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Energy savings in the total site Heat integration across many plants

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Abstract

In this paper, an extension of previous work performed for a system of two plants is presented. For a set of *n* plants, heat transfer leading effectively to energy savings occurs at temperature levels between the pinch points of supplying and receiving plants. In some cases, additional heat transfer in other regions is required to attain maximum savings. A systematic procedure, based on LP and MILP models, is used to identify energy-saving targets for the two forms of integration and find the location of the intermediate fluid circuits. Finally, the optimal location of these circuits allowing restricted operation is discussed. Alternative solutions exist, which allow flexibility for the subsequent design of the multipurpose heat exchanger network.

Keywords: Heat integration; Energy savings; Process synthesis; Process design; Total site integration

1. Introduction

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 when 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 in the special case of two plants. Application of pinch analysis showed that the heat transfer effectively leading 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 allows for the detection of unassisted and assisted cases. Distinction between these two cases was overlooked by procedures that make use of combined grand composite curves (Dhole & Linnhoff, 1992), or methods developed to determine heat transfer between zones (Ahmad & Hui, 1991; Amidpour & Polley, 1997). In addition, 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 originally developed for two plants (Rodera & Bagajewicz, 1999a) to the case of multiple plants. Preliminary results of the application of these models were presented by Rodera and Bagajewicz (1999d). First, an LP model that considers all possible heat transfer among plants leading to savings is presented. This formulation identifies energy-saving targets for the two forms of integration by determining the amounts of heat to be transferred within established temperature intervals. By the use of an MILP model, a procedure to locate the intermediate fluid circuits for indirect integration is then introduced. Finally, the optimal location of these circuits allowing flexibility of operation can be easily added to this formulation. Examples showing the different features of this approach are presented.

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2. Maximum transferable heat

Background material for the case of two plants was presented by Rodera and Bagajewicz (1999a). The extension to a site consisting of a set of *n* plants is introduced next.

2.1. Heat transfer region leading to savings

Consider a set of *n* plants sorted from left to right in order of increasing pinch temperatures for which minimum utility targets have been calculated independently. When any two plants of the set are taken into account, the region between pinches is the region where effective transfer leading to utility savings takes place. Indeed, only these regions are the 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. This type of heat transfer is called *effective heat transfer*. The existing relationship between the plants during integration requires the following definitions:

- Effective-supplier plant: plant that releases effective heat to the plant in which savings are obtained by a reduction of its heating utility demands.
- Effective-receiver plant: plant that receives effective heat from the plant in which savings are obtained by a reduction of its cooling utility demands.

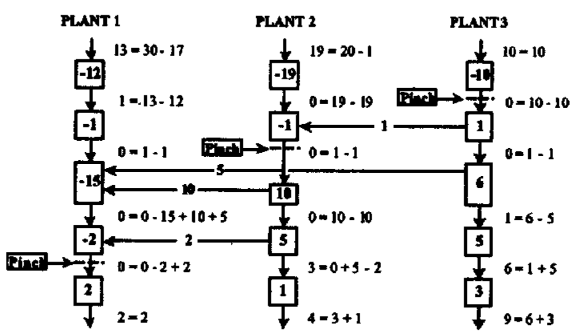

Fig. 1. Unassisted heat transfer.

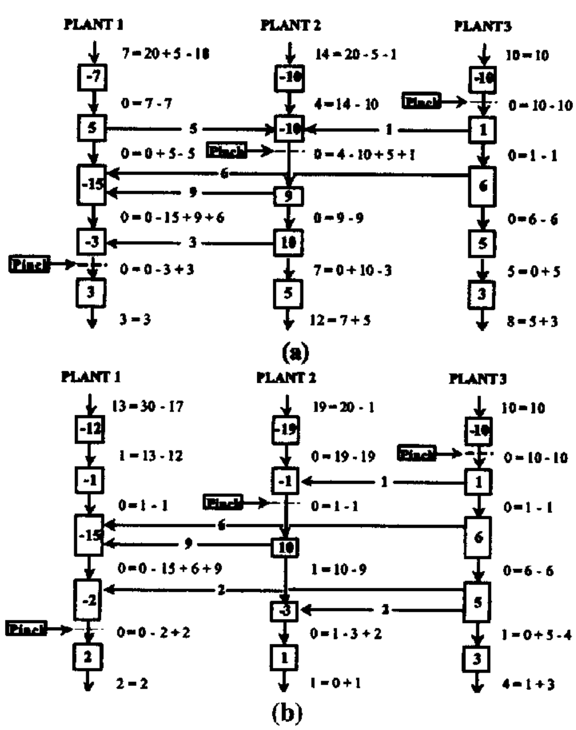

Fig. 2. Assisted heat transfer.

2.2. Unassisted and assisted heat transfer

When maximum energy savings are attained by only transferring heat in the region between pinches, an unassisted heat transfer case is present. Fig. 1 shows an instance of unassisted heat transfer among a set of three plants. In this diagram, plants 2 and 3 are effective-suppliers of plant 1, while plant 3 is the effective-supplier of plant 2. Moreover, plant 1 is the effective-receiver of plant 2, while plants 1 and 2 are effective-receivers of plant 3.

Rodera and Bagajewicz (1999a) showed that to attain maximum energy savings in certain cases, effective heat transfer across two plants (i.e. taking place between both pinches) must be accompanied by heat transfer in the reverse direction and outside the region between pinch points. The interaction among plants becomes more complex for the case of more than two plants. In this case, assisted heat does not have to come from the same plant that is receiving the heat as it can be supplied by other plants. Since it is not known a priori which plant will be providing assisting heat, we introduce the following definitions:

- Assisted plant: plant that releases assisting heat above its pinch, or receives assisting heat below its pinch.
- Assisting plant: plant that receives assisting heat above its pinch, or releases assisting heat below its pinch.

Fig. 2(a) shows an instance of assisted heat transfer among a set of three plants in the opposite direction to the heat received in order to attain effective savings. In this case, plant 2 is both an assisting plant and an effective-supplier of plant 1. Conversely, plant 1 is both an assisted plant and an effective-receiver of plant 2. Fig. 2(b) shows a case in which the assisted transfer from plant 3 to plant 2 is parallel to the effective heat transferred from these plants. In this example, plant 2 and 3 are effective-suppliers of plant 1. For plant 2, plant 3 is an effective-supplier and at the same time, an assisting plant. Conversely, for plant 3, plant 2 is an effective-receiver and an assisted plant.

3. Targeting model for heat integration

3.1. Maximum energy savings model for the total-site

A transshipment model was introduced by Rodera and Bagajewicz (1999a) to establish the heat that can be transferred within each interval for the particular case of two plants. The extension of this model for n plants follows. First, the following sets of plants are introduced.

- P Set of n plants considered for direct or indirect integration.
- R_j^A Set of assisting plants k receiving heat from plant j in the region above the pinch.
- S_j^A Set of assisted plants k supplying heat to plant j in the region above the pinch.
- R_j^E Set of effective-receiver plants k receiving heat from plant j.
- S_j^E Set of effective-supplier plants k supplying heat to plant j.
- R_j^B Set of assisted plants k receiving heat from plant j in the region below the pinch.
- S_j^B Set of assisting plants k supplying heat to plant j in the region below the pinch.
- R_{ij}^A Set of assisting plants $k \in R_j^A$ present in interval i.
- S_{ij}^A Set of assisted plants $k \in S_j^A$ present in interval i.
- R_{ij}^E Set of effective-receiver plants $k \in R_j^E$ present in interval i.
- S_{ij}^E Set of effective-supplier plants $k \in S_j^E$ present in interval i.
- R_{ij}^B Set of assisted plants $k \in R_j^B$ present in interval i.
- S_{ij}^B Set of assisting plants $k \in S_j^B$ present in interval i.

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

$$\mathbf{P} = Max\,\{2 \cdot Q_E - \varepsilon(Q_A + Q_B)\}$$

$$s.t.\quad \left.\begin{array}{l}
\delta_o^j = \hat{\delta}_o^j - \sum_{k \in S_j^E} Q_{kj}^E + \sum_{k \in R_j^A} Q_{jk}^A - \sum_{k \in S_j^A} Q_{kj}^A \\
\delta_i^j = \delta_{i-1}^j + q_i^j - \sum_{k \in R_{ij}^A} q_{ijk}^A + \sum_{k \in S_{ij}^A} q_{ikj}^A \\
\qquad\qquad\qquad \forall i = 1,\ldots,p^n \\
\delta_i^j = \delta_{i-1}^j + q_i^j + \sum_{k \in S_{ij}^E} q_{ikj}^E - \sum_{k \in R_{ij}^A} q_{ijk}^A + \sum_{k \in S_{ij}^A} q_{ikj}^A \\
\qquad\qquad\qquad \forall i = p^n+1,\ldots,p^j;\ j \neq n \\
\delta_i^j = \delta_{i-1}^j + q_i^j - \sum_{k \in R_{ij}^E} q_{ijk}^E + \sum_{k \in S_{ij}^B} q_{ikj}^B - \sum_{k \in R_{ij}^B} q_{ijk}^B \\
\qquad\qquad\qquad \forall i = p^j+1,\ldots,p^1;\ j \neq 1 \\
\delta_i^j = \delta_{i-1}^j + q_i^j + \sum_{k \in S_{ij}^B} q_{ikj}^B - \sum_{k \in R_{ij}^B} q_{ijk}^B \\
\qquad\qquad\qquad \forall i = p^1+1,\ldots,m \\
\delta_m^j = \hat{\delta}_m^j - \sum_{k \in R_j^E} Q_{jk}^E + \sum_{k \in S_j^B} Q_{kj}^B - \sum_{k \in R_j^B} Q_{jk}^B \\
\delta_i^j, q_{ijk}^A, q_{ikj}^E, q_{ijk}^B \geq 0 \qquad \forall k, \forall i
\end{array}\right\} \forall j \in P$$

where ε is a small number (e.g. 0.01) that eliminates the influence of the assisted heat over the effective heat in the objective function. The overall heat amounts Q_{jk}^E, Q_{jk}^A, and Q_{jk}^B are obtained by adding for each pair of plants the respective heat transferred amounts in each interval q_{ijk}^E, q_{ijk}^A, and q_{ijk}^B. 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.

4. Targeting model for circuit location

The location of the intermediate fluid circuits used for indirect integration is found by solving an extension of the MILP model presented by Rodera and Bagajewicz (1999a) for the special case of two plants. In this extension, temperature constraints are added to model **P** to assure that any single circuit between two plants follows the second law restrictions. Moreover, the starting and ending intervals for these circuits are represented by binary variables that allow heat transfer where the circuits span. This model establishes single independent circuits between any two plants.

In these models indirect integration (and particularly the issue of having intermediate circuits transferring heat in different directions) is resolved by considering that the variables corresponding to heat transfer between plants correspond to upward and downward diagonal transfer between equal intervals that are a fixed number of intervals apart. A procedure is used in order to obtain this generalized structure of intervals. This procedure will be presented in an extension of the present work.

4.1. Multiple-operation circuits

An extension of the MILP model discussed in the previous section is constructed to take into account cases in which one or more plants go out of service. The different scenarios are considered by accounting for all the possible operational modes. These modes are the instances in which two or more plants are in operation. Therefore, the maximum possible number of modes $w_{\max}$ is:

$$w_{\max} = \sum_{r=2}^{n} \frac{n!}{r!(n-r)!}$$

where r is the number of plants in operation. The purpose of the model is the maximization of the heat transfer leading to savings on each of the modes. Therefore, it is constructed by adding an extra sub-index to all variables and parameters representing the heat flows, and maximizing the sum of the effective heat transfer in each mode.

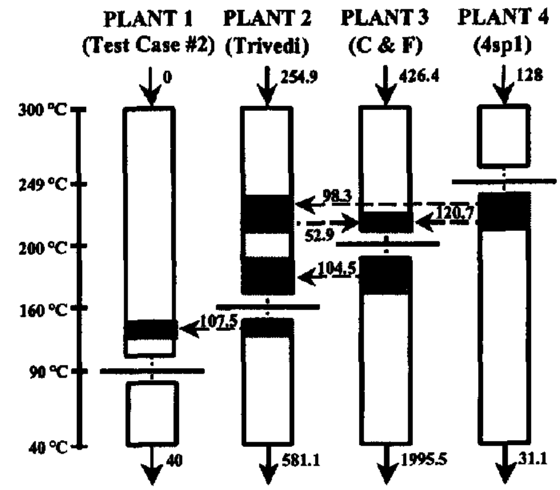

Fig. 3. Direct integration solution.

Table 1
Amount of savings for direct integration

Problem	Savings (kW)	
	Heating	Cooling
Test case #2	107.5	0.0
Trivedi (1988)	149.9	107.5
Ciric and Floudas (1991)	173.6	104.5
4sp1	0.0	219.0
Total savings	431.0	431.0

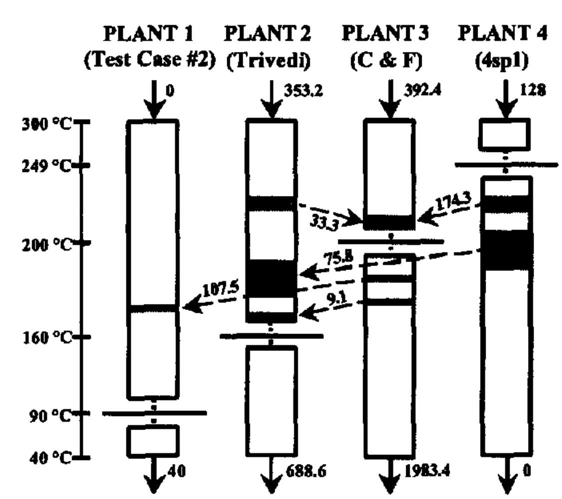

Fig. 4. Indirect integration solution.

By the use of the same set of binary and continuous variables to represent the span of the circuits in all modes, it is guaranteed that a single arrangement of circuits is selected. Restrictions to the use of a single pipe to transfer heat from a plant to all of its receivers can be easily added by asking the corresponding binary variables to take the same value at the same temperature interval.

5. Example 1

This example was constructed using a combination of examples 4 and 5 from Rodera and Bagajewicz (1999a) and shows the integration among a set of four plants.

5.1. Direct integration solution

Fig. 3 shows the result of applying direct heat integration to this example by solving model P. This is an instance of an assisted heat integration case because heat is sent from plant 2 to plant 3. Table 1 shows the amount of savings achieved in each of the plants as well as the entire maximum savings for the system. Because each interval allows heat to be transferred between each pair of plants or cascaded first in one of them and then transferred, the model has alternative solutions.

5.2. Indirect integration solution

Indirect integration applied in this example reflects a lower amount of savings than in the direct integration case. The region leading to effective savings is reduced since diagonal transference between equal intervals is required in order to use an intermediate fluid. Fig. 4 shows the solution for the assisted indirect heat integration, where heat transfer is represented in a diagonal form to reflect the temperature difference required for the use of the intermediate fluid. Note that although plant 3 continues to assist plant 2, the pattern of effective heat transfer changes with respect to 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.

5.3. Indirect integration using independent circuits

For illustration purposes, only three of the plants employed in this example are considered for indirect heat integration using intermediate fluid circuits. In order to have an unassisted heat integration case, test case #2, Trivedi (1988) and Ciric and Floudas (1991) are selected. Fig. 5 shows the result of solving the

Table 2
Amount of savings for indirect integration

Problem	Savings (kW)	
	Heating	Cooling
Test case #2	107.5	0.0
Trivedi (1988)	149.9	107.5
Ciric and Floudas (1991)	173.6	104.5
4sp1	0.0	219.0
Total savings	431.0	431.0

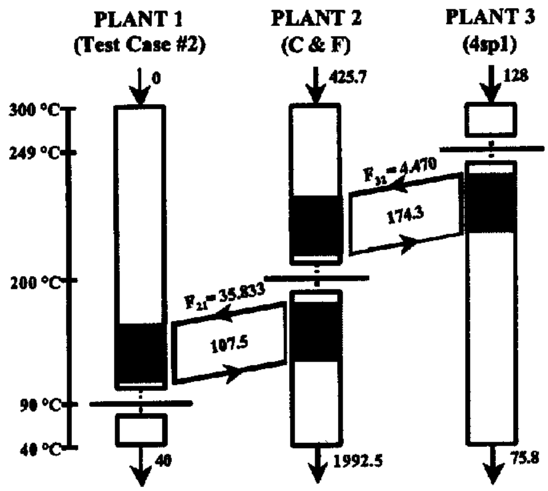

Fig. 5. One circuit per pair of plants.

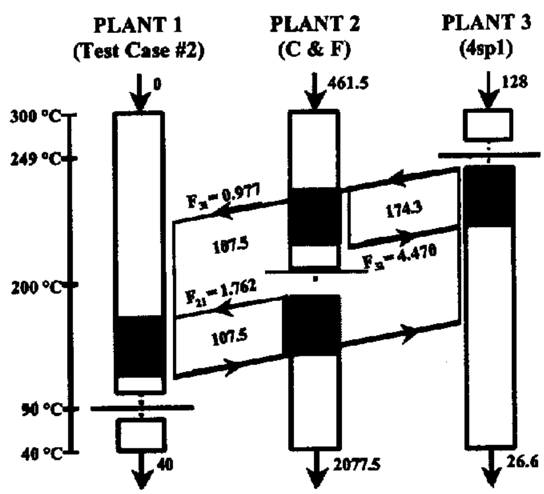

Fig. 6. Multi-operation circuits.

MILP model. Two circuits are required to achieve maximum savings, one between plants 1 and 2, and the second between plants 2 and 3. However, maximum savings are not possible in this case, as there are limitations in the amount that plant 3 can transfer below its pinch. Notice that the arrangement only works when all three plants are in operation.

5.4. Indirect integration using multi-operation circuits

In order to attain the maximum possible saving in any operating condition, the extended MILP model is solved with the restrictions of a single pipe arrangement. Fig. 6 shows the circuit required for this task.

6. Example 2

To test this tool in a large and realistic problem the heat integration between seven units representing the instance of an entire oil refinery was solved. The data for these units can be found in Fraser and Gillespie (1992) where the authors applied pinch technology to energy integrate the system.

Effective direct integration savings of 19.5 MW were obtained. This represents a 23% saving of the total heating utility of the site. Assisted heat integration in the opposite direction to the effective heat is required for maximum savings. A total of 3.3 MW are transferred above the pinch, and a total of 2.3 MW are transferred below the pinch. A comparison of these results with those of Fraser and Gillespie (1992) is not straightforward, since their savings are based on current plant heating utility usage, as none of the existing plants is completely energy integrated. Thus, their savings have a retrofit component.

7. The concept of heat belt

One of the characteristics of the scheme in Fig. 6 is that certain parts of the two circuits are common. Thus, it was considered practical to join these fluids in a single pipe by restricting the, extended MILP model. Moreover, the heat transfer circuits can be thought of as a 'belt' circuit from which the different plants take and/or discharge fluid to extract and/or release heat.

This concept, which will be addressed in future work, is not exempt from complications. For example, it needs to be taken into account what happens when one of the plants goes out of service. Will this unified circuit respond in the same way as independent circuits do? If not, what penalty is paid? Finally, plants are not always geographically positioned in increasing order of pinch temperature. The distances among them play an important role in the operating and capital costs.

8. Indirect integration using the utility system

A common suggestion for indirect integration in the total site is the use of the steam mains or steam headers (Dhole & Linnhoff, 1992; Hui & Ahmad, 1994). In this case, the steam supply from source plants and the steam demand of sink plants are balanced by the production of steam and generation of power in the utility system. Rodera and Bagajewicz (1999a) have pointed out that in certain cases, integration opportunities might be lost. Consider a system of three plants and suppose that two fixed levels of steam are used for integration. The shaded regions of Fig. 7 indicate energy integration opportunities. However, notice that parts of the region between pinches cannot be used for integration. Therefore, savings that may be possible to achieve using other intermediate fluids, are lost for the case of fixed steam levels.

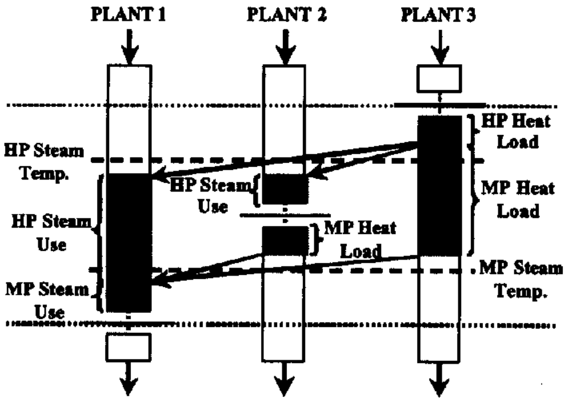

Fig. 7. Indirect integration using steam.

9. Conclusion

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. Important new aspects are revealed. The pattern corresponding to assisted heat transfer between two plants changes for many plants. In particular, assisting heat can be transferred in both opposite and parallel directions to the effective heat transfer. For indirect integration, transfer between equal intervals that are a fixed number of intervals apart is used to account for the presence of the fluid circuits. Finally, the resulting problem exhibits alternative solutions, and flexibility is gained by optimizing the different operational modes. Future work will concentrate in screening these alternatives with additional criteria, as well as exploring the concept of a heat belt.

10. Notation

i temperature interval
j chemical plant
k auxiliary chemical plant
m total number of intervals
n total number of plants
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^j heat surplus or heat demand in plant j
δ_0 minimum surplus to the first interval
$\hat{\delta}_0$ original minimum surplus to the first interval
δ minimum cascaded heat
$\hat{\delta}$ original minimum cascaded heat

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

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