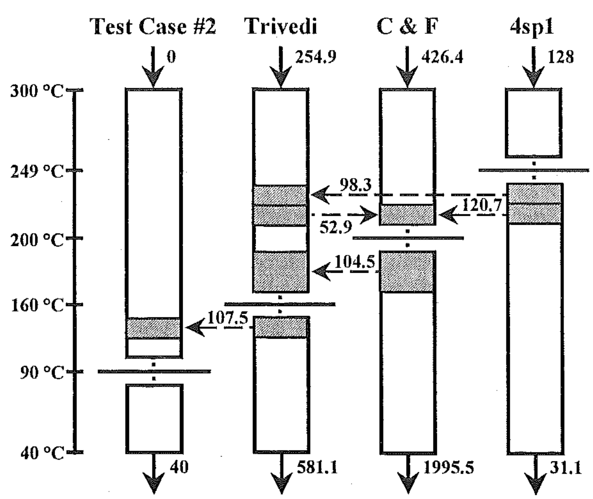

Figure 5. Direct integration.

Table 2 shows the amount of savings achieved in each of the plants as well as the entire maximum savings for the system.

Table 2. Direct Integration savings

Problem	Heating Savings (kW)	Cooling Savings (kW)
Test Case #2	107.5	0.0
Trivedi	149.9	107.5
Ciric & Floudas	173.6	104.5
4sp1	0.0	219.0
Total Savings	431.0	431.0

4.2 *Indirect Integration*

Indirect integration applied on the same example reflects a lower amount of savings as the temperature difference for heat transfer is doubled because of the use of the intermediate fluid. Moreover, the scale shifting used when heat integration between two plants is performed is not applicable to the integration among a set of *n* plants. Therefore, it is replaced by transfer between equal intervals separated by a defined temperature difference. Figure 6 shows the solution for the assisted indirect heat integration. Heat transfer is represented in a diagonal form to reflect the temperature difference required for the use of the intermediate fluid.

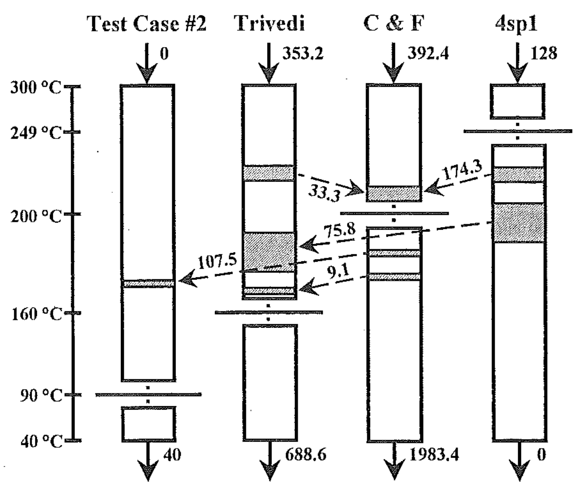

Figure 6. Indirect integration.

Table 3. Indirect Integration savings

Problem	Heating Savings (kW)	Cooling Savings (kW)
Test Case #2	107.5	0.0
Trivedi	51.6	0.0
Ciric & Floudas	207.6	116.6
4sp1	0.0	250.1
Total Savings	366.7	366.7

Table 3 shows the amount of savings achieved in each of the plants as well as the entire maximum savings for the system when an intermediate fluid is used.

4.2 *Alternative Solutions*

Since within each interval, heat can be transferred between each pair of plants or it can be cascaded first in one of them and then transferred, the model has alternative solutions. One of such alternative solutions, when direct integration is applied to the example under analysis is shown in Figure 7.

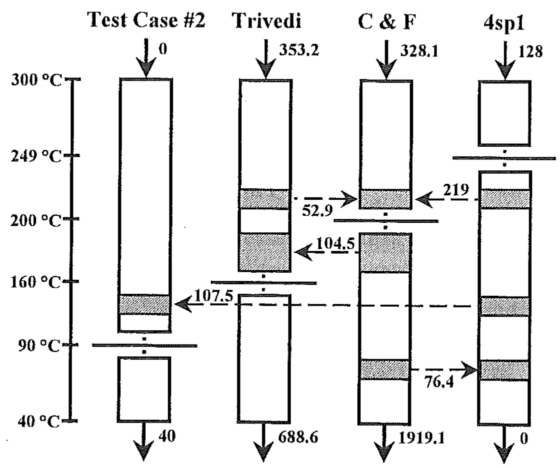

Figure 7. Alternative direct integration

Table 4 shows the amount of savings for this case. The total amounts are equal that in the previous alternative (Table 2). However, the individual savings reflect the different characteristics of this alternative.

Table 5. Alternative direct integration savings

Problem	Heating Savings (kW)	Cooling Savings (kW)
Test Case #2	107.5	0.0
Trivedi	51.6	0.0
Ciric & Floudas	271.9	180.9
4spl	0.0	250.1
Total Savings	431.0	431.0

5. Conclusions

A targeting method for heat integration between plants presented earlier by Rodera and Bagajewicz (1999a) was extended to consider a total site composed by a set of *n* plants. Two important aspects are revealed. The scale shifting performed when heat integration between two plants was studied has to be abandoned. It is replaced by transfer between equal intervals separated by a defined temperature difference. The resulting problem exhibits alternative solutions that require further exploration. This is left as future work.

Notation

I = temperature interval
J = chemical plant
K = auxiliary chemical plant
m = total number of intervals
n = total number of plants
p^I = last interval above the pinch of plant 1
p^{II} = last interval above the pinch of plant 2
p^j = last interval above the pinch of plant *j*
Q_A = total heat transferred in the zone above pinches
Q_B = total heat transferred in the zone below pinches
Q_E = total heat transferred in the zone of effective transfer of heat (between pinches)
q = heat surplus or heat demand / heat transferred
q^I = heat surplus or heat demand in plant 1
q^{II} = heat surplus or heat demand in plant 2
q^j = heat surplus or heat demand in plant *j*
d_0 = minimum surplus to the first interval
$\hat{\delta}_0$ = original minimum surplus to the first interval
d = minimum cascaded heat
$\hat{\delta}$ = original minimum cascaded heat
δ^I = minimum cascaded heat in plant 1
δ^{II} = minimum cascaded heat in plant 2

Superscripts

A = zone above both pinches
B = zone below both pinches
E = zone of effective transfer of heat (between pinches)
j = chemical plant

Subscripts

A = zone above both pinches
B = zone below both pinches
E = zone of effective transfer of heat (between pinches)
i = temperature interval
j = chemical plant
k = auxiliary chemical intervals
p^I = last interval above the pinch of plant 1
p^{II} = last interval above the pinch of plant 2

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